Sedimentology and Depositional Environments of the Lower Permian Yeso Formation, Northwestern New Mexico

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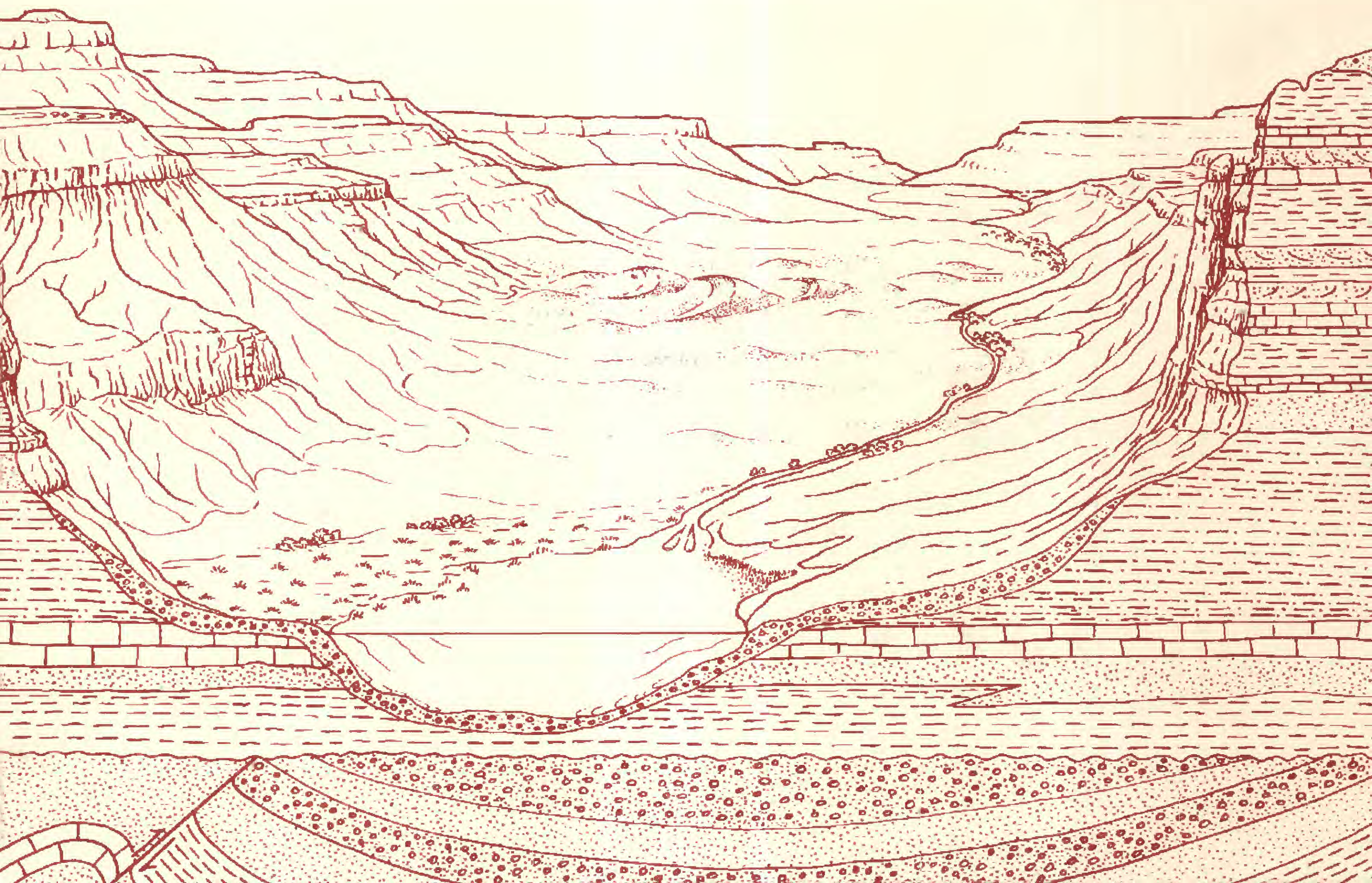

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Chapter M

Sedimentology and Depositional Environments of the Lower Permian Yeso Formation, Northwestern New Mexico

By JOHN D. STANESCO

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

U.S. GEOLOGICAL SURVEY BULLETIN 1808

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

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

U.S. GEOLOGICAL SURVEY
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Sedimentology and Depositional Environments of the Lower Permian Yeso Formation, Northwestern New Mexico

By John D. Stanesco

Abstract

In the Nacimiento Mountains of northwestern New Mexico, the Lower Permian (Leonardian) Yeso Formation is divided into a lower member, the Meseta Blanca, and an upper member, the San Ysidro. Farther south, the San Ysidro interval is equivalent to, in ascending order, the Torres and Joyita Members in the Zuni Mountains, the Los Vallos Member in the Lucero uplift, and the Torres, Cañas, and Joyita Members at Mesa del Yeso.

The Yeso Formation is composed of several lithofacies that suggest a north to south transition from continental to marine depositional environments. These lithofacies and their interpreted environments of deposition include cross-stratified and horizontally stratified sandstones of eolian dune and sand-sheet origin, wavy-bedded sandstones formed in sand-dominated sabkhas, gypsiferous rocks formed in coastal sabkhas and hypersaline lagoons, ripple-laminated sandstones originating in coastal-plain and tidal settings, and carbonate rocks formed in coastal sabkha, restricted-marine, and marine-shelf environments.

Facies in the Meseta Blanca Member indicate a juxtaposition of eolian-dune and sand-sheet environments in the northern part of the study area with sabkha and tidal-flat environments in the southern part of the study area. Strata in the Torres, Los Vallos, and Cañas Members formed in sabkha, lagoonal, restricted-marine, and marine-shelf settings during a northward transgression of Permian Basin seas. Strata in the upper part of the San Ysidro Member and in the Joyita Member represent southward progradation of eolian dune, sand-sheet, and inland sabkha environments. Eolian facies in the Yeso Formation are probably southward extensions of the erg represented by the Leonardian De Chelly Sandstone in northeastern Arizona.

Superimposed on this transgressive and regressive pattern is a smaller scale cyclic pattern involving the lateral migration of eolian dune and sand-sheet strata over supratidal mud-flat and coastal sabkha deposits. At least 12 such eolian-sabkha cycles are present in the Yeso Formation.

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INTRODUCTION

The Yeso Formation in northwestern New Mexico consists of interbedded sandstone, siltstone, gypsum, limestone, and dolomite. The relative abundance of these lithologies changes from north to south across northwestern New Mexico: gypsum and carbonate rocks become more prevalent to the south. This north to south variation in lithologies suggests that the Yeso Formation formed in several depositional settings.

Although marine deposits have long been recognized in the Yeso Formation in southeastern New Mexico, little work has been done on the depositional environments north and west of the Yeso Formation type section near Socorro, New Mexico (fig. 1).

