Deposition and Diagenesis of Permian Evaporites and Associated Carbonates and Clastics on Shelf Areas of the Permian Basin

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ABSTRACT

During Medial Permian (Guadalupian) time the following spectrum of depositional environments characterized shelf areas surrounding the Delaware Basin: 1) reef, 2) backreef apron, 3) lagoon, 4) intertidal zone, 5) coastal sabkha, 6) continental sabkha, 7) deflation flat. Maximal widths of Guadalupian shelf lagoons ranged up to 30–40 miles; coastal plains ranged up to 250–300 miles in width. Outer shelf sediments consist predominantly of carbonates (subtidal, intertidal, supratidal), while middle and inner shelf deposits consist dominantly of clastics containing evaporites (coastal sabkha, continental sabkha, and deflation flats).

Permian coastal and continental sabkha sediments contain a suite of sulfate deposits similar in all aspects to that described from the southern margin of the Persian Gulf. Brine pan deposits, containing sulfates and chlorides, are extensively preserved in Permian continental sabkhas along with halite-cemented deflation flat sandstones.

During high stands of sea level, Permian shelves were characterized by arid climates, carbonates accumulated on outer shelf areas, and evaporites were deposited in coastal and continental sabkhas of middle and inner shelves. Early dolomitization of coastal sabkha carbonates occurred. Progradation of coastal and continental sabkhas and deflation flats took place during stillstands (and regressions), lagoons became infilled and gypsum became progressively replaced by anhydrite.

During maximum low stands of sea level, outer—and portions of middle shelf areas received increased rainfall, while much of the middle and inner shelf area remained arid. Subaerially exposed subtidal-intertidal carbonates were subjected to early fresh water diagenesis and became mineralogically stabilized (to calcite), leached and lithified; paleoleaching and replacement of sulfates by silica also took place in the belt of increased rainfall.

During burial subtidal-intertidal limestones, stabilized and lithified in a fresh water environment, became dolomitized, and leached porosity was occluded by sulfate precipitation. Pattern and degree of late dolomitization indicate that it resulted from regional, long-continued, predominantly lateral and downward hydrodynamic reflux of brine enriched in Mg^{++} and $SO_4^{=}$. Such brines probably evolved in adjacent clastic coastal and continental sabkha facies wherein early dolomitization did not occur.

INTRODUCTION

The Permian Basin (Fig. 1) represents one of the classical geological provinces of the world. The areas became a mecca for geologists largely because of the magnificent published works of King (1942 and 1948) and Newell and others (1953) and because of the prolific hydrocarbon production and potash mining. Probably in no other part of the world does such diversity in lithofacies and depositional environments exist in so relatively small an area. It is all the more remarkable when one considers the lack of significant subsequent tectonic deformation and that late Guadalupian depositional topography has been quite accurately resurrected by Cenozoic uplift and erosion of the Guadalupe Mountains and western Delaware Basin (Fig. 1). Permian strata dip gently to the east and constitute significant hydrocarbon reservoirs in the subsurface, and the area represents one of the world's major petroleum provinces. Because of the wealth of subsurface data and the opportunity to compare outcrop and subsurface data the Permian Basin constitutes an unparalleled sedimentological analogue to a course in comparative anatomy.

In Guadalupian Time the paleogeography depicted in Fig. 1 evolved (King, 1948; Newell and others, 1953) and the Delaware Basin became bordered by reefs (Goat Seep-Capitan, Fig. 2) whose steeply dipping forereef talus slopes descended to water depths ranging from 1500–3300

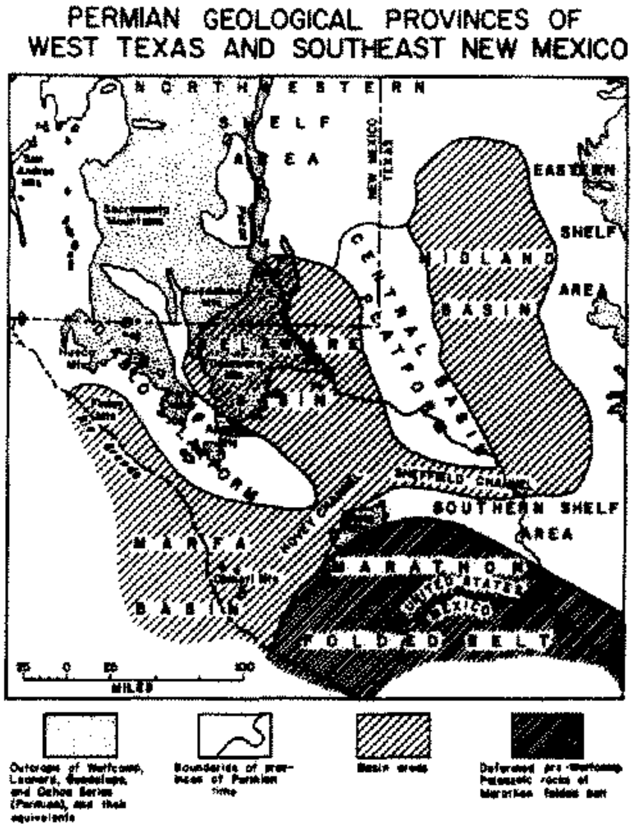

Figure 1. Index map of Permian Basin depicting depositional topography that characterized the Guadalupian interval (adapted from King, 1948).

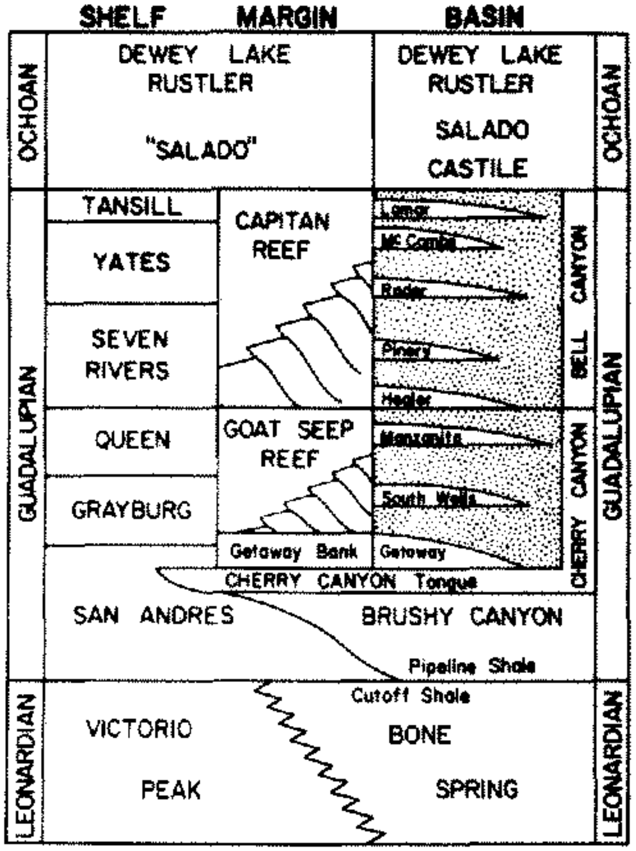

Figure 2. Correlation chart for Permian Basin (adapted from Newell and others, 1953).

feet. Margins of the Delaware Basin were incised by large submarine canyons which extended well back into the shelves (Jacka and others, 1969).

In ascending order Guadalupian formations of the Northwest shelf and Central Basin Platform (Fig. 1) of the Permian Basin include the Grayburg, Queen, Seven Rivers, Yates and Tansill Formations (Fig. 2) which constitute the Artesia Group.

Largely because of the nature of exposures in the Guadalupe Mountains, the Permian Basin has been regarded as a major carbonate province. Guadalupian carbonates of the Grayburg, Queen, Seven Rivers, Yates and Tansill Formations extend shelfward as far as 40 miles (Grayburg time) and commonly no more than 4–8 miles (Yates time). In Guadalupian Time the Northwest Shelf area was up to 250–300 miles wide, and except for the narrow band of outer shelf carbonates the entire province consisted of clastics and evaporites.

Subsurface cores from the Grayburg and Queen Formations of the Northwest Shelf were analyzed from Chaves, Eddy and Lea Counties, New Mexico (Fig. 3). Cores from the Grayburg, Queen, Yates and Tansill Formations were studied from the subsurface of the Central Basin Platform in Lea County, New Mexico, and Winkler, Ector, Ward and Pecos Counties in Texas (Fig. 3). Characteristics of different types of "electric" logs (gamma ray–sonic, gamma ray–neutron, gamma–formation density) were studied for cored intervals; it then became possible to determine characteristics of the formations much farther to the north and east than the limits of core control.

Because so little has been written about the predominantly clastic Guadalupian shelf sediments, one of the major objectives of this paper will be to describe characteristics of these wide-spread evaporite-bearing clastics. It would not be possible to determine characteristics of these clastics from outcrop studies because extensive leaching of all halite and much of the sulfate has obscured their original characteristics.

PREVIOUS WORK

Early workers who contributed to general knowledge of Permian Basin stratigraphy include Crandall (1929), Lloyd (1929), Lang (1937), DeFord and Riggs (1938), Adams (1939 and 1940), DeFord and Riggs (1941) and Adams and Frenzel (1950).

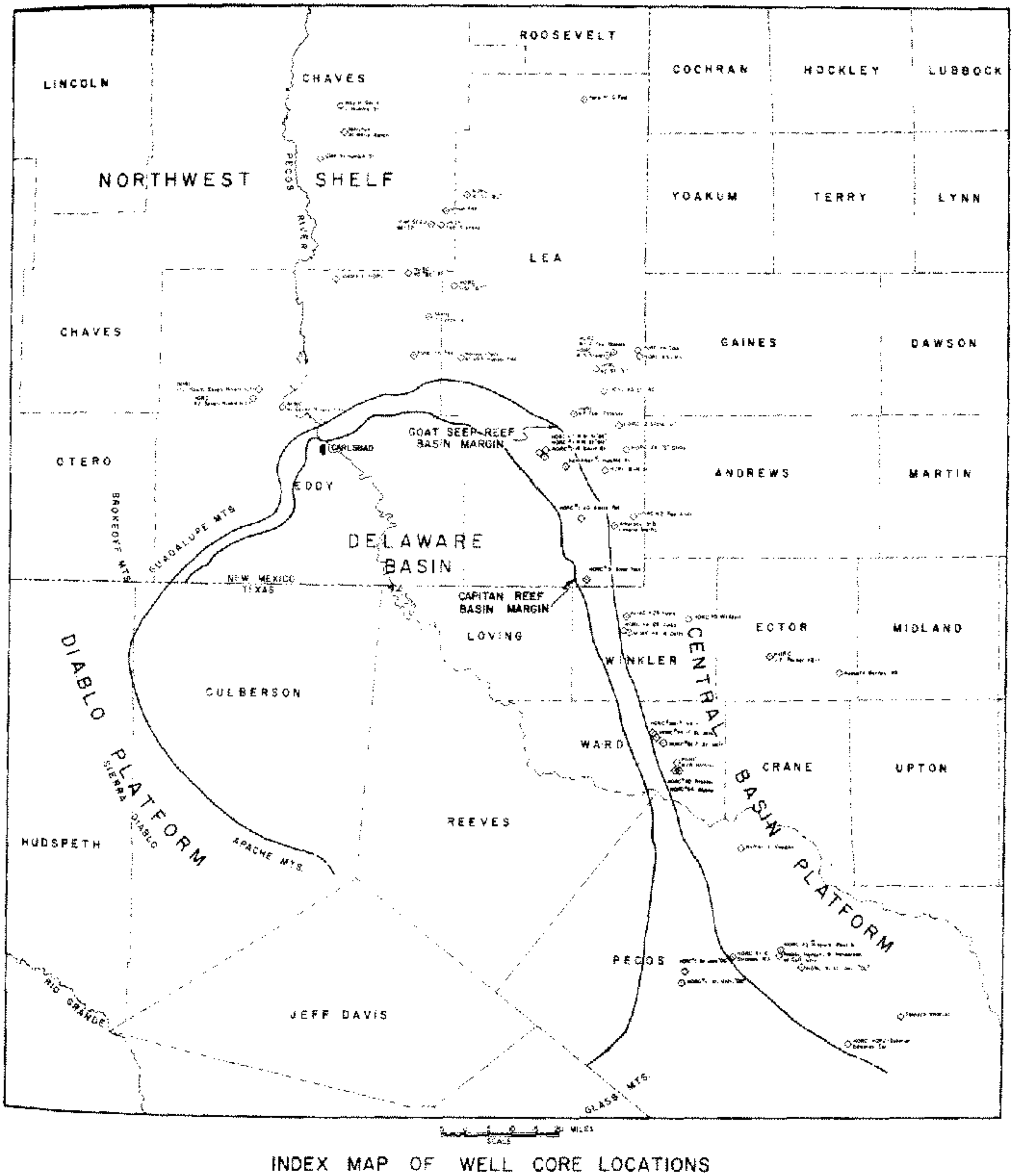

Figure 3. Location map for Guadalupian cores examined from subsurface of Northwest Shelf and Central Basin Platform.

King (1942, 1948) prepared the first detailed maps and established the stratigraphic-sedimentary framework utilized by subsequent investigators. King's original maps have been extended by Boyd (1958), Motts (1962), and Hayes (1964). Newell and others (1953) conducted the first detailed investigation of depositional environments, paleoecology and petrography.

The concept of seepage refluxion as a viable mechanism for dolomitization was proposed by Newell and others (1953), but it was resurrected and popularized by Adams and Rhodes (1960) from study of Permian Basin shelf sediments.

Tait and others (1962) proposed the term Artesia Group to include in ascending order the Grayburg, Queen, Seven Rivers, Yates and Tansill Formations.

Galley (1958) and Adams (1965) have outlined the structural evolution of the Permian Basin.

Dunham (1965 and 1969) and Thomas (1965) studied backreef pisolites and postulated that they represent ancient vadose caliche soils.

Kendall (1969) presented a reevaluation of Guadalupian carbonate-evaporite shelf sediments of the Guadalupe Mountains. He presented convincing evidence that most Permian pisolites represent algal accretions rather than in place concretionary soil structures.

Jacka and St. Germain (1967), Jacka and others (1969), and Meissner (1969) have related sediment economics and depositional dynamics of deep water submarine fan deposits of the Delaware Basin to alternating episodes of emergence and submergence of surrounding shelf areas. It has been possible to relate depositional history of basin and shelf areas within the context of glacially controlled eustatic sea level changes and associated climatic cycles (Jacka and others, 1969).

Silver and Todd (1969) have also interpreted depositional cycles in Permian shelf deposits as having been produced by glacially controlled eustatic sea level changes.

Achauer (1969) proposed that the Capitan Reef originated as an organic bank rather than a barrier reef. Cys (1970) presented evidence disputing the interpretation of Achauer (1969).

