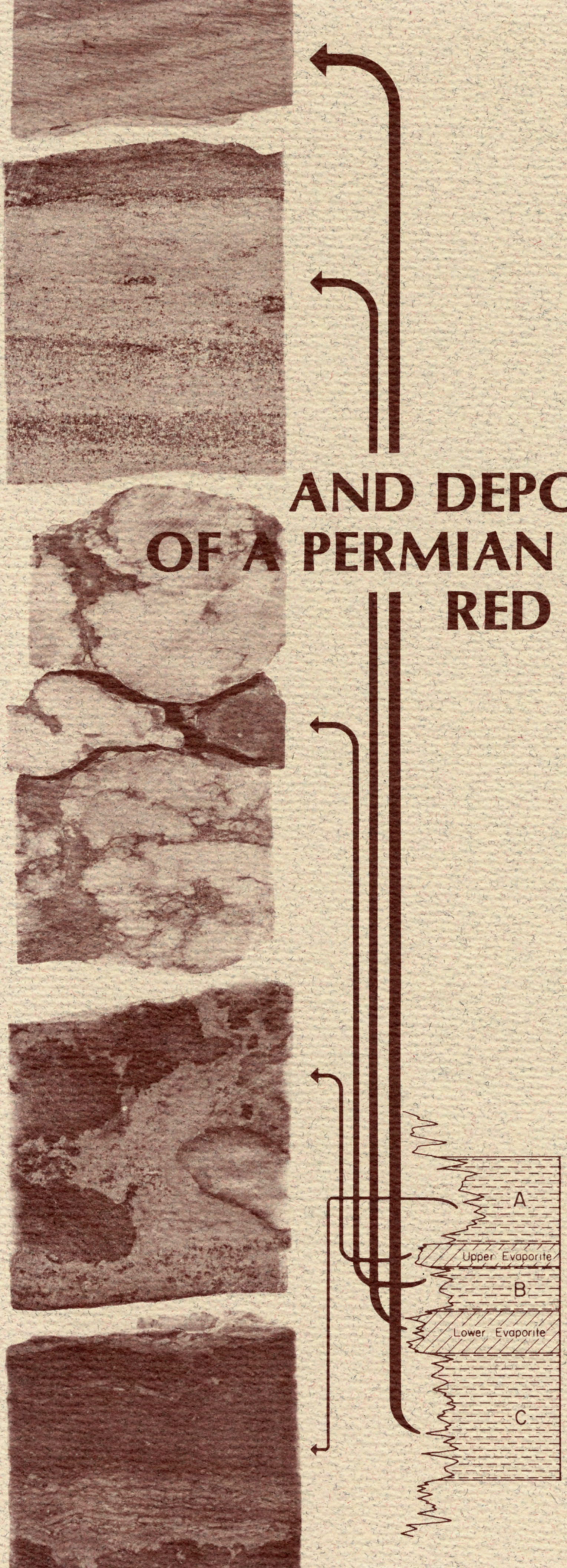

GEOLOGICAL CIRCULAR 80-9

FACIES PATTERNS AND DEPOSITIONAL HISTORY OF A PERMIAN SABKHA COMPLEX: RED CAVE FORMATION, TEXAS PANHANDLE

by C. Robertson Handford
and Paul E. Fredericks

BUREAU OF ECONOMIC GEOLOGY
THE UNIVERSITY OF TEXAS AT AUSTIN
W. L. FISHER, DIRECTOR

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ABSTRACT

The Red Cave Formation (Permian, Leonard Series) in the Texas Panhandle consists of cyclic, red-bed clastic and carbonate-evaporite members that reflect deposition in extensive coastal sabkhas. These environments were bounded on the north by a desert wadi plain and on the south by a carbonate inner shelf that bordered the northern Midland Basin. Evaporite members were deposited in carbonate-evaporite coastal sabkhas, and clastic members were deposited in mud-rich coastal to continental sabkhas that passed inland to wadi-plain environments.

Inner shelf dolomites include slightly fossiliferous, faintly laminated to burrowed mudstone and pellet wackestone. These lithofacies are overlain by and interfinger northward with dolomite and anhydrite deposited in coastal sabkhas. Oolitic or pellet packstone and grainstone with well-developed cross-lamination suggest shallow subtidal to intertidal deposition. Supratidal facies include dolomitic mudstone with algal laminations and some intraclasts. Sabkha sequences are commonly capped with nodular anhydrite; mud-rich sabkha sequences culminate with red to green mudstone and anhydrite. Carbonate and evaporite facies pinch out generally toward the northwest and northeast into wadi-plain red beds. These facies include ripple-drift, cross-laminated siltstone and sandstone, adhesion-rippled siltstone, and red to green mudstone. Desiccation features, intraclasts, root zones, and paleosol horizons cap braided fluvial deposits and attest to subaerial exposure and probable non-marine conditions.