This report describes lithofacies of the Yeso Formation in northwestern New Mexico, interprets depositional environments associated with these lithofacies, and reconstructs the paleogeography of northwestern New Mexico for each member of the Yeso. To this end, sections were measured at seven locations and then correlated to a section of De Chelly Sandstone in the Defiance Plateau of northeastern Arizona (fig. 1).

Previous Work

Several workers have identified marine depositional environments in the Yeso Formation of southeastern and south-central New Mexico (Lee and Girty, 1909; Kott-

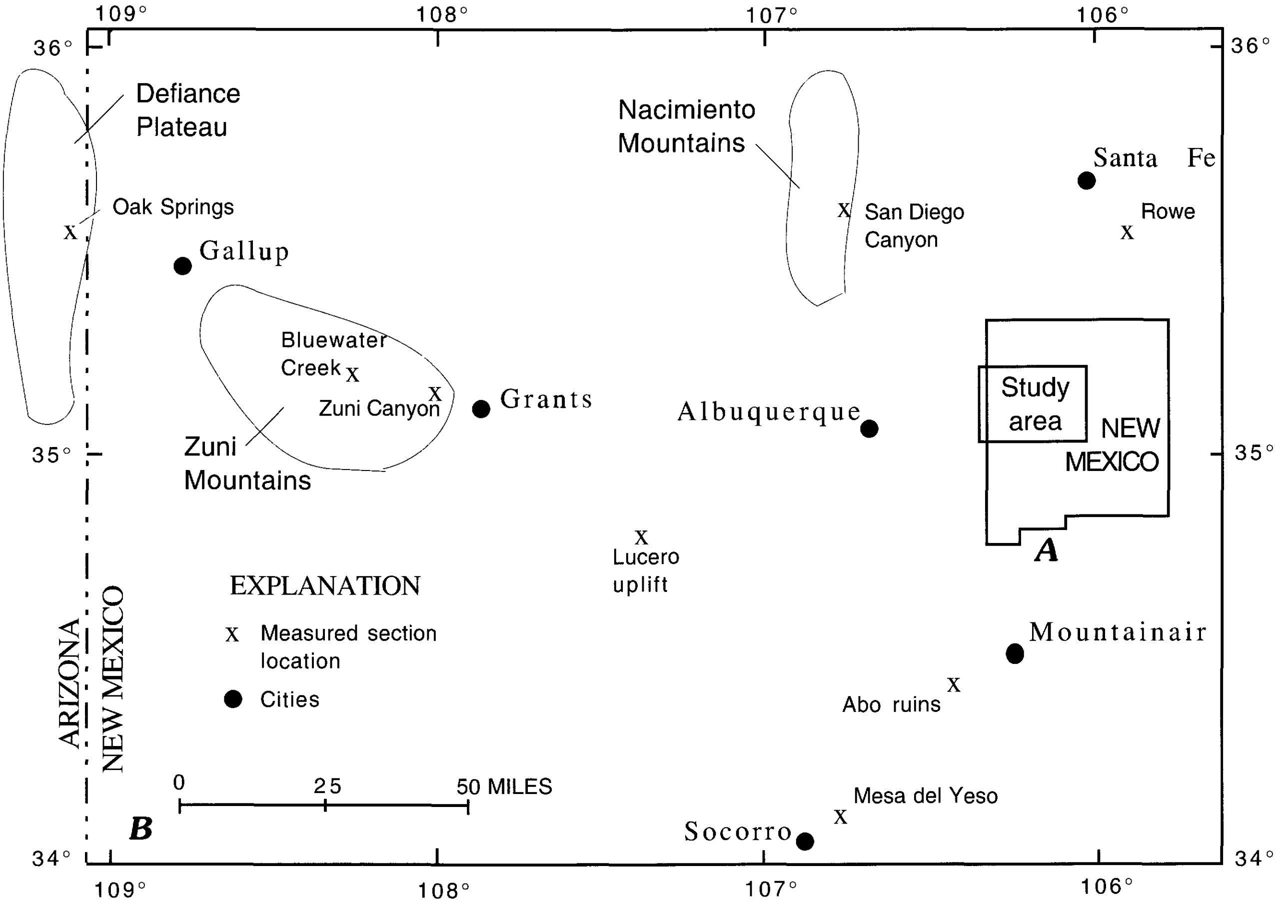

Figure 1. *A*, Index map showing location of study area. *B*, Map of study area showing names and locations of measured sections, selected cities, and major geographic features.

lowski and others, 1956). Hunter and Ingersoll (1981), in a study of the evaporites of the Cañas Member of the Yeso Formation, interpreted the depositional setting as a hypersaline lagoon representing a shallow arm of the Permian sea to the south and east. Baars (1961, 1962) suggested that the Yeso was deposited in restricted-marine and coastal mudflat environments. Broadhead and others (1983) postulated a beach or shallow marine origin for clastics in the Meseta Blanca Member near Mesa del Yeso, east of Socorro, New Mexico (fig. 1).

Stratigraphy

The Yeso Formation was named by Lee and Girty (1909) and redescribed by Needham and Bates (1943) for outcrops near Mesa del Yeso, east of Socorro, New Mexico (fig. 1). The Yeso Formation ranges in thickness from 170 m at the San Diego Canyon measured section to more than 400 m at the Lucero uplift measured section (fig. 1). Four members are recognized in the Yeso Formation at Mesa del Yeso. Listed in order of decreasing age, they are the Meseta Blanca (Wood and Northrop, 1946), Torres, Cañas, and Joyita Members. Northwest of Mesa del Yeso, in the Lucero uplift (fig. 1), the Yeso is divided into the Meseta Blanca and Los Vallos Members (Kelley and Wood, 1946). In the Nacimiento Mountains (fig. 1), two members are also defined: the Meseta Blanca and the overlying San Ysidro Members (Wood and Northrop, 1946). This terminology was also used in the Zuni Mountains (fig. 1) by Read and Wanek (1961). Colpitts (1989) recently proposed extending the stratigraphic terminology from Mesa del Yeso, near Socorro, northwestward into the Zuni Mountains. Consequently, three members of the Yeso Formation are currently recognized in the Zuni Mountains: the Meseta Blanca, Torres, and Joyita Members. The stratigraphic terminology used in different parts of the study area is summarized in figure 2.