Motts (1972) presented an interpretation of depositional environments that conflicts with many "standard" concepts of the area.

Kelley (1972) reviewed shelf to basin correlations along the Guadalupe escarpment.

DEPOSITIONAL ENVIRONMENTS AND FACIES RELATIONSHIPS RECORDED IN GUADALUPIAN FORMATIONS

Landward from outer shelf areas the following spectrum of depositional environments is represented in Guadalupian shelf formations: 1) reef, 2) backreef apron, 3) lagoon, 4) intertidal zone, 5) coastal sabkha, 6) continental sabkha, and 7) deflation flats (Figs. 4–6). Characteristics of each depositional environment are described below, with emphasis on coastal and continental sabkha and deflation flat facies.

1. *Reef.* The reef facies consists predominantly of a sponge-algal framework with the following niche dwellers: fusulines, tetracorals, bryozoans, brachiopods, pelecypods, gastropods, cephalopods, trilobites, ostracodes, crinoids and echinoids. Carbonate rock types include boundstones, packstones and wackestones.

2. *Backreef Apron.* The backreef apron is a coarse-grained facies consisting of oolites, pisolites, calcarenites and coarse skeletal detritus washed behind the reef during storms and through surge channels. Rock types include grainstones and packstones.

3. *Lagoon.* Lagoonal deposits consist predominantly of micrites, in part indigenously produced and in part derived from the outer shelf. An indigenous molluscan

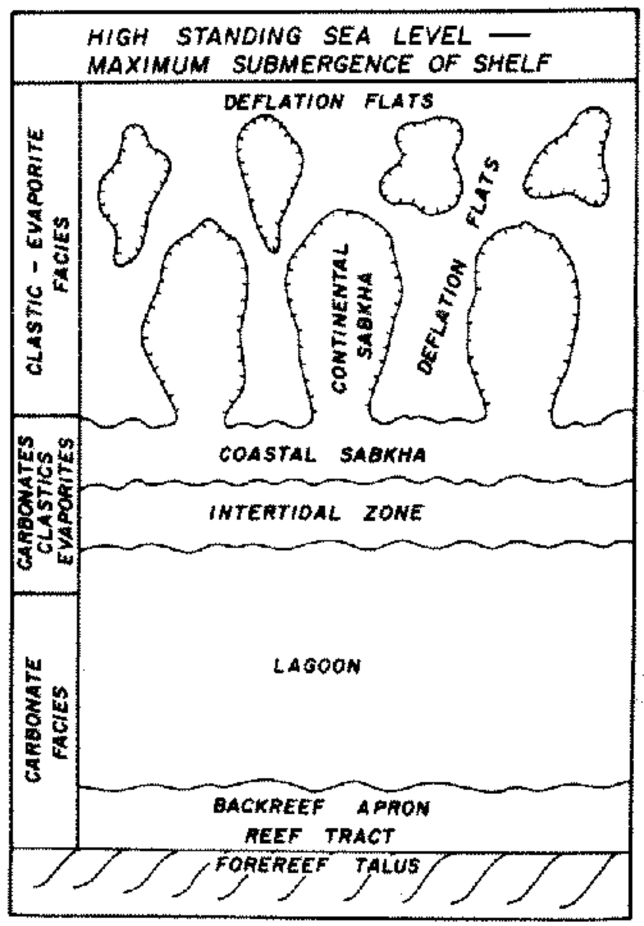

Figure 4. Facies relationships that characterized Permian high stands of sea level when climates were arid (interglacial-interpluvial interval).

fauna is dominated by gastropods. Rock types include molluscan and algal pelmicrites (Fig. 7A).

4. *Intertidal Zone.* Environments consist of intertidal algal flats (in quiet protected places), tidal channels and interchannel flats (Fig. 7) are sparsely represented. Algal flats exhibit stromatolitic structures, such as laterally linked hemispheroids and club-shaped and flat laminated stromatolites (Fig. 8, this report; see Logan and others, 1964 and Logan, 1961). Intertidal zone deposits commonly contain vertical or interconnected vertical and horizontal burrows. Tidal channels contain skeletal material, oolite, calcarenite or sand and exhibit scour and fill structures and small and large truncation current ripples (Figs. 7 and 8).

5. *Coastal Sabkha.* This is a supratidal zone consisting of mixed carbonates, clastics and evaporites. Carbonate material was derived from the lagoon and intertidal zone. Clastic materials were transported by eolian processes from the surrounding land areas. Adhesion ripples (Figs. 9 and 14) are abundantly represented in coastal sabkha clastics. Adhesion ripples appear as thin, irregular, wispy layers of sand with crude development of microforeset lamination (Fig. 14) and record deposition of sand on moist surfaces (see Glennie, 1972). Desiccation clasts are also abundantly represented in clastic coastal sabkha deposits (Fig. 9). Algal flats extended into the supratidal zone and were subjected to periodic episodes of wetting and drying. Supratidal carbonates are also characterized by fenestral (birdseye) vugs, flat pebble conglomerates and mud crack clasts (Figs. 9 and 11). The same varieties of gypsum crystals found in recent Persian Gulf sabkha deposits (see Butler, 1969 and Kinsman, 1969) are well represented in subsurface Guadalupian coastal sabkha deposits; varieties include rosettes, vertically oriented blades and swallow tail crystals and lensoid crystals with long axes oriented parallel to bedding. Early dolomitization of sabkha carbonates and replacement of gypsum by anhydrite occurred in Guadalupian coastal sabkhas as in the

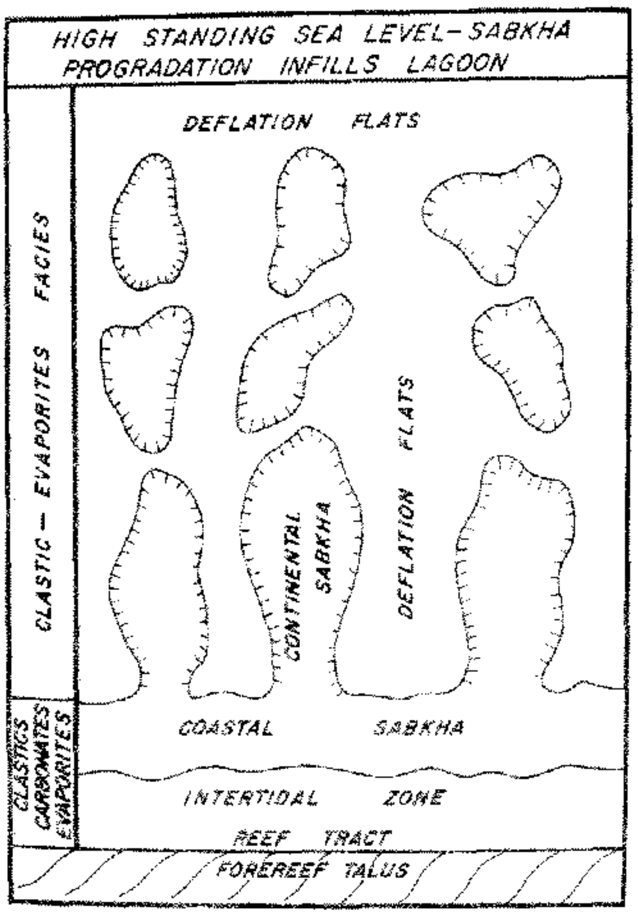

Figure 5. Facies relationships that reflect progradation of coastal and continental sabkhas and deflation flats with progressive lagoonal infilling.

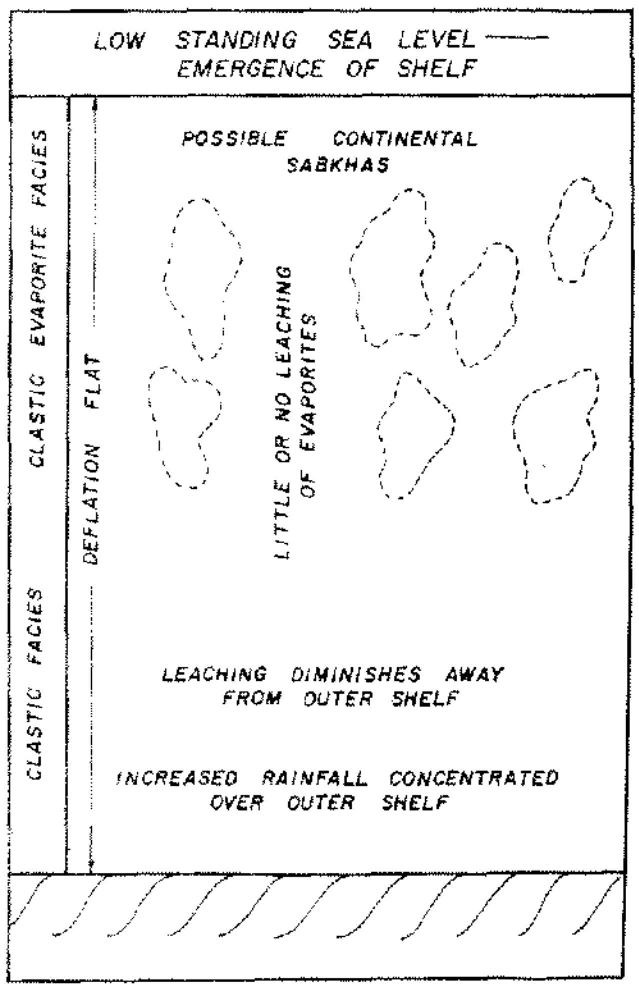

Figure 6. Facies relationships that characterized Permian low stands of sea level when the outer shelf received increased rainfall (glacial-pluvial interval).

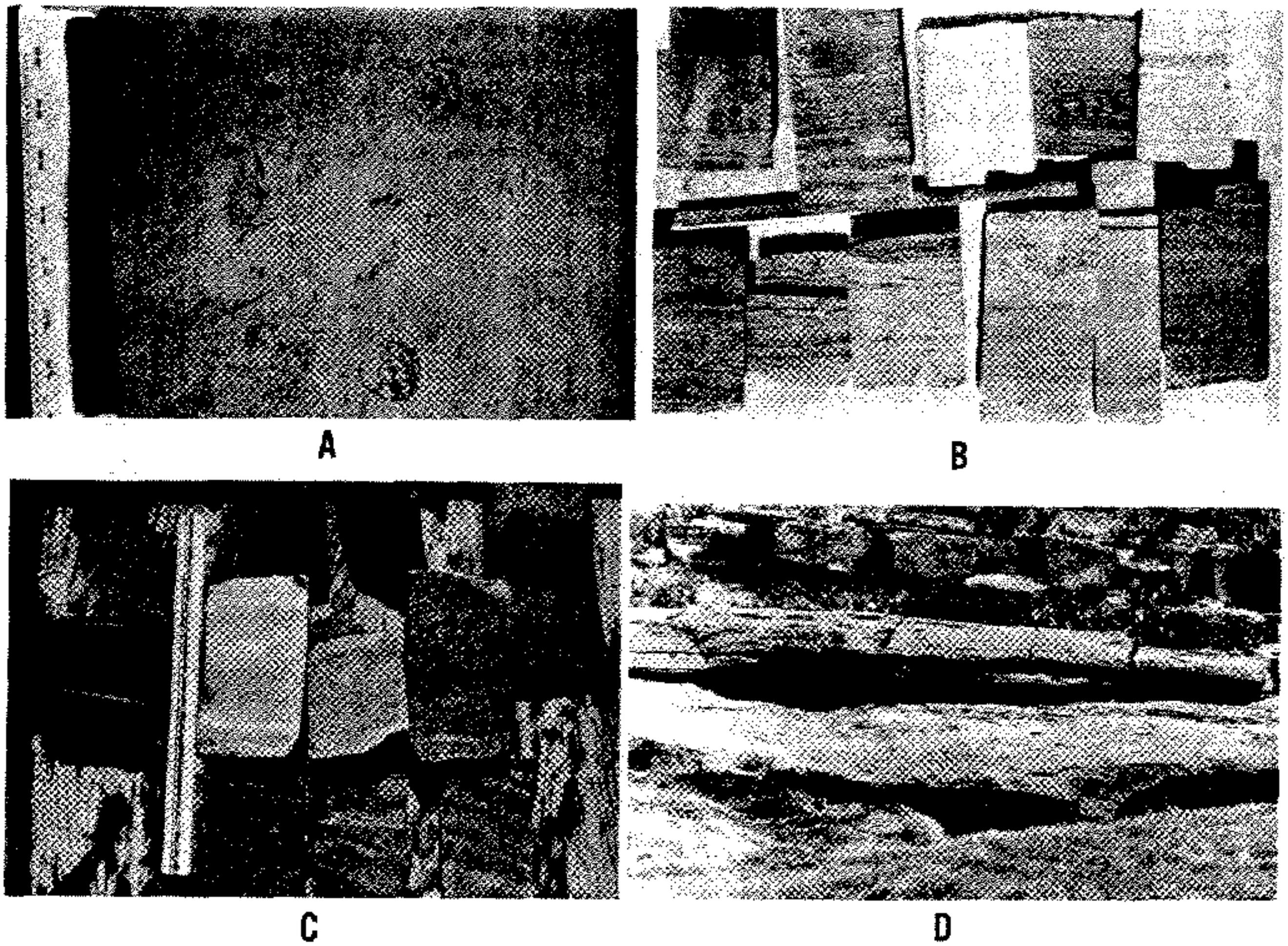

Figure 7. Guadalupian depositional facies. A—Lagoonal facies—molluscan pelmicrite was subjected to mineralogic stabilization, lithification and leaching in a subaerial diagenetic environment. Molds of aragonitic molluscs became filled with anhydrite during dolomitization (subsurface core slab). B—Intertidal flats consist of laminated clastic and carbonate materials. Sedimentary structures include parallel lamination, small current ripple crossbedding, eroded wave ripples and flaser bedding (subsurface core slabs). C—Tidal channel deposits consists of crossbedded sands and oolites (subsurface core slabs). D—Tidal channel—longitudinal cross section. Crossbedded units deposited by ebb and flood currents record 180° reversals in direction (Grayburg exposure in Last Chance Canyon).

modern analogue. Replacement of gypsum by anhydrite may form pseudomorphs of gypsum crystals, or isolated nodules or nodular mosaics (chicken wire structure) may be produced (Figs. 10 and 11). Carbonate rock types found in coastal sabkhas include pelmicrites, pelletal intramicrudites or intramicrites, and algal intramicrites.

6. *Continental Sabkha.* According to Kinsman (1969) a continental sabkha is an inland deposit, containing evaporites, which may include earlier cycle marine or continental sediments and the associated evaporites are precipitated from evaporation of continental waters. As defined by Kinsman (1969) continental sabkhas and their contained evaporites represent inland areas in arid regions where the water table lies close to the surface (down to one meter) or intersects the surface to form a salina or brine pan.

