Environments of deposition within the carbonate members of the San Andres Formation (Leonardian-Guadalupian), central Socorro County, New Mexico

by

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ABSTRACT

Environments of deposition within the carbonate members of the San Andres Formation (Leonardian-Guadalupian) in central Socorro County, New Mexico are dominated by lithotypes suggesting low-energy, restricted marine subtidal and intertidal facies. Two types of cyclic sedimentary sequences aided interpretation of environments of deposition and correlation between stratigraphic sections. Correlation between cyclic sedimentary sequences allowed an estimation of time synchronous changes in relative sea level between stratigraphic sections. Asymmetric shallowing-upward sequences describe five of the six sedimentary sequences that can be correlated between sections.

Paleogeographic relief, accentuated by a broadly-dipping, extensive shallow-marine shelf may have influenced sedimentation. Consistently shallower environments of deposition, limited biotic diversity, and thin, incomplete sequences within eastern and northwestern stratigraphic sections during early sedimentary cycles suggest that residual topography of the Pedernal Positive Element and the Joyita Positive Element may have affected sedimentation through cycle 3. Cycle 4, characterized by a symmetrical sedimentary sequence, contains higher-diversity subtidal deposits and probably represents the furthest incursion of marine conditions into central New Mexico during San Andres time. Asymmetric sequences 5 & 6 are dominated by highly-variable intertidal and possibly supratidal deposits leading into evaporitic units of the Four Mile Draw Member.

Two thin asymmetric sequences occurring below cycle 1 in the eastern stratigraphic section may testify to an early marine incursion into the easternmost region of the field area. Absence of these two cycles within northwestern and western sections

of the field area suggests that the Joyita Positive Element may have inhibited development of marine sedimentation prior to cycle 1.

ACKNOWLEDGMENTS

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TABLE OF CONTENTS

LIST OF FIGURES

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Student's Signature

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Date

INTRODUCTION

History of Previous Work

The type section for the San Andres Formation is located west of Rhodes Pass within the San Andres Mountains in south-central New Mexico. It was originally described as the "San Andreas" by Lee and Girty (1909) as part of the Manzano Group. Exact nature of the lithologies at the type section were re-described by Needham and Bates (1943) establishing the San Andres as a formation.

Profound interest in the stratigraphic nature of the San Andres Formation in central New Mexico started in the 1950's and peaked in the 1970's as a response to oil and gas production within the Permian Basin located in western Texas and southeastern New Mexico. In 1951, Wilpolt and Wanek produced a map detailing some of the stratigraphy within eastern Socorro County, correlating the San Andres between outcrops by means of the Glorieta Sandstone Member. A few early interpretations of the San Andres depositional environment were attempted within central New Mexico, based mainly upon analysis of the Glorieta, including stochastic grain size analysis, provenance studies, and insoluble residue analysis (Huntington, 1949; Chisholm, 1950; Huber, 1961).

In the early 1970's, detailed descriptions of regional stratigraphy of the San Andres Formation within central and south-central New Mexico were used to attempt to constrain the lateral extent of members of the San Andres using outcrop and subsurface data (Harbour, 1970; Kelly, 1971; Kelly, 1972; Foster, 1972; Baars, 1972).

More recent work has attempted to discern environments of deposition within the San Andres Formation of central New Mexico and includes detailed sedimentological studies within Lincoln, Chaves, Otero, and Roosevelt Counties (Milner, 1974; Milner, 1976; Elliot and Warren, 1989; Whitman, 1992).

Paleogeography

Factors affecting Permian sedimentation have largely been associated with declining effects of tectonic deformation which began in the Carboniferous (Lang, 1937; Dixon, 1967; McKee, 1967; Milner, 1974, Milner, 1976; Elliot and Warren, 1989). Collision of Laurasia and Gondwanaland produced numerous basins and highlands which had probably formed completely by Early Permian (Milner, 1974; Elliot and Warren, 1989; Baars, 1972). Subsequent sedimentation filled in much of the accommodation space by late Leonardian time, however, subsidence allowed for continued sedimentation from Late Pennsylvanian throughout the Permian (McKee, 1967; Dixon, 1967; Baars, 1972).

Permian paleogeography in New Mexico is defined by a number of positive and negative topographic elements, including the Delaware Basin, the Pedernal Positive Element, the Orogrande Basin, the Joyita Positive Element, the Florida Range, the Zuni Positive Element, the Roosevelt Uplift, the Sierra Grande Arch, and the Uncompahgre-San Luis Highlands (Dixon, 1967; McKee, 1967; Milner, 1974; Milner, 1976; Elliot and Warren, 1989). Figure 1 shows the relationships among these elements during Permian time.

The Pedernal Positive Element and Sierra Grande Arch, which acted as the western-most and northern-most extent of shelf sedimentation (respectively) in Early Permian time, had probably been reduced to broad gently raised areas by Middle Permian (McKee, 1967; Milner, 1974; Elliot and Warren, 1989). Analysis of sediment thickness

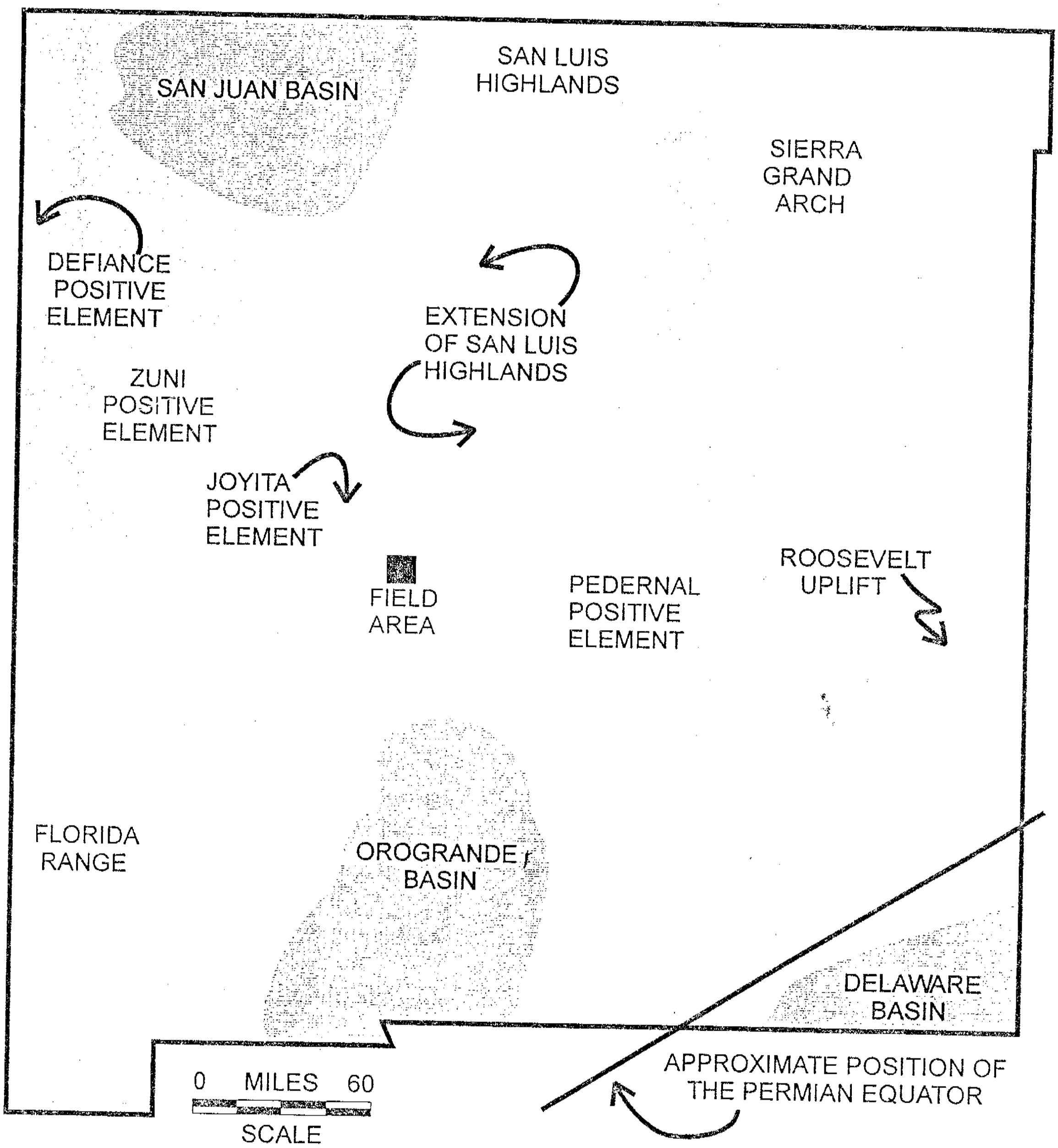

Figure 1. Relationships among paleogeographic elements during Permian time (after Dixon, 1967; McKee, 1967; and Milner, 1974).

across central New Mexico suggests that the Orogrande Basin, the Florida Range, and the Joyita Positive Element were probably reduced to marginal influences by Middle to Late Permian (McKee, 1967). Sedimentation within basins resulted in broad regional land forms characterized by a gently southeast-sloping surface. Gradual subsidence probably allowed relatively constant shallow marine sedimentation (Lang, 1937; McKee, 1967; Milner, 1974; Elliot and Warren, 1989).

Marine transgressions in the Permian reached a maximum with the San Andres Formation. Marine sedimentation was inhibited in north-central New Mexico by steady clastic sedimentation and regional uplift in south-central Colorado (McKee, 1967; Baars, 1972). Cyclic sedimentary sequences of the San Andres are usually explained by regional changes in subsidence rates and glacio-eustatic changes in sea level (Milner, 1976; Kinney, 1969; Lindsay, 1994; Kerans and Ruppel, 1994). Local tectonism is presumed to have had little influence, however, shallow epieric sedimentation may have been strongly affected by pre-existing paleotopographic relief and shelf geometry (Elliot and Warren, 1989).

Paleoclimate

During Middle to Late Permian, New Mexico was positioned near the equator. The presence of ubiquitous evaporite sediments within the San Andres Formation suggests that the climate was consistently hot and dry (Lang, 1937; Milner, 1976).

Poor marine circulation, a broad gently dipping slope, and rapid growth of reef carbonates within the Permian Basin probably resulted in hypersaline marine conditions on the Northwestern Shelf. Periodic elevation of relative sea level may have allowed forshort periods of better water circulation, during which stenohaline organisms may have encroached into previously restricted marine environments (Lang, 1937).

Direction of paleowind, based upon idealized wind patterns, would have blown from northeast to southwest across central New Mexico. During low stands of relative sea level, wind-blown clastic sediments would have generally come from the northeast and may have temporarily dominated sedimentation (Lang, 1937; Baars, 1972; Milner, 1976).

Purpose

The purpose of this study is to explore environments of deposition within the carbonate members of the San Andres Formation in central Socorro County. This study differs from previous studies in that it examines a region that is separated from the Northwest Shelf in terms of distance and paleotopography. Previous studies have speculated that a sabkha environment may be responsible for most of the deposition of the San Andres east of Lincoln County, however a detailed analysis of sedimentology and depositional environments of the carbonate members of the San Andres within Socorro County has never been published. This study is an attempt to increase our understanding of carbonate environments within the San Andres of central Socorro County and to extend the regional model for the San Andres westward across central New Mexico.

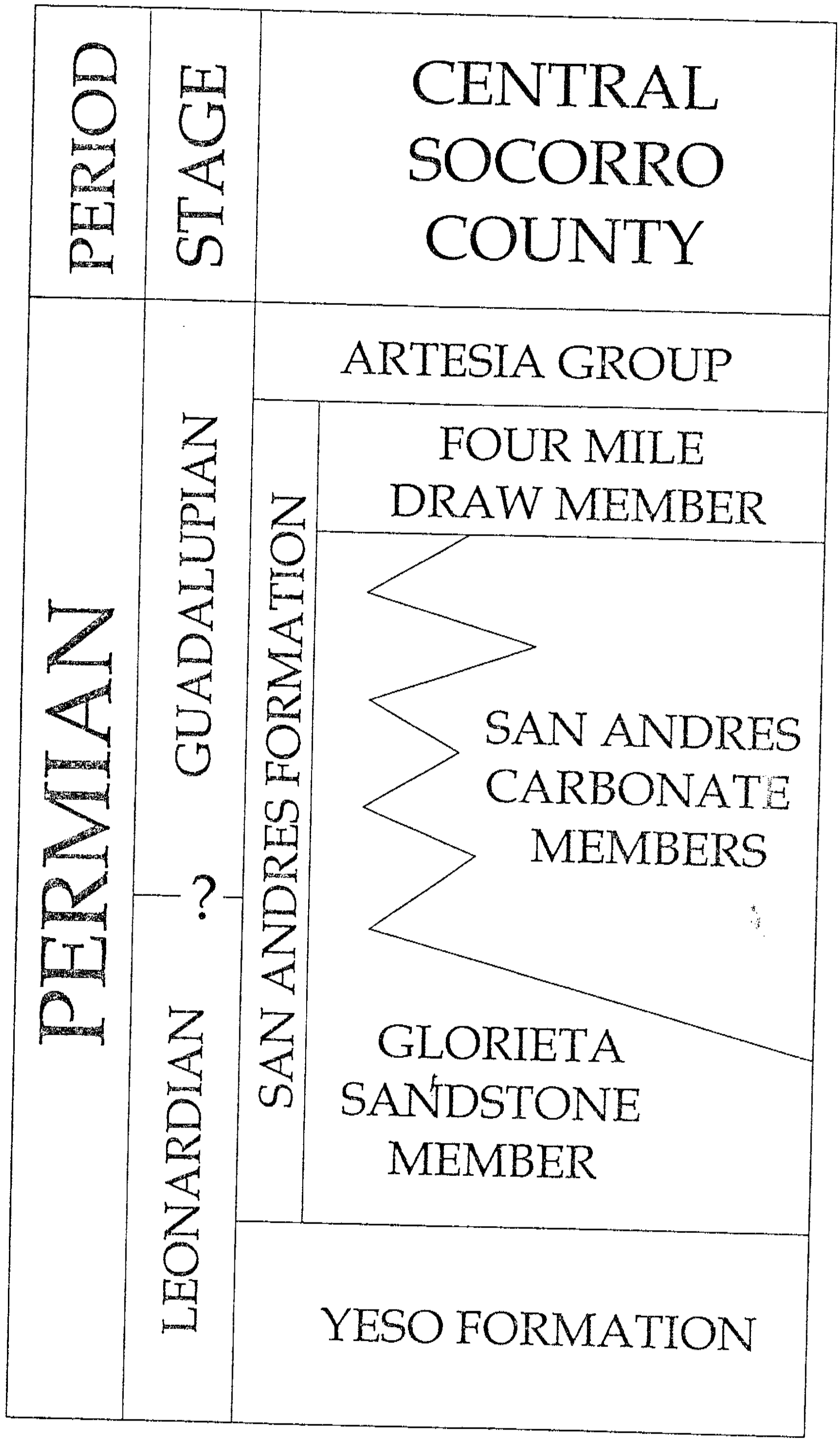

Figure 2. Late Permian stratigraphic reference for central Socorro County (after Kelly, 1971 and Milner, 1974).

REGIONAL STRATIGRAPHIC SETTINGS

Reported thicknesses for the San Andres Formation range from about 250 meters up to approximately 530 meters in southeastern New Mexico. San Andres lithology within central Socorro County is dominated by interbedded dolostone, sandstone, limestone and gypsum. Estimated thicknesses for the San Andres within the study area range from 100 to about 300 meters (Wilpolt and Wanek, 1951).

The San Andres Formation is considered to be mostly Upper Permian (Guadalupian) in age (Fig. 2) and throughout central New Mexico is generally grouped into four members (Kelly, 1971): the Glorieta Sandstone Member, a lower carbonate member (Rio Bonito Member), an upper carbonate member (Bonney Canyon Member) and an upper evaporite member (Four Mile Draw Member).

The Glorieta Sandstone Member is composed of thickly-bedded and cross-bedded mature sandstones. Thickness of the Glorieta within central Socorro County generally ranges between 50 and 75 meters and several tongues of the Glorieta interfinger with the carbonate members of the San Andres Formation.

This study is concerned primarily with determining environments of deposition within the carbonate members of San Andres Formation exposed above the thick basal Glorieta Sandstone Member. The Rio Bonito and Bonney Canyon Members, distinguished on the basis of bed thickness, are not practical for use in this study nor well defined within central Socorro County. As a result, no attempt has been made to distinguish between these two members.

Exposed San Andres Formation within Socorro County caps many low-lying hills. Resistant dolomitic limestone and sandstone units are usually well preserved, however evaporitic units tend to be completely removed. The Four Mile Draw Member and overlying Artesia Group were rarely observed within the field area of this study and were never well exposed in continuous section along with the carbonate members of the San Andres.

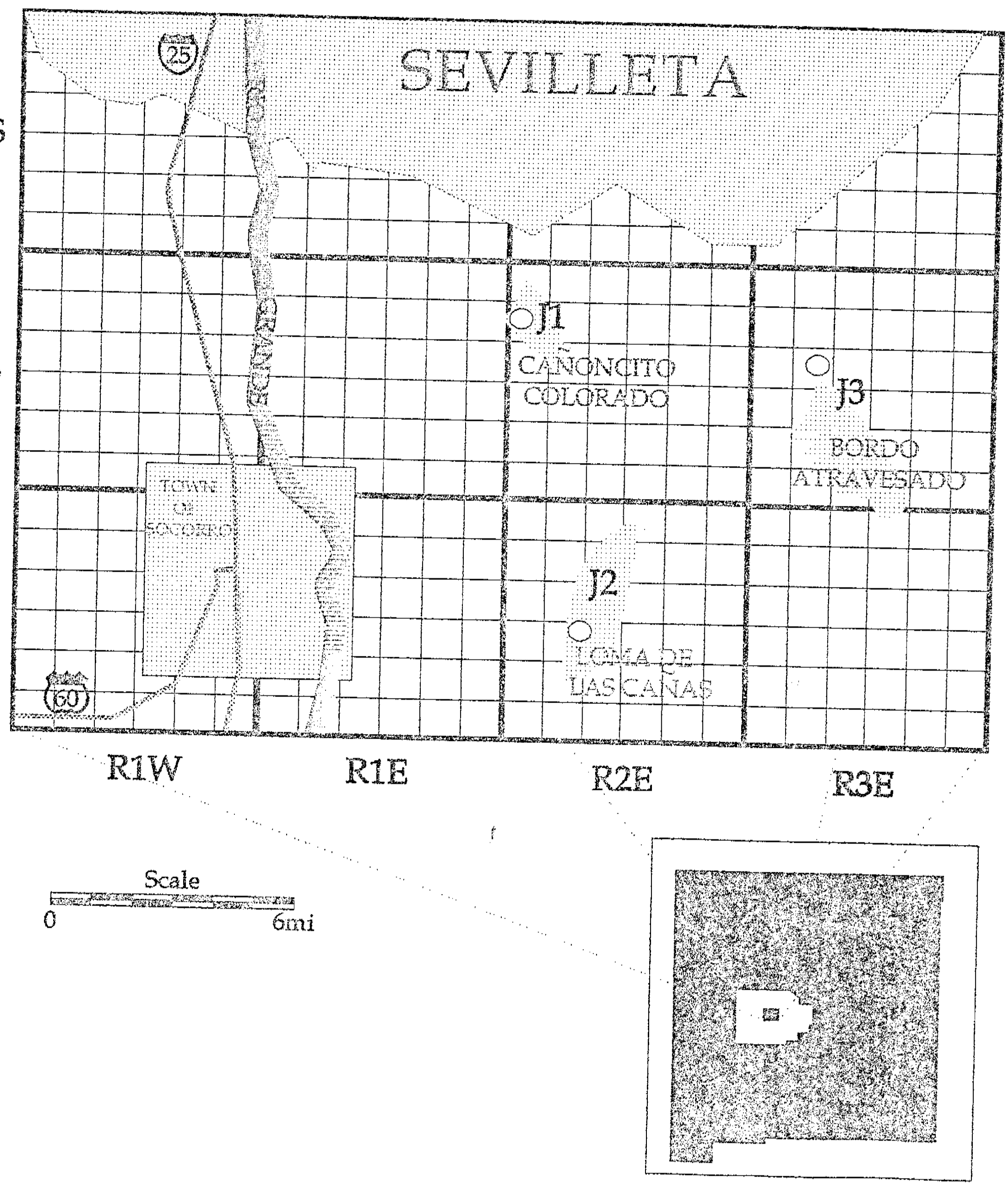

Figure 3. Location of study area and stratigraphic columns within central Socorro County.