Partial modern analogs to Red Cave sabkha depositional elements include coastal mud flats and alluvial fans in the northwestern Gulf of California, tidal flats and the Wooramel ephemeral stream delta in Gladstone Embayment, Shark Bay, Australia, and Trucial Coast sabkhas in the Persian Gulf. Each setting has certain facets that are remarkably similar to interpreted paleoenvironments and lithofacies of the Red Cave Formation.

INTRODUCTION

During Middle and Late Permian time, an arid coastal plain or sabkha dominated the landscape of the Texas Panhandle, across which extensive, sheetlike red beds and evaporites were deposited. The oldest of the major red-bed deposits is the Red Cave Formation (Leonardian, Clear Fork Group), which consists of cyclically bedded, offlapping stratigraphic units that record the first major pulses of marine evaporite and continental red-bed deposition in the Panhandle. These sabkha deposits are marginal to those of shallow carbonate shelf and shelf-margin environments that bordered deeper marine environments in the northern Midland Basin (Jeary, 1978; Silver and Todd, 1969).

Purpose

Although many recent and ancient examples of humid region, clastic and carbonate tidal-flat deposits, and carbonate-evaporite sabkha sequences have been previously documented (Ginsburg, 1975; Illing and others, 1965; La Porte, 1969; Lucia, 1972; Reineck, 1972; Roehl, 1967; and Shinn and others, 1969), few examples of ancient, clastic-dominated coastal and continental sabkhas have been described in detail. Exceptions include those studied by Glennie (1972), Jacka and Franco (1974), and Smith (1974). Modern examples of clastic-dominated sabkhas were described by Amiel and Friedman (1971), Thompson (1968), and Glennie (1970). The present study documents both clastic- and carbonate-evaporite-dominated sabkha complexes that formed across the Texas Panhandle during Middle Permian (early Leonardian) time.

This report (1) identifies Red Cave lithofacies and delineates their vertical and lateral distribution; (2) determines their environments of deposition; and (3) outlines the depositional history of a coastal sabkha system.

Lithofacies of the Red Cave Formation are relatively thin but widely distributed in broad, arcuate belts across the Texas Panhandle. Subsurface maps of approximately synchronous stratigraphic units were generated, facilitating a detailed regional study of red-bed and evaporite facies through time. Results presented in this report rely strongly upon regional geometry of lithofacies tracts, and comparison of rock types (including composition, textures, and fabrics), sedimentary structures, and vertical sequences with sedimentary facies from modern depositional analogs. Knowledge of physical processes that led to the development of modern coastal mud sabkhas facilitated interpretations of mechanisms responsible for development of Red Cave sabkha facies.

Methods

Approximately 400 geophysical logs (gamma ray, neutron, sonic, caliper, spontaneous potential, and resistivity) and numerous sample logs served as a data base for lithofacies mapping and stratigraphic correlation. In addition, six cores of the Red Cave Formation from Moore, Potter, and Randall Counties were examined in detail. General facies types were calibrated to geophysical logs to enhance regional lithofacies interpretations. Careful examination of cores resulted in recognition of specific depositional environments that aided in paleogeographic reconstruction of the Texas Panhandle.

Locations of well sites (including core samples) from which cross sections published in this report were made are shown in figure 1 and listed in Appendices 1 and 2. All data (logs, maps, and cross sections) are filed at the Bureau of Economic Geology.

REGIONAL SETTING AND STRATIGRAPHY

Several basins and uplifts underlie the Texas Panhandle (fig. 1). The Palo Duro, Dalhart, and Hardeman Basins are shallow cratonic basins ($\leq$ 10,000 ft [3,000 m] deep) bounded by prominent uplifts, arches, and domes that are generally composed of Precambrian silicic igneous rocks. The Anadarko Basin is much deeper (> 30,000 ft [9,100 m] in Washita County, Oklahoma, according to Wroblewski, 1975) and apparently formed as a result of Pennsylvanian tectonism of the Southern Oklahoma Aulacogen (Wickham, 1978). At about the same time, the Delaware Aulacogen (Walper, 1977) was deformed, leading to the development of the Delaware and Midland Basins. Proximity of the Palo Duro Basin to these major tectonic features and similar geologic histories shared by each indicate that the Palo Duro and Dalhart Basins also formed because of Pennsylvanian tectonism of the Southern Oklahoma and Delaware Aulacogens, along what was the southern continental margin.