The Yeso Formation was designated as Leonardian in age based on fossils in the correlative Bone Spring Limestone of eastern New Mexico and West Texas (Skinner, 1946). The Yeso Formation is conformable with both the underlying Abo Formation and the overlying Glorieta Sandstone. Though differing in terms of exact correlation, both Baars (1977) and Peirce (1966) defined parts of the

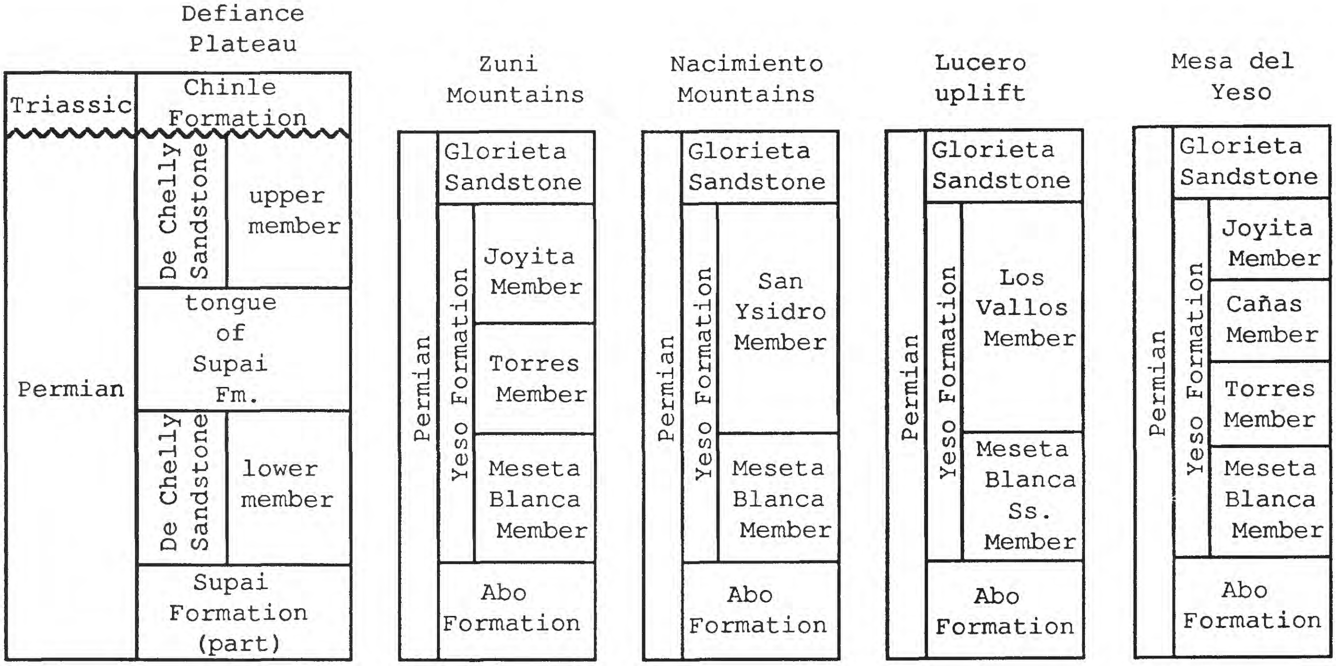

Figure 2. Stratigraphic terminology of the Permian Yeso Formation and De Chelly Sandstone in northwestern New Mexico and northeastern Arizona. Terminology in the Defiance Plateau after Read and Wanek (1961); in Zuni Mountains, after Colpitts (1989); in Nacimiento Mountains, after Wood and Northrop (1946); in Lucero uplift, after Kelley and Wood (1946); and in Mesa del Yeso, after Needham and Bates (1943).

Yeso as equivalent to the De Chelly Sandstone of the Defiance Plateau of northeastern Arizona (fig. 1).

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I thank Russell Watts for his capable assistance in the field. I also thank Chris Schenk, Christine Turner, Curt Huffman, David Rubin, and Ralph Hunter of the U.S. Geological Survey for helpful discussions at the outcrop. The manuscript was improved as the result of comments by Tom Ahlbrandt and Chris Schenk of the U.S. Geological Survey.

LITHOFACIES DESCRIPTIONS

The lithofacies described in this report are defined on the basis of field descriptions of lithology, grain size, stratification, and sedimentary structures.

Cross-Stratified Sandstone Facies

The cross-stratified sandstone facies consists of tabular-planar, wedge-planar, and trough cross-sets of fine- to medium-grained sandstone (fig. 3*A*). Stratification is dominated by inversely graded, climbing translatent strata of probable wind-ripple origin. Grain-flow layers of sand-avalanche origin (fig. 3*B*) are common in the tabular-planar and wedge-planar cross-sets but are rare in trough cross-sets. Sets of tabular-planar and wedge-planar sandstones several m thick (fig. 3*A*) are common in the San Diego Canyon measured section (fig. 1), which is the northernmost measured section in this report.

Paleo-transport directions in this facies, determined from vector slip-face orientations or trough orientations, are dominantly toward the south. In the Zuni Mountains, however, trough cross-sets in the Meseta Blanca Member and in the lower part of the Torres Member indicate transport to the north. In the southern part of the study area, trough cross-sets indicate both northerly and southerly directions of transport.

The cross-stratified sandstone facies occurs most commonly in the Meseta Blanca and Joyita Members and in the upper part of the San Ysidro Member of the Yeso. It is rare in the Torres, Los Vallos, and Cañas Members.

Horizontally Stratified, Wind-Rippled Sandstone Facies

The horizontally stratified, wind-rippled sandstone facies consists of very fine to fine-grained sandstone containing common discontinuous laminae of well-rounded, medium-grained sandstone. The horizontal to low-angle