METHODS

Field methods included detailed description and measurement of 3 stratigraphic sections. Three regions from central Socorro County (Fig. 3) were chosen for this study based upon the presence of relatively continuous exposure of the carbonate members of the San Andres Formation and local relative lack of structural deformation (Fig. 4). The base of each section was consistently set at the first appearance of rocks above the Yeso Formation dominated by thick carbonate strata, presumed to be the contact between the Glorieta Sandstone and carbonate members of the San Andres. Using a brunton compass as a level and a jacob staff for measurements, section was measured until exposure dictated uncertainty of continuous section. Based upon field determination of prominent lithotypes, approximately 45 samples were collected throughout each measured section. Lithotypes were classified according to depositional texture (Dunham, 1962).

Laboratory methods included preparation of standard petrographic thin sections. All thin section samples were stained with Alizarin Red-S and potassium ferrocyanide (Friedman, 1959) and examined using petrographic and binocular microscopes. Samples exhibiting very high relative diversity were treated with dilute formic acid (15%) for 24 hours. The insoluble residue was examined using a binocular microscope.

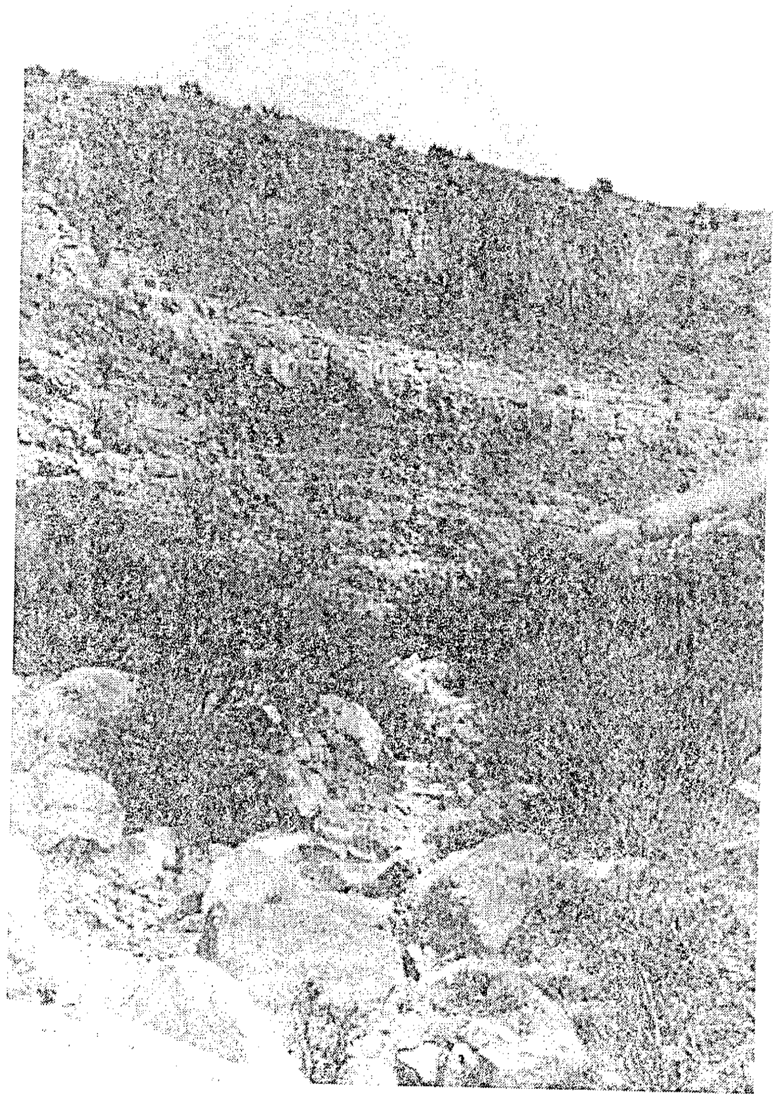

Figure 4. Outcrop exposure at field site J3 near Bordo Atravesado.

RESULTS

Stratigraphy

Stratigraphy of the San Andres carbonate members within central Socorro County is complicated by intense structural deformation. The three stratigraphic sections used in this study were measured in relatively undeformed regions where approximately 50 meters of continuous section was exposed (Fig. 5 & 6).

Stratigraphic integrity is maintained throughout each of the stratigraphic sections, with the exception of discrepancies produced by zones of brecciation bound by strata above and below. Unconformity surfaces were not observed within the field area.

Each of the three stratigraphic sections include a variety of lithotypes. Carbonates of the San Andres Formation are dark gray, dolomitic, and have a distinctive fetid odor. Carbonate composition usually varies between dolomitized fossiliferous wackestones to packstones and dark laminated dolomitic mudstones. Three prominent sandstone units above the Glorieta are reported to intertongue with the carbonate members of the San Andres in central New Mexico. In central Socorro County, interfingering sandstone units show much less consistency, varying between 2 and 4 packages.

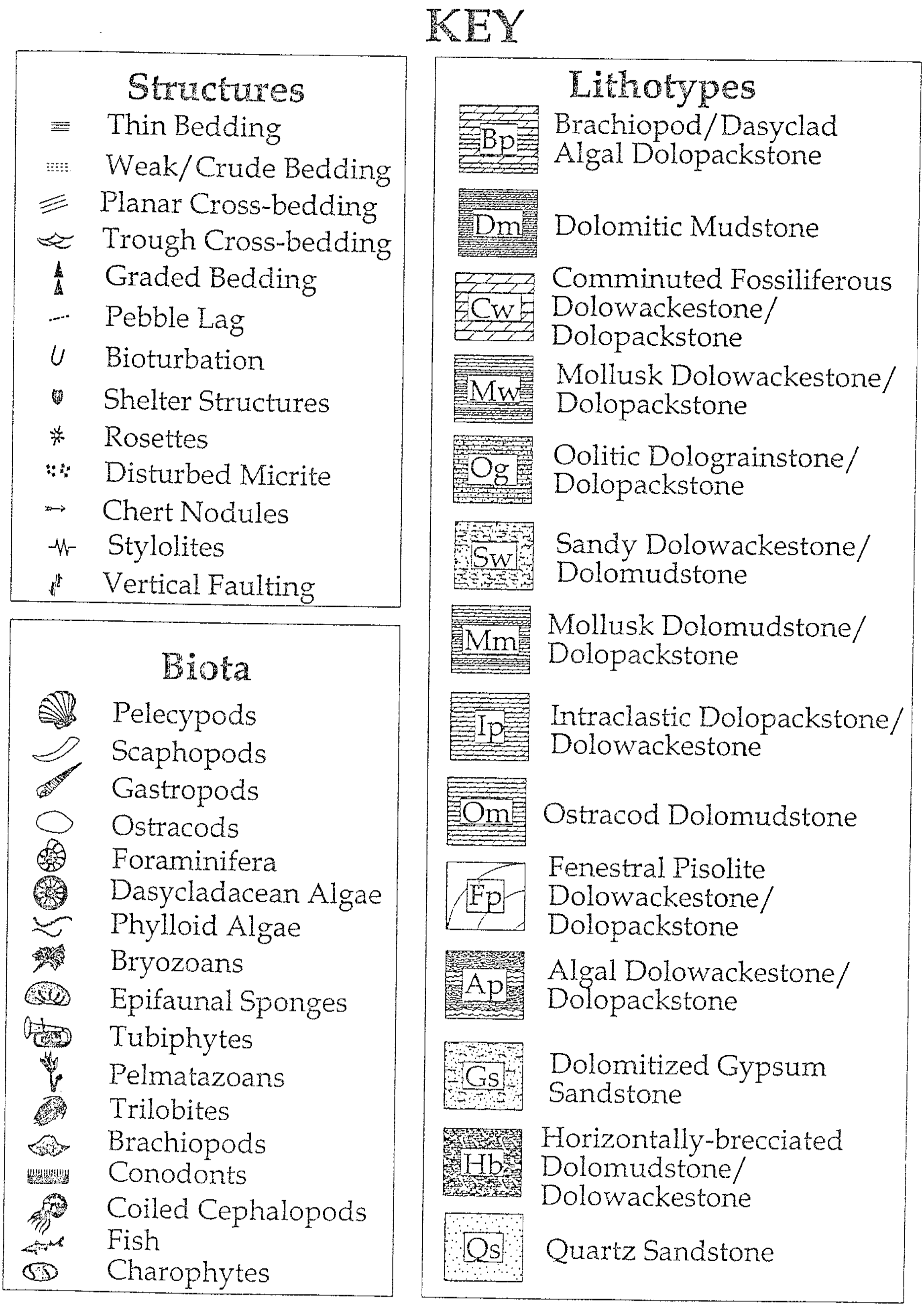

Figure 5. Key to symbols used in Figures 6, 29, and 30.

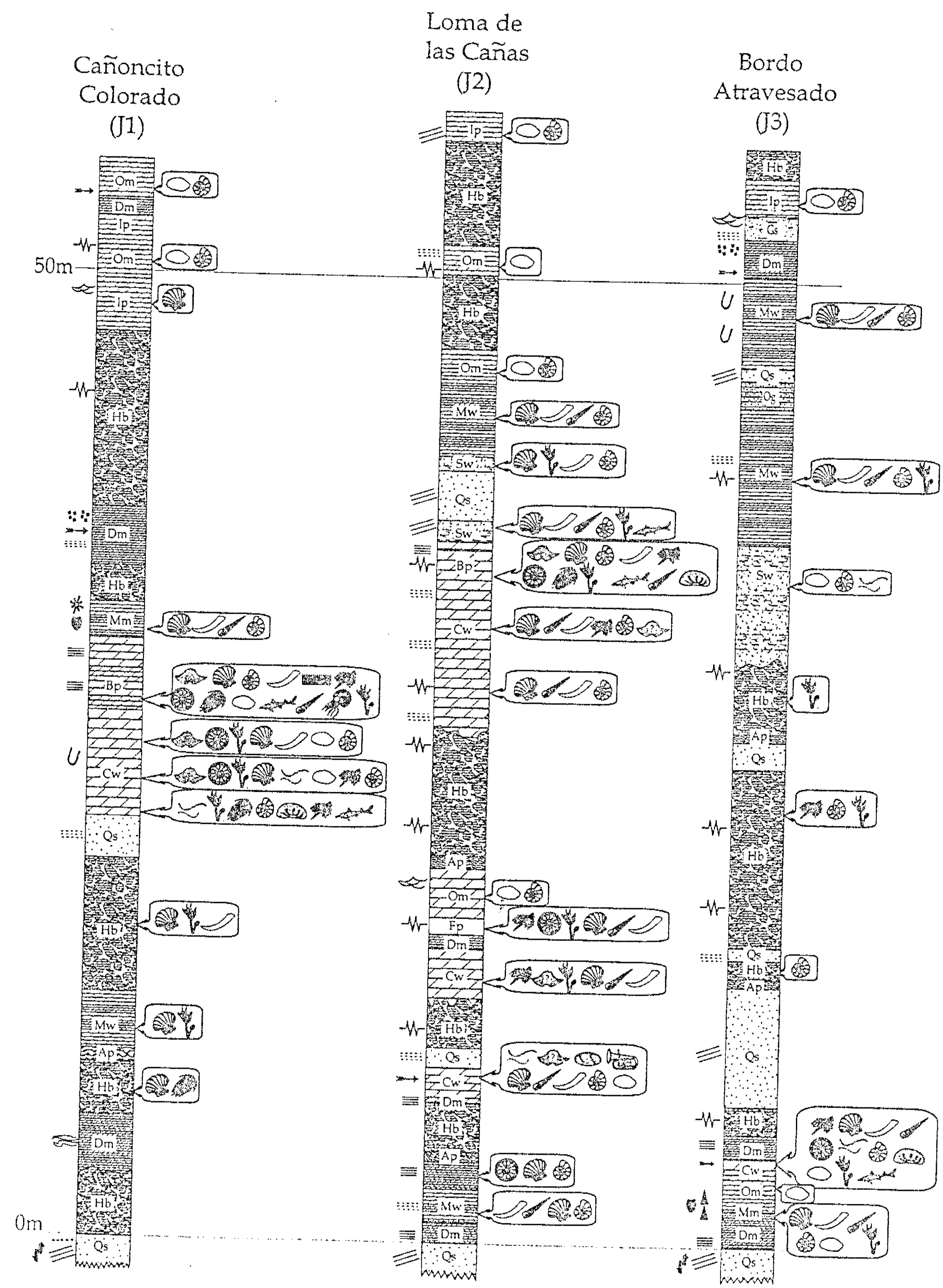

Figure 6. Stratigraphic sections of the carbonate members of the San Andres Formation from three locations within the study area. (Sedimentary structures and biota keyed to Figure 5.)

Lithotypes

Thinly-bedded Brachiopod/Dasycladacean Algal Dolopackstone: a densely-fossiliferous packstone containing diverse biota. Skeletal material is unsorted, maintains well-preserved internal structures, and displays evidence of dolomitization. Biota typically considered stenohaline within this lithotype include: large pseudo-punctate brachiopods, pelmatozoans, fenestrate bryozoans, fish, trilobites, conodonts, and coiled cephalopods. Dasycladacean algae, epifaunal sponges, scaphopods, thin-shelled pelecypods, gastropods, inflated ostracods, and foraminifera are also incorporated within biotic assemblages.(Fig. 7).

Skeletal grains have random orientations and lack transport indicators. Large pseudo-punctate brachiopods and thin-shelled pelecypods are typically articulated and whole.

Matrix always exhibits high levels of replacement by dolomite, occasionally forming straight-edged megacryst rhombs with dark oxide stains around their margins. Crinoid grains are typically dolomitized; other skeletal grains typically exhibit automorphic penetration by dolomite around grain margins. Patchy silica rarely replaces brachiopod and mollusk grains, sometimes preserving internal structures. Nodular and laminated stylolites, identified by a brownish-red insoluble residue and crenulated surfaces, are present locally.

Dolopackstone units are typically resistant to weathering, standing out as blocky or cliffy features in outcrop. Contacts between beds are sharp and often stylolitized. Bedding is typically continuous and slightly irregular with thicknesses between 10 and 30 cm.

Figure 7. Photomicrograph of a dolopackstone from Thinly-bedded Brachiopod/Dasycladacean Algal Dolopackstone/Dolowackestone lithotype from Section J1 at 27.7m. (Nicols are crossed. Scale bar is 1mm)

Dolomitic Mudstone: a dark laminated dolomitic mudstone, completely devoid of preserved fossils, usually with a component of well sorted quartz silt or fine-grained sand. The micrite has a dark gray-brown color, while laminations are wispy and slightly darker (Fig. 8). Laminations have a red-brown color associated with them. Silt grains are dispersed throughout units when present, but tend to occur in greater abundance along laminations. Sand grains, where present, comprise a minor portion of the total volume.

Dolomitic muds locally contain irregular-shaped vugs, distributed throughout the rock, filled by coarsely-crystalline blocky calcite (Fig. 9). Vugs have scalloped or rounded margins and average approximately 2 centimeters in diameter. Small gypsum(?) rosettes replaced by dolomite or chert are also preserved as displacive elements within the matrix. Lenticular chert nodules with concentric banding are uncommon, but occur preferentially within units containing vugs and rosettes.

Beds are poorly resistant to weathering, thin (10 - 30 cm), and usually are exposed poorly in outcrop. Contacts with surrounding units, where exposed, are very sharp. Where exposure is good, units are continuous for at least hundreds of meters.

Comminuted Fossiliferous Dolowackestone/Dolopackstone: a cliffy, lithofacies with a tendency to become more biotically diverse from base to top. Presence of diverse biota, including scaphopods, pelecypods, dasycladacean algae, pseudo-punctate brachiopods, trilobites, fish, epifaunal sponges, and fenestral bryozoans may occur near the top of well-developed units. The base of units is often composed of phylloid algal packstones containing intermixed crinoid columnals, mollusks, foraminifera, and ostracods (Fig. 10).

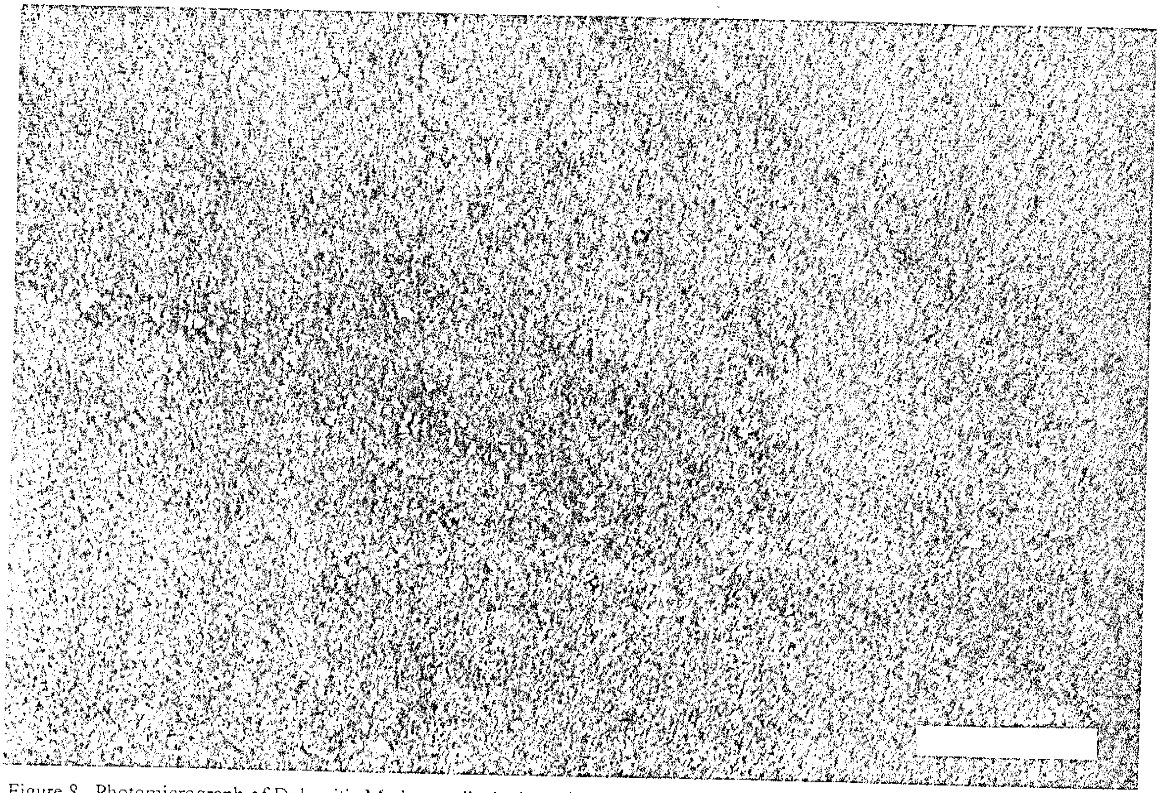

Figure 8. Photomicrograph of Dolomitic Mudstone displaying wispy, silt-rich laminations from Section J2 at 15.5m. (Nicols are crossed, scale bar is 1mm.)