Kinsman (1969) described the following characteristics of continental sabkhas. Laminated deposits, consisting of laminae of sulfate and silt or clay or carbonate (including magnesite), commonly form in modern continental sabkhas. Needle crystals of gypsum are rapidly precipitated in brine pan environments, while other types of gypsum crystals, like those found in the coastal sabkha, form interstitially and include sediment. Replacement of gypsum by anhydrite to form gypsum pseudomorphs and nodules is also recorded. Massive cementation of clastic sediment by gypsum to form gypsum rock is common in continental sabkhas, but not in coastal sabkhas.

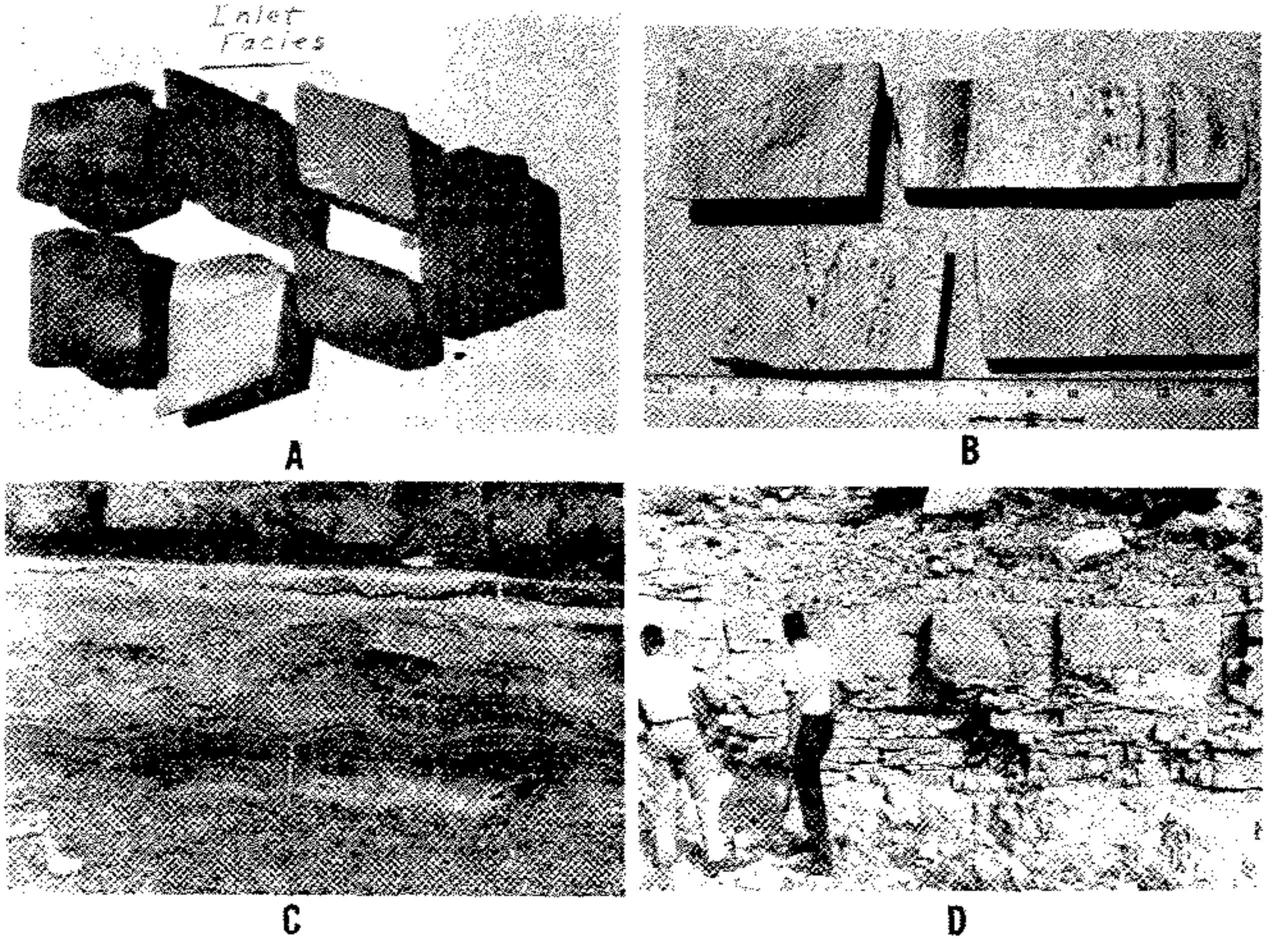

Figure 8. Guadalupian depositional facies—intertidal deposits. A—Tidal inlet facies contains large-scale crossbedded sandstone (subsurface core slabs). B—Algal stromatolites of the high intertidal—low supratidal zone. Crinkly desiccation features are evident. These became dolomitized early in their history (subsurface core slabs). C—Algal stromatolites—laterally linked domes of a protected intertidal zone are recorded in a silty sandstone of the Grayburg Formation. D—Stromatolites -laterally linked hemispheroids and domes in carbonate of Seven Rivers Formation.

Brine pan deposits are well represented in Guadalupian continental sabkhas, and they contain laminae of anhydrite, clastic material and magnesite (Figs. 12 and 13). Anhydrite laminae commonly exhibit pseudomorphed needle crystals of gypsum (Fig. 13A). Intercalated with laminated deposits is red silty shale containing halite crystals which grew interstitially (Figs. 12 and 13A). Red silty shale contains abundant mud crack casts and clasts. Red-brown sandstones cemented by halite and/or anhydrite are also represented in continental sabkha deposits (Figs. 12 and 13A). Examples of sandstone massively cemented by anhydrite are recorded: these probably represent analogues to the massive "gypsum rock" of modern continental sabkhas.

Laminar anhydrite- magnesite-clastic intervals attain thickness of up to 3-4 feet and form the basal unit of rhythmic sequences that also contain, in ascending order, red halitic silty shale, halite-cemented sandstone and sandstone and siltstone cemented by anhydrite and dolomite (Fig. 12). This vertical sequence may record the following sequence of events: 1) steady state existence of brine pan, 2) ephemeral existence of brine pan, and 3) infill of salina by wind blown sand and silt. Halite-cemented sands also contain features indicative of eolian deposition (see following section on deflation flats).

Permian continental sabkhas share many attributes in common with coastal sabkhas (i.e., similar suites of sulfate deposits, adhesion ripples, desiccation features), but are marked by a lack of carbonates (except for magnesite in brine pan deposits). Coastal sabkha deposits all contain dolomitized carbonates, but they do not contain brine pan or salina deposits.

With the exception of certain brine pan or salina deposits, all clastic sediments of continental sabkhas were

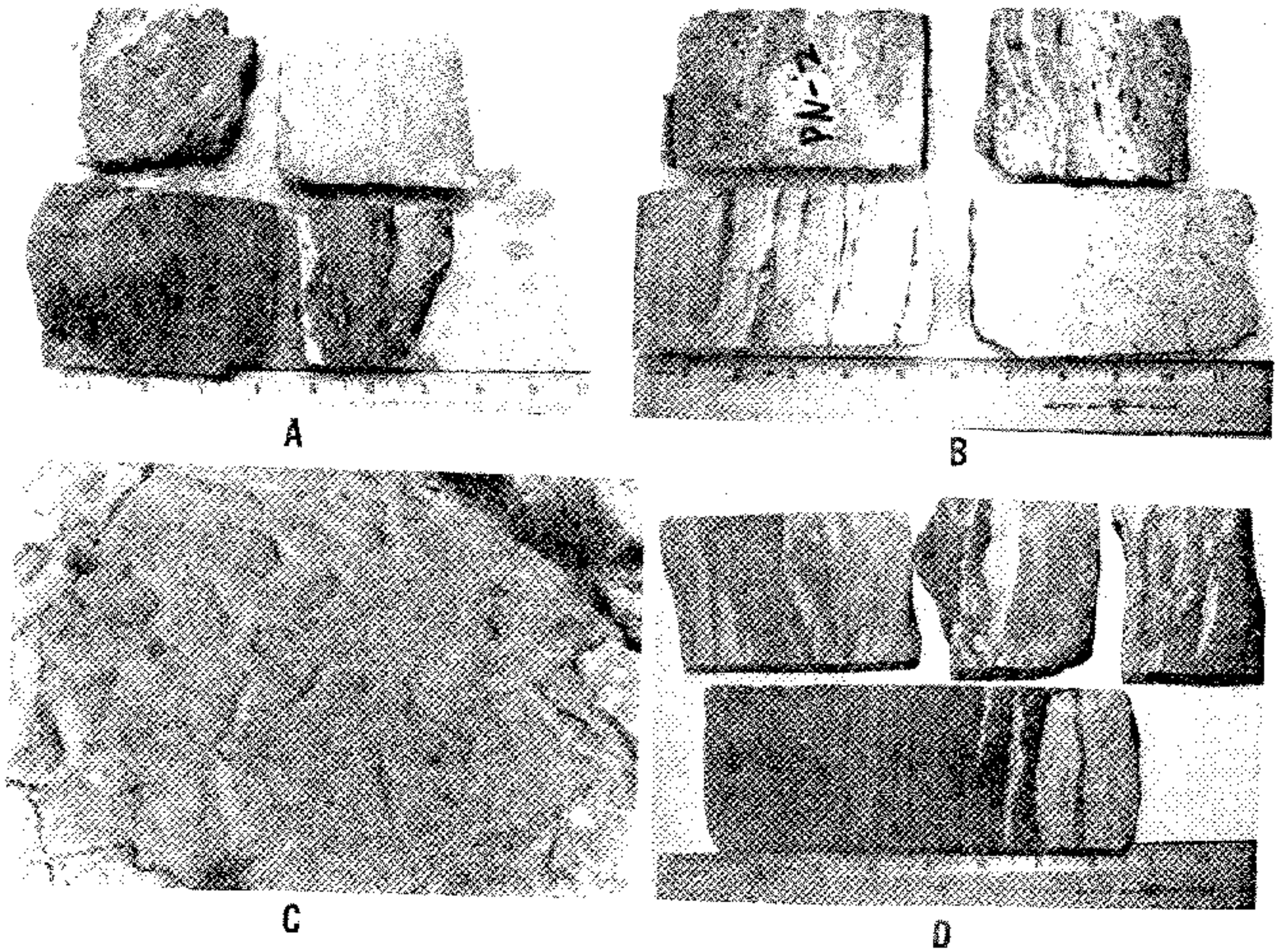

Figure 9. Guadalupian depositional facies—coastal sabkha deposits. A—Supratidal carbonates with flat pebble conglomerates were dolomitized within the sabkha environment (core slabs). B—Supratidal dolomites with fenestral (birdseye) voids (subsurface core slabs). C—Mud crack casts in Grayburg exposure. D—Carbonate clasts in clastic supratidal deposits (subsurface core slabs).

deposited by deflation and may contain any or all of the features described under deflation flats. Continental sabkhas include deflation flats where the water table was probably no more than one meter below the surface.

Recognition of extensive continental sabkhas in the Permian Basin is significant because, as pointed out by Kinsman (1969), the term *megasabkha* (exceptionally broad coastal sabkha) has been employed in evaporite literature to explain widespread ancient evaporitic deposits, such as those of the Permian Basin. Data presented herein corroborates the opinion of Kinsman (1969) that ancient deposits interpreted as megasabkhas record progressive infill of shallow lagoons by prograding sabkhas to produce extensive deposits. Along the Trucial Coast of the Persian Gulf rates of sabkha progradation may be as high as 1 m./year (Kinsman, 1969). The occurrence of sabkha-type evaporites in Guadalupian shelf sediments of the Permian Basin records rapid progradation of coastal sabkhas and extensive evaporite deposition landward of coastal sabkhas in continental sabkhas.

7. *Deflation Flat.* Deflation flats occur inland from coastal sabkhas and they surround or engulf continental sabkhas (Figs. 4–6). Deflation flat lithology consists of fine- to very fine grained sandstone, silty sandstone and sandy silt-stone cemented by dolomite and anhydrite (probably during burial—see section on diagenesis). Sedimentary structures include: 1) mud crack casts and clasts (Figs. 9 and 14); 2) adhesion ripples record deposition of sand and silt by wind on moistened surfaces (Glennie, 1972; Figs. 9 and 14, this report); 3) crust clasts (Fig. 14) record differential cementation of surficial crusts (by gypsum or halite) which subsequently were subjected to short transport by wind or surface runoff; 4) thin lenses of spheroidal, medium to coarse quartz grains represent lag concentrations of larger grains which became trapped in small deflation hollows (Fig. 14D).