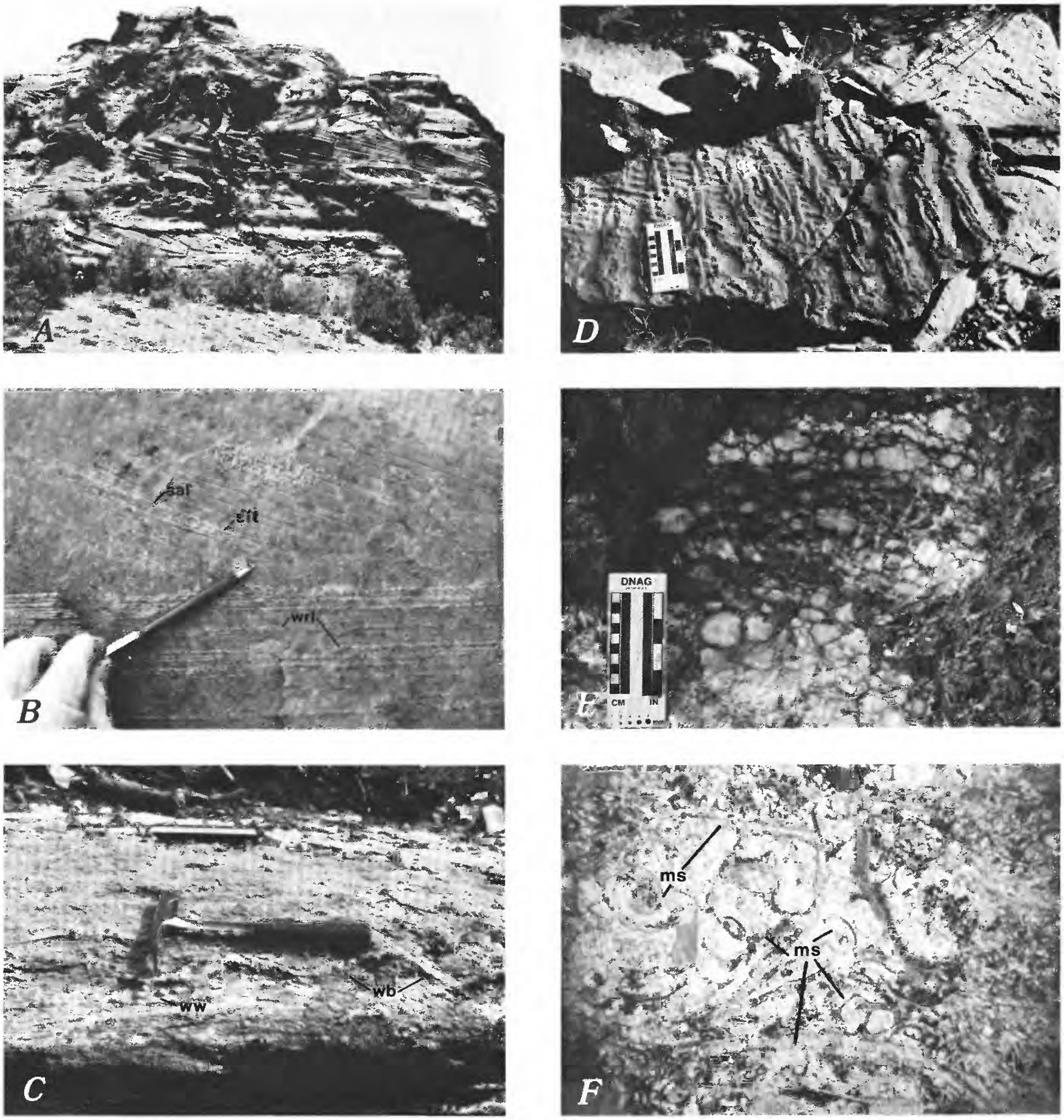

Figure 3. Photographs of selected facies of the Yeso Formation, northwestern New Mexico. *A*, Large-scale, tabular-planar and wedge-planar cross-sets of the cross-stratified sandstone facies in the Meseta Blanca Member at the San Diego Canyon measured section (fig. 1). Note person for scale in lower left-hand corner. *B*, Steeply dipping sand-avalanche layers (sal) and sand-flow toes (sft) of the cross-stratified sandstone facies overlying horizontal wind-ripple laminae (wrl) of the horizontally stratified, wind-rippled sandstone facies. Meseta Blanca Member at the San Diego Canyon measured section (fig. 1). Pencil is 14 cm long. *C*, Wrinkled bedding (wb) and "warty" weathering (ww) of the wavy-bedded, wind-rippled sandstone facies in the Torres Member at the Zuni Canyon measured section (fig. 1). Hammer is 27 cm long. "Warts" may represent calcite pseudomorphs after gypsum. *D*, Double-crested ripples (dcr) overlying ripples with a different orientation on bedding-plane surface of the ripple-laminated sandstone facies in the Torres Member at the Zuni Canyon measured section. Such features are common on tidal flats. *E*, Nodular, "chicken-wire" texture in gypsum in the Los Vallos Member at the Lucero uplift measured section (fig. 1). Dark zones surrounding nodules consist of carbonaceous silt. *F*, Photomicrograph showing mollusc shell fragments (ms) in bioclastic limestone of the carbonate rock facies in the Torres Member at the Zuni Canyon measured section. Field of view is 4 mm from bottom to top.

stratification consists largely of inversely graded, wind-ripple laminations and commonly includes medium-grained lag grains and granule ripples (fig. 3*B*). Ripple foresets within the stratification occur locally.

This facies is found throughout the study area and is most common in the Meseta Blanca and Joyita Members and in the upper part of the San Ysidro Member. It is typically associated with the cross-stratified sandstone facies (fig. 3*B*).

Wavy-Bedded, Wind-Rippled Sandstone Facies

The wavy-bedded, wind-rippled sandstone facies (fig. 3*C*) is texturally similar to the horizontally stratified, wind-rippled sandstone facies. The strata, however, are wrinkled and contorted and have contortion amplitudes ranging from one to several cm. Laminae consisting of medium-grained lag grains are common. Wavy-bedded sandstones commonly exhibit calcareous weathering "warts" that are approximately one cm in diameter (fig. 3*C*). This facies is found throughout the study area and is most common in the Torres and Los Vallos Members and in the lower part of the San Ysidro Member.

Ripple-Laminated Sandstone Facies

The ripple-laminated sandstone facies is comprised of very fine to fine-grained sandstone and lesser amounts of siltstone. Bedding is tabular and channel forms are rare. Strata consist primarily of ripple laminations. Small, discontinuous layers of micaceous silt and clay commonly occur along parting surfaces. Salt hoppers are common, mudcracks less so.

Low-index symmetric (wave) and asymmetric (current) ripples are common on bedding-plane surfaces. Double-crested ripples and ripples with bimodal orientations also occur (fig. 3*D*). In the southern part of the study area, siltstone units as much as 0.4 m thick interbed with ripple-laminated sandstones.

Gypsiferous Rocks

Gypsum occurs in a variety of associations including relatively pure, massive layers; interstitial gypsum in sandstone and siltstone; and vug infillings in limestone and dolomite. Most commonly, gypsum displaces sandstone and siltstone and exhibits a "chicken-wire" texture (fig. 3*E*) or a vein-like habit. Some gypsiferous sandstone is cross-stratified and wavy bedded. In the southeastern part of the study area, thick units of massive gypsum and laminated gypsum occur. Some gypsum layers locally interbed with thin limestones. Gypsiferous units are commonly associated with underlying carbonates and overlying wavy-bedded sandstones.

Gypsum is found mainly in measured sections in the southern part of the study area, although its occurrence has recently been reported in the southern end of the Zuni Mountains (Colpitts, 1989). In the southern part of the study area, it is most common in the Cañas Member but is also found in the Torres and Los Vallos Members.

Carbonate Rocks

Thin to thickly bedded limestones and dolomites, mostly micritic, occur throughout the study area but are much more abundant in the southern part of the study area. Symmetric (oscillation) ripples, small desiccation polygons, pseudomorphs after halite and gypsum, and possible stromatolitic structures are rare. Oolites are reported from one of the dolomites in the Zuni Mountains (Colpitts, 1989). In the Lucero uplift and Abo ruins measured sections (fig. 1), some carbonate units are vuggy and have voids infilled with gypsum. Fossils are rare, but forams, small bivalves, conispiral gastropods, and infilled burrows were found during the present study in one of the limestones in the Zuni Mountains (fig. 3*F*). Colpitts (1989) reported scaphopods and possible brachiopods from the same area. In the Abo ruins measured section (fig. 1), several large, coiled cephalopods were found. The number of carbonate beds within the Yeso Formation increases to the south; these beds are confined to the Torres, Los Vallos, and Cañas Members.

DEPOSITIONAL MODEL

Previous work on the Yeso Formation and correlative Leonardian strata in Arizona, New Mexico, and Texas has established a transitional position for the Yeso between an eolian erg to the northwest, i.e., the De Chelly Sandstone (Blakey, 1979; Stanesco, in press) and a marine environment to the southeast, i.e., the Bone Spring Limestone and the upper part of the Clear Fork Group (Kottlowski and others, 1956; Handford, 1981). Marine environments have also been shown in Leonardian paleogeographic reconstructions by Blakey and others (1988) and Peterson (1988). Environments of deposition that are associated with each of the lithofacies within the Yeso Formation indicate a transition from eolian to marine settings. These inferred depositional environments are described in the following section.