Pennsylvanian and Permian strata comprise most of the sedimentary fill in each basin. Pennsylvanian and Lower Permian strata consist of carbonate and terrigenous-clastic sedimentary rocks that record deposition in a complete spectrum of environments ranging from deep marine with depths less than 500 ft (150 m) to shallow shelf

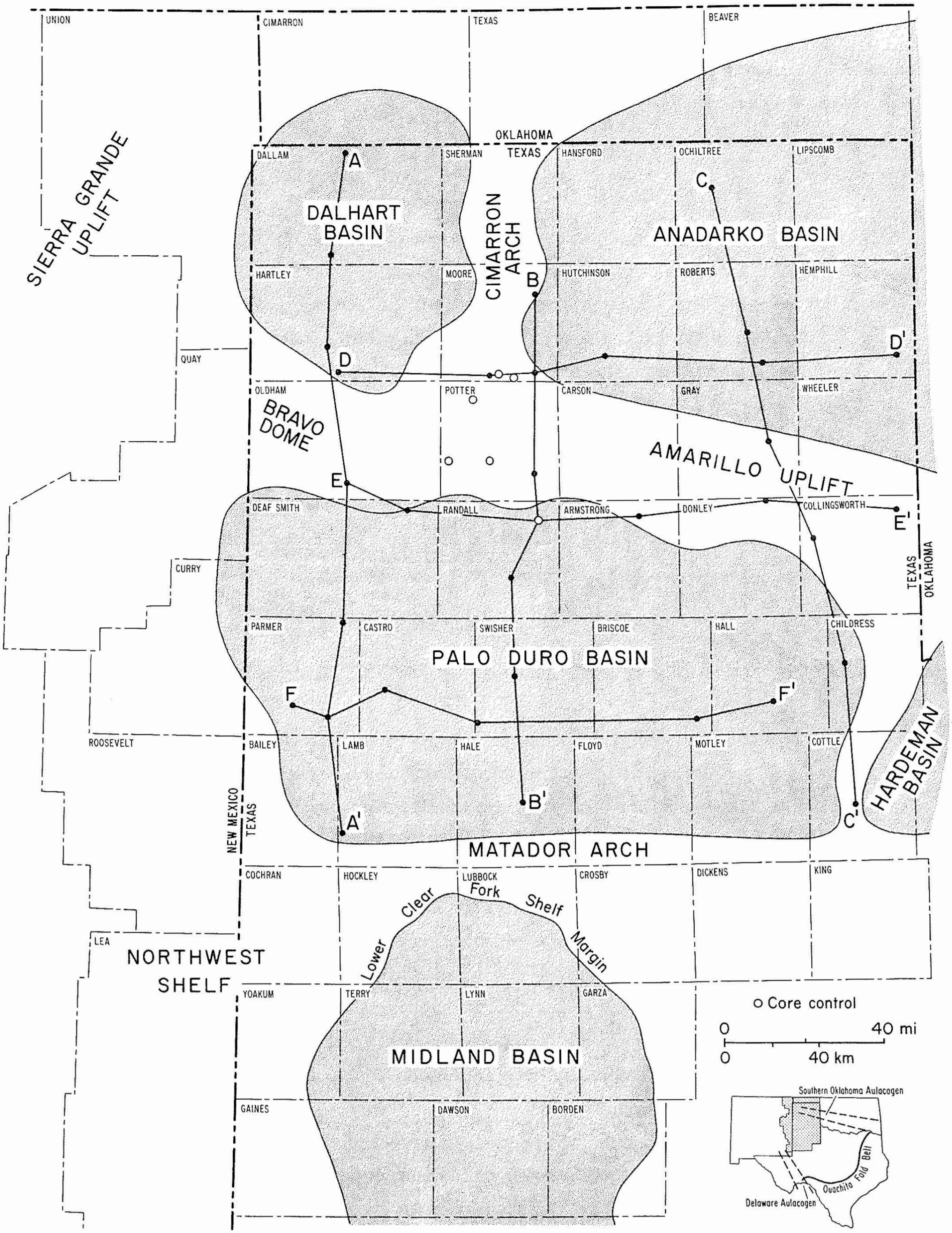


Figure 1. Regional geologic setting of Texas Panhandle. Map shows cross section lines and core locations.

and fluvial-deltaic (Handford and Dutton, 1980). During Early Permian time, the deepest parts of the basins were filled, transforming the Texas Panhandle into a wide, very shallow shelf environment. Middle and Upper Permian strata consist almost entirely of evaporites and red beds that record deposition across an extensive sabkha plain that passed southward into a shallow-marine, carbonate shelf and shelf-margin complex in the northern Midland Basin (Dutton and others, 1979).