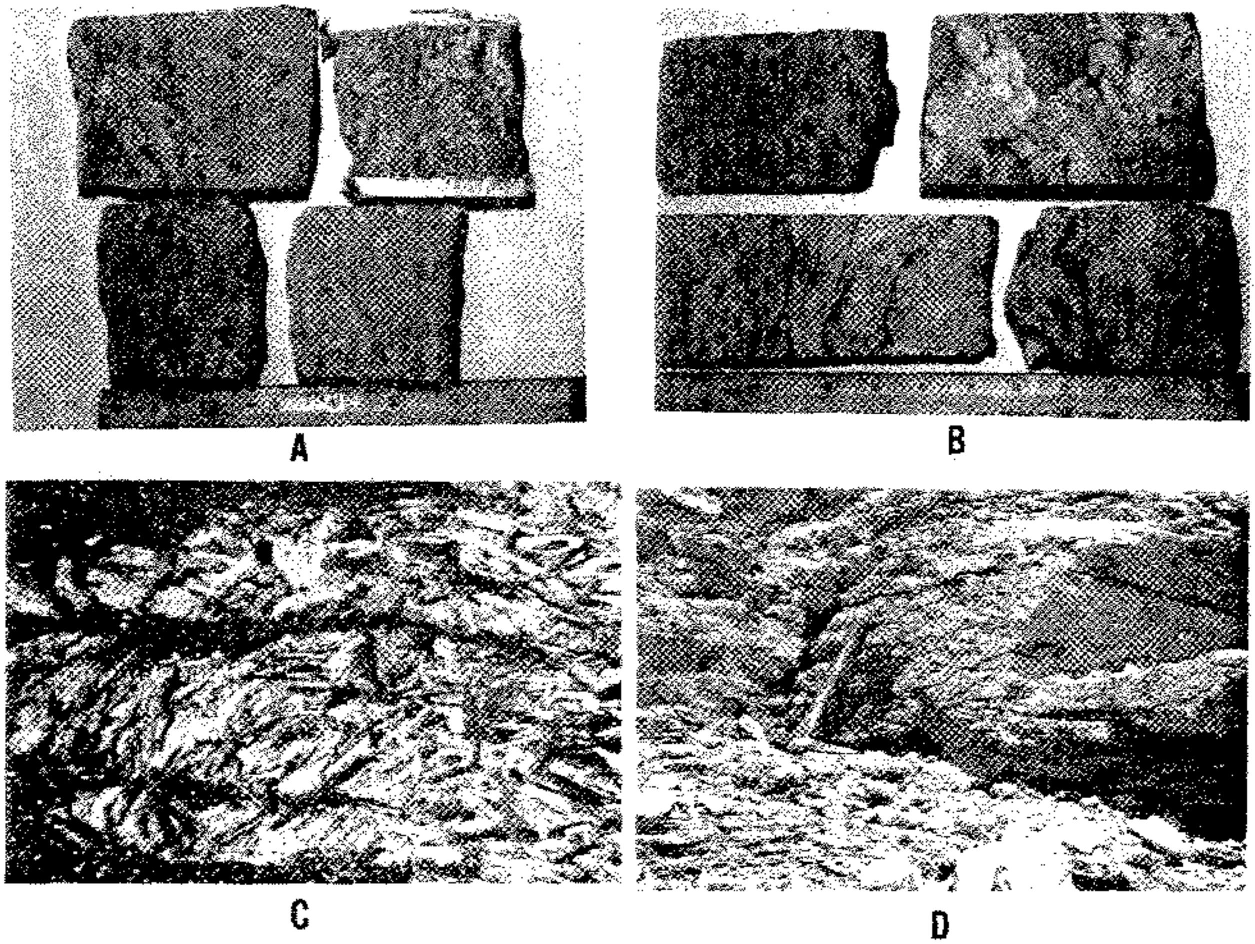

Figure 10. Guadalupian depositional facies—coastal sabkha deposits. A—Subsurface core slabs illustrating anhydrite pseudomorphs of bladed and lensoid gypsum crystals and rosettes. B—Subsurface core slabs depicting nodular anhydrite which replaced gypsum during sabkha progradation. C—Photomicrograph showing felted lath texture of replacement anhydrite nodules (from subsurface core slab). D—Exposure of Queen Formation illustrating anhydrite pseudomorphs of gypsum crystals and rosettes which became leached and partially replaced by calcite.

Evidence indicates that nearly all clastic materials of the shelf area were wind-deposited and most represent deflation flats rather than dune fields. Occurrences of truncated cross-bedding, that may record eroded dunes, are sparsely represented in Guadalupian shelf deposits. Not even one example of fluviatile deposits was observed in cores or outcrops from outer, middle or inner shelf areas. With these relationships in mind, it becomes evident that continental sabkhas include deflation flats where the water table was close enough to the surface to permit precipitation of interstitial evaporites. In some cases precipitation of interstitial evaporites obscured or destroyed sedimentary structures of deflation flat deposits; in other cases anhydrite nodules or anhydrite pseudomorphs of gypsum crystals occur within sediment still retaining deflation flat structures (Fig. 14B). Thus, concepts of continental sabkha and deflation flat must take into account the subsequent history of the deposit.

Evidences of desiccation in deflation flat deposits reflect drying that followed infrequent episodes of rainfall. Deflation flat surfaces became reworked from time to time by surface runoff. The abundance of adhesion ripples in deflation flat deposits records deposition of sand and silt by deflation on rainfall-moistened surfaces or around margins of brine pans or salinas.

INTERPRETATION OF DEPOSITIONAL CYCLES

Examination of outcrops and subsurface data from Guadalupian formations reveals the existence of well-defined depositional cycles. In outcrops along the outer platform (Guadalupe Mountains), the following vertical sequence of depositional environments is recorded and reflects alternating submergence and emergence of the shelf.

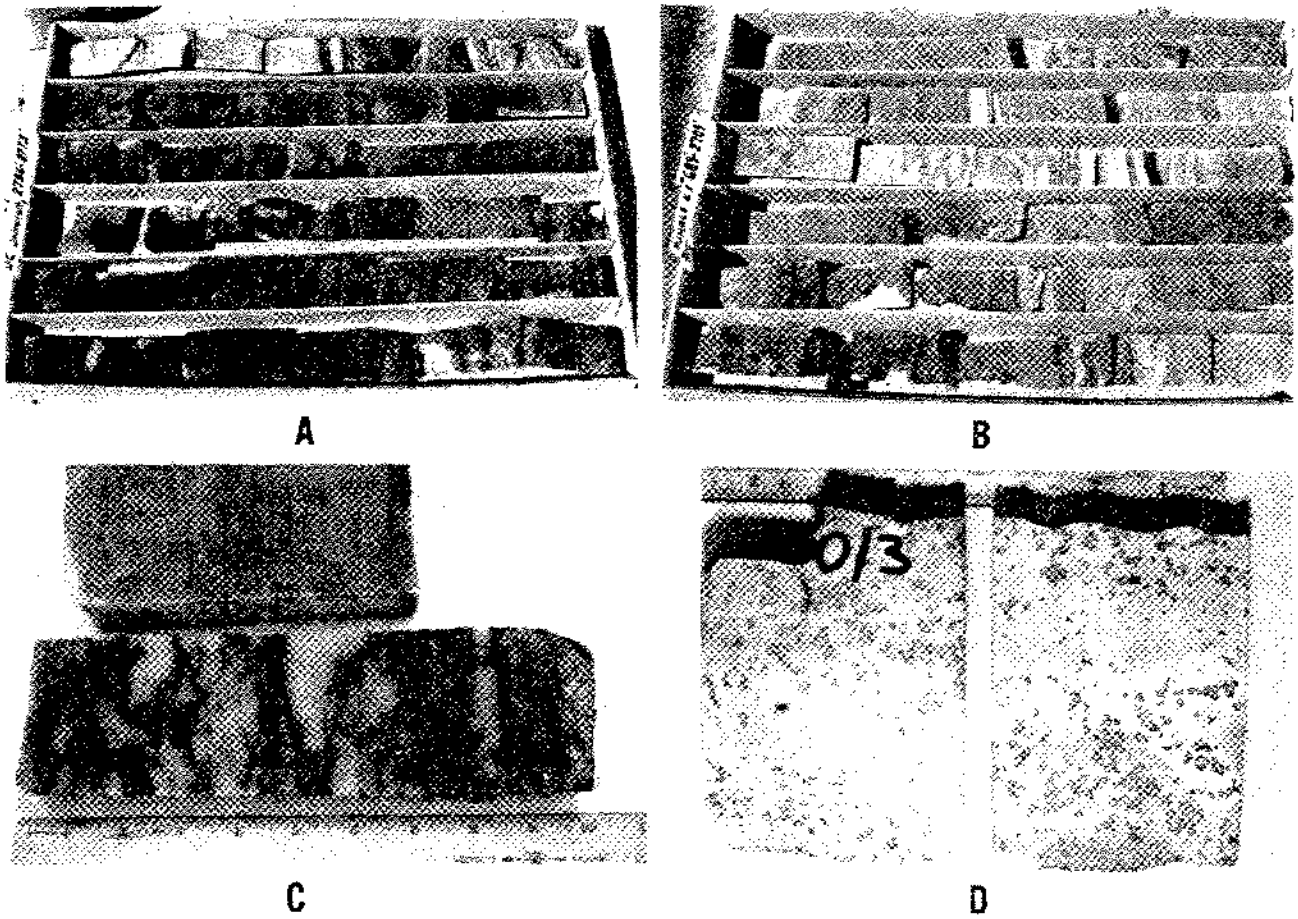

Figure 11. Guadalupian depositional facies—subsurface core slabs illustrating coastal sabkha deposits and early diagenesis. A—Core slab sequence showing red brown clastic coastal sabkha deposits containing nodular anhydrite with light-colored dolomitized carbonate units in right compartment (top). B—Carbonate sequence depicting nodular mosaics of anhydrite and replacement of laminar stromatolites by anhydrite (subsurface core slabs). C—Nodular mosaic of anhydrite (chicken wire structure) in core slab. D—Core slab illustrating replacement anhydrite, which may form early or during burial, within dolomicrite. This had no gypsum precursor and seems to represent an exsolution phenomenon.

deflation flat (maximum regression)
sabkha
intertidal zone
lagoon-backreef apron (maximum submergence)
intertidal zone
sabkha
deflation flat (maximum regression)

In some localities sabkha deposits can be subdivided into coastal- and continental sabkha facies.

Three general hypotheses may be considered in order to explain the mechanism of Guadalupian depositional cycles.

1. Alternating tectonic subsidence and uplift caused intervals of submergence and emergence.

2. Seaward progradation of coastal and continental sabkha deposits progressively infilled shelf lagoons. Continuous subsidence of the shelf area somehow or other eventually caused an episode of submergence, followed again by progradation and progressive infill of lagoons.

3. Glacially controlled eustatic sea level fluctuations, superimposed upon continuous subsidence of shelves, caused alternating submergence and subaerial exposure.

Tectonic processes are not known to rhythmically reverse themselves within relatively short time intervals. Evidence indicates that during Guadalupian Time the Permian Basin was characterized by extreme tectonic quiescence (Gailey, 1958; Adams, 1965). For these reasons, any tectonic control hypothesis must be rejected.

Regressive phases of depositional cycles reflect seaward progradation of coastal and continental sabkha facies and progressive lagoonal infilling; this may have largely occurred during high stillstands of sea level when climates were arid. It is difficult to explain repeated episodes of

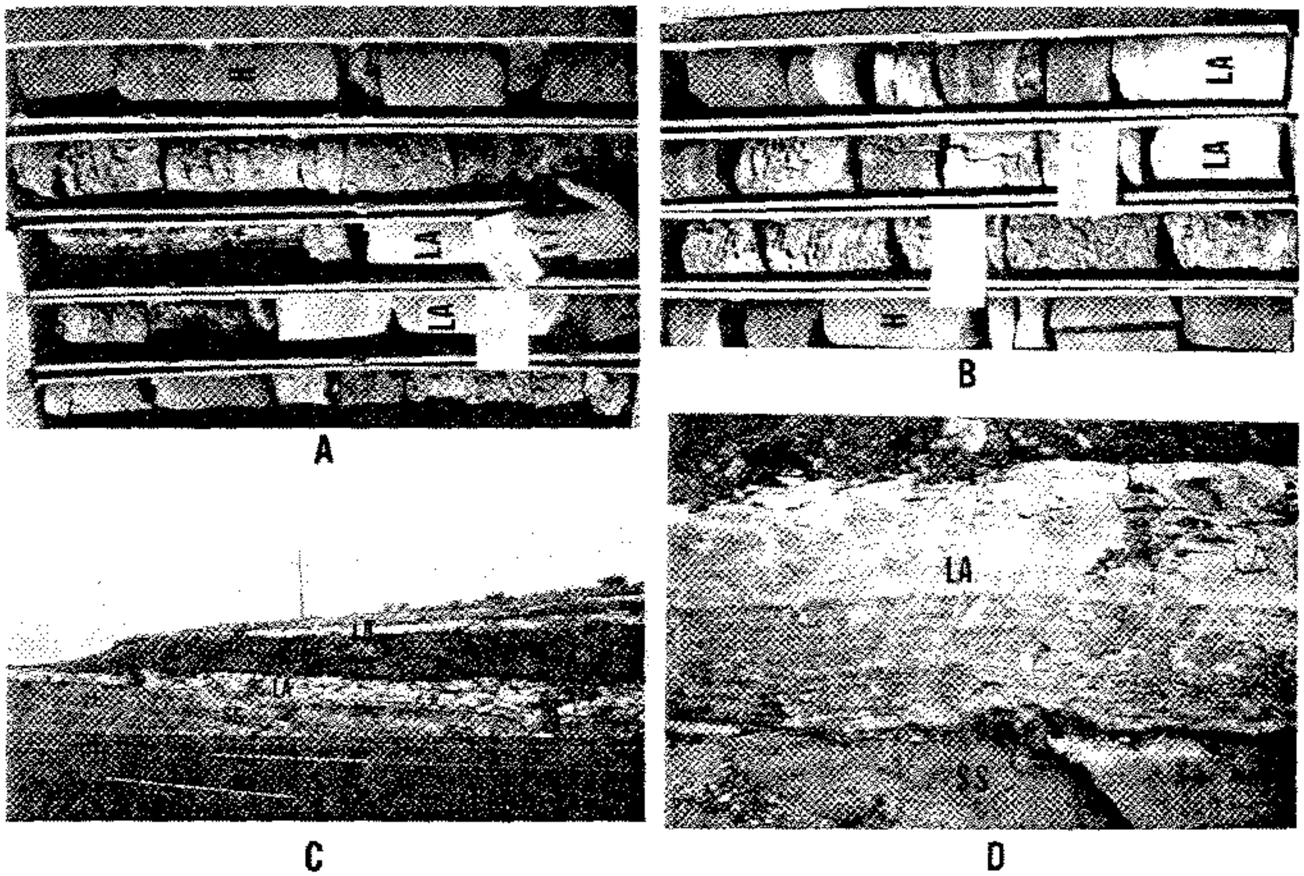

Figure 12. Guadalupian depositional facies--continental sabkha brine pan or salina deposits. A and B—Subsurface core slab sequences illustrating vertical successions of: (1) laminar interval of anhydrite (containing pseudomorphed needle crystals of gypsum); magnesite and slit-clay laminae (LA), (2) red halitic shale, and (3) red-brown sandstone cemented with halite (H). C Exposure of Queen Formation near Roswell, New Mexico, reveals vertical sequence of brine pan or salina deposits similar to A and B (above), except that halite has been leached from red shale (SH) and sandstone (H) intervals. D--Close view of C (to left) illustrating characteristics of laminar interval (LA); anhydrite has been converted to gypsum. Red-brown sandstone (SS) has been reduced to gray-green color.

submergence (transgressions), which followed regressive phases, wholly within the context of continuous subsidence and sediment economics. Evidence will be presented in following sections on diagenesis and Guadalupian climates to indicate that climatic changes accompanied major sea level fluctuations. Because of the magnitude and frequency of sea level fluctuations and because of associated climatic changes, the glacio-eustatic hypothesis is favored as the major cause of transgression and regression.

In continental sabkha-deflation flat deposits of middle and inner shelf areas a depositional cycle different from that of the outer shelf is commonly recorded; upward from the base the following intervals are represented.

4. Deflation flat sands and silts—cemented after burial by dolomite and anhydrite.

3. Red-brown sandstone—cemented early by halite or halite and anhydrite.

2. Red halitic shale—halite precipitated interstitially.

1. Laminated interval—contains intercalcated laminae of anhydrite (with pseudomorphed needle-crystals of gypsum), magnesite and silt-clay.