INTERPRETATION OF DEPOSITIONAL ENVIRONMENTS

Cross-Stratified Sandstone Facies

The two most common stratification types in the cross-stratified sandstone facies (inversely graded, climbing translatent strata and grain-flow, sand avalanche layers; fig. *3B*) are both good indicators of deposition in eolian dunes (Hunter, 1977; Kocurek and Dott, 1981). This is particularly true when these two stratification types are found interbedded with each other—this configuration suggests deposition on the lower slip-face and dune apron.

In the measured sections in the northern part of the study area, particularly in the San Diego Canyon measured section (fig. 1), the size of the cross-sets and the consistent southerly slip-face orientation in tabular-planar and wedge-planar cross-stratified sandstones indicates deposition in transverse or barchanoid dunes migrating toward the south-southwest (Blakey and Middleton, 1983). In the Zuni Mountains, however, dunes in the Meseta Blanca Member exhibit northerly transport directions. Farther to the south and east, in the Lucero uplift and Abo ruins measured sections, bimodal north-south transport is evident. This fluctuation in eolian transport direction may reflect onshore winds or seasonal changes in wind directions that are commonly associated with coastal dunes (Blakey and Middleton, 1983).

Horizontally Stratified, Wind-Rippled Sandstone Facies

The abundance of inversely graded, wind-ripple laminations; granule ripples; and lag grains in horizontally stratified to low-angle, cross-stratified sandstones suggests an eolian sand-sheet origin for the horizontally stratified, wind-rippled sandstone facies (Ahlbrandt and Fryberger, 1982). This facies is commonly associated with the cross-stratified sandstone (eolian dune) facies and probably formed in low-lying sand plains surrounding, or in advance of, dune-fields (Fryberger and others, 1979). Some of the units in this facies may also have formed in interdunes within dune fields.

Wavy-Bedded, Wind-Rippled Sandstone Facies

The occurrence of wind-ripple laminae and evenly disseminated lag grains along bedding surfaces in this facies suggests an eolian origin. The wrinkles and contortions in the laminae indicate disruption of the layering. Similar features have been found in modern sabkha environments and have been attributed to displacive growth of evaporites in sand (Fryberger and others, 1983). The wavy-bedded, wind-rippled sandstone facies formed in sand-dominated sabkhas in both inland and coastal settings.

The "warty" weathering that characterizes this facies may represent small calcite replacements after gypsum in sand (D.M. Rubin, oral commun., 1988). This facies is commonly found in vertical association with sand-sheet deposits and sandy gypsum units. It may be considered transitional between the drier sand-sheet deposits and the wetter, more evaporitic, sandy gypsum deposits.

Ripple-Laminated Sandstone Facies

The presence of both wave and current ripples in the ripple-laminated sandstone facies suggests that it was deposited subaqueously. The occurrence of mudcracks and salt hoppers, however, indicates intermittent subaerial exposure (Baldwin, 1973). The mud drapes that commonly coat ripple laminae originate under conditions alternating between current deposition and suspension deposition (Klein, 1977).

Several features found in this facies commonly form in supratidal and intertidal settings. These include bidirectional ripples, double-crested ripples (fig. *3D*), and interference ripples (Klein, 1977) as well as mudcracks and salt hoppers (Baldwin, 1973). In the southern part of the study area, interbedded sandstone and siltstone form a subfacies to the ripple-laminated sandstone facies—this is also consistent with a tidal interpretation for the environment of deposition.

The measured sections in the northern part of the study area are farther removed from the influence of Permian Basin seas (Hunter and Ingersoll, 1981), and it is less likely that the ripple-laminated sandstone facies in these sections formed in a tidal environment. Here, deposition in playa mud flats or in coastal-plain or inter-fluvial settings is postulated (Kendall, 1984; Handford, 1981).

Gypsiferous Rocks

The variety of habits and associations of gypsiferous rocks in the Yeso Formation suggests several depositional settings for this facies. Massive and laminated gypsum found in the Mesa del Yeso, Abo ruins, and Lucero uplift measured sections (fig. 1) probably formed subaqueously (Kendall, 1984). This interpretation is supported by the stratigraphic association of massive and laminated gypsum with marine limestones in these sections. Hunter and Ingersoll (1981) interpreted the environment of deposition for this type of gypsum in the Cañas Member as a salina or hypersaline lagoon associated with an arm of the Permian Basin sea in southeastern New Mexico.

Other gypsiferous outcrops in the same measured sections exhibit displacive or replacive characteristics including "chicken-wire" texture (fig. 3*E*), vug infillings in carbonate rocks, and interstitial growth within siltstones and inferred eolian sandstones (Kendall, 1984). In these instances, deposition in a coastal sabkha is postulated.

Carbonate Rocks

Limestones and dolomites in the Yeso Formation are vertically associated with gypsiferous rocks, eolian sandstones, and supratidal sandstones. The presence of desiccation polygons, salt casts, algal mats, possible stromatolitic structures, and vugs infilled with gypsum suggest that some of the carbonates are of sabkha to intertidal origin (Shinn, 1983). The middle carbonate unit in the Zuni Canyon measured section (figs. 1 and 4) contains casts of selenite crystals. It also contains forams, very small bivalves, gastropods, and scaphopods and may have formed in a restricted marine embayment. In the southeastern part of the study area, the presence of definitive marine megafossils (in the form of large, coiled cephalopods) indicates connection to an open marine environment. Here, origin on a shallow marine shelf is inferred.

LATERAL AND VERTICAL DISTRIBUTION OF FACIES

The various facies in the Yeso Formation are not uniformly distributed throughout the study area. Measured sections in the northern part of the study area are interpreted to consist primarily of eolian sandstones representing dunes, sand sheets, and inland clastic sabkhas. The southern measured sections include gypsiferous rocks, interbedded sandstones and siltstones, and carbonate rocks that formed in sabkha, tidal, restricted-marine, and marine-shelf environments (fig. 4).

Stratigraphically, eolian deposits are most prominent in the lowermost part of the Yeso Formation (the Meseta Blanca Member) and in the uppermost part of the Yeso Formation (the Joyita Member and the upper part of the San Ysidro Member) (figs. 2 and 4). Conversely, sabkha, tidal, restricted-marine, and shelf deposits are more prevalent in the middle part of the Yeso (the Torres, Los Vallos, and Cañas Members) (fig. 4).

This pattern suggests a large-scale cyclicity in which two major episodes of eolian progradation from the north were separated by a marine transgression from the south.