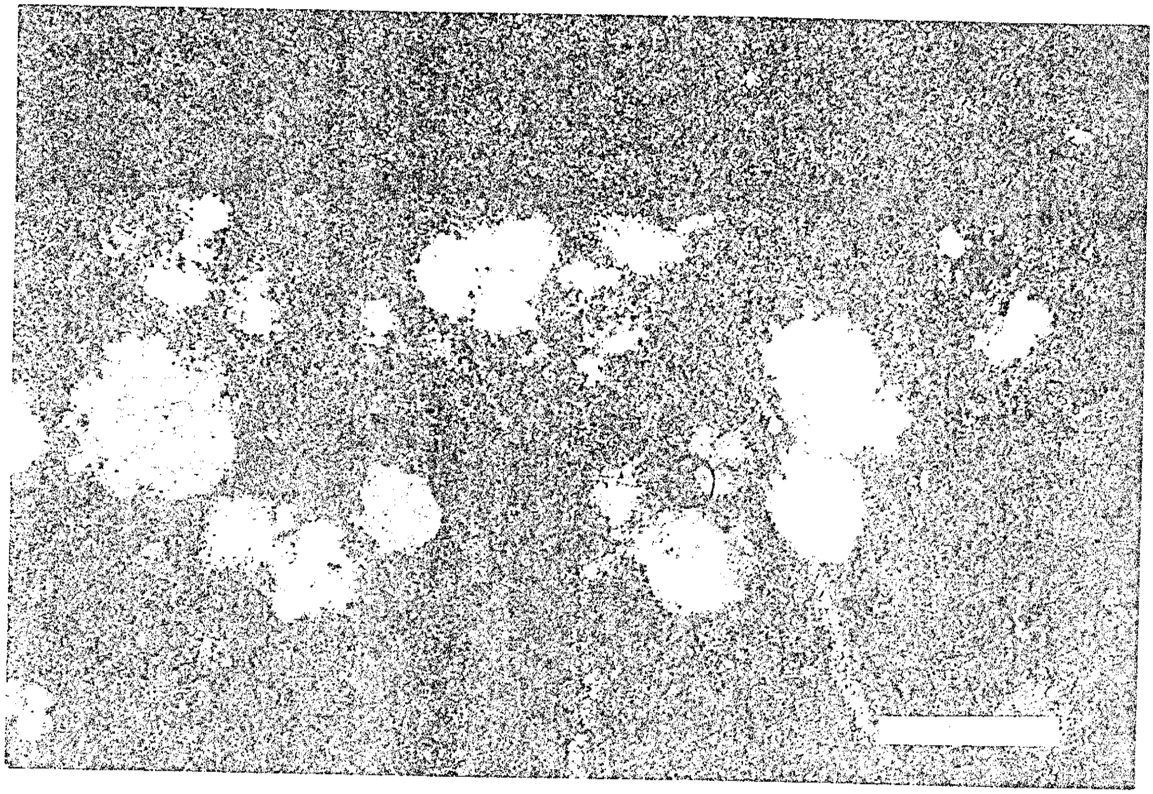

Figure 9. Irregular calcite-filled vugs within Dolomitic Mudstone lithotype from Section J3 at 52.0m. (Nicols are crossed, scale bar is 1 mm)

Skeletal grains exhibit transport fabrics, fracturing, and poor preservation. Laminations and sub-horizontal skeletal fragments are uncommon, however, grains occasionally show signs of mechanical sorting and algal coating at the base of units. Coated phylloid algae are found together with fragments of crinoid columnals. Small rounded micritic intraclasts comprise up to 3% of the rock volume at the base of units but are not present near the top. Mud content increases from base to top of units.

The matrix has been completely replaced by dolomite, whereas skeletal grains are partially replaced by automorphic dolomite rhombs. Silicification is spotty, replacing coarsely-crystalline calcite within articulated skeletal grains. Micro-stylolitization is common.

Comminuted Dolowackestone/Dolopackstone units are typically very resistant, forming cliffy ridges in outcrop. Bedding is extremely thick (up to 6 meters) and continuous for at least hundreds of meters.

Fossiliferous Mollusk Dolowackestone/Dolopackstone: a very abundant lithotype within the field area consisting of the remains of biota capable of tolerating a wide range of salinities including scaphopods, thin-shelled bivalves, gastropods, ostracods, and foraminifera (Fig. 11). Grain preservation varies from fairly good to very poor depending upon severity of dolomitization.

Micritic intraclasts, peloids, and pellets often comprise a fairly large proportion of packstone units. Skeletal grains typically appear along grain-rich horizons. Skeletal grains appear locally as whole, sediment-filled clasts or less commonly as comminuted sands or silt-sized particles.

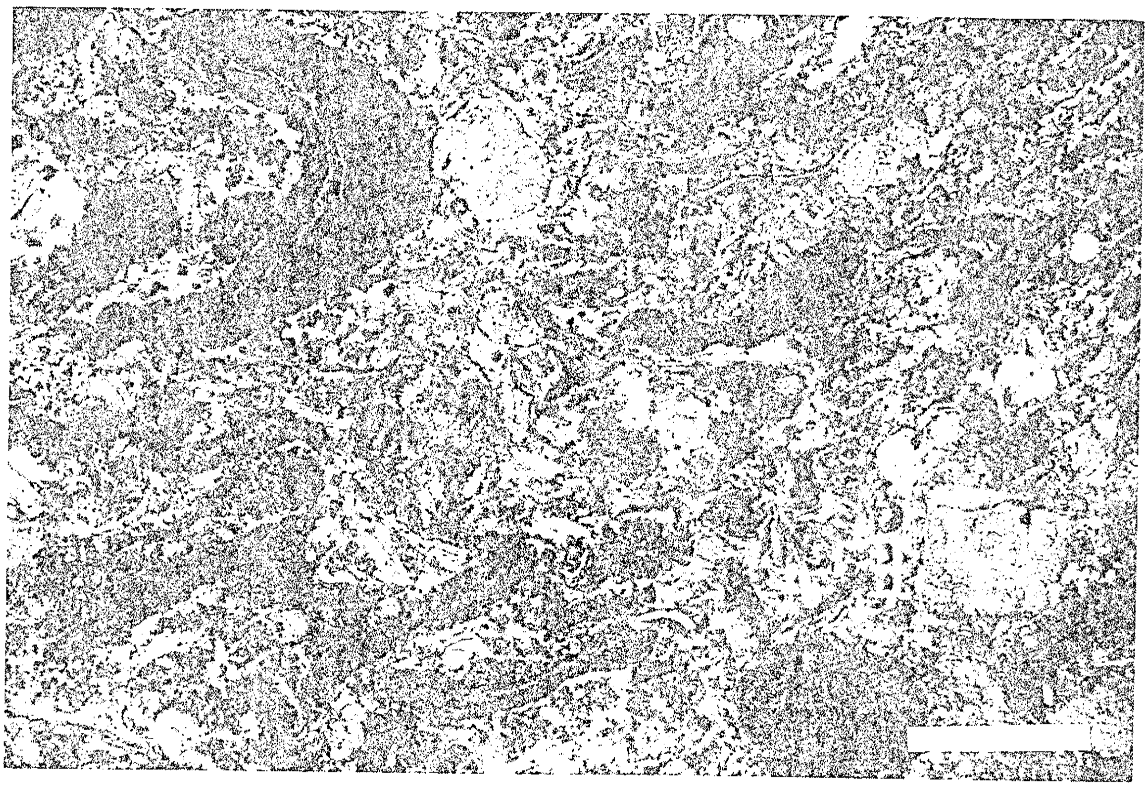

Figure 10. Phylloid algal packstone with intermixed crinoid columnals typically occurring at the base of Comminuted Fossiliferous Dolowackestone/Dolopackstone lithotype from Section J1 at 22.3m. (Nicols are crossed, scale bar is 1mm).

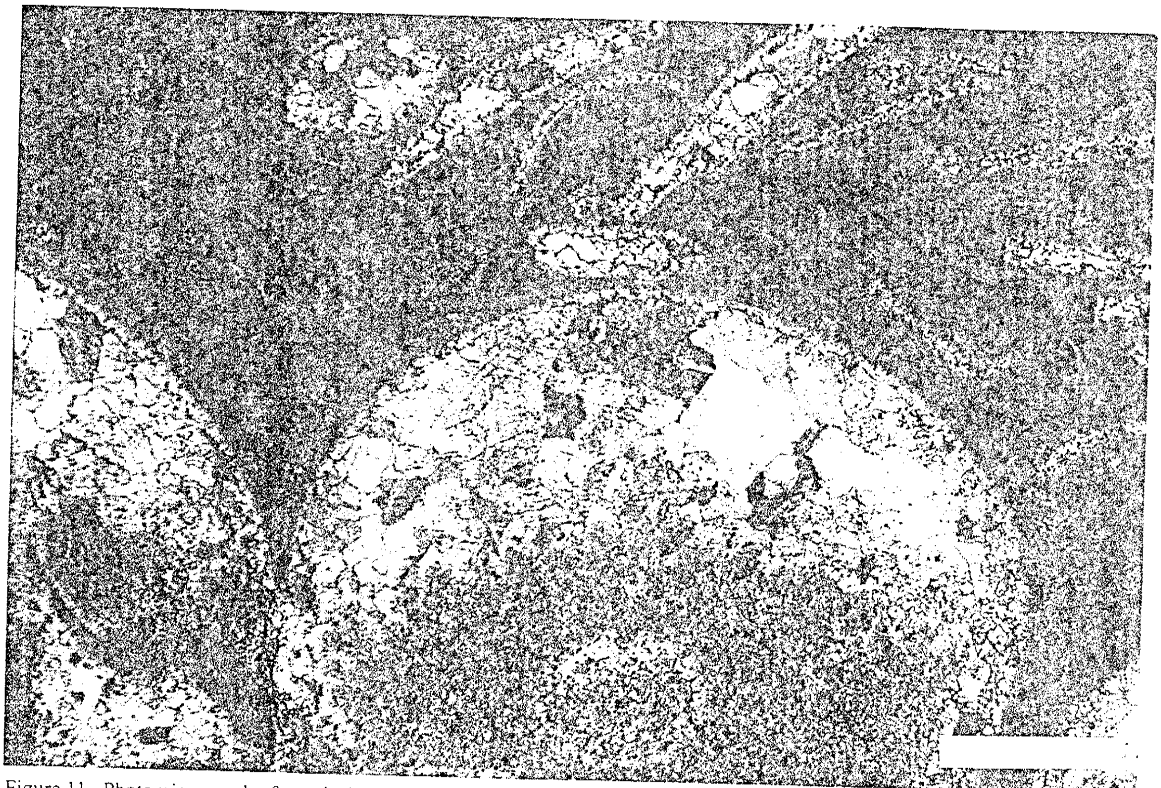

Figure 11. Photomicrograph of a typical Fossiliferous Mollusk Dolowackestone/Dolopackstone lithotype biotic assemblage from Section J2 at 1.6m. (Nicols are crossed, scale bar is 1mm).

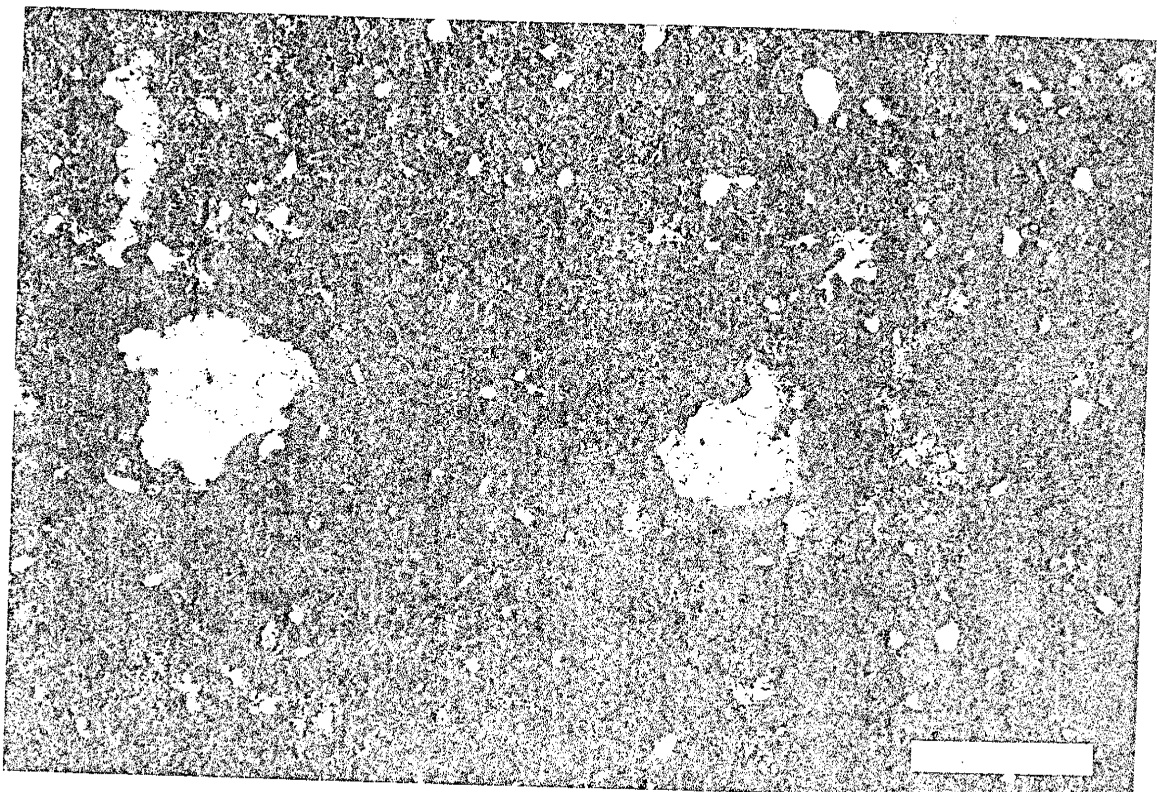

Figure 12. Irregular calcite-filled vugs with 'packed mud' margins surrounding crystals within Fossiliferous Mollusk Dolowackestone/Dolopackstone lithotype from Section J2 at 41.9m. (Nicols are crossed, scale bar is 1mm)

Irregular regions within the matrix, usually composed of coarsely-crystalline calcite, are surrounded by regions of micrite which appear to be less porous than the surrounding mud (Fig. 12). Regions of 'packed mud' do not appear laminated and may be the result of displacive mineral growth compacting mud sediments by force of crystallization prior to complete lithification. Irregular calcite grains with 'packed mud' margins are relatively common within packstone and wackestone units.

Mollusk Dolowackestone/Dolopackstone units display a mottled appearance in outcrop; occasionally units show well preserved burrows. Cylindrical sub-vertical burrows, 2-4 cm in diameter, are present locally as a dense network or with a discrete well-defined U-shape.

Mollusk Dolowackestone/Dolopackstone units typically appear as highly resistant cliff-forming horizons. Within units, severe stylolitization has occurred, often along horizontal planes. Units are usually thickly bedded (30 cm - 1 m) but range in thickness up to 8 meters and are continuous for hundreds of meters.

Oolitic Dolograinstone/Dolopackstone: small, concentric, micritic ooids comprise approximately 99% of grains in this rare lithotype. Ooid grains are locally bound together by a large crypt-algal coating producing aggregate grains up to 5cm in the long dimension (Fig. 13). Individual ooids usually range between 0.05mm and 0.5mm. Individual ooids and grain aggregates are cemented by a poikilotopic sparry calcite, whereas ooids within aggregate grains are cemented by a dark dolomitic micrite. Ooid nuclei are cryptic, micritic in nature, and may be related to rounded micritic intraclasts, peloids, or pellets. A few ooids are nucleated around arcuate shell fragments. Sorting of individual ooids is moderate whereas ooid grain aggregates are very poorly sorted.

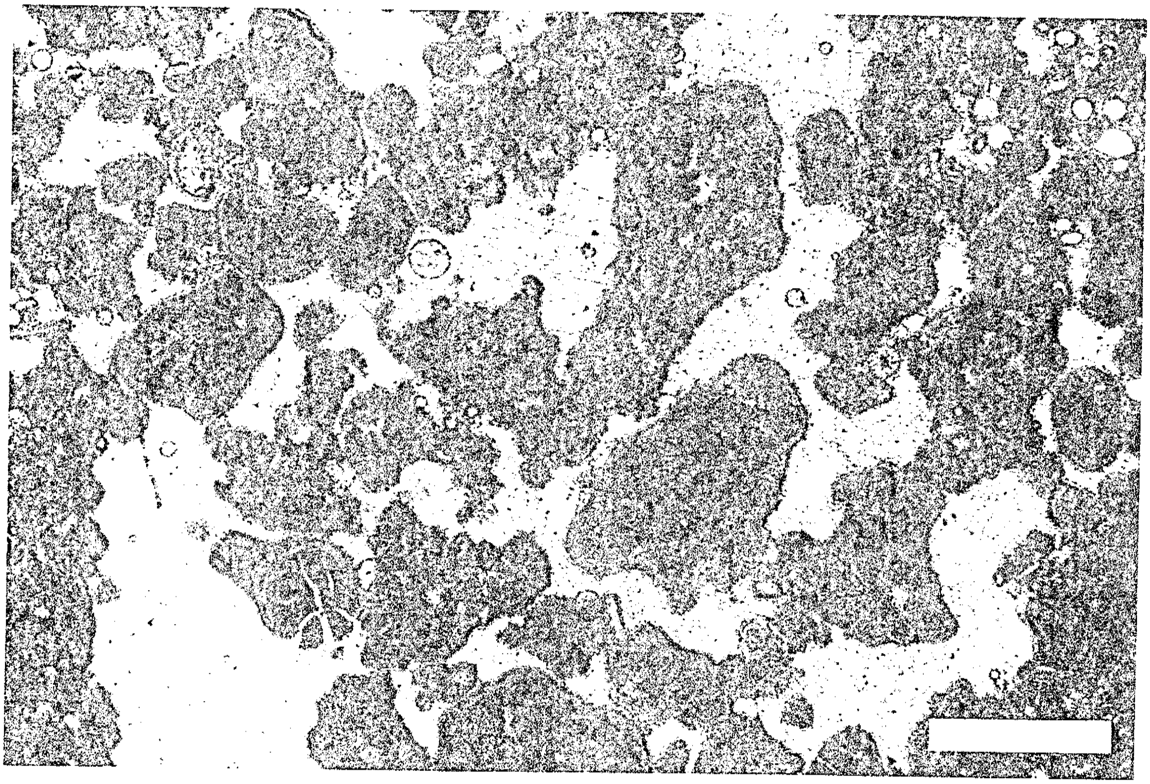

Figure 13. Aggregate ooid grains from Ooid Dolograinstone/Dolopackstone lithotype from Section J3 at 43.9m. (Nicols are crossed, scale bar is 1mm.)

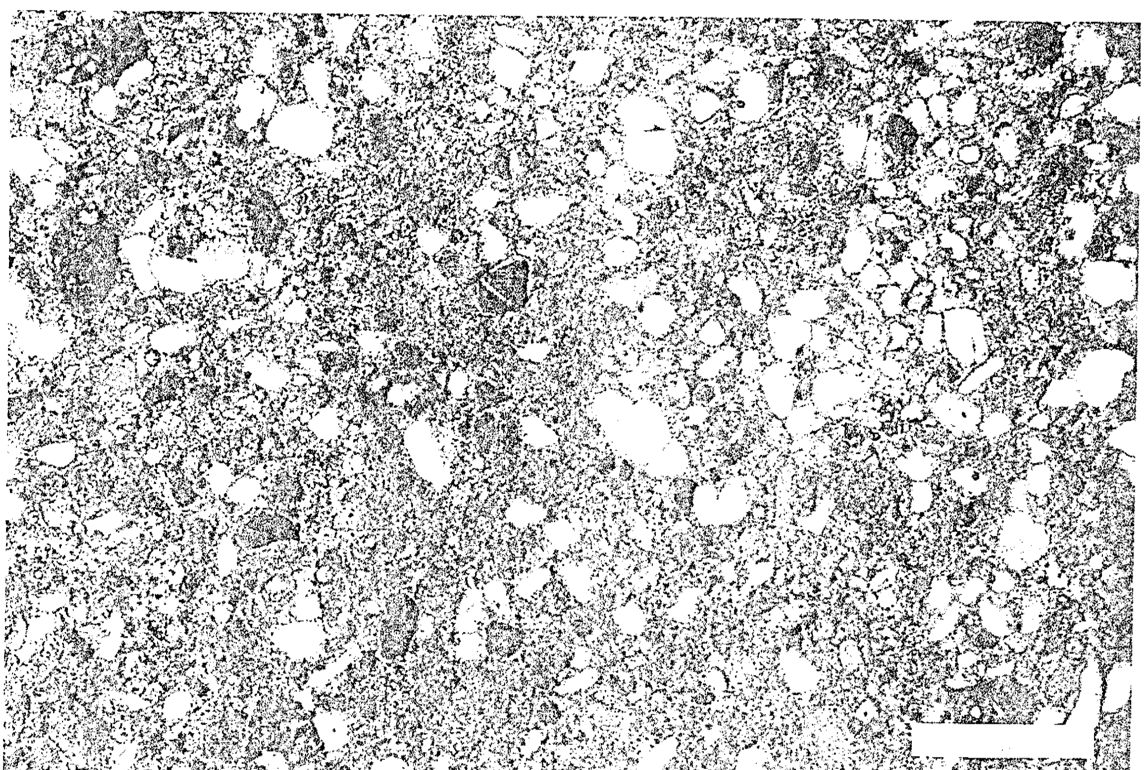

Figure 14. Photomicrograph of Sandy Dolowackestone/Dolomudstone lithotype from Section J2 at 40.1m. (Nicols are crossed, scale bar is 1mm)

Ooid laminations and nuclei are most commonly dolomitized. Small ghost grains, accentuated by remnant algal laminations, suggest that individual ooids were subject to dissolution.

Ooid Dolograinstone/Dolopackstone units are resistant to weathering, have gradational contacts, and lack well developed bedding in outcrop. Ooid Dolograinstone/Dolopackstone units are continuous for 100's of meters.