This sequence (Fig. 12) is inferred to represent brine pan or salina deposits, as previously indicated. The basal interval of anhydrite–magnesite–clastic laminae records a well-developed salina where the water table intersected the surface. Red halitic shale records an ephemeral stage of the salina when halite was precipitated within the shale below a mud cracked surface. Halite-cemented sand probably represents infilling by wind blown sand and subsequent cementation during the ephemeral phase which also included the subjacent, red halitic shale. The fact that

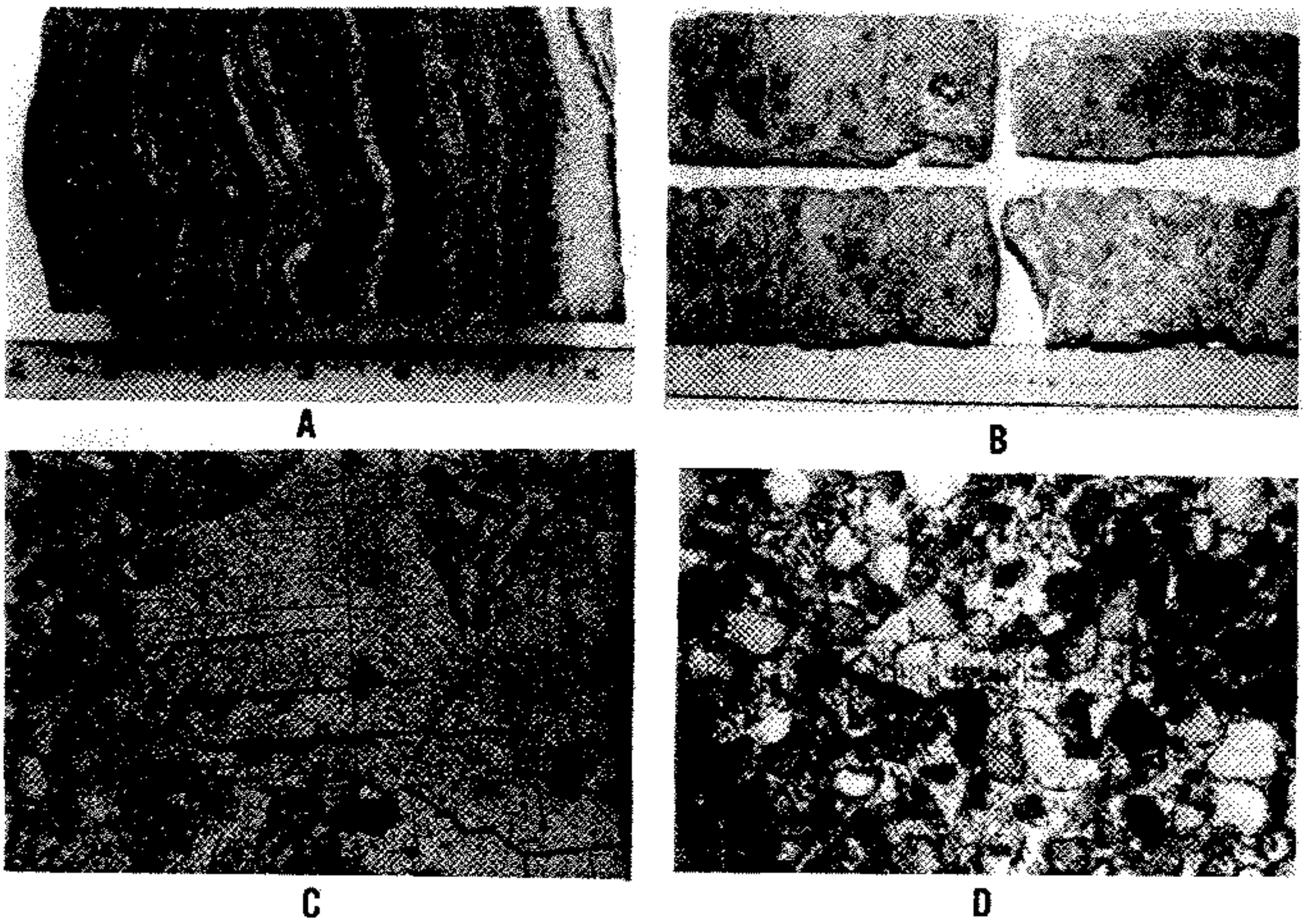

Figure 13. Guadalupian depositional facies—subsurface examples of continental sabkha brine pan or salina deposits. A—Close view of laminar interval with laminae of anhydrite with pseudomorphed needle crystals of gypsum, magnesite and slit-clay. B—Red halitic silty shale; halite was precipitated interstitially within red mud-cracked material. C—Photomicrograph of halite-cemented sandstone; cleavage traces in halite are evident. D—Photomicrograph of sandstone poikilotopically cemented with gypsum from depth of over 3000 feet; each small division equals 11 microns; crossed polarizers.

quartz and orthoclase in halite-cemented sandstones contain no overgrowths indicates that halite-cementation was early. In overlying deflation flat deposits, the presence of well-developed overgrowths on quartz and orthoclase grains suggests that dolomite and anhydrite cements were precipitated later at depth. Several repetitions of the aforementioned cycles are commonly represented in an individual core, and this suggests that rhythms may have been caused by fluctuations in position of the ground water table. Whether or not depositional cycles of the middle to inner shelf are equivalent to those of the outer shelf has not been determined.

DIAGENESIS OF CARBONATE SEDIMENTS

Early diagenesis in marine environments

In Guadalupian intertidal-subtidal environments micritization of certain invertebrates is abundantly recorded (Fig. 15A). In micritization original shell texture is obliterated by conversion to micrite. Kendall and Skipwith (1969) present an excellent analysis of the process of micritization in modern lagoons of the Persian Gulf. Calcareous shells of dead invertebrates became inhabited by blue-green algae which bore into the shell with tiny filaments, dissolving original shell material and precipitating aragonite or high magnesium calcite. In Guadalupian carbonates fusulinid foraminifera and calcareous green algae have been most susceptible to micritization. Shells of many larger invertebrates have been coated by micrite films, some of which seem to have been of algal origin.

Probable examples of beach rock have been noted in Permian intertidal carbonates (Fig. 15A). Grains were cemented by films of micrite and crusts of fibrous to bladed crystals that may originally have consisted of high magnesium calcite. These deposits subsequently were wholly replaced by dolomite.

Early diagenesis in sabkha environments

Predominantly aragonitic Guadalupian carbonates which had been deposited in supratidal zones (coastal

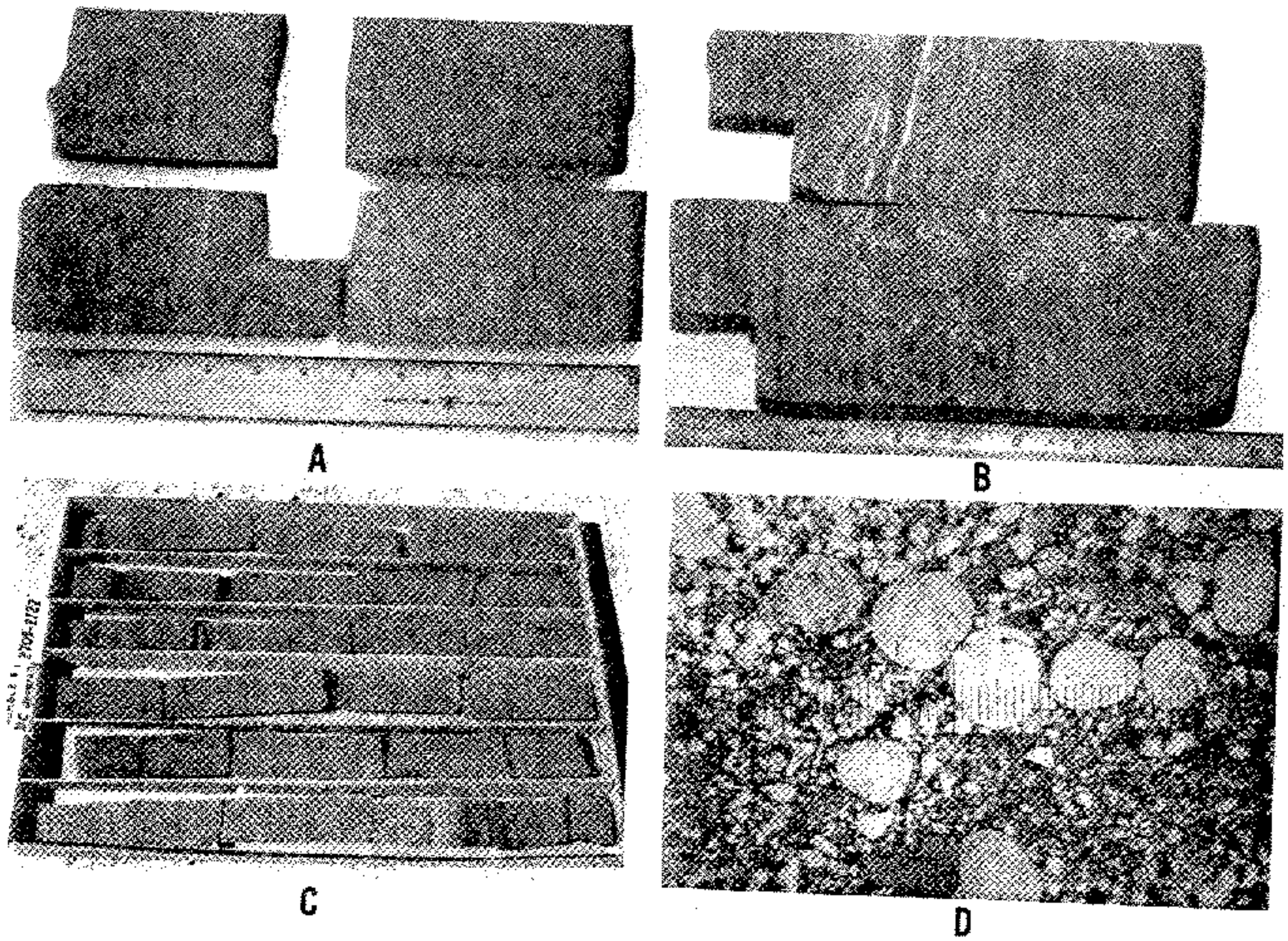

Figure 14. Guadalupian depositional facies- subsurface examples of deflation flat and continental sabkha deposits. A—Deflation flat deposits with crust clasts, desiccation clasts and adhesion ripples. B—Continental sabkha deposits containing anhydrite pseudomorphs of gypsum crystals and rosettes and kinkly layers of anhydrite; deflation flat structures, desiccation clasts and adhesion ripples, are present. C—From lower left (bottom) core slab sequence illustrates laminar brine pan interval (anhydrite-magnesite-silty shale) and deflation flat clastics with crust and desiccation clasts and adhesion ripples. D—Photomicrograph of deflation flat deposit showing small lense of medium and coarse-grained spheroidal quartz grains, which were trapped in small deflation hollows, enclosed within a matrix of fine grained sand and silt. Each small division equals 42 microns.

sabkhas) by spring or storm tides became dolomitized early in their history (Figs. 7, 8 and 9). Modern examples of supratidal dolomitization have been found in Andros Island, Bahamas (Shinn and others, 1965), along the Trucial coast of the Persian Gulf by Wells (1962), Illing and others (1965), Kinsman (1966 and 1969), Butler (1969) and Kendall and Skipwith (1969), in south Florida by Shinn (1965) and in Bonaire, Netherlands Antilles by Deffeyes and others (1965).

Mechanisms of dolomitization are not yet well understood. In order to explain dolomitization of the Permian reef complex, Newell and others (1953) postulated that dense brines, enriched in Mg^{++} and $SO_4^{=}$, originated in restricted, hypersaline lagoonal waters and seeped downward through outer shelf carbonates, displacing interstitial water, and thoroughly dolomitizing them. The concept of seepage refluxion, as a viable mechanism for dolomitizing Permian shelf carbonates, was resurrected and popularized by Adams and Rhodes (1960). We reject the seepage refluxion hypothesis of Newell and others (1953) and Adams and Rhodes (1960) because it is predicated upon the existence of broad hypersaline lagoons in which evaporites were deposited. The Permian reef was broken by numerous tidal and surge channels and by large submarine canyons. Open circulation and interchange of open sea and lagoonal waters would have prevented formation of dense hypersaline brines and precipitation of evaporites. As previously indicated, all Permian shelf evaporites accumulated in coastal or continental sabkhas, and not in lagoons.

Deffeyes and others (1965) investigated recent dolomitization on Bonaire Island, Netherlands Antilles, and inferred that dolomitization results from downward percolation (reflux) of dense hypersaline waters which origi-