Cyclicity

On a smaller scale, vertical repetition of facies within each member of the Yeso Formation also indicates cyclic deposition. These cycles generally occur over an interval of 1 to 8 m and commonly mimic the lateral distribution of lithofacies described in the previous section. Two representative cycles (from the Torres and Los Vallos Members at two different locations) are illustrated in figures 5*A* and 5*B*. In each case, the cycles are initiated by a limestone with a sharp lower contact. This may indicate a rapid marine transgression (Blakey and Middleton, 1983). The cycles coarsen upward and are regressive because they represent the lateral migration of eolian sand-sheet and dune strata over supratidal mud-flat and coastal sabkha deposits. In measured sections from the northern part of the study area that are farther removed from direct marine influence, cycles are manifested in the alternation of eolian dune and sand-sheet deposits with wetter inland sabkha and mud-flat deposits (fig. 5*C*).

Poor outcrop exposure hinders determination of the exact number of cycles in the Yeso Formation. In several of the measured sections, however, twelve small-scale cycles averaging 5 m in thickness were identified.

Cyclic deposition is a common feature of Permian strata in the western United States (Mack and James, 1986; Blakey and Middleton, 1983; Johnson, 1989). Most workers have related these cycles to Milankovitch orbital parameters (Johnson, 1989) or to eustatic changes in sea level caused by fluctuating ice volumes in southern hemisphere ice sheets (Blakey and Middleton, 1983). The Yeso depositional cycles in the southern part of the study area appear to be the result of small-scale transgressions and regressions along a coastal plain of low relief, and, as such, it is likely that these transgressions and regressions were caused by fluctuating ice volumes in the southern hemisphere. The lack of age control on strata in the Yeso Formation precludes correlation of either the large- or small-scale Yeso cycles with Milankovitch parameters.

Cycles observed in measured sections in the northern part of the study area may reflect climatic changes induced by Milankovitch parameters but may also be the result of changes in the ancient water table caused by transgressive and regressive events farther south. Chan and Kocurek (1988) have postulated that marine transgression could induce rising water tables and could possibly generate inland sabkhas more than 100 km from a shoreline.

The number and regularity of cycles present in the Yeso interval and the absence of coarse-grained deposits in the formation favor eustatic as opposed to tectonic processes to explain the cyclicity.

GEOLOGIC HISTORY

Meseta Blanca Member

Deposition of the Meseta Blanca Member (fig. 6*A*) represents the encroachment of eolian facies in the form of dunes, sand sheets, and sand-dominated sabkhas southward

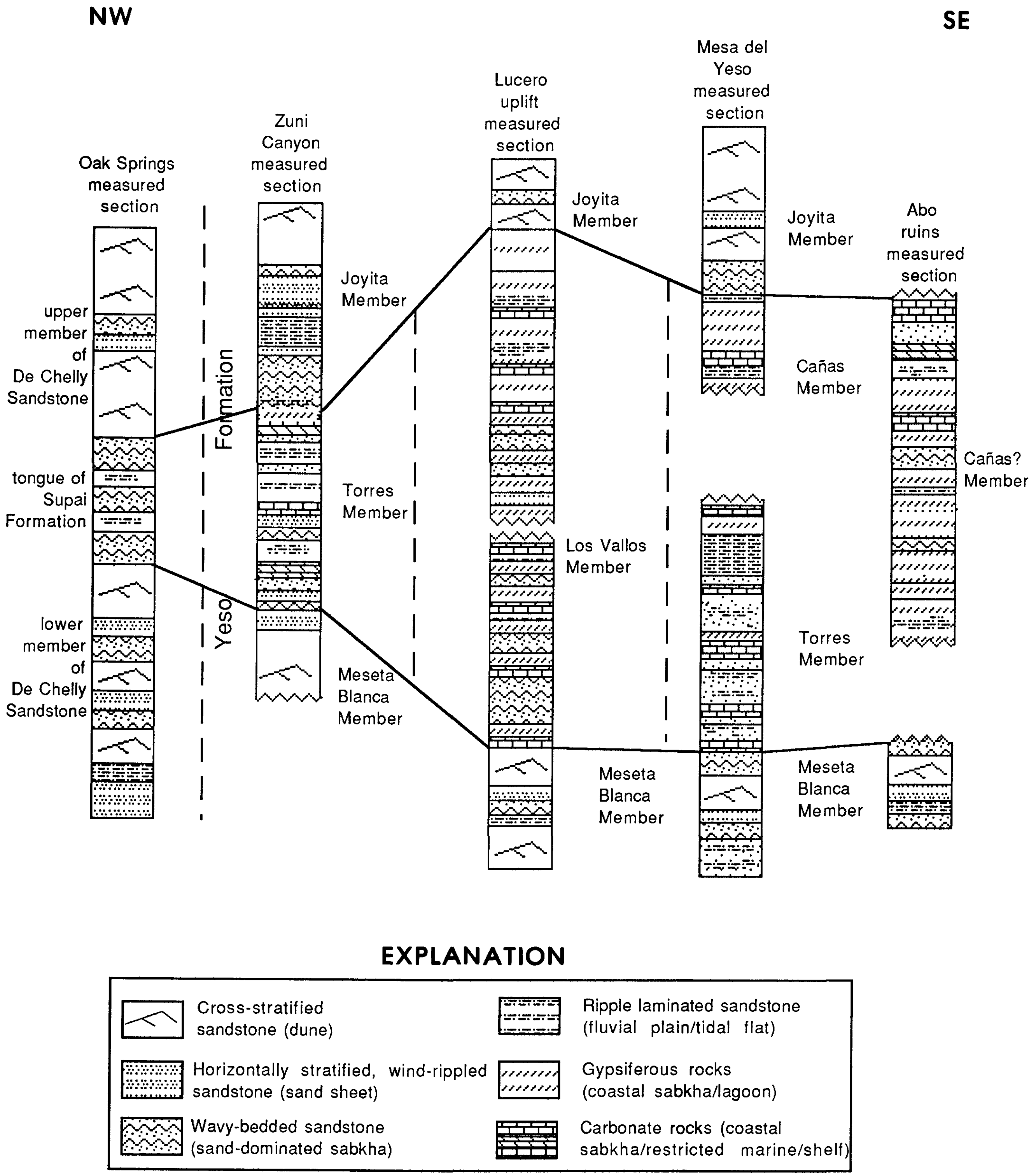

Figure 4. Schematic distribution of lithofacies and inferred environments of deposition in selected measured sections of the Yeso Formation and De Chelly Sandstone in northwestern New Mexico and northeastern Arizona. See figure 1 for location of measured sections. Gaps within sections indicate covered intervals. Stratigraphic nomenclature changes at vertical dashed lines. The Torres and Los Vallos Members of the Yeso Formation probably correlate with the tongue of Supai Formation that separates the upper and lower members of the De Chelly Sandstone on the Defiance Plateau (Oak Springs measured section).