Sandy Dolowackestone/Dolomudstone: a heavily dolomitized unit comprised of dark lime mud supporting numerous sand-sized particles (Fig. 14). Sand grains are very well sorted, well rounded, and average 0.25mm. Sand grains are most commonly quartz, but may include numerous well-rounded calcite and chert grains. Calcitic grains, if they are limestone fragments, never retain evidence of original internal skeletal structures. A few rounded large (.25 - .75mm) micritic intraclasts may be present, typically appearing darker and containing less sand-sized particles than the surrounding matrix.

Calcitic grains are most often replaced by a single crystal of calcite and locally exhibit simultaneous optical extinction with other calcite grains producing an inverted poikilotopic texture. Inverse poikilotopic texture may be a result of grain dissolution where resultant pores have been filled by syntaxial calcite (Figs. 15 & 16).

In outcrop, units are often very resistant and grade vertically into Quartz Sandstone lithotypes. Sandy Dolowackestone/Dolomudstone units locally exhibit a weak cross-bedded fabric, leading into overlying Quartz Sandstone lithotype cross-beds.

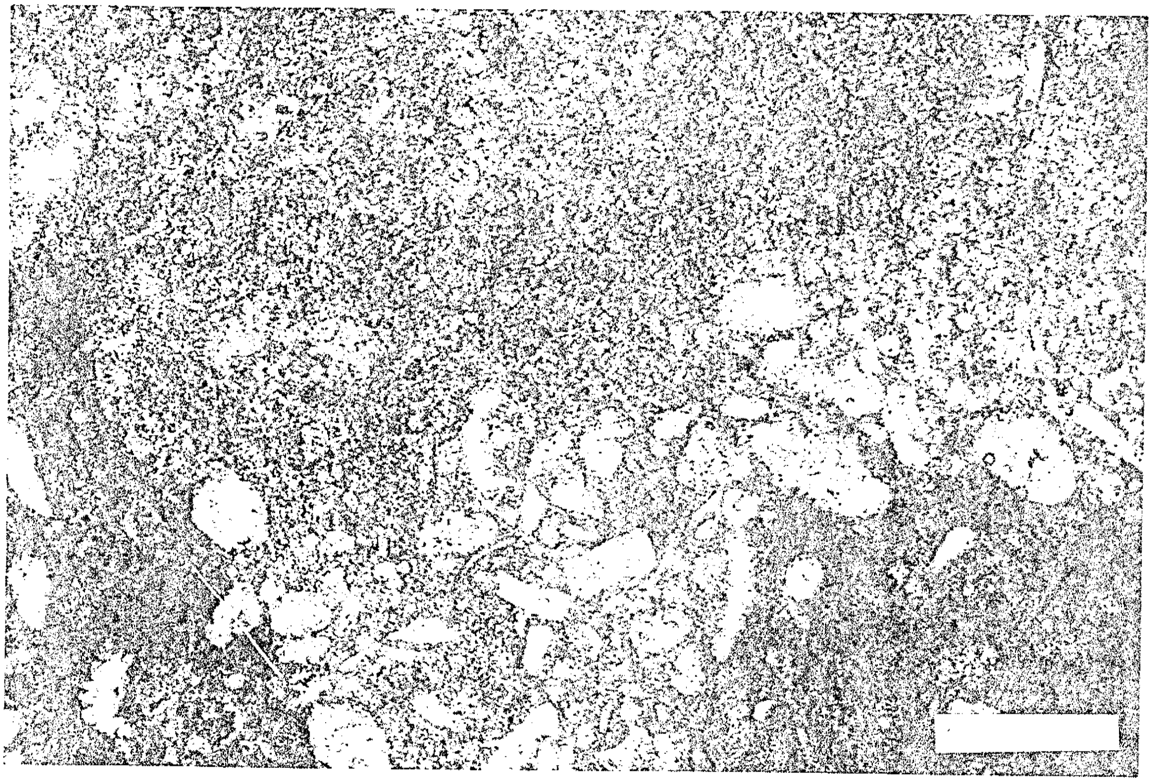

Figure 15. Inverse poikilotopic diagenetic texture replacing calcite sands within Sandy Dolowackestone/Dolomudstone lithotype from Section J3 at 33.8m. (Nicols are crossed. Scale bar is 1mm).

Figure 16. Inverse poikilotopic texture from Figure 15 rotated to optical extinction. (Nicols are crossed, scale bar is 1mm.)

Sparsely-fossiliferous Mollusk Dolomudstone/Dolopackstone: a dark dolomitic mudstone punctuated by dense, very thin to thin (0.5 mm -0 5 cm) layers of skeletal grains. Skeletal grains are dominated by thin-shelled, arcuate, easily transported grains showing an obvious preference for concave down orientations. Skeletal grains typically present consist of thin-shelled bivalves, gastropods, scaphopods, ostracods, and foraminifera (Fig. 17).

A small percentage of very fine grained quartz sand and silt is commonly admixed with skeletal packstone horizons. Small, well-sorted pellets locally comprise up to 20% of the volume of packstone horizons. Bivalves occasionally create small shelter structures protecting underlying sediment and preserving pellets (Fig. 18). Small rounded peloids and intraclasts (up to .25mm in diameter) are often associated with packstone horizons as well. The interface between mudstone and packstone horizons typically exhibits microscopic scouring.

Micritic matrix is always replaced by dolomite. Skeletal grains are partially replaced by rhombic dolomite grains penetrating along shell margins. Chert and stylolitization are rare.

Mudstone horizons appear dark gray to black in outcrop with packstone horizons standing out as a result of lighter colors and weathering differences. Contacts with surrounding units are usually sharp and well defined. Resistant beds are typically thick (30 cm - 1 m), continuous, and well exposed.

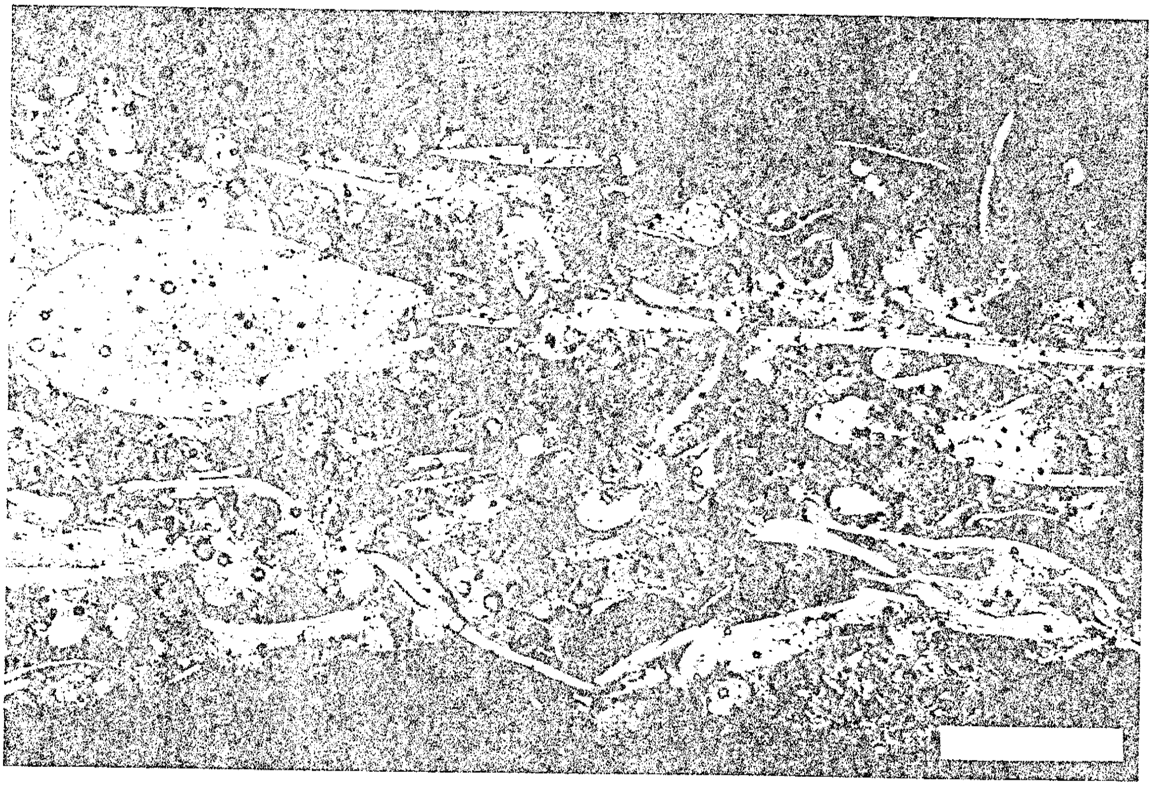

Figure 17. Sparsely-fossiliferous Mollusk Dolomudstone/Dolopackstone detailing typical biotic assemblage and preservation. Sample from Section J1 at 18.6m. (Nicols are crossed. Scale bar is 1mm).

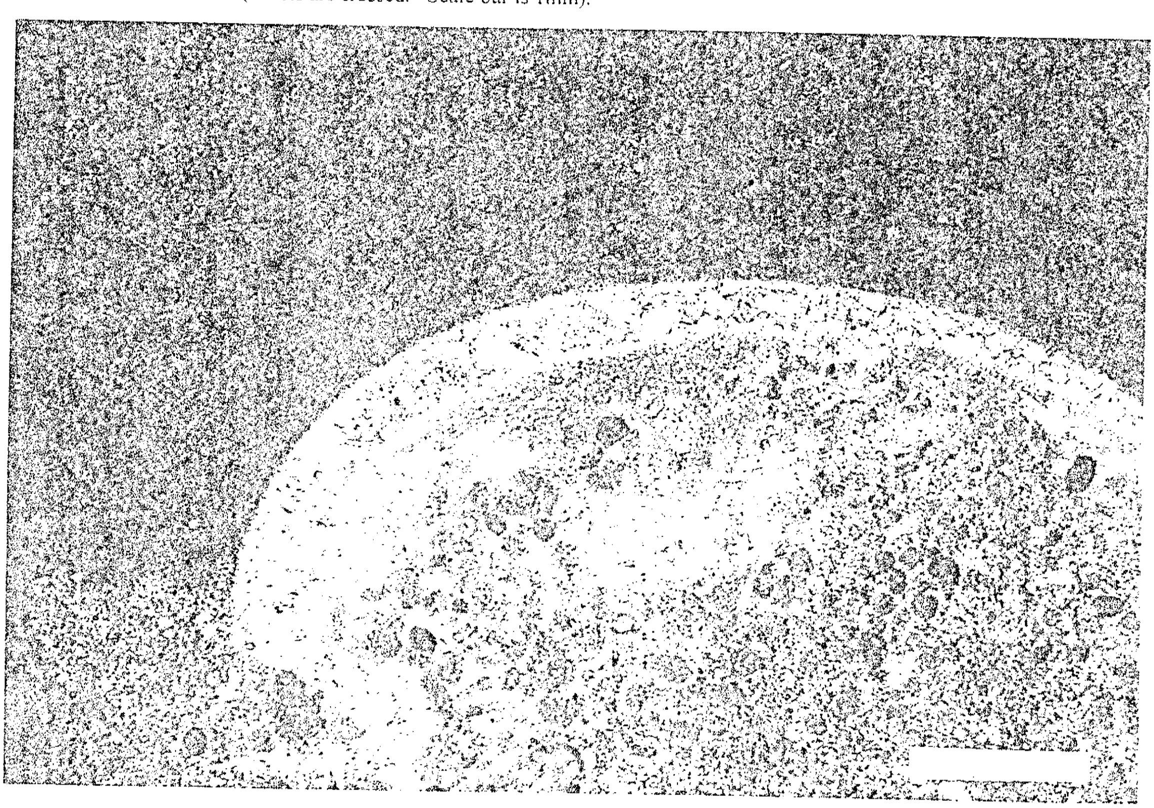

Figure 18. Shelter structures within Sparsely-fossiliferous Dolomudstone/Dolopackstone lithotypes preserving underlying pellets. Sample from Section J3 at 2.3m. (Nicols are crossed. scale bar is 1mm.)

Intraclastic Dolopackstone/Dolowackestone: muddy intraclast-rich rocks including assemblages of biota capable of tolerating a wide range in salinities. Ostracods, forams, and mollusks occur sparsely, typically as poorly preserved and fragmented framework grains. Intraclasts are composed of lime mud clasts lacking internal structure or exhibiting a weak internal lamination. They are mainly rounded to sub-angular grains, typically <1 cm in diameter, but clasts can also be very angular and very large (>5cm). Algal coatings may exist surrounding intraclasts and skeletal grains and, less commonly, as discrete laminated layers preserved within an intraclastic grain framework.

Micritic matrix and lime mud intraclasts are always replaced by dolomite. Sparse skeletal grains exhibit automorphic penetration of dolomite along margins. Micro-brecciation and fracturing of intraclasts is common; fractures are filled by sparry calcite (Fig. 19). Weak algal laminations are typically high-lighted by a red-brown oxide stain.

Intraclastic units occur as highly resistant blocky ridges and are thickly bedded (30cm - 1 m). Beds are continuous for at least hundreds of meters.

Fenestral Pisolite Dolowackestone/Dolopackstone : thinly bedded, discontinuous units containing algal-bryozoan pisolites and biota capable of tolerating a wide range in salinity. Pisolites are nucleated around poorly preserved peloidal grains or bryozoan fragments. Pisolite laminations are composed of alternating encrusting bryozoan and crypt-algal layers (Fig. 20). Algal laminations are dark, irregular, and may contain fenestral fabrics.

Micritic matrix is completely dolomitized and supports sparse, well-preserved gastropods, ostracods, and foraminifera. Matrix micrite is unlaminated and skeletal grains exhibit random orientations. Skeletal grains are often whole and partially dolomitized.

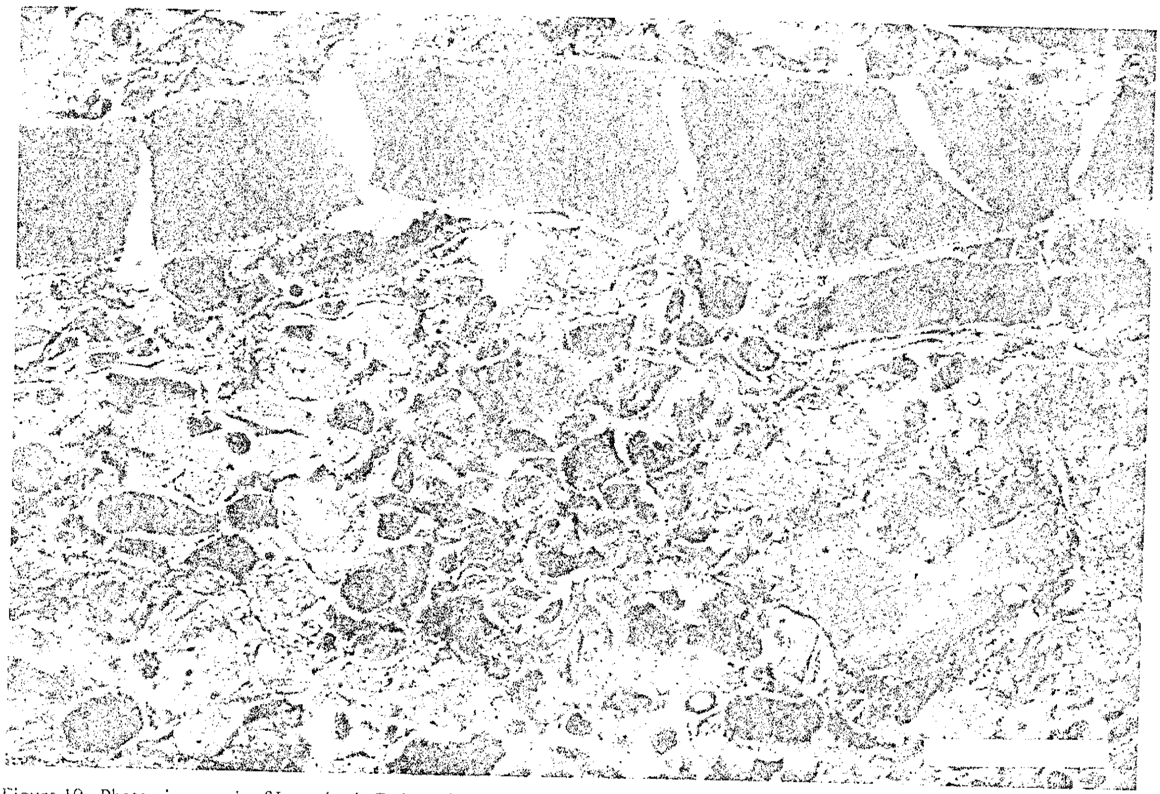

Figure 19. Photomicrograph of Intraclastic Dolopackstone/Dolowackestone lithotype exhibiting micro-brecciation of 'flat-pebble' intraclasts from Section J3 at 54.7m. (Nicols are crossed, scale bar is 1mm.)

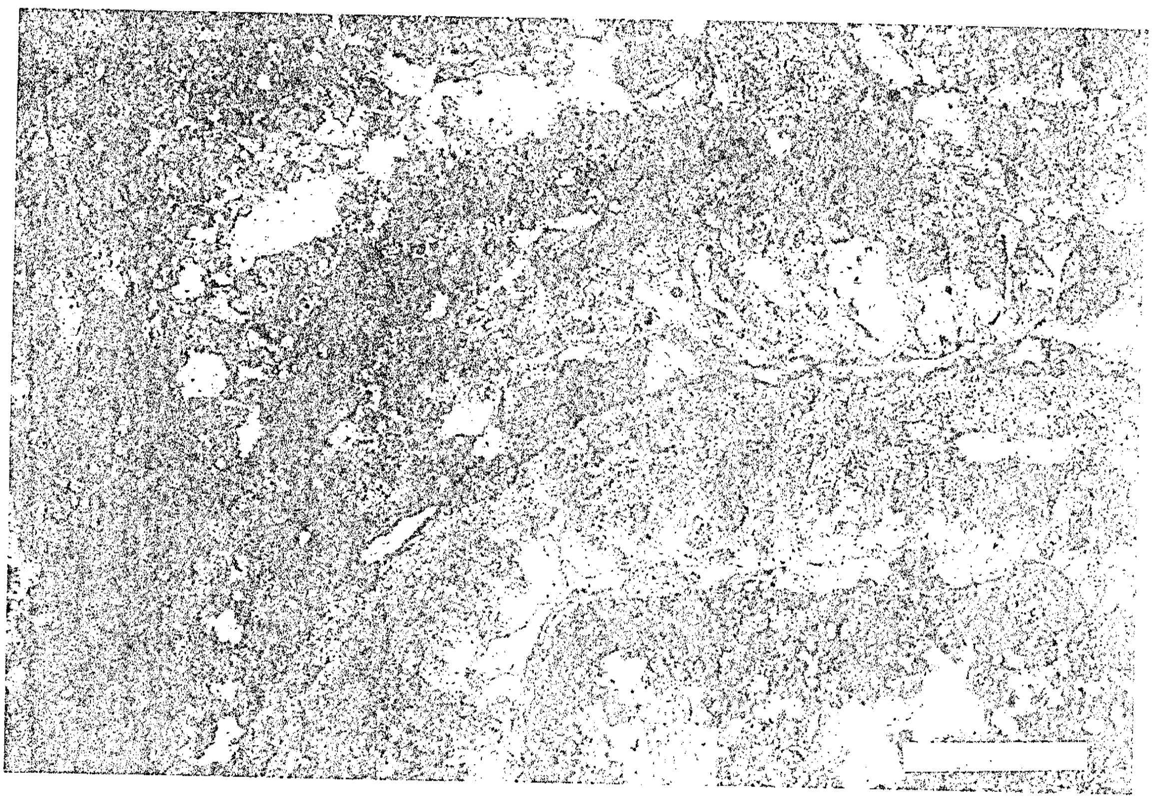

Figure 20. Alternating bryozoan and crypt-algal laminations within Fenestral Pisolite Dolowackestone/Dolopackstone lithotype from Section J2 at 16.6m. (Nicols are crossed, scale bar is 1mm.)

Pisolite Dolowackestone/Dolopackstone units are highly resistant to weathering and are cliffy in outcrop. Contacts with neighboring units are gradational and bedding is thick (30 - 50 cm).

Ostracod Dolomudstone: inflated ostracods occur sparsely throughout the matrix of most units from this lithotype. Ostracods are articulated and filled with large calcite crystals (Fig. 21). Ostracod tests exhibit automorphic penetration of dolomite which often grow to completely replace interiors, making recognition of original form difficult.

Matrix is completely replaced by dolomite. Matrix is structureless and unlaminated, often cross-cut by small calcite-filled fractures.