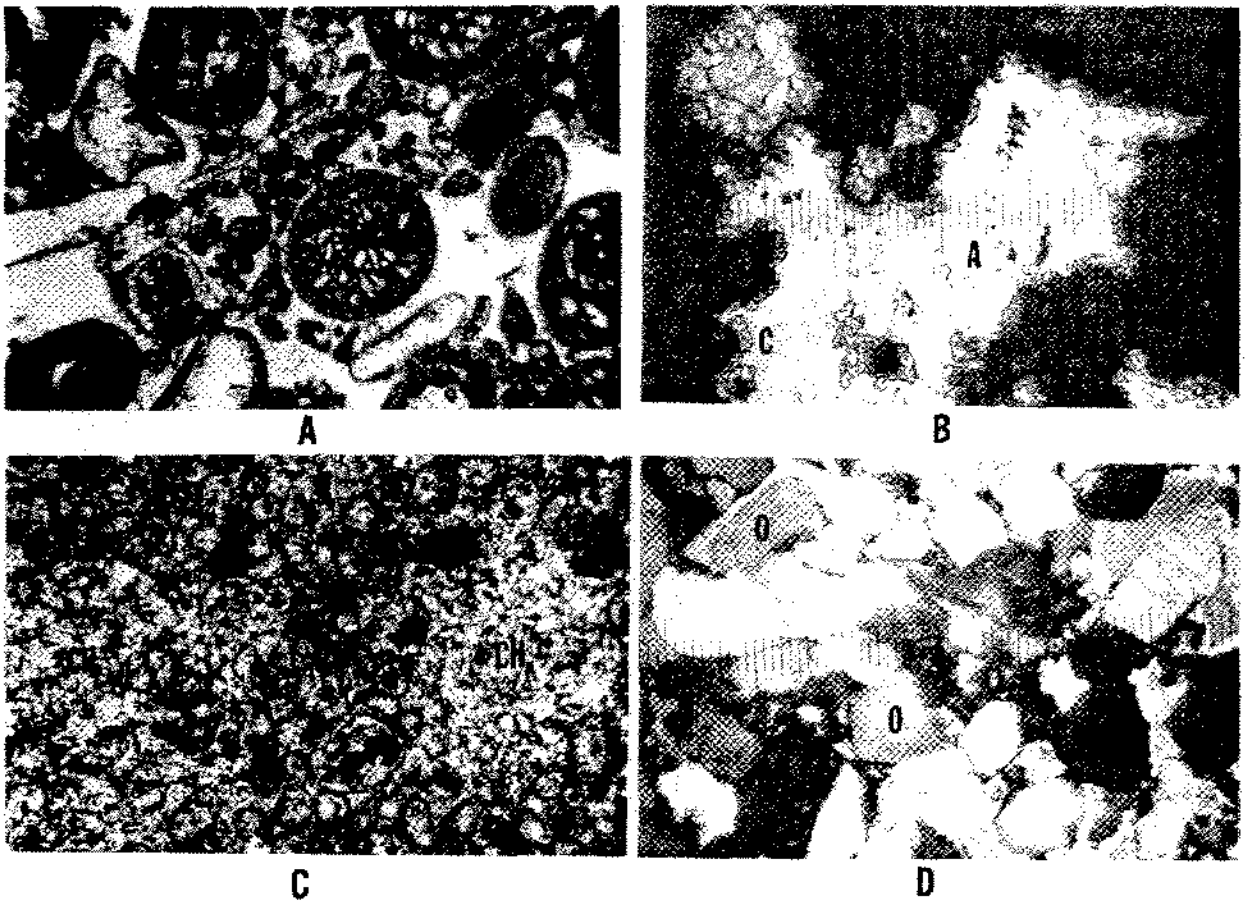

Figure 15. Photomicrographs of thin sections illustrating diagenesis of Guadalupian shelf sediments. A—Biosparrudite from outcrop of Yates Formation, Guadalupe Mountains. Fusulines and green algae were thoroughly micritized by blue-green algae (after death) in the marine environment. Mollusc shell fragments were coated by micrite envelopes and subsequently aragonitic shell material was dissolved, leaving hollow micrite envelopes which became filled by calcite cement. This sample represents a paleo-beachrock deposit which became cemented in the intertidal zone by drusy calcite crusts. During burial, beachrock became dolomitized and all remaining voids were filled by anhydrite. After Cenozoic uplift anhydrite became leached and cemented or replaced by calcite. X 75. B—Subsurface sample of lagoonal pelmicrite which was mineralogically stabilized (to calcite), lithified and leached in a fresh water diagenetic environment. Leached vugs became partially filled by a crust of dogtooth calcispar (C) cement in the vadose zone. During burial the limestone became dolomitized and the remaining vug filled by anhydrite (A). Each small division equals 42 microns. C—Subsurface sample of anhydrite nodules in outer shelf dolomite which became replaced by length—slow chalcedony (CH). This occurred during an eustatic sea level drop under conditions of increased rainfall. Each small division equals 42 microns. Crossed polarizers. D—Deflation flat sandstone from Yates Formation. Overgrowths on orthoclase grains (O) were precipitated during burial; quartz grains also have overgrowths. Sandstone later (during burial) became cemented by dolomite and anhydrite. Each small division equals 11 microns; crossed polarizers.

nated in supratidal lakes or flats. The mechanism of Deffeyes and others differs from that of Newell and others and Adams and Rhodes only in the environment where concentration of brine occurs (backreef lagoon vs. supratidal lakes or flats).

Most major mechanisms of dolomitization require that the Mg/Ca ratio be increased above that of normal sea water by evaporation and precipitation of gypsum. Butler (1969) in his study of Persian Gulf Sabkhas found that the Mg/Ca ratio increases from 5.3 in the lagoons to a maximum of 35 in interstitial brines of inner recharge zones of the coastal sabkha. This increase of Mg/Ca ratios is achieved by precipitation of gypsum and aragonite. The magnesium rich brine reacts with preexisting aragonite mud, replacing it with dolomite.

Another early diagenetic reaction occurring in the sabkha environment is replacement of gypsum by anhydrite (Butler, 1969; Kinsman, 1969). As in modern analogues, replacement of gypsum by anhydrite in Guadalupian sabkhas forms isolated nodules, nodular mosaics (chicken wire structure), or pseudomorphed gypsum crystals or rosettes (Figs. 10 and 11). Anhydrite nodules and pseudomorphs of gypsum crystals and rosettes exhibit a felted texture of lath-shaped crystals in thin sections (Fig. 10C).

Numerous examples of sulfate replacing ooids and algal stromatolites were noted (Fig. 11) and such replacements are inferred to have been early diagenetic reactions. Whether or not replacement of carbonate by sulfate occurred during or after dolomitization cannot be definitely established.

One peculiar type of anhydrite replacement of carbonate, which could have taken place either early or late (or both), occurred wholly within dense micrite matrix. Areas of anhydrite replacement are delineated by crudely- to sharply rectangular borders which outline margins of anhydrite crystals (Figs. 11D and 18D). In thin sections, outer borders of areas of anhydrite replacement are fuzzy and contain aureoles of disseminated, unreplaced micritic material. Murray (1964) coined the term replacement anhydrite for this phenomenon but offered no explanation. Replacement anhydrite represents an enigmatic phenomenon that seemingly constitutes an exsolution reaction, such as might be observed in igneous or metamorphic rocks.

Early subaerial exposure and fresh water diagenesis

Because modern marine carbonates consist predominantly of aragonite and high magnesium calcite, they become unstable in a fresh water environment. In a fresh water diagenetic environment, aragonite either inverts to stable low magnesium calcite or dissolves. Matthews (1968), from study of subaerially exposed Pleistocene carbonates on the island of Barbados, has shown that reefs consisting of aragonitic lime muds and aragonitic corals become mineralogically stabilized in the following manner. Aragonitic lime mud contains a relatively homogeneous distribution of calcitic nuclei (skeletal material) and inverts to low magnesium calcite by coalescive solution of aragonite and precipitation of calcite, with the reaction initiating on calcite nuclei. Aragonitic skeletal material tends to dissolve, forming moldic porosity, rather than inverting to calcite. The solution precipitation process that characterizes inversion of aragonite to calcite occurs along a migrating film and solution of aragonite is immediately followed by precipitation of calcite. This has been termed voidless solution by Schmidt (1965). Because aragonite is denser than calcite, solution of aragonite supplies an 8% excess of Ca^{2+} and CO_3^{2-} ions to be locally precipitated calcite cement (Matthews, 1968). On Barbados mineralogic equilibration of reefs containing aragonitic corals has yielded a densely lithified micrite matrix and moldic porosity, representing dissolution of corals. Some corals have inverted to calcite but most have dissolved (Matthews, 1968).

Land (1967) has shown that high magnesium calcite will stabilize to low magnesium calcite by incongruent dissolution of Mg^{2+} ions. Gavish and Friedman (1969) have shown that in carbonates subaerially exposed along the coast of Israel that all high magnesium calcite has stabilized within ten thousand years. Friedman (1964) has shown that stabilization of high- to low magnesium calcite represents a paramorphic change (no change in texture). Bathurst (1964) and Friedman (1964) have shown that inversion of aragonitic skeletal material to low magnesium calcite represents a neomorphic change wherein fibrous to prismatic texture is altered to coarse anhedral mosaic of calcite crystals.

Subtidal-intertidal Guadalupian carbonates were subaerially exposed (by eustatic lowering of sea level) soon after deposition and became stabilized and lithified in a fresh water diagenetic environment according to the Barbados model described by Matthews (1968). Selective solution of aragonitic molluscan shells occurred while calcitic shells were relatively unaffected (Figs. 15A and 18).

Granular backreef apron deposits of skeletal material, oolite and pisolite became subjected to considerable internal solution resulting in development of non-tectonic fractures (see Dunham, 1965, 1969, and Thomas, 1965) which subsequently became enlarged by ground water solution to form solution vugs, small- to large solution channels (Figs. 16 and 18), and in the upper third of the Yates interval cave formation was recorded (Fig. 16). A collapsed cave deposit, exposed in Walnut Canyon, is shown in Fig. 16. Large tumbled blocks can be seen with bedding planes now being vertical or at high angles. The largest block has a maximum diameter of 130 feet (Fig. 16A, bottom-center). Tumbled blocks are interlaced with clastic internal sediment. Several large solution channels can be seen entering the paleo-cavern (Figs. 16A and B). Some solution channels extend all the way to the top of the carbonate interval within which the cave system formed. The largest solution channels represent enlargement of joints. Solution channels became filled upward from the base (Fig. 16B) by sandy internal sediment. An underground stream deposit of sand containing current ripple structures can be seen in the exposure. The sand-filled solution channels shown in Fig. 16B enter the large solution gallery containing the underground stream. The cave exposure occurs less than one half mile from the equivalent reef margin and records a drop in sea level of at least 130 feet (thickness of paleo-vadose zone). This represents the largest definitely established eustatic drop of sea level in the Guadalupian interval. Evidence for a similar system in the same Yates interval was noted in a core sequence from the Yates on the Central Basin Platform (Fig. 16C).

Origin of Guadalupian backreef pisolitic deposits (Figs. 16D and 17) remains a subject of controversy. Kendall (1969) presents an excellent review of the topic. Ruede-

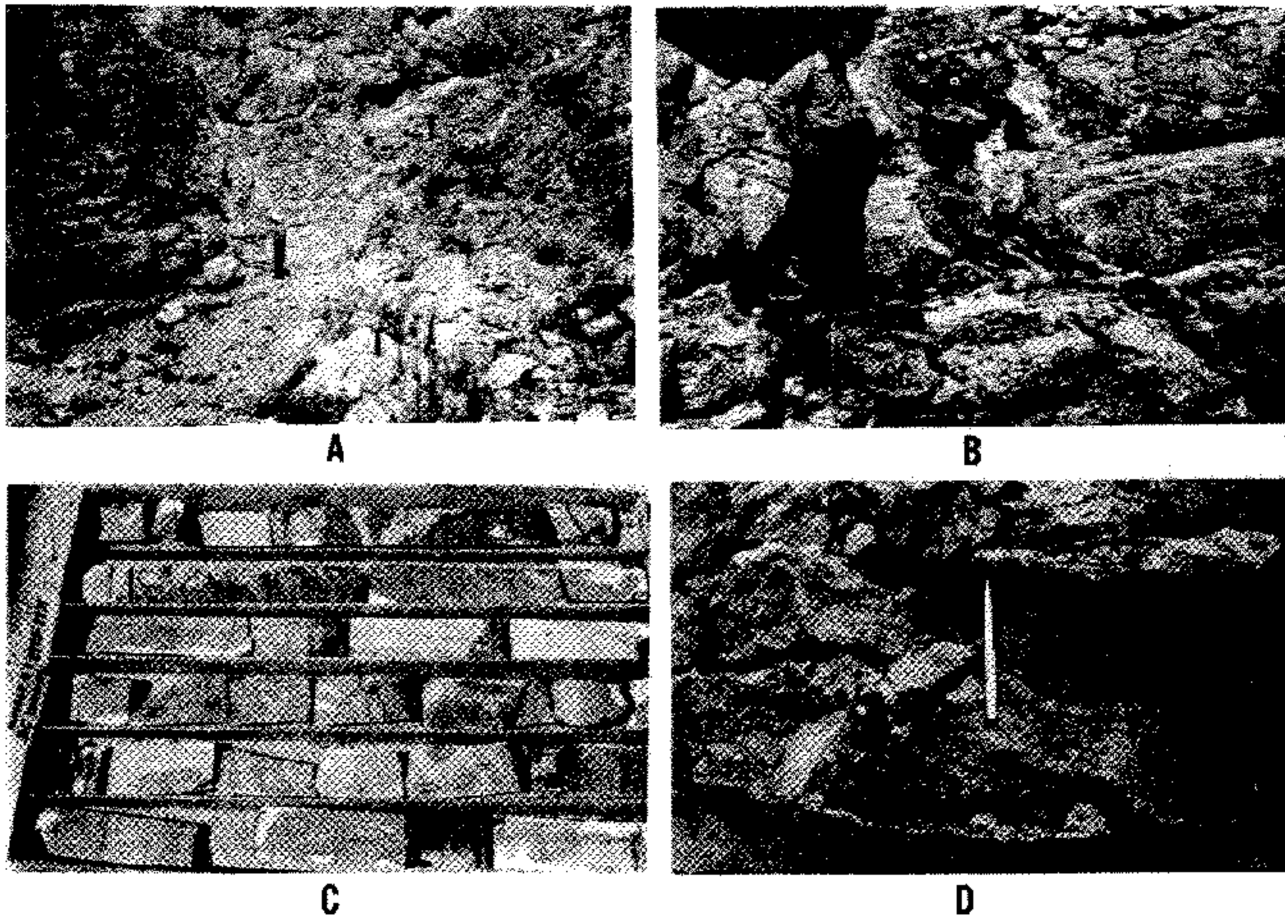

Figure 16. Cave formation and other indications of fresh water diagenesis of Guadalupian outer shelf carbonates. A—Exposure of paleo—collapsed cave fill in upper third of Yates Formation, Walnut Canyon, Carlsbad Caverns National Park. Large tumbled blocks (T) are intermeshed with clastic and carbonate internal sediment. Maximum diameter of largest block is 130 feet. Underground stream channel (US) enters cave and is filled with current rippled and laminated clastic internal sediment. Large solution channel (SC) formed by enlargement of joint, enters paleo-cave and was filled, upward from the bottom by clastic internal sediment. B—Close view of solution channel (SC), shown in A (to left), which was filled upward from base with horizontally layered clastic internal sediment. C—Subsurface core slab sequence from upper Yates interval of Central Basin Platform—shows tumbled blocks and large solution channels, to the right (top), which became intermeshed and filled with clastic internal sediment. D—Exposure of algal pisolites in Tansill Formation, in Carlsbad Caverns National Park exhibits solution channels (SC) which became filled with internal sediment and dark laminated micritic "dripstone" cement precipitated in the vadose zone. During burial the limestone became dolomitized.

mann (1929), Lang (1937), Johnson (1942), and Newell and others (1953) all proposed that pisolites are marine and probably of blue-green algal origin. Pia (1940) considered the pisolites to be of inorganic origin. Thomas (1965) and Dunham (1965 and 1969) inferred that pisolites formed as soil concretions (caliche pisolites) in the vadose zone.

Kendall (1969) postulates that pisolites and associated fenestral material are marine in origin, and that subsequent diagenesis and cementation in the vadose-phreatic zone produced phenomena inferred by Thomas (1965) and Dunham (1965 and 1969) to have formed in the vadose zone. According to Kendall (1969), marine pisolites formed in agitated waters just landward of the platform margin where well sorted bioclastic debris, intraclasts, pellets and ooids became coated by micrite laminae whose precipitation was probably caused by blue-green algae. The fact that quartz grains adhered to pisolite surfaces indicates they were initially sticky. The abundance of broken pisolites suggests that pisolites were brittle. Folk (in Kendall, 1969) suggested that pisolites may have been soft when submerged but became brittle when dried. Kendall also infers that pisolites were subsequently deposited by storm waves as gravely pisolitic cays.