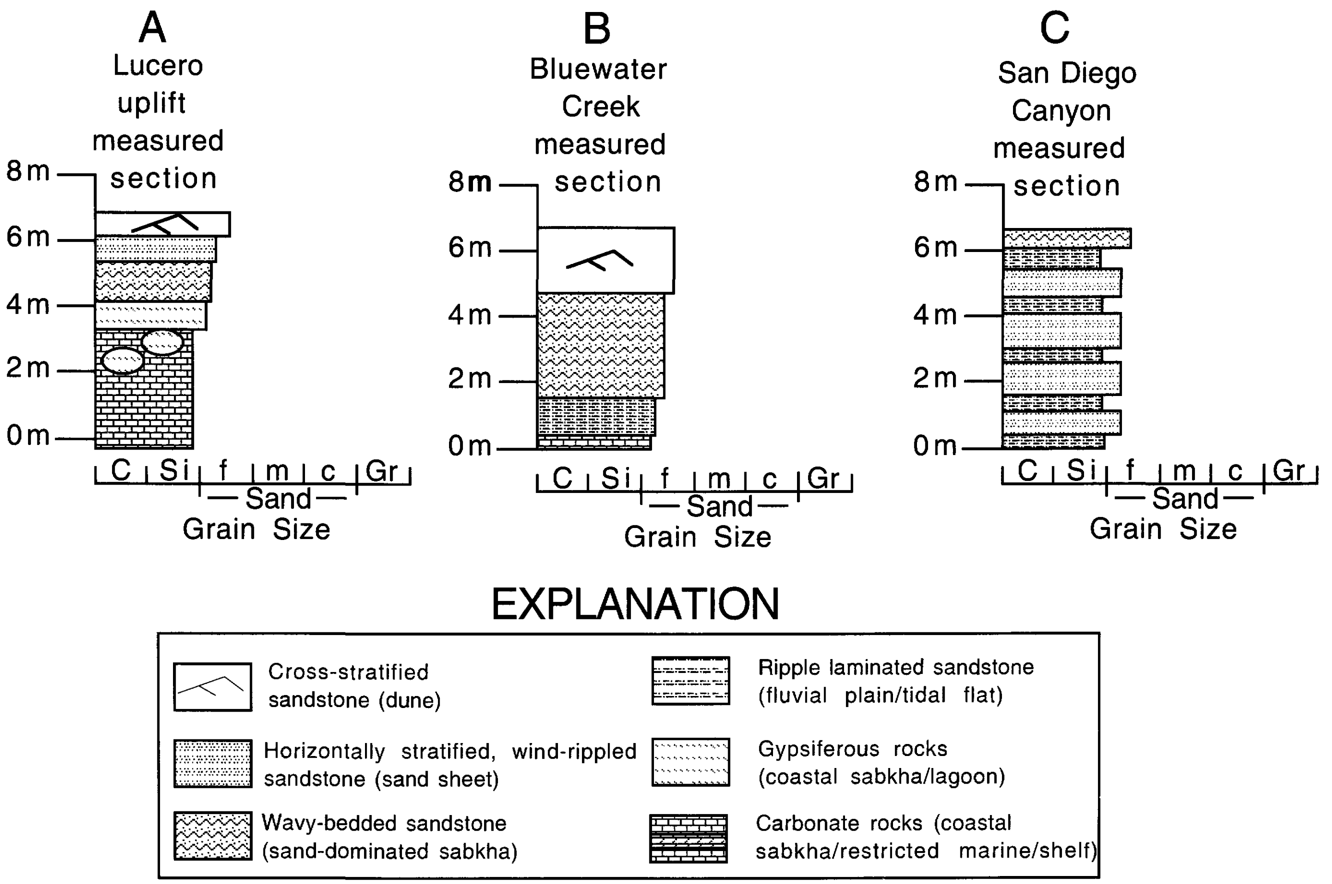

Figure 5. Examples of cyclic deposition in the Yeso Formation of northwestern New Mexico. Grain size is indicated at base of each cycle. C, clay; Si, silt; f, fine sand; m, medium sand; c, coarse sand; Gr, granules. *A*, Coarsening upward regressive cycle indicating progradation of eolian dune and sand-sheet deposits over sabkha sandstones, evaporites, and carbonates. *B*, Coarsening upward regressive cycle indicating progradation of eolian dune and sand-sheet deposits over sabkha sandstones, supratidal mudflats, and restricted-marine carbonates. *C*, Repetitive interbedding of eolian sand-sheet and sand-dominated sabkha deposits with coastal plain, fluvial, or supratidal mud-flat deposits. Cycles probably resulted from eustatic sea level changes caused by fluctuations in the volume of southern hemisphere ice sheets.

onto fluvial, flood-plain, and tidal deposits of the underlying Abo Formation (Broadhead and others, 1983). The Abo–Meseta Blanca contact is gradational and intercalated, suggesting a gradual change of environments. In the northern part of the study area, strike and dip data indicate that Meseta Blanca dunes were of the barchan or transverse-ridge type. These dunes were probably part of a southern extension of the prograding De Chelly erg in northwestern New Mexico (Stanesco, in press). Coastal dunes exhibiting northerly or bimodal north-south directions of transport developed in the Zuni Mountains and Lucero uplift regions.

In measured sections in the southeastern part of the study area, the Meseta Blanca Member is dominated by sand-sheet and sabkha deposits; fewer cross-stratified dune deposits are represented. Near Socorro, New Mexico, the Meseta Blanca Member was most likely deposited in an intertidal setting.

Torres, Los Vallos, and Cañas Members and Lower Part of the San Ysidro Member

Facies of the middle Yeso interval (fig. 6*B*) indicate a marine transgression from the south and a concurrent northward shift of sabkha and sand-sheet environments. In the northern part of the study area, sand-dominated sabkhas and lower coastal-plain mud flats developed in areas previously dominated by dunes and sand sheets. Farther south, coastal, evaporite-dominated sabkhas and supratidal mud flats formed. Sand sheets and small dunes migrated intermittently over the sabkha surfaces. Limestones and dolomites deposited during this interval originated in sabkhas, restricted marine embayments, and inner-shelf environments.