In outcrop Ostracod Dolomudstone units often have dark irregular spotty discoloration which does not follow bedding surfaces. Beds are usually thick, resistant, and continuous for 100's of meters, occasionally acting as blocky ridges. Units are typically found interstratified with Horizontally-brecciated Dolomudstone / Dolowackestone units.

Laminated Algal Dolowackestone/Dolopackstone: dark gray, algally-laminated limestones constitute a relatively minor portion, by volume, of the existing lithotypes within the field area. Individual laminations are approximately 1mm thick, micritic, and display a weak fabric parallel to the lamination trend. Regions between laminations are roughly 1mm thick. Interlaminar regions are calcite (Fig. 22) and locally contain small lenticular regions filled with calcite or dolomite. Lenticular regions often have an appearance similar to fenestral fabric.

Micritic laminations are replaced by dolomite, while inter-laminar regions are typically larger-grained and exhibit automorphic penetration of dolomite. Bedding is

Figure 21. Photomicrograph of Ostracod Dolomudstone displaying typical preservation of inflated ostracods from Section J2 at 51.3m. (Nicols are crossed, scale bar is 1mm.)

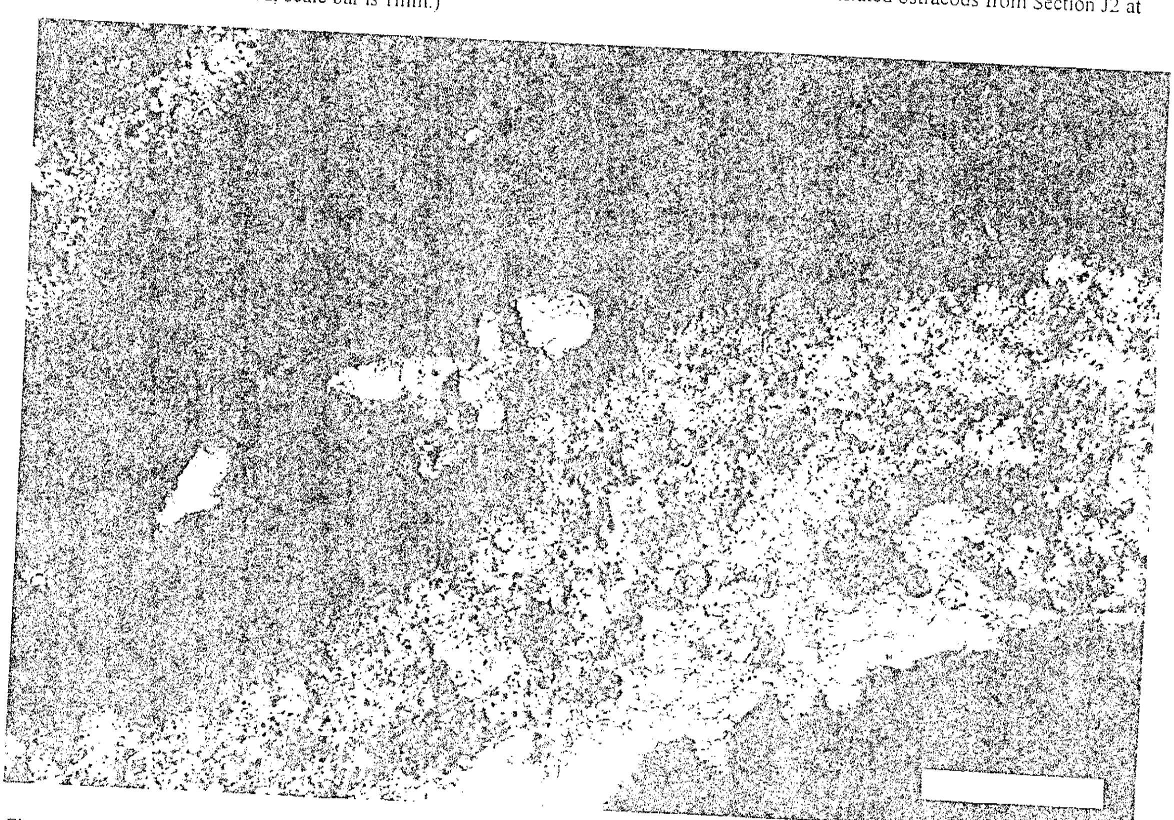

Figure 22. Photomicrograph of Laminated Algal Dolowackestone/Dolopackstone from Section J2 at 19.6m. (Nicols are crossed, scale is 1mm.)

highly resistant to weathering and laterally continuous for 100's of meters. Algal Dolopackstone/Dolowackestone units are thickly bedded (10 - 30 cm) and slightly undulose. Units usually occur directly below Horizontally-brecciated Dolomudstone / Dolowackestone and associated lithotypes.

Calcite-cemented Dolomitized Gypsum Sandstone: a volumetrically rare lithotype composed of detrital dolomitized gypsum sands cemented by sparry calcite. Gypsum grains are typically tabular, .1 - .25 mm, and coated by dark clay(?) minerals (Fig. 23). Quartz crystals are rarely present, constituting less than 1% of the total volume of grains, usually with well-developed quartz overgrowths. Thin irregular laminations appear in hand sample and thin section. Grain-rich laminations are offset by sparry calcite cement horizons (Fig. 24).

Gypsum grains have been preserved by pseudomorphic replacement by dolomite, completely replacing grains and overgrowing grain margins. Sparry calcite and dark brown oxide stains occlude the porosity between overgrown grains.

Dolomitized Gypsum Sandstone units have a yellow-brown, sandy appearance in the field. As a result of very poor exposure, horizontal continuity and bed thickness is difficult to establish.

Horizontally-brecciated Dolomudstone/Dolowackestone: a common lithotype, usually found in association with Fossiliferous Mollusk Dolowackestone / Dolopackstone and Ostracod Mudstone lithotypes. Units are composed of numerous micritic breccia clasts which commonly have angular, irregular, and micro-stylolitized margins (Fig. 25).

Brecciation locally includes the base of overlying Quartz Sandstone lithotypes, suggesting that brecciation occurred after lithification as a result of faulting or solution

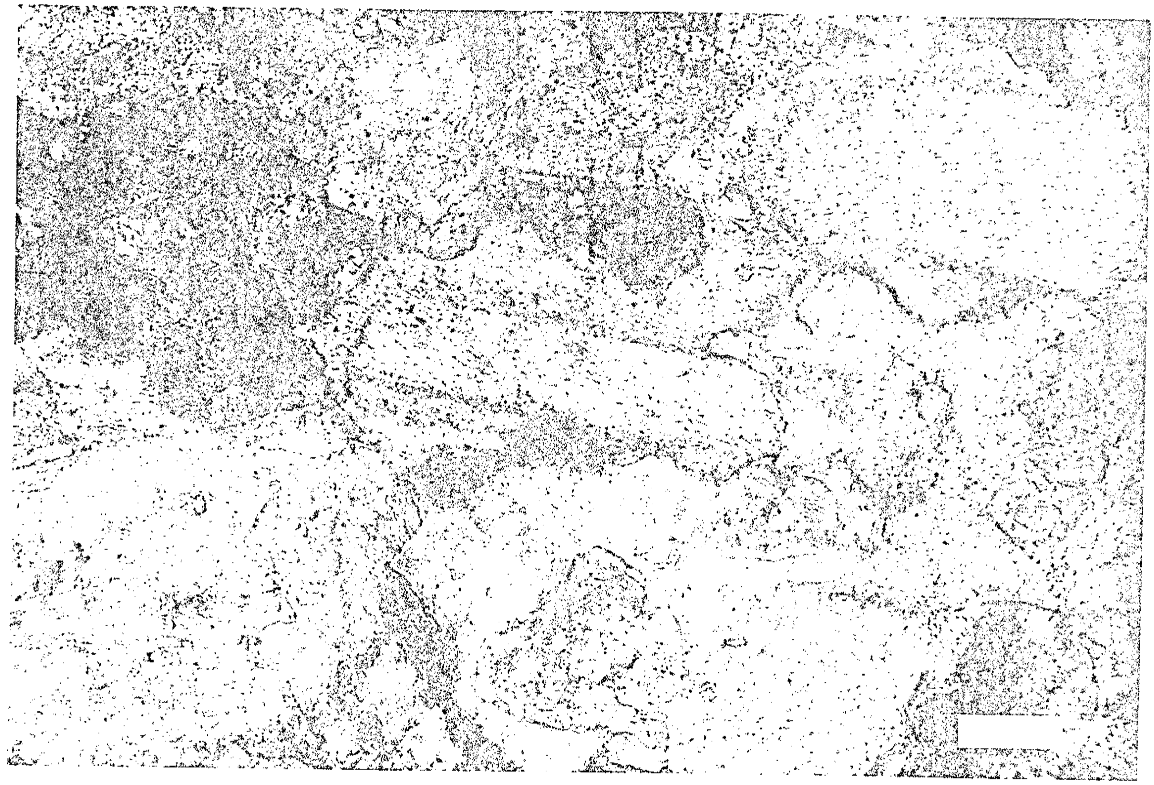

Figure 23. Dolomitized gypsum crystal with micritic (?) coating from Calcite-cemented Dolomitized Gypsum Sandstone lithotype from Section J3 at 52.7m. (Nicols are crossed, scale bar is .1mm.)

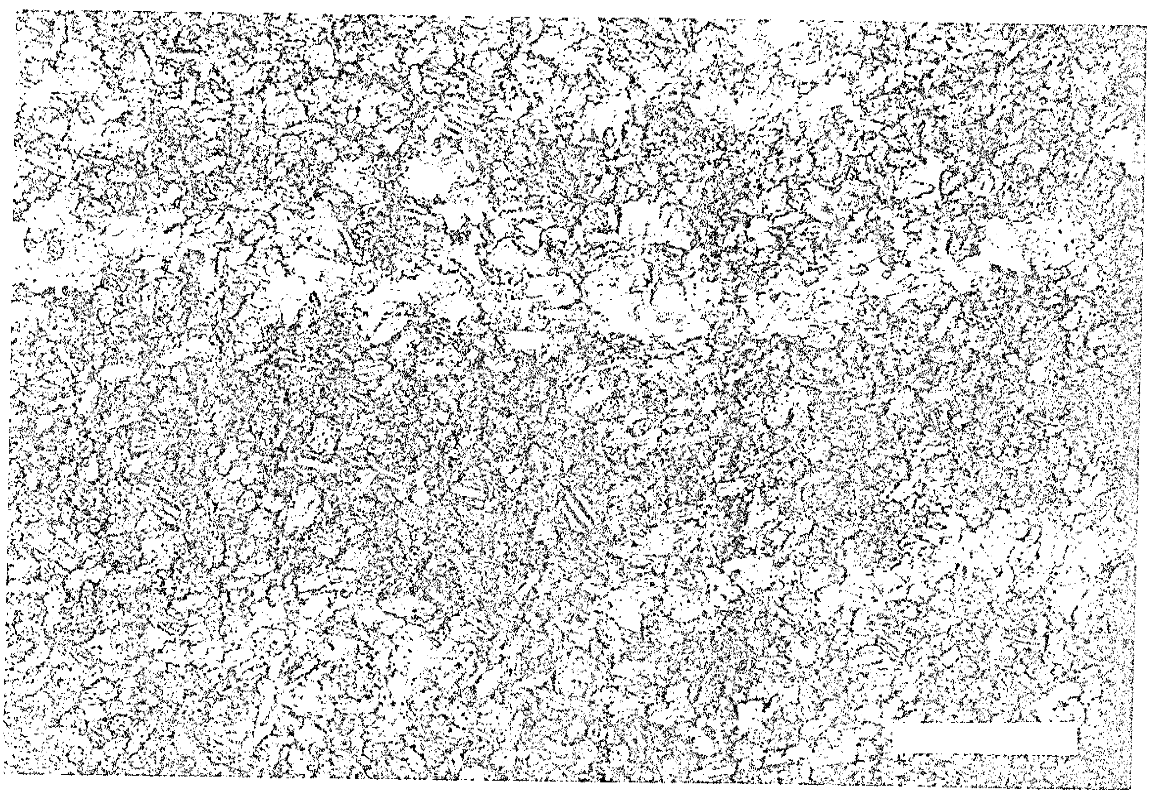

Figure 24. Irregular grain-rich laminations within Calcite-cemented Dolomitized Gypsum Sandstone lithotype from Section J3 at 52.7m. (Nicols are crossed, scale bar is 1mm.)

collapse. Micritic breccia clasts show a wide variation in size, sometimes ranging up to boulder-sized blocks. Skeletal grains are poorly preserved within breccia clasts but tend to show on weathered surfaces as silt-sized particles, especially within boulder-sized breccia clasts (Fig 26).

Breccia clasts tend to be completely dolomitized, with few regions where recrystallization is apparent. Between breccia clasts, coarsely-crystalline, blocky calcite spar grows along the margins of clasts, unaffected by dolomitization.

Horizontally-brecciated Dolomudstone/Dolowackestone units may be very poorly exposed where brecciation is severe or stand out as very resistant, cliffy ridges. Brecciation in outcrop typically occurs along horizontally continuous boundaries which originate at the margin between beds and decreases away from the interface. Very thick units may have several interfaces of horizontal brecciation acting as discrete horizons, possibly representing previous bedding planes.

Quartz Sandstone: a quartz-rich sandstone dominated by very well sorted, well rounded to sub-angular grains. Sand grains are consistently between 0.15mm and 0.25mm, tightly packed, and well-cemented by syntaxial quartz overgrowths (Fig. 27). A small population of grains (less than 1%) are chert, calcite, and feldspar in composition.

Overgrowths are commonly well-formed and accentuated by a thin dust ring surrounding the original grain. Units may also be cemented by sparry calcite and micrite, typically filling in gaps where quartz overgrowths have failed to occlude interstitial porosity. Feldspar grains exhibit partial dissolution. Units may contain randomly-oriented gypsum ghosts (Fig. 28).

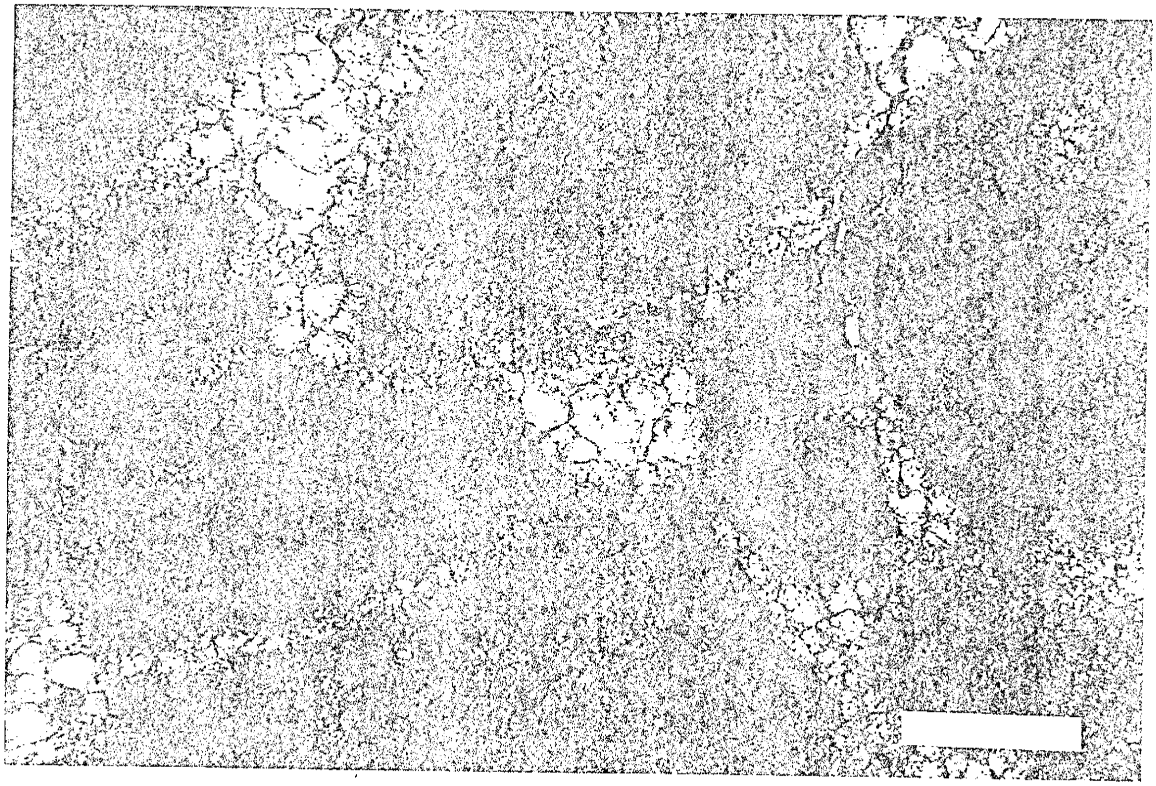

Figure 25. Breccia clasts with stylolitized margins within Horizontally-brecciated Dolomudstone/Dolowackestone lithotype from Section J1 at 16.4m. (Nicols are crossed scale bar is 1mm.)

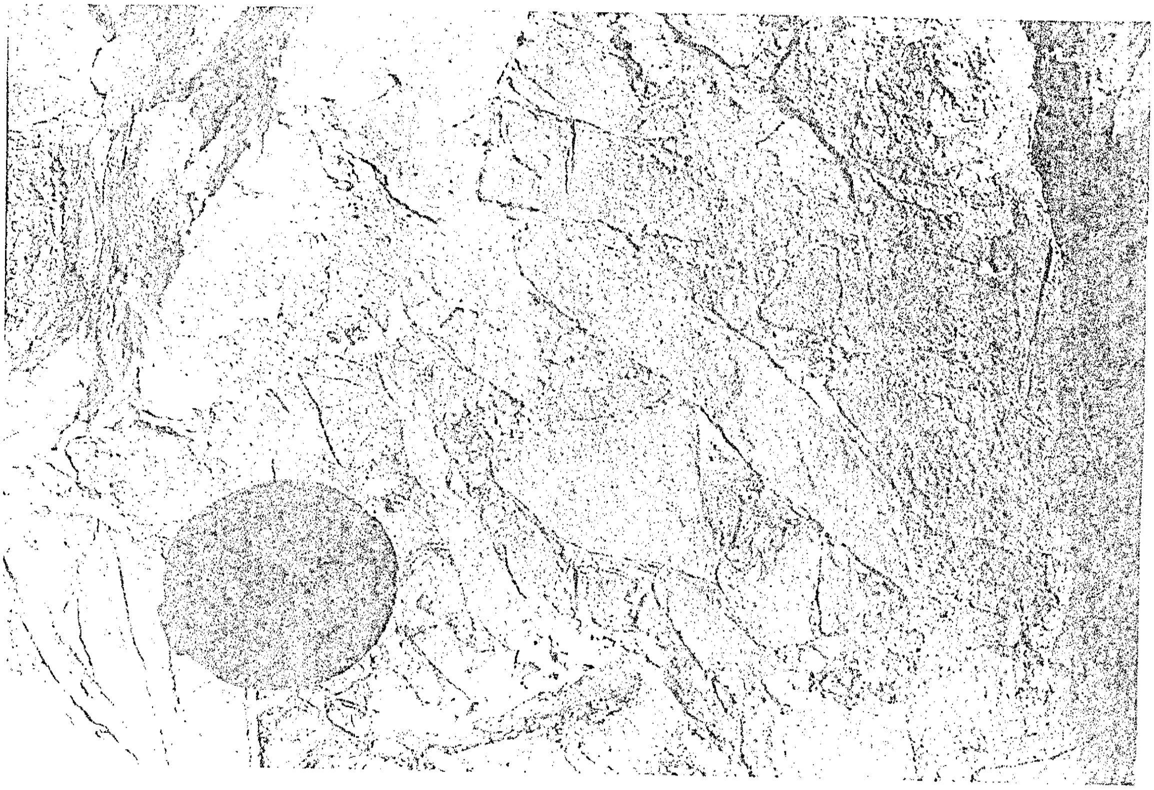

Figure 26. Angular boulder-sized breccia clasts within Horizontally-brecciated Dolomudstone/ Dolowackestone lithotypes.