We agree with Kendall (1969) that probably most Guadalupian pisolites are of marine- and probably blue-green algal origin, and that pisolitic grainstones subsequently became diagenetically modified in the vadose-phreatic zone, during low stands of sea level, to produce vadose phenomena noted by Thomas (1965) and Dunham (1965 and 1969).

Voids among gravely pisolitic deposits and solution vugs and channels in other outer shelf carbonate facies became partially to completely filled by the following vadose deposits; these criteria for vadose exposure were also noted by Dunham (1965 and 1969) and Thomas (1965) and constitute additional evidence for fresh water diagenesis during eustatic lowerings of sea level.

1. Icicle structures commonly occur in large interstices among pisolites. These record precipitation of stalactitic, gravitational cement which was precipitated in pendulous water films.

2. Laminar micritic ("dripstone") cement (Figs. 16D and 17A) commonly lines solution vugs and channels. These micritic laminar cements closely resemble algal laminations of pisolites. Because laminar algal pisolites commonly became cemented by laminar, "dripstone" cement, it is easy to imagine how confusion as to the origin of these deposits could arise.

3. Drusy, dogtooth calcite cement (Figs. 15 and 16) was commonly precipitated in solution vugs and channels or among pisolitic interstices. Drusy cement may be intercalated with laminar, "dripstone" cement.

4. Layered internal sediment, consisting of granular clastic or carbonate material, was deposited by rapidly percolating vadose water on floors of large interstices among pisolites and in solution vugs and channels (Figs. 16 and 17). Layered internal sediment commonly alternates with laminar and drusy cements.

Kendall describes fibrous calcite cement that coats pisolites as having been deposited by percolating water during subaerial exposure. The writers believe that most of the fibrous calcite cement reported by Kendall represents fibrous recrystallization of fine micritic laminae. In nearly all cases noted by the writers, calcitic fibers diagenetically transect micrite laminae which also became partially recrystallized to microspar or pseudospar. Similar fibrous recrystallization of micrite laminae is formed in stalactites, particularly within inner (older) portions of a stalactite. Newly deposited outer stalactitic laminae, precipitated rapidly by evaporation, exhibit concentric micrite laminae. Within the core of a stactite the former micrite laminae become recrystallized to fibrous calcite with ghosts of the ring structure still preserved.

During paleoleaching intervals, associated with eustatic lowering of sea level, some leaching of evaporites is inferred to have occurred along the outer platform and replacement of sulfate by length-slow chalcedony is recorded (Fig. 15C). Folk and Pittman (1971) have proposed that replacement of sulfates by length-slow chalcedony is a widespread phenomenon in evaporite-bearing sediments. Folk and Pittman (1971) have also inferred that chalcedony precipitated as void-filling is length-fast. Replacement of sulfate by length-slow chalcedony in Guadalupian sediments clearly occurred in the Permian because it is found in subsurface samples.

Burial diagenesis

As previously indicated, supratidal carbonates of Guadalupian formations became dolomitized early in the coastal sabkha environment. Subtidal-intertidal carbonates, which had previously become stabilized to low magnesium calcite and lithified in a fresh water diagenetic environment became dolomitized during burial and all existing effective porosity became occluded by precipitation of void-filling anhydrite (Figs. 15, 16, 17 and 18). Thus, backreef limestones, including pisolitic intervals, containing small-to-large solution vugs and channels, became converted to dolomite and all voids became filled with sulfate cement (Figs. 15, 17 and 18). Precipitation of void-filling anhydrite probably reflects "feedback" of calcium ions which were released by the dolomitization process and precipitated as calcium sulfate. Whether the original void-filling sulfate was anhydrite or gypsum, has not been determined. Replacement of calcitic limestones by dolomite must have been a very slow process, because not one example of dolomitization of calcite during the Holocene is known to the writers; all Holocene dolomitization involves aragonitic precursors. Dolomitization of Guadalupian calcitic limestones and precipitation of void-filling sulfate indicates that dolomitizing fluids were enriched in magnesium and sulfate ions.

Guadalupian outer shelf carbonates were subjected to cycles of emergence and submergence and climatic changes early in their history. It is inferred that dolomitization of aragonite precursors within the sabkha environment could be accounted for within this context of relatively short term fluctuations. Massive dolomitization of calcitic limestones must have occurred at a much slower rate than dolomitization of aragonitic precursors within the sabkha environment, and it must therefore have required the security of an environment not subjected to relatively short term fluctuations and interruptions. It is thus inferred that burial to some depth below that of eustatic sea level drops would have permitted dolomitization of calcitic limestone to proceed without interruption. In a following chapter, precipitation of anhydrite cement in certain sandstones is inferred by independent criteria to have been precipitated at some depth. It is possible that precipitation of porosity occluding sulfate in dolomitized carbonates during burial is related to precipitation of sulfate in intercalated sandstones.

Diagenesis related to Cenozoic uplift

Guadalupian formations exposed in the Guadalupe Mountains area became uplifted and subjected to block-faulting in mid-Tertiary-Pleistocene time. This initiated

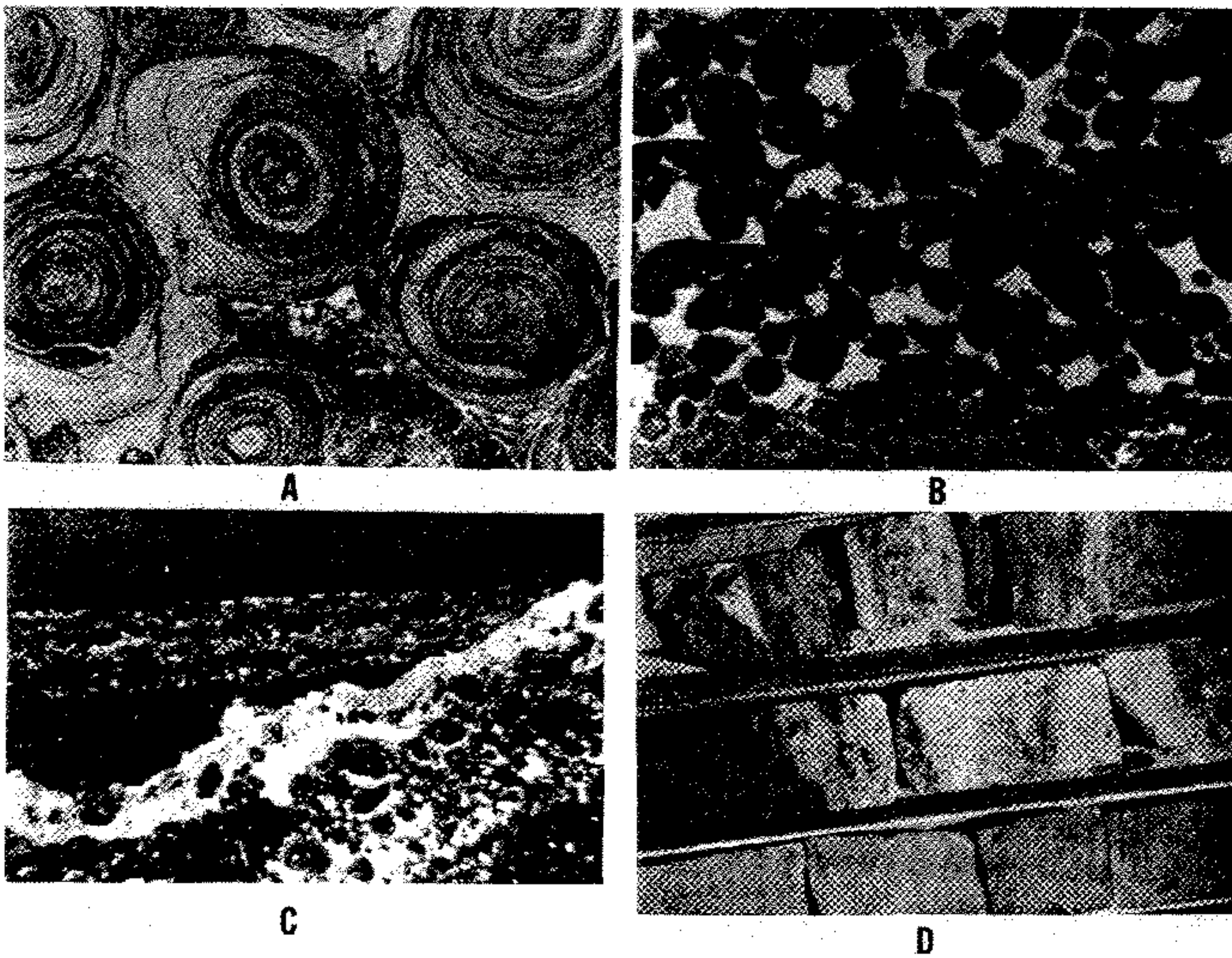

Figure 17. Indications of early lithification and leaching of outer shelf carbonates in a fresh water diagenetic environment, during low stands of sea level, and subsequent dolomitization and occlusion of porosity by anhydrite during burial. A Photomicrograph (from Yates outcrop in Guadalupe Mountains) illustrating algal pisolites which became cemented in the vadose zone by laminar, micritic calcite cement and had vadose internal sediment (IS) deposited in larger interstices by percolating ground water. Laminar, micritic cement films are almost indistinguishable from algal laminations. Dolomitization occurred during burial. Void-filling anhydrite was leached after Cenozoic uplift. X 10. B—Photomicrograph of subsurface sample from Seven Rivers Formation of Northwest Shelf. Algal pisolitic grainstone was subjected to internal sedimentation (gray lenses), cementation and leaching in the vadose zone. During burial dolomitization and occlusion of porosity by anhydrite (white) occurred. X 10. C—Photomicrograph of Yates subsurface sample showing lens of layered carbonate internal sediment deposited in solution channel by vadose percolation. Late dolomitization occurred during burial. Each small division equals 90 microns. D—Subsurface core slab sequence from Yates Formation of Northwest Shelf—shows algal pisolitic grainstone containing layered clastic internal sediment deposited in solution channels. Pisolites were abruptly overlain by clastic deflation flat sediment, to the left (bottom). Dolomitization and filling of voids by anhydrite occurred during burial.

an episode of fresh water diagenesis that is still in progress. Leaching of sulfates (Figs. 15A and 18), hydration of anhydrite to gypsum, replacement of sulfates by calcite and length-slow chalcedony and dedolomitization have occurred and are now in progress. Development of Carlsbad Caverns cave system has included Guadalupian formations. Erroneous interpretation of paragenesis would result if one failed to compare outcrop and subsurface data. Nearly all void-filling sulfate has either been leached from Guadalupian outcrops and filled with calcite cement or replaced by calcite (Figs. 15A and 18) and length-slow chalcedony. Observation in outcrops of Guadalupian dolomites with solution vugs and channels, now either open or filled by calcite cement or length-slow chalcedony, would yield a deceptively fallacious reconstruction of paragenesis.

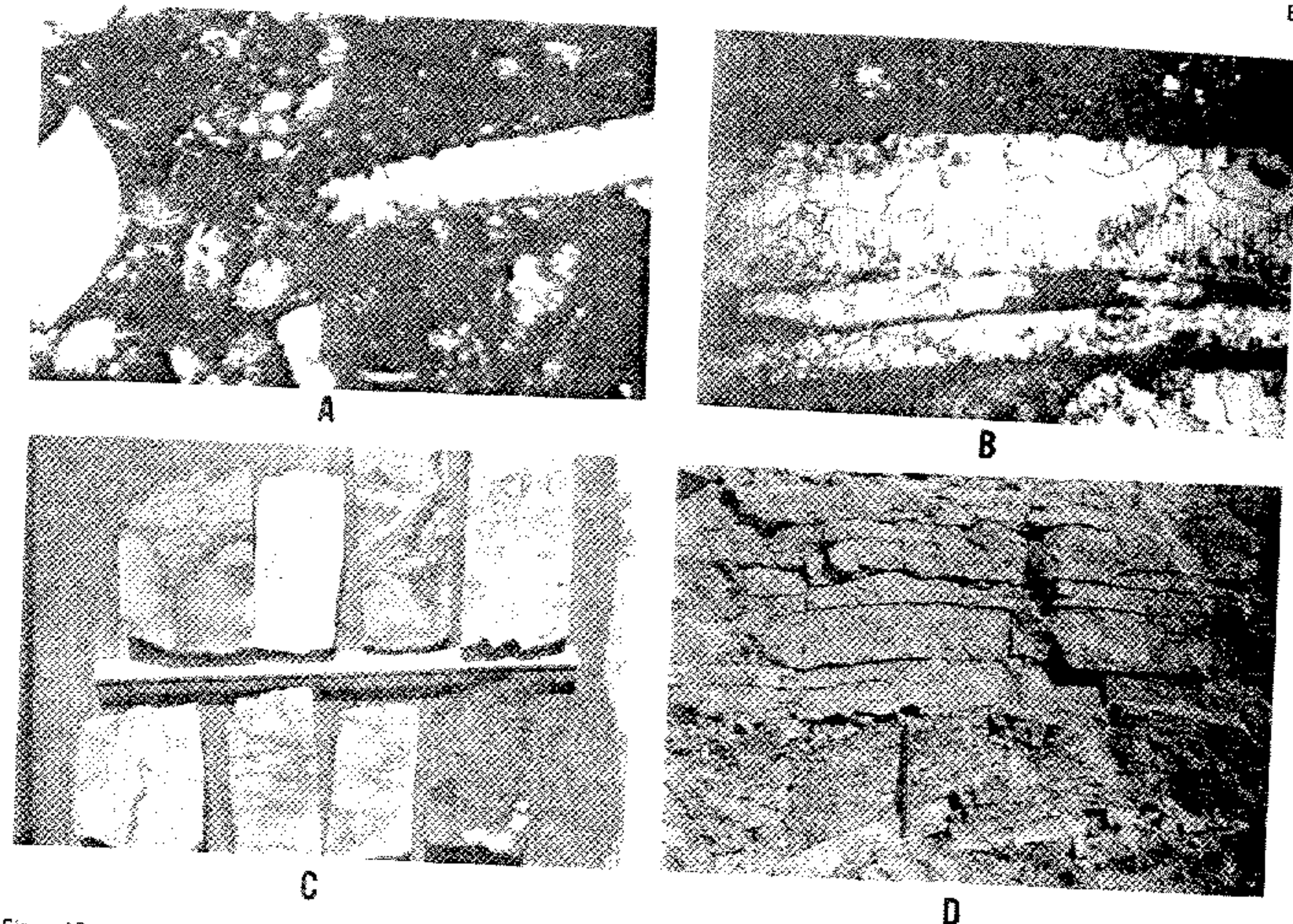

Figure 18. Indications of early lithification and leaching of outer shelf carbonates in a fresh water diagenetic environment, during low stands of sea level, and dolomitization during burial. A–Photomicrograph of biopelmicrite from subsurface sample of Yates Formation. Mineralogic stabilization and lithification occurred during subaerial exposure; aragonitic molluscs became selectively leached and molds and interiors of calcite bivalves became filled by calcite cement. Complete dolomitization of calcite cement calcitic skeletal material and micrite matrix occurred during burial. Each small division equals 42 microns. B–Photomicrograph of Yates outcrop sample from Guadalupe Mountains. Leaching of aragonitic mollusc shell and lithification occurred during early subaerial exposure; dolomitization and filling of mold by anhydrite occurred during burial; after Cenozoic uplift anhydrite became leached (and cemented) or replaced by calcispar. Each small division equals 42 microns. C–Subsurface core slabs showing paleo leached zones and a collapse breccia, which were formed in fresh water diagenetic environment. During burial wholesale dolomitization and occlusion of porosity by anhydrite occurred. D–Exposure of Seven Rivers Formation in Guadalupe Mountains. Paleo-collapse breccia was formed by early internal solution in interval containing pen. Dolomitization and precipitation of void-filling anhydrite and replacement anhydrite (above pen) occurred during burial; leaching of sulfates took place after Cenozoic uplift.