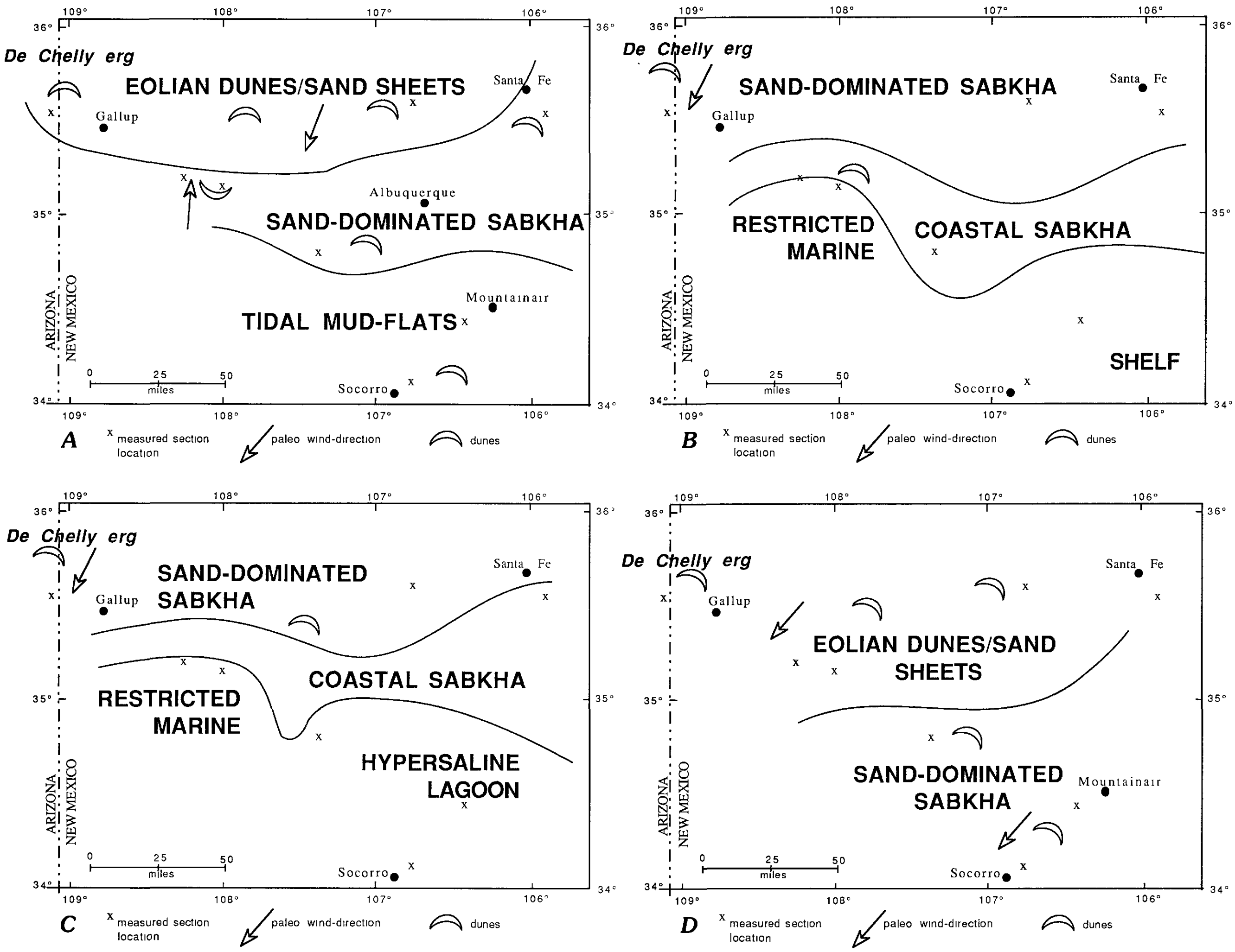

Figure 6. Paleogeographic maps of study area during deposition of the Yeso Formation. Facies boundaries, marked by curved lines, fluctuated during cyclic deposition. *A*, Meseta Blanca Member. Note north-south juxtaposition of eolian dunes and sand sheets with sand-dominated sabkhas and tidal mud flats. During this time, the anomalous northward wind direction, west of Albuquerque, may result from onshore winds associated with coastal dunes. *B*, Torres, Los Vallos, lower San Ysidro Members. Marine shoreline transgresses northward. Coastal and sand-dominated sabkhas cover northern part of the area. *C*, Cañas, Torres, Los Vallos, lower San Ysidro Members. Transgression stabilizes. Restricted-marine and hypersaline lagoon environments, characterized by massive and laminated gypsum deposits, develop in near-shore settings. Coastal and sand-dominated sabkha environments continue in northern part of the area. *D*, Joyita and upper San Ysidro Members. Eolian progradation from the north. Marine environment regresses southward. Sand-dominated sabkhas develop in southern part of the area. Eolian dunes and sand sheets are probably part of the De Chelly erg in northeastern Arizona.

The middle Yeso interval contains numerous regressive cycles involving the progradation of eolian sandstones over coastal sabkha evaporites and carbonates. This suggests several oscillations of the marine shoreline during an overall transgression.

Portions of the Torres Member in the Zuni Mountains and the Los Vallos Member in the Lucero uplift probably correlate with the Cañas Member, which is recognized in the measured section near Socorro (Needham and Bates, 1943). This correlation is particularly apparent in the Lucero uplift, where the upper part of the Los Vallos Member contains abundant gypsum. Hunter and Ingersoll (1981) determined that the Cañas evaporites formed in a hypersaline lagoon or salina (fig. 6*C*) that was connected to the Permian sea to the south and east. Some gypsum units in the Lucero uplift probably formed in these same lagoonal or salina environments; other gypsum units are interbedded with definite eolian sandstones and probably represent coastal sabkha deposits. Carbonate rocks interbed with gypsum as far north as the Zuni Mountains (Colpitts, 1989). These rocks formed during periods of more normal salinity that may have been caused by influxes of marine waters associated with transgressive high stands. Transgressive deposits that are evident in the middle Yeso interval probably correlate with sandy sabkha deposits in the tongue of the Supai Formation that separates the upper and lower members of the De Chelly Sandstone in the Defiance Plateau of northeastern Arizona (figs. 2 and 4).

Upper Part of the San Ysidro Member and Joyita Member

Deposits formed during this interval represent a general southward regression of the sea and a return to eolian dune, sand-sheet, and sand-dominated sabkha conditions in the northern part of the study area (fig. 6*D*). This regression is probably associated with the progradation of the upper member of the De Chelly Sandstone (fig. 2). Cross-stratified dune deposits are found in all measured sections. The dominant direction of transport was toward the southwest. The eolian deposits grade upward into similar cross-stratified sandstones of the overlying Glorieta Sandstone.

CONCLUSIONS

Six lithofacies are recognized in the Yeso Formation in northwestern New Mexico. They include cross-stratified sandstones; horizontally stratified, wind-rippled sandstones; ripple-laminated sandstones; wavy-bedded sandstones; gypsiferous rocks; and carbonate rocks. These lithofacies formed in eolian dune, sand-sheet, fluvial-plain, playa, inland and coastal sabkha, tidal, restricted-marine, and marine-shelf environments.

Interbedding of lithofacies on a scale of 1 to 8 m indicates at least twelve depositional cycles within the Yeso Formation. The cycles are dominantly regressive and suggest eolian progradation from the north. Cyclic deposition was probably the consequence of eustatic changes in sea level resulting from fluctuations in southern hemisphere ice sheets.

Strata in the Meseta Blanca Member formed in eolian dunes and sand sheets that graded southward into sand-dominated sabkha and tidal flat deposits. Strata in the Torres, Los Vallos, and Cañas Members represent a northward transgression of sabkha, lagoonal, and marine-shelf environments associated with Permian seas to the south and southeast. Strata in the upper part of the San Ysidro Member and in the Joyita Member indicate a return to eolian dune, sand-sheet, and sand-dominated sabkha conditions. The Joyita Member and the upper part of the San Ysidro Member grade upward into similar strata of the overlying Glorieta Sandstone.

The eolian deposits of the Yeso Formation were probably southward extensions of the De Chelly erg in the Defiance Plateau of northeastern Arizona.

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