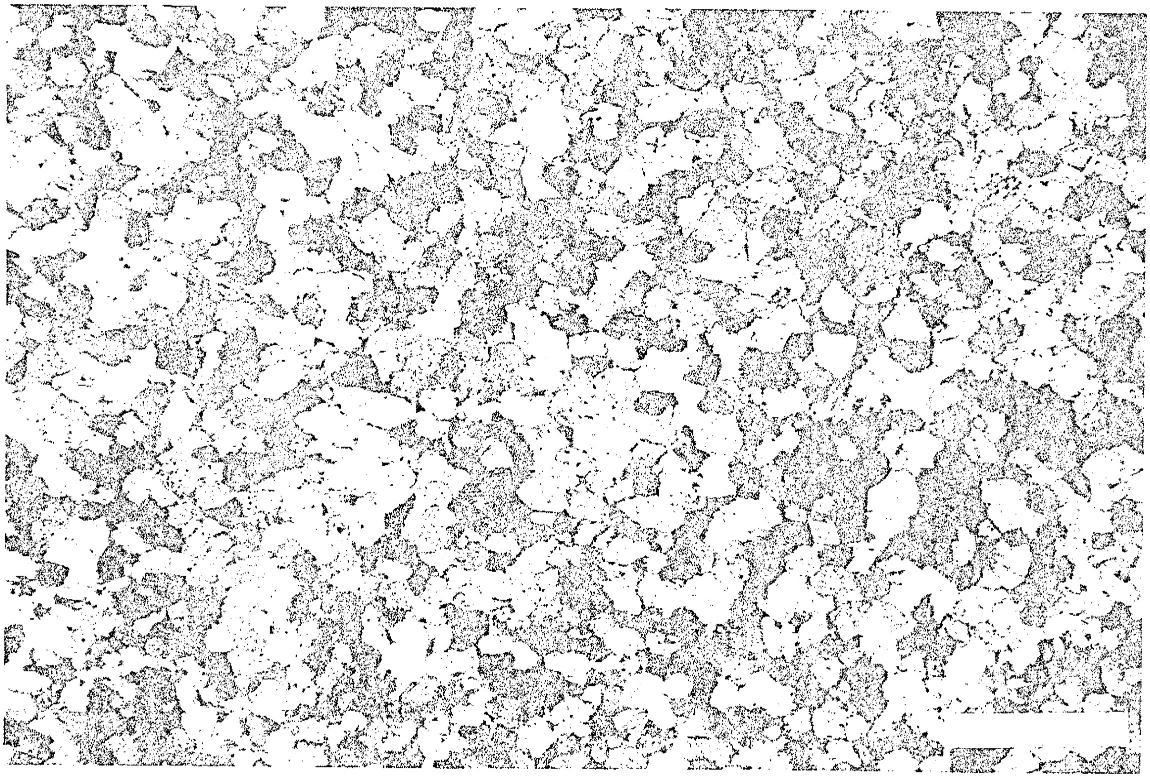

Figure 27. Photomicrograph of Quartz Sandstone lithotype from Section J2 at 38.5m. (Nicols are crossed, scale bar is 1mm.)

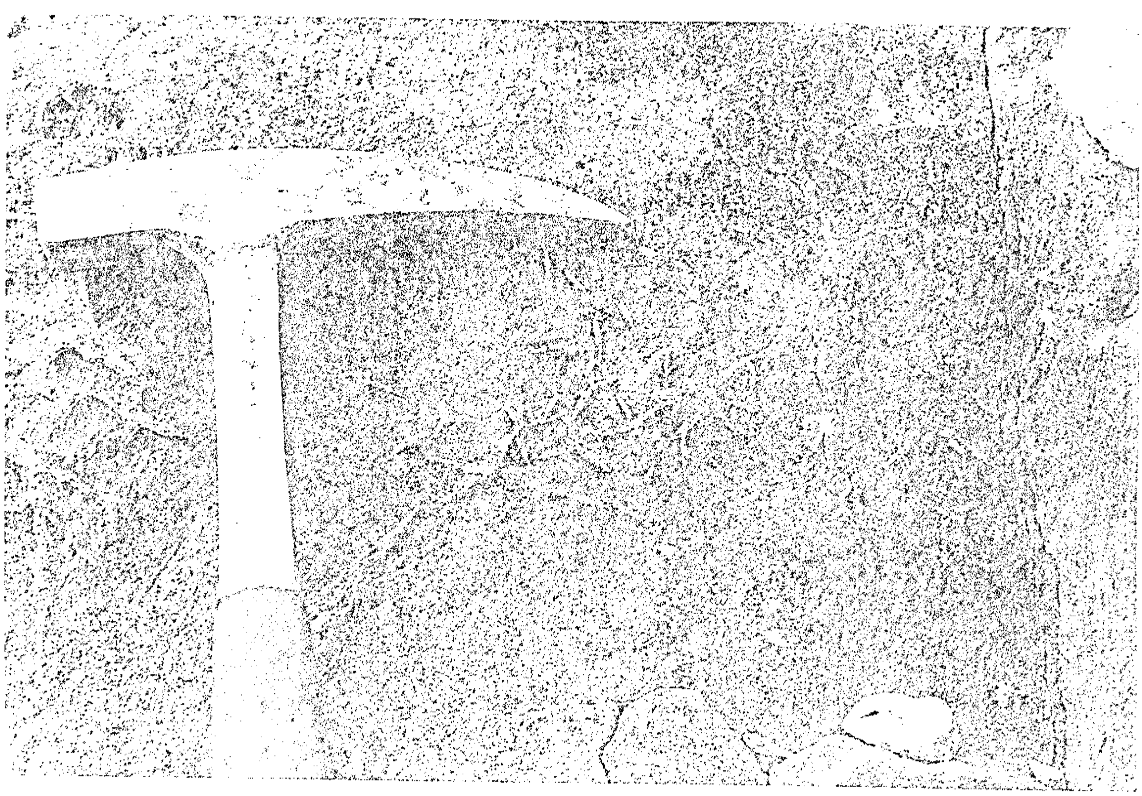

Figure 28. Gypsum ghosts within Quartz Sandstone lithotype.

Sand units often have a pink or brown weathered surface; fresh surface is commonly buff or white. Contacts with surrounding units vary between extremely sharp and gradational. Very thickly-bedded sandstone units (1-3 m) are very resistant and stand out as dark, brown-stained ridges among the dark gray limestones of the San Andres. Units typically exhibit large, low- to high-angle cross-bedding bounded by laterally continuous, tabular bedding planes.

Cyclic Sedimentary Sequences

Lithotypes within the carbonate members of the San Andres Formation in Socorro County exhibit repeated patterns of sedimentation in vertical sequence. Cyclic sequences of lithotypes can be broadly grouped into two types of sequences. Figure 29 shows the relationship between lithotypes in two highly-idealized cyclic sedimentary sequences which occur throughout the San Andres.

Type A cyclic sedimentary sequences are typically thin and poorly developed within the field area. An idealized 'Type A' cyclic sedimentary sequence consists of: (1) thinly-bedded Dolomitized Mudstone lithotypes leading into (2) poorly-developed, Comminuted Fossiliferous Dolowackestone/Dolo-packstone lithotypes and (3) well-developed, burrowed Fossiliferous Mollusk Dolowackestone/Dolopackstone lithotypes; Mollusk Dolowackestone/ Dolopackstone lithotypes exhibit decreasing amounts of bioturbation, eventually becoming bedded units with sparse bioturbation and which give way to (4) Ostracod Dolomudstone, (5) cross-bedded Intraclastic Dolopackstone/Dolo-wackestone, and (6) Algal Dolowackestone/Dolopackstone lithotypes; sequences are capped by (7) Horizontally-brecciated Dolomudstone and (8) Quartz Sandstone lithotypes.

Type B cycles are much less common in the field area, being represented once in each of the three stratigraphic sequences. An idealized 'Type B' cyclic sedimentary sequence includes: (1) well developed Comminuted Fossiliferous Dolowackestone/Dolopackstone lithotypes disrupted by intense bioturbation and gradually increasing in biotic diversity into (2) Thinly-bedded Brachiopod/Dasycladacean Algal Dolopackstone/Dolowackestone lithotypes; high-diversity units are overlain by (3) Mollusk Dolomudstone/Dolopackstone lithotypes with evaporite molds and (4) Horizontally-brecciated Dolomudstone /Dolowackestone lithotypes; sequences are capped by (5) Sandy Dolowackestone /Dolomudstone and (6) Quartz Sandstone lithotypes.

Idealized Cyclic Sedimentary Sequences

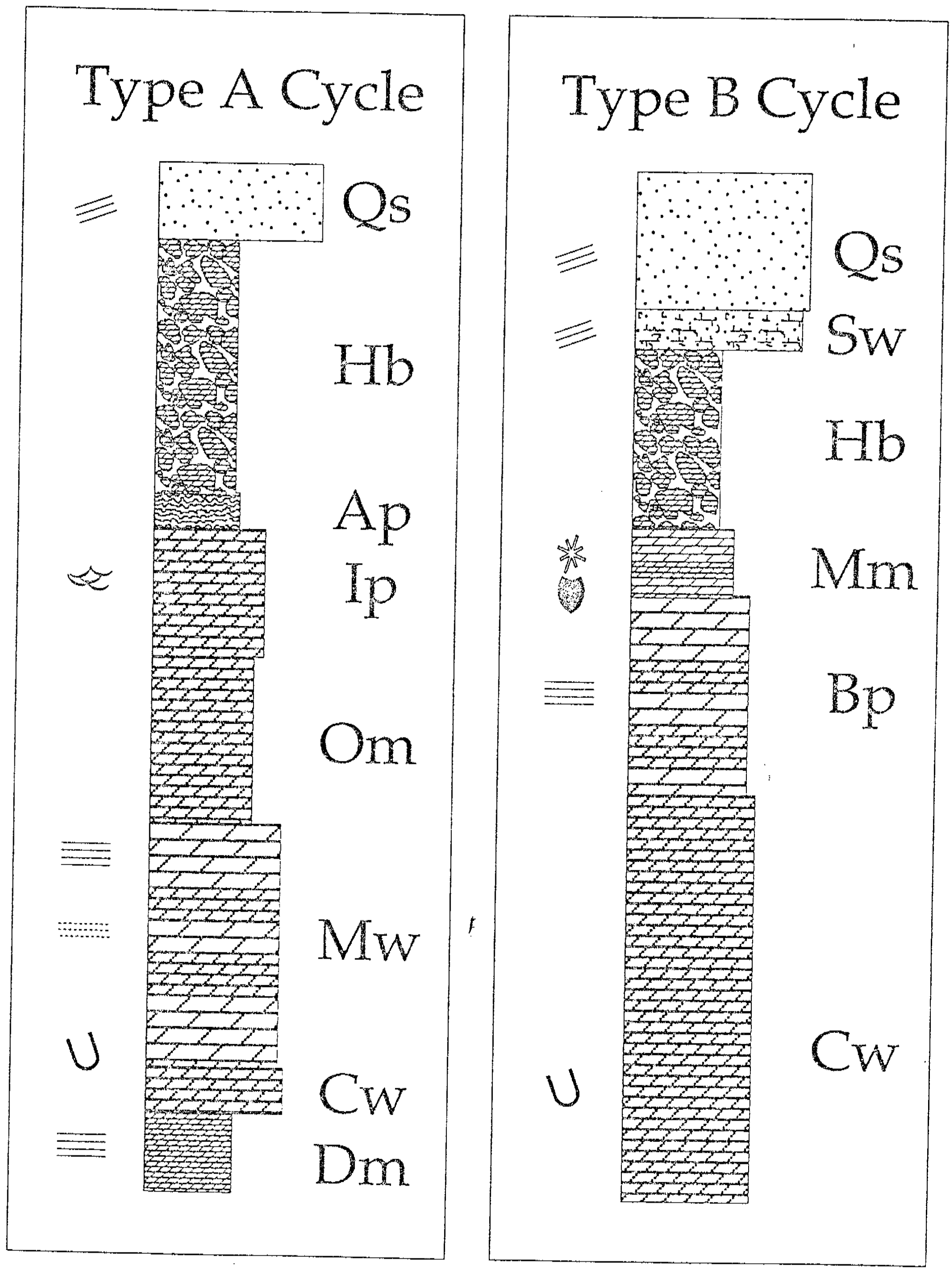

Figure 29. Two types of idealized cyclic sedimentary sequences found within the carbonate members of the San Andres Formation. (Symbols and lithotypes keyed to Figure 5.)

DISCUSSION

Criteria Used for Interpretation of Environments of Deposition

Environmental inferences are based upon distinctive sedimentary structures including bioturbation, laminations, bedding, and fenestral fabrics as well as diversity and type of biota, presence of allochems, evidence of evaporite growth, vertical sequence and composition of lithotypes.

Presence of bioturbated sediment implies that biota had ample opportunity to churn sediment, destroying any pre-existing bedding planes or laminations. Where bioturbation occurs, sedimentation rates must have remained relatively slow to inhibit forming adverse conditions for burrowing biota. Destruction of bedding by bioturbation often results in thick units with few sedimentary structures preserved. Conversely, where well-preserved sedimentary structures and bedding exist, adverse conditions probably existed, inhibiting bioturbation. High sedimentation rates and hypersaline water conditions are two common conditions that may inhibit loss of bedding through bioturbation.

Fenestral fabrics are used to indicate subaerial exposure. Fenestral fabrics form as a result of compressed gas bubbles trapped in sediments and through shrinkage produced by desiccation of sediments (Shinn, 1965). Where fenestral fabrics occur sediments are inferred to have been exposed to at least periodic subaerial conditions, most likely to be preserved in high intertidal and supratidal environments.

'Flat-pebble' intraclasts form through erosion and re-deposition of desiccation cracks and partially lithified algal mats (Shinn, 1983: Pratt et al., 1992). Moderate to high energy conditions are required to erode partially lithified sediments. Proximity to environments exposed to subaerial conditions is suggested where preservation of fragile, angular grains occurs.

Environments with low to moderate water agitation are evidenced by poor sorting, lack of grain orientation, and high mud composition (even in most grain-rich lithotypes). Ooids and carbonate sands suggest persistent high-energy conditions, whereas shelter structures, micro-scouring, and intraclasts all suggest stormy, higher energy levels punctuated regions that were dominantly lower-energy. Presence of mud-rich sediments is used partially as evidence of lower energy conditions. Artificially-low energy conditions may be produced by environments lacking accessible egress for winnowed lime muds. In order to reduce the risk of error in interpretation, presence of mud-rich sediments were used as evidence of energy conditions in conjunction with textural fabrics including: sorting, grain orientation, and abrasion.

Presence of flora which probably required high light levels to subsist, such as phylloid and dasycladacean algae, requires that water depths remain fairly shallow. Light levels are a product of water depth and turbidity.

Water restriction is characterized by chemical and physical variance from normal marine ocean water resulting from lack of communication with open marine waters, poor circulation, and elevated temperatures (Irwin, 1965; Purser and Seibold, 1973; Wilson, 1975; Kendall, 1992). Presence of restricted marine conditions in ancient deposits is most easily observed by examining indicators of salinity and temperature of the water. Diversity of organisms present often reflects stability of an environment with respect to normal marine environments. (Heckel, 1972; Wilson, 1975) . Environments capable of supporting a high relative diversity of biota are generally considered more stable than low diversity environments. Highly restricted environments are typically unstable and produce sediments with a low diversity of biota.

Interpretation of Lithotypes

Four sedimentary environments are represented by the majority of lithotypes present in the San Andres Formation in central Socorro County: marine subtidal, restricted marine subtidal, intertidal, and terrestrial. Direct evidence of unequivocal supratidal deposits was not observed. The most prevalent facies in terms of volume of rock is restricted marine subtidal deposits which comprise approximately 50 to 60 percent of the rocks within each of the three locations. Intertidal and possible supratidal deposits are less common, typically comprising 30 to 40 percent, while terrestrial and marine subtidal deposits are relatively uncommon.

Marine Facies

Marine facies containing relatively high biotic diversities occur as minor elements in the vertical sequences measured. Subtidal marine facies are represented by Thinly-bedded Brachiopod/Dasycladacean Algal Dolowackestone/Dolopackstone lithotypes and are characteristic of Type B cyclic sedimentary sequences. Very high relative diversity and an abundance of stenohaline organisms implies an environment approaching normal marine conditions. Biota present may have been limited by migration time and distance from stable normal marine conditions (Lang, 1937). Predominance of nektonic and motile biota supports the idea that salinity fluctuations were fairly rapid and may have excluded biota with slow migration times. Lack of extensive burrowing and micritization of skeletal grains coupled with a high diversity and abundant biota suggests that sedimentation rates must have been relatively rapid. Low water energy conditions are implied by high mud content paired with random grain orientation and skeletal grains lacking abrasion.

Rocks from this facies may represent environments similar to modern shallow marine shelves with open marine sedimentation, such as shelf deposits occurring in the Bahamas (Hardie and Ginsberg, 1977; Enos, 1983; Halley, Harris, and Hine, 1983).

Restricted Marine Facies

Restricted marine conditions constitute the principle environment of sedimentation within the field area. Lithotypes produced within restricted marine conditions vary depending upon intensity of restriction, paleo-geographic position, water depth, and energy conditions. Lithotypes from restricted marine facies typically occur at the base of well developed Type A and Type B cyclic sedimentary sequences.

Sediments similar to those which formed in this facies are being produced on restricted marine shelves associated tidal flats of the modern Persian Gulf (Wagner and van der Togt, 1973; James and Kendall, 1979; Purser, 1985; Pratt et al., 1992).

Basal Restricted Marine Subtidal Subfacies: this subfacies includes Dolomitic Mudstone lithotypes which act as the base of an ideal Type A cyclic sedimentary sequence. Wispy laminations accentuated by thin silt deposits suggest that these lithotypes were produced in sediment starved conditions where water energy was too low to winnow muds. The dark color and lack of biota imply that the rocks formed in a reducing environment adverse to burrowing organisms. The presence of possible evaporite molds and rosettes suggests hypersaline water conditions. Textural inversions, created by an abundance of quartz sand floating in a micritic matrix suggest that muds were commonly within reach of eolian processes.

The position of this subfacies at the base of cyclic sedimentary sequences paired with sediment-starved, hypersaline conditions suggest that it is most likely a result of deposition during restricted low-water stands on the shelf during the initial stages of marine incursion.

Transitional Restricted Subtidal Subfacies: this subfacies is comprised of Comminuted Fossiliferous Dolowackestone/Dolopackstone lithotypes. Increase in diversity trends from base to top suggests a general transition from more restricted to less restricted conditions. Increasing water depth from the base to top is suggested by a decrease in the abundance of coated grains and sorting from base to top and a concomitant increase in mud content. Low sedimentation rates are implied by high levels of bioturbation, producing very thickly bedded units with a mottled appearance.

Lithotypes of this subfacies occur in both Type A and Type B cyclic sedimentary sequences, characteristically developed better in Type B sequences. Well-developed Transitional Subtidal Restricted Subfacies lead into Marine Facies at the sections near Canoncito Colorado and Loma de las Canas.

Restricted Marine Subtidal Subfacies: an abundant subfacies including rocks of the Mollusk Dolowackestone/Dolopackstone lithotype. Low biotic diversity and exclusive presence of typically euryhaline organisms suggests that water conditions were restricted, but not enough to discourage salinity-tolerant organisms from burrowing the sediment. Periods of hypersalinity may have occurred, evidenced by the presence of evaporite molds and an association with Horizontally-brecciated Dolomudstone lithotypes, especially in poorly developed Type A cyclic sedimentary sequences.

Wave energy conditions were probably low, given the high mud content and random orientation of skeletal grains. Periodic fluctuations in water energy are suggested by the presence of intraclasts and mechanically transported skeletal grains.

Marine Subtidal Shoal Subfacies: a subfacies unique to the upper portion of the section near Bordo Atravesado represented by Ooid Dolograinstone/ Dolopackstone lithotypes. Ooid packstone aggregates cemented by sparry calcite suggest periodically high energy conditions punctuated by periods of subdued water energy. Sedimentation was probably slow: an idea supported by heavy micritization of ooid grain margins, which would require slow burial rates, and a lack of preserved sedimentary structures, perhaps as a result of bioturbation. Coated skeletal grains present consist exclusively of euryhaline organisms. The paucity of this subfacies suggests that sedimentation was dominated by very local environmental conditions. The presence of coated grains and grainstone textures, which require agitated water conditions, suggest that sedimentation occurred above wave base.

Marine Subtidal/Intertidal Channel Subfacies: represented by Sandy Dolowackestone lithotypes, channel facies are principally composed of rounded, well sorted fine-grained quartz, calcite, and possibly evaporite sands. Quartz, calcite, and evaporite (?) grains may have been deposited by wave action, current activity, or eolian processes. Grain-rich sediments dominated by rounded and well-sorted sands suggest higher energy conditions than surrounding environments.

Restricted water conditions are implied by low diversity of biota and absence of stenohaline organisms. Energy conditions fluctuated between low and moderate, as evidenced by the presence of lime muds between well sorted sand grains and pellets. Skeletal grains appear damaged by transportation but do not preserve transport fabrics or preferred orientations, suggesting that bioturbation probably played a role in destruction of original sedimentary structures. No indications of subaerial exposure were observed.