DIAGENESIS OF CLASTICS

Original mineralogy

Permian clastic sediments accumulated predominantly in the following depositional environments: 1) coastal sabkha, 2) continental sabkha, and 3) deflation flat.

Quartzose and subarkose sandstone predominate in Guadalupian shelf sandstones. Dominant feldspar minerals include orthoclase and microcline with minor amounts of plagioclase. Accessory minerals include muscovite, and detrital grains of dolomite, sulfate, chert and carbonate clasts.

Early diagenesis in sabkha and deflation flat environments

Previously described varieties of gypsum crystals and rosettes were interstitially precipitated in clastic coastal and continental sabkha (Figs. 10–14). During progradation of sabkhas, anhydrite replaced gypsum to form nodules, nodular mosaics and pseudomorphed gypsum crystals (Figs. 10–14). Halite was precipitated within red shales (Figs. 12 and 13) and as a cement in red-brown sandstones (Figs. 12 and 13) within continental sabkha brine pan and saline deposits. Massive cementation of sands by original gypsum (Fig. 13D) occurred in continental sabkhas; this is a probable analogue to the massive gypsum rock described by Kinsman (1969) in continental sabkhas inland from the Persian Gulf. Not all original gypsum cement in Guadalupian shelf sediments was replaced by anhydrite during early diagenesis or burial, and some gypsum still exists at depths of greater than 3,000 feet (Fig. 13D).

Early subaerial exposure and fresh water diagenesis

As previously indicated, Guadalupian sediments of the outer shelf area were subjected to subaerial exposure, during low stands of sea level, and the climate was characterized by increased rainfall. Original evaporites were subjected to dissolution, hydration of anhydrite to gypsum, and replacement of some sulfate by length-slow chalcedony.

Development of pisolitic caliche soils on some sandy parent materials converted them into dense petrocalcic horizons. Petrocalcic (caliche) horizons, which formed on sandy parent materials, exhibit concretionary pisolites, grains coated by micritic films and replacement of quartz by carbonate.

Late diagenesis—including burial and subsequent uplift

During burial silica was precipitated as optically continuous overgrowths on quartz grains and orthoclase overgrowths were precipitated on orthoclase grains (Fig. 15D). Overgrowth precipitation occurred on sands that either had not been cemented early in their history, by halite, sulfate or carbonate, or had been subjected to paleoleaching of evaporites. Overgrowths were not formed on grains which contained clay or oxide films.

During burial sands, which were uncemented or from which sulfate or halite cement had been leached, became cemented by dolomite and/or anhydrite after precipitation of overgrowths had occurred on quartz and orthoclase grains. The dolomite cement was a primary precipitate and it consists of small to large (poikilotopic) rhombic crystals. Anhydrite cement, precipitated during burial, may also have been primary because it consists of large individual crystals and does not exhibit the felted lath texture that characterizes replacement of gypsum by anhydrite (Fig. 10C).

Original calcitic material in clastics, such as invertebrates, pisolites and intraclasts, became dolomitized during burial, as in the case of undolomitized carbonates.

Comparison of outcrop and subsurface data enables diagenetic changes that took place during subsequent uplift to be recognized. Uplift of Guadalupian formations in the Guadalupe Mountains occurred in mid-Tertiary-Pleistocene time and the following diagenetic changes were recorded and are still in progress. Anhydrite has been hydrated to gypsum, leached (Figs. 15–18) or replaced by length-slow chalcedony or calcite. The brown-red color of most clastic intervals has been altered to buff, tan or green-gray by flow of ground water through the material and reduction of ferric iron. In layers that still exhibit the brown-red color, local reduction of ferric iron to produce green-gray zones is recorded along fractures or joints. It may be inferred that some decementation of carbonate-cemented sands has occurred.

DISCUSSION OF DOLOMITIZATION MECHANISM

It has been previously indicated that volumetrically most dolomite within Guadalupian shelf carbonates records replacement of outer shelf, subtidal-intertidal carbonates which had been mineralogically stabilized and lithified in a fresh water diagenetic environment. Early dolomitization of predominantly aragonitic coastal sabkha carbonates produced a relatively minor volume of dolomite.

Dolomitization of subtidal-intertidal calcitic limestones did not destroy previous textures and fabrics formed during fresh water diagenesis. Original calcitic cements (laminar, micritic "dripstone" and drusy dogtooth spar) retained their original texture and crystal morphology after dolomitization. Coarsely recrystallized calcitic pseudospar, associated with solution vugs and channels, and layered, granular, calcitic internal sediment also became dolomitized without change in texture or fabric. Xenotopic fabrics predominate in dolomitized calcitic limestones.

Dolomites which were formed early in the sabkha environment are characterized by neomorphic textures, idiotopic to hypidiotopic fabrics and contain features indicative of supratidal deposition (birdeye vugs, desiccation features, flat pebble conglomerates and anhydrite nodules or anhydrite pseudomorphs of gypsum crystals).

Pattern and degree of late dolomitization of calcitic limestones indicates that it resulted from regional, long-continued, predominantly lateral and downward movement of brine enriched in Mg^{++} and $SO_4^{=}$ ions. The Goat Seep reef and its shelf equivalents, the Grayburg and Queen Formations (Fig. 2), are completely dolomitized. The younger Capitan reef is only partially dolomitized and backreef carbonates of the Seven Rivers, Yates and Tansill Formations are completely dolomitized, except in immediate backreef areas where some intervals were only partially dolomitized. In fact, Guadalupian shelf carbonates probably exhibit more intensive dolomitization than carbonates in any other known geologic province. In subsurface samples collected from 2–40 miles behind the Goat Seep-Capitan reef tract no examples of undolomitized Guadalupian carbonates were found. Basinal carbonate turbidites equivalent to the intensively dolomitized Goat Seep reef, the South Wells and Manzanita carbonate intervals of the Cherry Canyon Formation, exhibit greater degrees of dolomitization than basinal limestones equivalent to the partially dolomitized Capitan reef, the Hegler, Pinery, Rader, McCombs and Lamar Members of the Bell Canyon Formation (Fig. 2). Older basinal limestones of the Bell Canyon, the Hegler, Pinery and Rader, exhibit progressively greater degrees of dolomitization than younger limestones, McCombs and Lamar. In all cases, dolomitization of basinal carbonate turbidite intervals attenuates basinward. Thus, dolomitization of reef and basinal carbonates was to a large degree time dependent. Sulfate ions within dolomitizing brine evidently became depleted before magnesium because porosity-occluding sulfates were not precipitated in partially dolomitized basinal carbonates. Massive occlusion of well-developed, leached porosity by void-filling anhydrite accompanied dolomitization of outer shelf calcitic limestones (Figs. 15, 17 and 18).

No hypersaline lagoon, as postulated by Newell and others (1953) and Adams and Rhodes (1960), existed in Guadalupian Time. With the exception of void-filling anhydrite, that was precipitated during dolomitization of calcitic limestone, all shelf evaporites were deposited in coastal or continental sabkhas. Thus, the model of seepage refluxion based upon concentration of brines in hypersaline lagoons cannot explain dolomitization of Guadalupian shelf carbonates. In view of the geologic history of Guadalupian shelves (i.e., subjected to repeated eustatic sea level and climatic fluctuations), it is difficult to explain intensive, wholesale dolomitization of calcitic limestones within the context of the model proposed by Deffeyes, Lucia and Weyl (1965) from the island of Bonaire.

It is postulated that wholesale, late dolomitization of outer shelf calcitic limestones records regional hydrodynamic reflux of brines enriched in magnesium and sulfate ions and chlorides. The brine originated in the vast middle to inner shelf, evaporite-bearing, clastic sequence (coastal sabkha, continental sabkha and deflation flats) and moved laterally and downward through outer shelf and basinal carbonates, dolomitizing them. The water may have been original fresh ground water whose density and salinity were progressively increased as it moved toward the relatively narrow band of outer shelf carbonates. According to Kinsman (1966), lack of dolomitization in clastic host materials would yield brines depleted in Ca^{++}, enriched in Mg^{++} and containing up to 60–70% of their original $SO_4^{=}$ (if derived from original sea water). The presence of magnesite and sulfates in evaporite-bearing clastics attests to high concentration of Mg^{++} and $SO_4^{=}$ ions.

CONCLUSIONS

1. The following depositional environments are recorded in Guadalupian shelf formations of the Permian Basin: 1) reef, 2) backreef apron, 3) lagoon, 4) intertidal zone, 5) coastal sabkha, 6) continental sabkha, 7) deflation flat.

2. Guadalupian outer shelf deposits contain well-developed depositional cycles which consist of vertical sequences of the following deposits: 1) subtidal carbonates (reef, backreef, lagoon), 2) intertidal clastics and carbonates, 3) coastal sabkha (clastics, carbonates and evaporites), 4) continental sabkha (clastics and evaporites) and 5) deflation flat clastics. These rhythms record alternate submergence and emergence of the shelf and are inferred to result from the following combination of factors: 1) glacially controlled eustatic sea level fluctuations, 2) continuous subsidence, and 3) progradation of coastal-continental sabkha and deflation flat deposits, during high stands of sea level, to progressively infill lagoons.

3. Vast extent of sabkha-type deposits, containing evaporites, in the Guadalupian does not reflect deposition in gigantic coastal sabkhas (megasabkhas). Widespread occurrence of Middle Permian sabkha deposits records: 1) deposition of continental sabkha deposits extending far inland from coastal sabkha deposits extending far inland from coastal sabkha and 2) seaward progradation of coastal sabkha, continental sabkha and deflation flat deposits and progressive infilling of lagoonal deposits during still stands of sea level, following transgression of the sea over all or part of the outer shelf.

4. In Guadalupian time high stands of sea level were characterized by arid climates and precipitation of evaporites in coastal and continental sabkhas. During low stands of sea level the shelf was emergent and the outer shelf area was characterized by increased rainfall.

5. The largest documented Guadalupian sea level change is recorded in the upper third of the Yates interval where a sea level drop of at least 130 feet is recorded by the previously described collapsed cave interval. The 130 feet represents partial thickness of a paleo-vadose zone. Based upon thicknesses of individual vadose zones, many sea level drops seem to have ranged from 10–15 feet to 30–50 feet (minimum). The 130 foot (minimum) drop may represent a full glacial interval and others may correspond to stadials.

6. From comparison of outcrop and subsurface data the following paragenesis can be reconstructed for Guadalupian sediments.

a. Deposition of reef, backreef, lagoonal, intertidal, coastal sabkha, continental sabkha and deflation flat facies.

b. Early hypersaline diagenesis in the coastal or continental sabkha environment. 1) precipitation of different types of gypsum crystals, 2) cementation of sands by original gypsum—especially in the continental sabkha environment, 3) dolomitization of aragonitic carbonates, 4) replacement of gypsum by anhydrite to form pseudomorphs of gypsum crystals or neomorphous nodules and chicken wire structure, 5) replacement of some carbonate by sulfate.

c. Eustatic lowering of sea level, change of climate to one of increased rainfall (for outer shelf area), and mineralogic stabilization (aragonite and high magnesium calcite to low magnesium calcite), leaching and lithification of undolomitized, subtidal-intertidal carbonates occurred in a fresh water environment to form calcitic limestones.

d. During burial calcitic limestones (including petrocalcic horizons), which had formed during early subaerial exposure in a fresh water diagenetic environment, became dolomitized and all effective porosity was occluded by precipitation of voidfilling anhydrite (originally gypsum?); this indicates that the dolomitizing fluid was enriched in Mg^{2+} and SO_4^{2-} ions. During burial of uncemented sands, epitaxial overgrowth of quartz on quartz grains and orthoclase on orthoclase grains was followed by precipitation of dolomite and anhydrite cements. Calcitic material within clastic intervals became dolomitized during burial, like calcitic limestones.

e. Uplift of Guadalupian sediments in mid-Tertiary to Pleistocene time initiated another episode of fresh water diagenesis which is still in progress and diagenetic reactions include: 1) enlargement of fractures by ground water solution and cave formation (Carlsbad Caverns), 2) solution and hydration (to gypsum) of anhydrite and replacement of sulfate by calcite and length-slow chalcedony, 3) precipitation of modern calcite cement in solution channels and vugs, 4) minor dolomitization, 5) precipitation of length-fast chalcedony in some voids (as a result of subaerial exposure), 6) alteration of originally brown-red sandstones to tan, buff or green-gray colors probably reflects reduction of ferric iron.

7. Most dolomite in Guadalupian shelf carbonates was formed by replacement of calcitic limestones, which had been stabilized and lithified in a fresh water diagenetic environment during low stands of sea level, rather than by early dolomitization of aragonitic lime mud in coastal sabkhas. Dolomitization of limestone occurred at a much slower rate than replacement of unstable aragonitic precursors; therefore, it required the security of an environment where it could proceed uninterrupted by short-term fluctuations in sea level and climate. Dolomitization of outer shelf limestones is inferred to have occurred during burial by brines enriched in magnesium, sulfate and chlorides. Dolomitizing brine evolved in evaporite-bearing clastic host materials of coastal and continental sabkhas wherein early dolomitization and attendant depletion of magnesium and sulfate did not occur. The brine, which may have originated as original fresh water, moved laterally and downward by hydrodynamic reflux, intensively dolomitized outer shelf limestones and partially dolomitized basinal carbonate turbidites with an unstable mineralogy.

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