Flooded Restricted Marine Subtidal Subfacies: this subfacies is comprised of Mollusk Dolomudstone/Dolopackstone lithotypes. Dark mudstones suggest conditions similar to basal restricted subtidal mudstones: low-energy, highly-restricted conditions. Sediment starved conditions were punctuated by rapid high-energy periods. Packstones of this subfacies include abraded and whole skeletal grains which display transport fabrics. Micro-scouring, sorting of pellets, grain-supported textures, and small shelter structures all suggest relatively high-energy conditions existed long enough to remove finer-grained material. Sharp transitions between mudstone and packstone deposition imply a rapid change from low to high-energy conditions.

This subfacies is thought to represent shallow, highly restricted environments produced during periodic low-stands in sea level. The position of this subfacies above subtidal facies within cyclic sedimentary sequences suggests that low-stands were a result of shallowing water conditions.

Intertidal and Supratidal (?) Facies

Intertidal facies most commonly cap poorly developed Type B cyclic sedimentary sequences or appear as the final marine deposits before the appearance of terrigenous deposits in a sequence. Intertidal deposits are usually thin and contain distinctive features which make them good marker beds for tracing units in the field. A number of the subfacies included within this facies represent environments that may be similar to tidal flat deposits of the modern Persian Gulf (Lucia, 1972; Wagner and van der Togt, 1973; Shearman, 1981; Purser, 1985; Warren and Kendall, 1985).

Low Intertidal / Tidal Channel Subfacies: a subfacies uniformly present high in stratigraphic sections, represented by Intraclastic Packstone lithotypes. Presence of "flat-pebble" intraclasts, poor to very poor sorting, and very large intraclasts (up to 5 centimeters in the long dimension) suggest short transport distances.

Energy conditions appear to have fluctuated from high energy storm activity to low energy periods dominated by current activity producing small-scale trough cross-beds. Algal laminations and low diversity of biota coupled with periodic preservation of sedimentary structures suggests that waters may have been highly restricted, creating adverse conditions for marine organisms. Indications of subaerial exposure were not observed.

Mixing-water Lagoon Subfacies: a rare subfacies, limited to the section near Loma de las Canas, represented by Fenestral Pisolite lithotypes. Pisolite encrustations alternate between crypt-algal and bryozoan laminations suggesting rapid fluctuation in water restriction. Fluctuating water salinity may be a result of seasonal variation in evaporation and run-off into small lagoons or supratidal ponds. Periodic subaerial exposure is suggested by the presence of fenestral structures which occur within algal laminations (Shinn, 1968; Shinn, 1983).

Pisolite grains, which require some agitation to form, are surrounded by a framework of transported skeletal grains, intraclasts, and peloids suggesting that moderate wave energy conditions dominated sedimentation, however, grains are not well sorted and lithotypes are dominantly mud-rich.

During rainy seasons, sabkha and salina environments in the modern Persian Gulf experience seasonal ponding of meteoric water which can produce environments with similar conditions (Purser, 1985).

Intertidal Lagoon Subfacies: a relatively common subfacies represented by Ostracod Mudstone lithotypes. Low water-energy conditions are suggested in this subfacies by high mud content which is coupled with a sparse, random distribution of articulated ostracod grains. Biotic diversity in this subfacies is very low, suggesting that water circulation was probably highly restricted. A wide range of environments may produce lithotypes similar to those found within this subfacies; lithotypes of this subfacies are commonly pinched between restricted subtidal deposits and high-energy intraclastic packstone deposits with flat-pebble clasts within vertical sequences suggesting that an intertidal lagoon is the most likely environment of deposition.

High Intertidal Subfacies: fenestral-like fabrics and possible interbedded evaporites suggest that this subfacies represents a high intertidal environment. Algal Dolopackstone lithotypes, which represent this subfacies in the field area probably formed under hypersaline conditions and were periodically exposed to subaerial conditions, allowing for formation of bird's-eye structures (Shinn, 1968; Shinn, 1983). Similar to algal mats which form in high intertidal regions of the modern Persian Gulf and Laguna Madre environments (Masson, 1955; Kinsman, 1969; Lucia, 1972; Butler et al., 1982; Purser, 1985;), this subfacies commonly occurs directly below supra-tidal(?) and terrestrial facies near the top of Type A cyclic sedimentary sequences in the field area.

Eolian / Tidal Channel Subfacies: a subfacies unique to the section near Bordo Atravesado, represented by Dolomitized Gypsum Sandstone lithotypes. Well-sorted, fine-grained gypsum sands have characteristics that support interpretations for both eolian and tidal channel deposition. Irregular, faintly cross-bedded laminations, may result from ripple cross-lamination produced by either eolian or tidal channel processes. Given the paucity of information available, either process or a combination of both process may ultimately be responsible for this subfacies. Presence of re-deposited pristine gypsum sands relies upon close proximity to a source of abundant gypsum crystals, such as supratidal gypsum sediments. Similar deposits can be found in tidal channels of the modern Persian Gulf, also produced by a combination of eolian and tidal channel activity (Kendall, 1992).

Evaporite Lagoon / Supratidal Evaporite Subfacies: rocks from this subfacies are represented in the field by Horizontally-brecciated Dolomudstone/ Dolowackestones. Horizontally-brecciated units are the dominant lithotype throughout the San Andres Formation in Socorro County. The presence of evaporites is implied by horizontal brecciation and presence of evaporite molds and rosettes within neighboring units (Hovorka, 1983, 1987; Warren and Kendall, 1985; Kendall, 1992). Horizontal brecciation may represent intense solution collapse or flat faulting, both of which would probably require the presence of evaporites. High salinities, which would be necessary to produce bedded evaporites, are also implied by very low diversity of biota within breccia fragments. Subaerial indicators were not observed, however poor preservation of sedimentary structures resulting from brecciation makes it impossible to discount an environment capable of supratidal evaporite production.

This subfacies may have been deposited by extensive evaporite lagoons, sabkhas, or salinas similar to those forming evaporites in the modern Persian Gulf (Kinsman, 1969; Lucia, 1972; Purser, 1985; Shinn, 1983; Warren and Kendall, 1985; Butler, 1969). It's position within shallowing-upward sequences often places this subfacies either directly above or below intertidal deposits, suggesting that more than one environment may be responsible for the formation of bedded evaporites within the carbonate members of the San Andres Formation.

Indirect evidence of evaporite deposits within the Lower San Andres of the field area is relatively abundant, however bedded evaporites are not exposed. References within this paper to displacive crystal growth, especially in conjunction with evidence of highly-restricted environments, presupposes diagenetic growth of evaporites within marine sediments. Validity of this assumption is based primarily on crystal habit and proximity to zones of horizontal brecciation, which typically occur directly above units containing evidence of displacive growth.

Zones of horizontal brecciation present a problem regarding preservation of sedimentary structures and grains. Several references are made within this paper regarding the possibility for zones of horizontal brecciation to result from the presence of bedded evaporites. These inferences are based mainly upon position of horizontally-brecciated units within stratigraphic sequences where increasingly restricting environments are represented leading into Horizontally-Brecciated Mudstone lithotypes.

Presence of bedded evaporites would facilitate 'flat-faulting', acting as a glide plane between more resistant units above and below. A combination of 'flat-faulting' and dissolution may be responsible for a complete absence of exposed evaporites within the carbonate members of the San Andres Formation in central Socorro County.

Evidence of brecciation at the base of quartz sandstone units adjacent to zones of horizontal brecciation suggests that 'flat-faulting' may be partially responsible for incomplete sedimentary cycles. Conspicuous absence of unequivocal supra-tidal deposits may be a product of thin deposits incorporated into brecciation horizons during faulting. However, without a detailed study of horizontally-brecciated units within the field area, it would be difficult to state without hesitation that horizontally-brecciated units are directly tied to supra-tidal or evaporite-producing environments.

Terrigenous Facies

Terrigenous deposits within the San Andres Formation of Socorro County are restricted to quartzarenites. Most commonly, these deposits have features that are indicative of either beach or eolian processes, in many cases lacking sufficient sedimentary structures to point decisively towards either environment. Where quartz sandstones occur, units consistently cap cyclic sedimentary sequences, occasionally before a cycle approaches completion. Quartz sandstones are remarkably consistent in grain size, shape, and sorting, and rarely vary in composition from quartz arenites. Textural and compositional features of the sandstone tongues are consistent with underlying Glorieta Sandstone Member. Low- and high-angle tabular cross-beds are common in all three stratigraphic sections, however, they do not consistently allow clear distinction between back-beach or dune deposition.

Low-energy water conditions abound within most of the carbonate depositional environments. The broad, shallow, gently-sloping nature of epieric sea environments often preclude a potential for high energy wave conditions and tidal currents, even in relatively shallow waters (Irwin, 1965). Due to nearly ubiquitous low energy water conditions, especially within surrounding marine environments, it is unlikely that well-developed beach environments formed. Ultimately, a combination of eolian and beach processes may be responsible for formation of terrigenous deposits within the intertonguing sandstones in the carbonate members of the San Andres Formation.

Comparing Ancient Environments to Modern Environments

Throughout this paper several references are made to tidal flat and associated shelf environments, with particular emphasis upon the Persian Gulf, as possible modern analogs to sedimentation patterns within the carbonate members of the San Andres Formation. True tidal deposits, formed by diurnal tidal fluctuation, were not found within the field area. Epieric sea sedimentation, suggested by extensive shallow restricted marine deposited across a gently-inclined slope, is likely to have had a limiting effect on tidal activity (Irwin, 1965). The deepest environments of San Andres sedimentation were probably limited to marine current activity, while the shallowest environments may have been dominantly influenced by wind currents only. True tidal currents producing characteristic funneling of sediment in and out of intertidal environments may have been limited to relatively local regions or non-existent within the field area.

Accordingly, the depositional model developed in this paper for the San Andres Formation environments of deposition departs from similar environments of deposition within the modern Persian Gulf. Disparities between the depositional model presented in this paper and the modern Persian Gulf include regional extent of sedimentary environments, water energy, and water circulation conditions (Purser and Seibold, 1973; Wagner and van der Togt, 1973). Widespread presence of lime mud and mud-dominated sediments, which differ from packstone and grainstone sediments in similar environments of the Persian Gulf (Wagner and van der Togt, 1973), probably result from lower energy conditions associated with shallow epieric sea sedimentation.

Correlation and Implications for Environments of Deposition

As a result of heavy brecciation, solution collapse, and the variable nature of environments of deposition, correlation between environments of deposition relied heavily upon comparison of cyclic sedimentary sequences. At least five Type A and one Type B cyclic sedimentary sequences can be correlated between the stratigraphic sections measured (Fig. 30).

Type A cycles describe asymmetric shallowing-upward sequences, defined by relatively thin marine deposits representing shallow environments at the base followed vertically by thick, well-developed deeper-water facies showing a gradual decline in water depth. Type A cycles are characteristically composed of low-diversity, restricted marine subtidal and intertidal facies and are typically capped by supratidal(?) and terrigenous facies.

In contrast, Type B cycles describe more symmetric sedimentary sequences, defined by lithotypes at the base representing well-developed shallow facies showing a gradual increase in water depth and diversity followed vertically by lithotypes which represent least-restricted marine environments present within a section. High-diversity lithotypes are replaced vertically by lithotypes representing increasingly restricted and shallower environments and capped by supratidal (?) and terrigenous facies.

In places within the stratigraphic sequences, sedimentary cycles are very poorly developed. Where intertidal, supratidal(?), and terrigenous deposits are found in sequence without subtidal deposits within the cycle, Type A cycles are assumed for correlation purposes. Foundation for this assumption is based on the nature of Type A cycles, which are characteristically asymmetrical in nature and typically poorly developed within the field area, especially in the early cycles of the sections measured.

Cycles 1 and 2 correlated between the stratigraphic sections are composed of poorly defined Type A sequences. Poor definition of these two cycles may result from heavy brecciation associated with 'flat-faulting', solution collapse, or paleotopographic highs preventing well-developed carbonate environments from forming. Cycles 1 and 2 describe incomplete asymmetric shallowing-

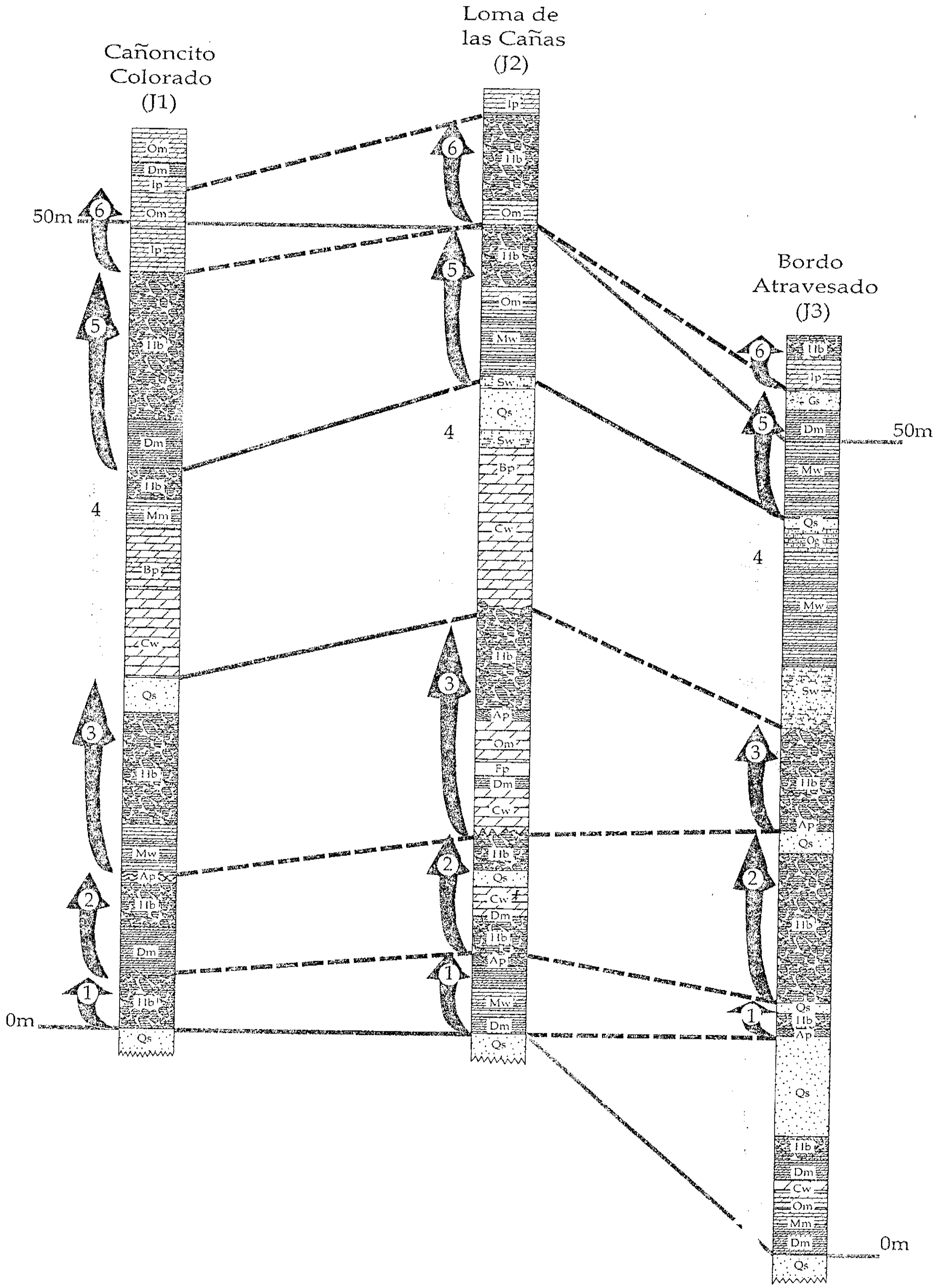

Figure 30. Correlation between stratigraphic sections of the carbonate members of the San Andres Formation. Lithotypes are keyed to Figure 5.

upward sequences, capped by either intertidal/supratidal(?) or terrigenous deposits. Cycles 1 & 2 from the section near Loma de las Canas tend to be better developed than in other sections, producing thicker and more complete cycles. Subtidal marine deposits gradually shallow into intertidal deposits. Progressive shallowing often leads into horizontally-brecciated units, occurring either just above or below intertidal deposits, probably resulting from environments capable of producing bedded evaporites, such as an evaporite lagoon, sabkha, or salina. Cycles 1 and 2 of the sections near Canoncito Colorado and Bordo Atravesado lack well-developed subtidal deposits and may have been affected by paleotopographic relief, limiting the development of marine environments.

Cycle 3 describes an asymmetric Type A cycle, composed of restricted subtidal marine and intertidal deposits which are thicker and better-developed than earlier cycles, especially within the sections near Loma de las Canas and Canoncito Colorado. The section near Bordo Atravesado remains underdeveloped throughout cycle 3, being composed entirely of intertidal and supratidal deposits.

Cycles 1 through 3 in the section near Bordo Atravesado lack well-developed sedimentary sequences and correlation relies heavily upon interstratified sandstone beds which commonly cap prominent shallowing-upward sequences. A number of features including overall decreased biotic diversity, dominance of grain-rich deposits, and a higher energy profile suggest that sedimentation in the section near Bordo Atravesado may have been heavily influenced by the Pedernal Positive Element, acting as a buried paleo-topographic feature (Figs. 31 & 32). Residual paleotopographic effects of the Pedernal Positive Element, which lies east of the field area has been shown to have influenced sedimentation throughout deposition of Yeso and into sedimentary cycles of the Lower San Andres in Lincoln, Chaves, and Roosevelt counties (Milner, 1974; Elliot and Warren, 1989). Sedimentation in the eastern stratigraphic section consistently produces shallower, terrigenous-rich deposits, suggesting that the Pedernal Positive Element strongly influenced sedimentation of Lower San Andres environments, probably through at least the first four sedimentary cycles.

Correlation between the sections near Canoncito Colorado and Loma de las Canas proved fairly reliable, especially between cycle 3 through cycle 6. Bordo Atravesado, the eastern-most stratigraphic section, often provided tenuous correlation, consistently proving to include deposits from shallower environments.

In contrast to previous cycles, cycle 4 correlated between sections defines a symmetrical Type B sedimentary sequence. Marine incursion into central New Mexico probably reached a maximum during cycle 4; deposits within sections during cycle 4 represent the least restricted, deepest water environments within the carbonate members of the San Andres Formation of central Socorro County.

Rapid shallowing-upward conditions within the fourth sedimentary cycle are particularly apparent in the section from Loma de las Canas, where conditions change vertically from deposits representing environments approaching open marine to eolian quartz sands within less than a meter of section. High-angle cross-beds produced by migration of eolian sands sweep down into the upper-most portion of marine sediments, implying that eolian sands migrated over recently exposed subtidal sediments, supporting the idea that even the deepest waters within the field area were relatively shallow.

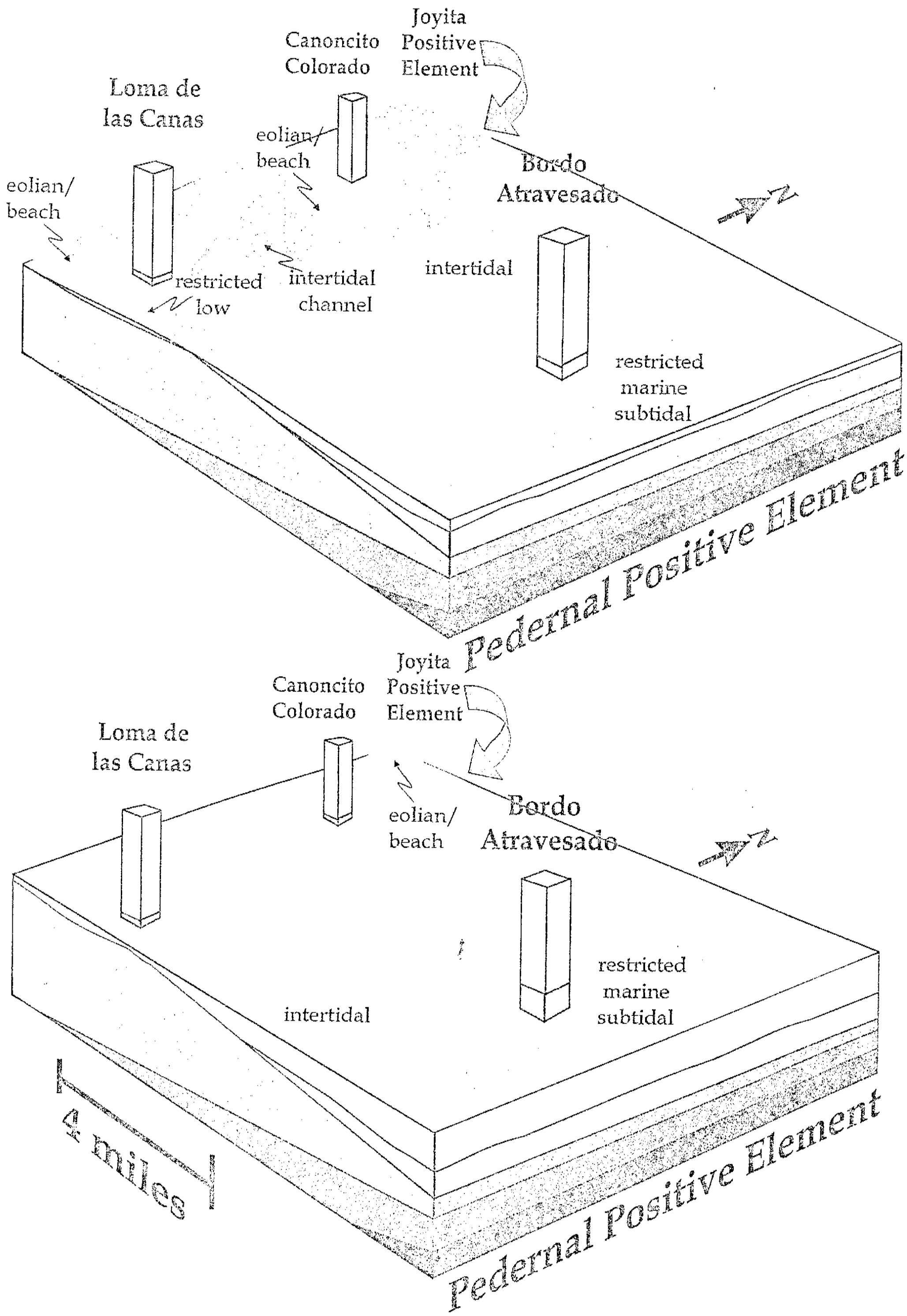

Figure 31. Interpretation of environments of deposition within the field area resulting from differences in paleotopography during deposition of the 2 'early' type A sequences that occur in the section near Bordo Atravesado. Carbonate environments are inhibited within western sections as a result of the Joyita Positive Element. Upper diagram displays environments resulting from low sea level stands; lower diagram displays environments resulting from high sea level stands. (North arrow relates to present-day positions.)

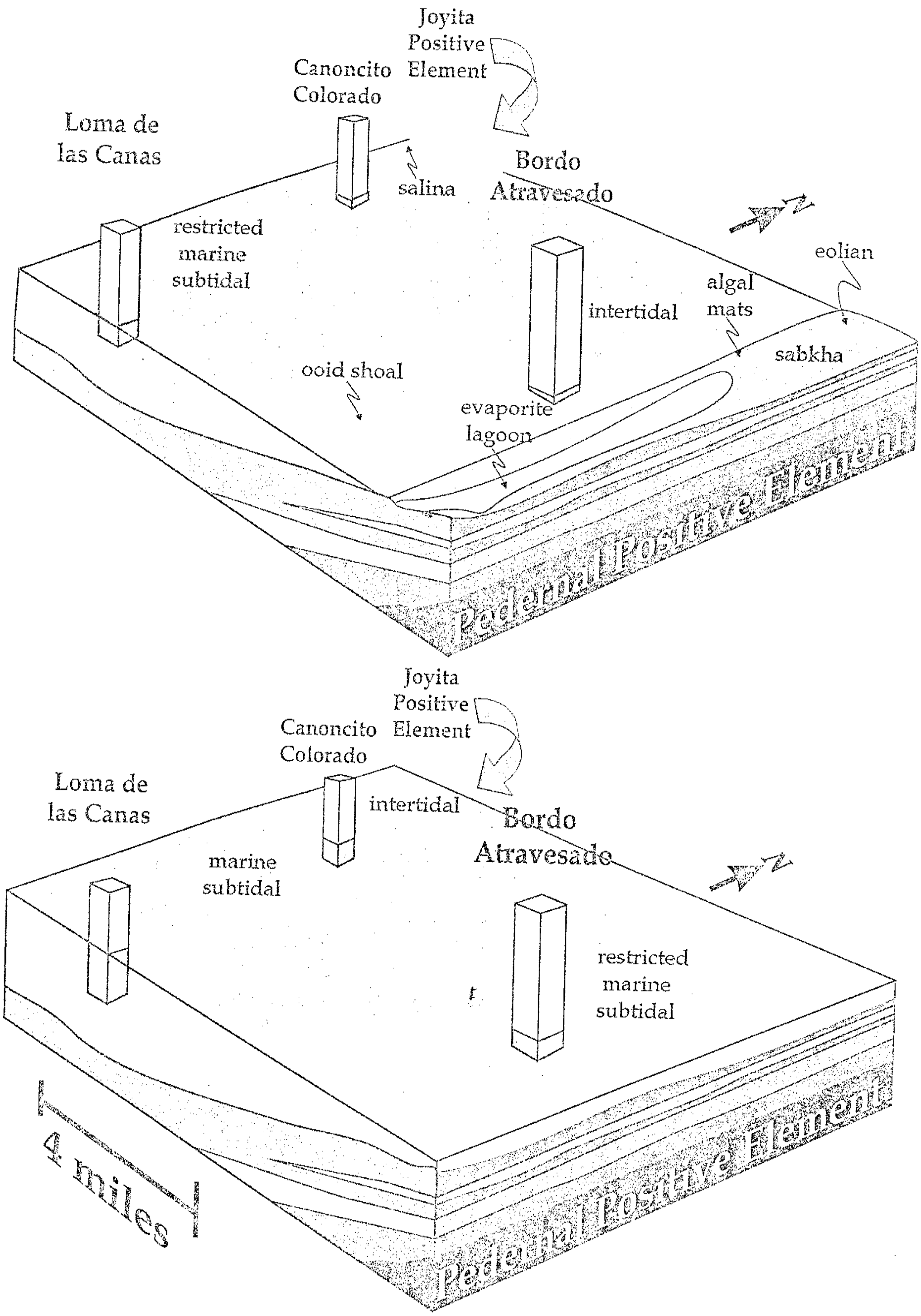

Figure 32. Interpretation of environments of deposition within the field area resulting from differences in paleotopography during deposition of correlated cyclic sedimentary sequences that occur in all three sections. Shallower carbonate environments result from paleotopographic differences produced by the Joyita and Pedernal Positive Elements east and northwest of the field area. Upper diagram displays environments resulting from low sea level stands; lower diagram displays environments resulting from high sea level stands. Evolution from Figure 31 may be a result of differences in subsidence rates between eastern and western regions of the field area. (North arrow relates to present-day positions.)

An under-developed symmetrical sequence containing only restricted subtidal, intertidal, and supratidal(?) deposits occurs in Cycle 4 of the section near Bordo Atravesado. Divergence from standard Type B cyclic sedimentation may be a result of shallower water conditions present within the region.

The fifth and sixth cycles of each section are defined by asymmetric Type A shallowing-upward sequences, comprised of well developed intertidal deposits. An overall increase in energy, associated with environments in shallower water conditions, prevailed. As a result of brecciation and thin deposits comprised almost entirely of intertidal and supratidal(?) facies, cycle 6 is very poorly defined, especially within the sections near Bordo Atravesado and Canoncito Colorado.

Variable elements and thinner deposits in the fifth and sixth cycles may be a result of an overall trend towards decreasing water depth increasing the effects of shelf geometry and paleotopography on local sedimentation. Overlying evaporite deposits, poorly exposed within the field area, may be a result of continued regional shallowing, producing an extensive region dominated by supratidal environments in the Four Mile Draw Member of the San Andres Formation in Socorro County.

Type A cycles at the base of the section near Bordo Atravesado are inconsistent with carbonates at the bases of the other two columns. Sedimentary sequences present are thinner, better-developed, and include two Type A asymmetric shallowing-upward cycles that are not clearly present elsewhere in the field area. These two extra Type A cycles in section J3 suggest that a difference in paleotopographic relief allowed marine environments to form earlier in the easternmost section (Figs. 31 & 32). Sections north and west of Bordo Atravesado may not have formed carbonate environments as a result of paleotopographic differences producing shallower environments and influx of terrigenous sediments. Differences in thickness and development of cycles may be explained by a difference in subsidence rates between eastern and western sections. A second possible explanation is that correlation between the western sections and section J3 is incorrect.

Several lines of evidence point towards positive correlation of cycles 1 through 3 between the eastern and western sections. A thick, prominent quartz sandstone bed which does not appear in other sections overlies the early sedimentary cycles in section J3. Sedimentary cycles 1 through 3 in section J3, which occur above the thick sandstone bed, are incomplete suggesting a decline in accommodation space produced by slower rates of subsidence. Difference in overall thickness between the sections can be explained by incomplete cycles in section J3. Poor exposure and intense faulting in the field area inhibits comparison of overall thicknesses between the underlying Glorieta Sandstone Member in each section. Cycles 1 & 2 within the section near Canoncito Colorado also include shallower, sandy under-developed intertidal and terrigenous deposits suggesting that the Joyita Positive Element may have been acting to influence sedimentation during early formation of carbonate environments (Fig. 32).

Cyclic sedimentary sequences within the section near Loma de las Canas are consistently more complete and better developed than other sections. Location of this section with respect to the Pedernal and Joyita Positive Elements supports the idea that both buried features may have been acting to influence sedimentation within the San Andres of Socorro County. Representative sections to the northwest and east of the field area would help confirm these assumptions, however very poor continuous exposure of

San Andres Formation within these regions resulting from structural complexity limits this approach.

Comparison to Regional Models

The carbonate members of the San Andres Formation in Socorro County are dominated by shallow, low-energy carbonates characterized by laterally extensive cyclic deposits. Similar cyclic sequences of restricted marine subtidal environments occur throughout the San Andres in central New Mexico (Milner, 1974, 1976; Elliot and Warren, 1989; Whitman, 1992) and are commonly attributed to glacio-eustatic changes in sea level combined with varying regional sedimentation and subsidence rates. Although local tectonism has not been discounted, the extensive nature of deposits combined with the record of widespread changes in relative sea level suggests that it is a less significant factor (Milner, 1976; Elliot and Warren, 1989).

Shelf geometry probably had a prominent influence on local sedimentation, exaggerating the effects of paleotopographic features (Elliot and Warren, 1989). Positive paleogeographic elements, including the Pedernal Positive Element and the Joyita Positive Element, although buried, may have influenced sedimentation by producing shallower water environments of deposition which occur in central Socorro County, especially in the easternmost and northwesternmost sections.

Early sedimentary cycles within the carbonate members of the San Andres Formation are composed of a fairly even mix of marine subtidal shelf and intertidal/tidal flat deposits. Early facies deposits represent shallower environments than associated subtidal shelf deposits to the east in Lincoln and northern Otero counties (Milner, 1974, 1976; Whitman, 1992) producing a broad regional shelf, gently inclined to the southeast (Fig. 33).

In contrast, later cycles of the carbonate members of the Lower San Andres Formation in Socorro County are dominated by intertidal deposits. Environments are highly variable and associated with increasingly restricted water conditions, suggesting that sedimentation rates may have overcome subsidence rates. Later cycles of the San Andres carbonates show greater degree of association with highly restricted environments than earlier cycles and pass vertically into poorly exposed evaporite deposits of the Four Mile Draw Member.

The results of this study show that although overall conditions proved to be shallower in nature than those to the east and southeast, environments approaching normal marine conditions occur during Type B sedimentary sequences. The residual effects of paleotopographic elements strongly effected the shelf geomoetry combining with glacio-eustatic fluctuations to produce a variety of shallow carbonate environments, especially during relative low sea level stands. Synchronous deposition of carbonates and evaporites during relative low sea level stands resulting from shelf geometry compares well with the depositional model developed by Elliot and Warren (1989) for shallow tidal flat enviroments within east-central New Mexico away from the Permian Basin.

Carbonate members of the San Andres Formation in neighboring eastern and southeastern counties are composed dominantly of limestone lithologies, whereas carbonates within Socorro County are strongly dolomitized. Increased diagenetic replacement by dolomite may be related to regionally shallower water conditions. Reflux of heavy Mg brines or mixing of hypersaline and fresh water within tidal flat environments may be responsible for severe dolomitization of carbonate deposits (Butler, 1969; Badiozamani, 1973; Bush, 1973; Folk and Land, 1975; Patterson and Kinsman, 1981). Diagenetic replacement by dolomite during burial cannot be discounted.

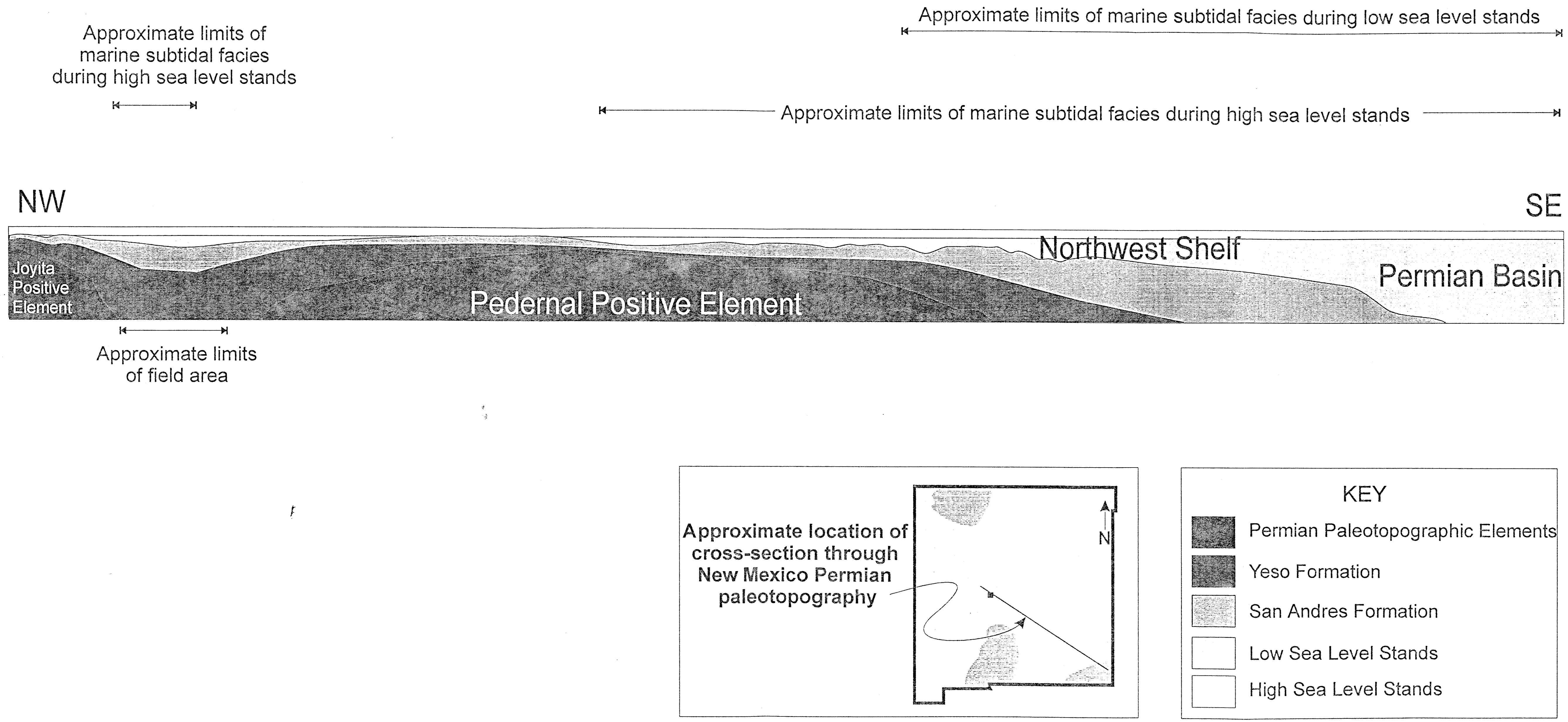

Figure 33. Idealized cross-sectional model of Permian paleotopographic elements and San Andres carbonate environments from the Joyita Positive Element to the Permian Basin. (Not drawn to scale. After Milner, 1974. Orientation relates to present-day positions)

Suggestions for Future Work

Ideally, continued research on the Lower San Andres of Socorro County would include a detailed analysis of units disrupted by horizontal brecciation and progressive environmental studies to the east, northwest, and southwest of the field area to confirm or deny interpretations made within this paper.

A detailed study of horizontally-brecciated unit geometry, composition, and lateral relations along with careful petrographic studies might produce valuable insight into facies relationships and add to our understanding of evaporite sedimentation and post-depositional modification within the carbonate members of the San Andres Formation.

Practical project size and time constraints and detail of the study limited the regional extent of the field area, however, this project will hopefully lay some groundwork for continued detailed research of the San Andres Formation within Socorro County. Outcrops to the northwest and east of the field area are of particular interest in helping to determine the degree of influence upon sedimentation on the San Andres produced by the Pedernal and Joyita Positive Elements.

CONCLUSIONS

Within the three sections measured, two types of cyclic sedimentary sequences have been identified based upon repeated patterns of lithotypes within the carbonate members of the San Andres Formation within central Socorro County. Interpretation of lithotypes within these cyclic sequences suggest that the cycles represent asymmetric and symmetrical sequences of sedimentation.

Very early marine incursion into the easternmost section (J3) may not have been strongly affected by the Pedernal Positive Element, which is suggested by two thin asymmetric shallowing sequences, dominated by restricted marine shelf and intertidal carbonates, which are not represented within northwestern and southwestern sections. Terrigenous deposits within the two western sections assumed to be time synchronous with carbonate deposition in the eastern section suggests that the Joyita Positive Element may have strongly influenced sedimentation, providing paleotopographic relief within the western sections creating adverse conditions for carbonate production.

Cycles 1 through 3 are represented as relatively under-developed asymmetric shallowing-upward sequences in the northwestern (J1) and eastern (J3) while equivalent cycles in the southwestern section (J2) produce consistently better developed thicker sedimentary sequences. Restricted marine subtidal, intertidal, and supratidal(?) deposits are typically capped by terrigenous deposits. Shallower correlative environments of deposition within the eastern (J3) and northwestern (J1) sections during cycles 1 through 3 may have been influenced by paleotopographic relief produced by the Pedernal and Joyita positive elements.

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Cycle 4, representing deepest marine subtidal conditions throughout all three sections, is represented by a well-developed symmetrical sedimentary sequence, characterized by restricted marine subtidal deposits leading into partly restricted or unrestricted subtidal marine environments, followed by a relatively rapid transition into restricted marine subtidal, intertidal, and supratidal or terrigenous deposits.

Cycles 5 and 6 are represented by variable and poorly developed restricted marine environments, dominated by intertidal and possibly supratidal deposits. Shallower conditions may have increased the influence of relatively minor paleotopographic features acting to produce a wide variety of environments largely affected by local sedimentation.

Declining influence of paleotopographic elements becomes apparent within cycles 4 -6. Increasingly restricted and shallower environments represented within cycles 5 & 6 and evaporitic facies of the Four Mile Draw Member of the San Andres Formation suggests a net decline in relative marine incursion throughout the remainder of San Andres deposition.

Application of the depositional model used within this paper compares to other regional models across central New Mexico to suggests that the carbonate members of the San Andres Formation in central Socorro County consistently represent environments which are shallower and more restricted than sediments to the east and southeast. Environments of deposition appear most similar to modern restricted tidal flat and associated shelf deposits of the Persian Gulf.

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APPENDIX A: Paleontology

Paleontological and biostratigraphic studies were not the primary focus of this project, however in an attempt to confirm a relative time frame, several organisms were examined for potential paleontological and biostratigraphical significance. Organisms, thin sections, photographs, and photomicrographs used to identify taxa are in the author's possession and can be examined on request.

Scaphopoda

Plagioglyptus c.f. *Canna* Girty 1909

Foraminifera

Globivalvulina sp. Schubert 1920 (Pennsylvanian - Permian)

Hemigordiopsida indet. (Permian)

Tolypammina ? Rhumbler 1895 (Silurian - Recent)

Geinitzina sp. Spandel 1901 (Pennsylvanian - Permian)

Nodosariida indet. (Permian? - Recent)

Agathammina sp. (Permian)

Conodonta

Neostreptognathodus c.f. *sulcoplicatus* (juvenile) (Late Permian)