During Leonardian time, a thick succession of terrigenous clastics, or red beds, accumulated across the northwestern corner of the Texas Panhandle and east-central New Mexico. The coarsest grained facies was deposited in New Mexico and is referred to as the Sangre de Cristo Formation (Foster and others, 1972). Where the formation passes into a finer grained facies in New Mexico its name changes to the Abo and Yeso Formations (Foster and others, 1972). These red-bed strata extend across the northern part of the Texas Panhandle where they pass into predominantly carbonate and evaporite facies comprising the Wichita and Clear Fork Groups (fig. 2).

The oldest stratigraphic unit of the Clear Fork Group is locally called the Red Cave Formation, an informal name that refers to the red color of the formation, its incompetency, and its tendency to cave in where boreholes are drilled (Pierce and others, 1964). This formation consists of southward-thinning, regionally extensive red to green mudstone and siltstone that coarsen to the northwest into conglomerate and

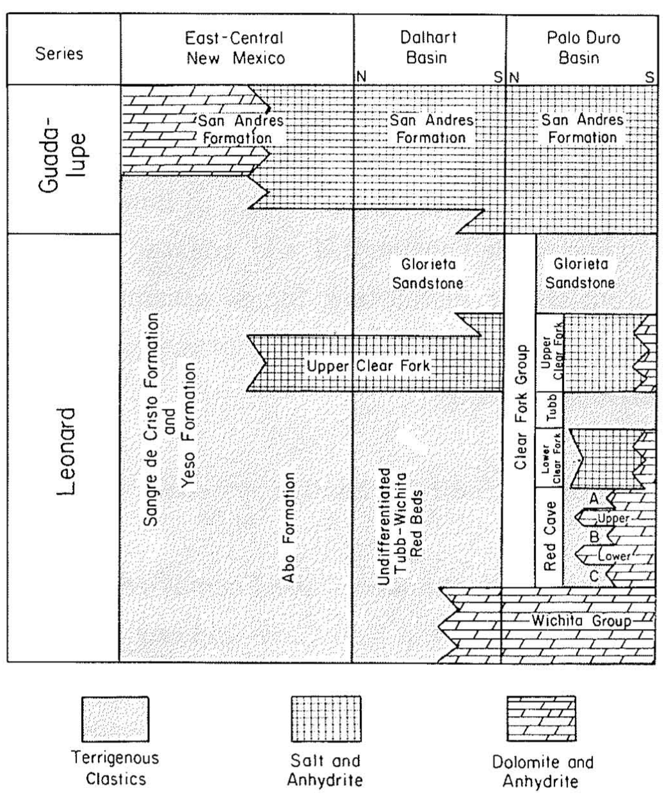


Figure 2. Stratigraphic nomenclature of Middle Permian strata in the Texas Panhandle and adjoining New Mexico.

arkose of the Abo Formation, and intertongue with anhydrite and dolomite to the south. The Red Cave is conformable with the Wichita Group below and the lower Clear Fork Formation above.

Informal stratigraphic members have been designated to subdivide the Red Cave Formation (fig. 2). Three clastic members that interfinger and pass southward into carbonate facies are referred to in this report (in descending order) as the A, B, and C members. Two carbonate-anhydrite members are sandwiched between the clastic members and are referred to as the upper and lower evaporites (figs. 3, 4, and 5).

Each stratigraphic member was mapped across the Panhandle, from the updip (north) pinchouts of the lower and upper evaporite members to the downdip (south) pinchouts of each clastic member (figs. 6 and 7). Sample logs complemented stratigraphic correlations and permitted discrimination of dolomite and anhydrite within each stratigraphic member. The updip limit of dolomite, illustrated in each map, probably represents the transition from intertidal or lower supratidal to sabkha environments. Therefore, sabkha terrain is inferred to occur updip of the dolomite limit in each stratigraphic member. For each clastic member, continental environments are inferred where isolith patterns assume dip-oriented, lobate shapes. These interpretations are substantiated by core analysis. Detailed facies analyses and depositional systems interpretations follow.

DEPOSITIONAL SYSTEMS

Sedimentary facies of the Red Cave Formation (figs. 6 and 7) were deposited in environments of the following depositional systems: (1) inner shelf carbonate system, (2) sabkha system, including both continental and coastal types, and (3) wadi plain system. Each system consists of distinctive facies assemblages comprising several facies tracts that display certain rock properties characteristic of facies deposited in analogous modern depositional settings.

Inner Shelf Carbonate System

Thin interbeds of dolomite in the Red Cave Formation, as well as dolomite that occurs south of the mapped limits of the Red Cave and north of the Clear Fork shelf-margin, were probably deposited in an inner shelf, marine environment. Lithologies include tan to gray dolomitic mudstone and pellet wackestone rocks (fig. 14), with occasional thin-shelled brachiopods and gastropods (fig. 8, cores C, D, and E). These rocks are generally structureless or have faint, wispy laminae of darker colored,

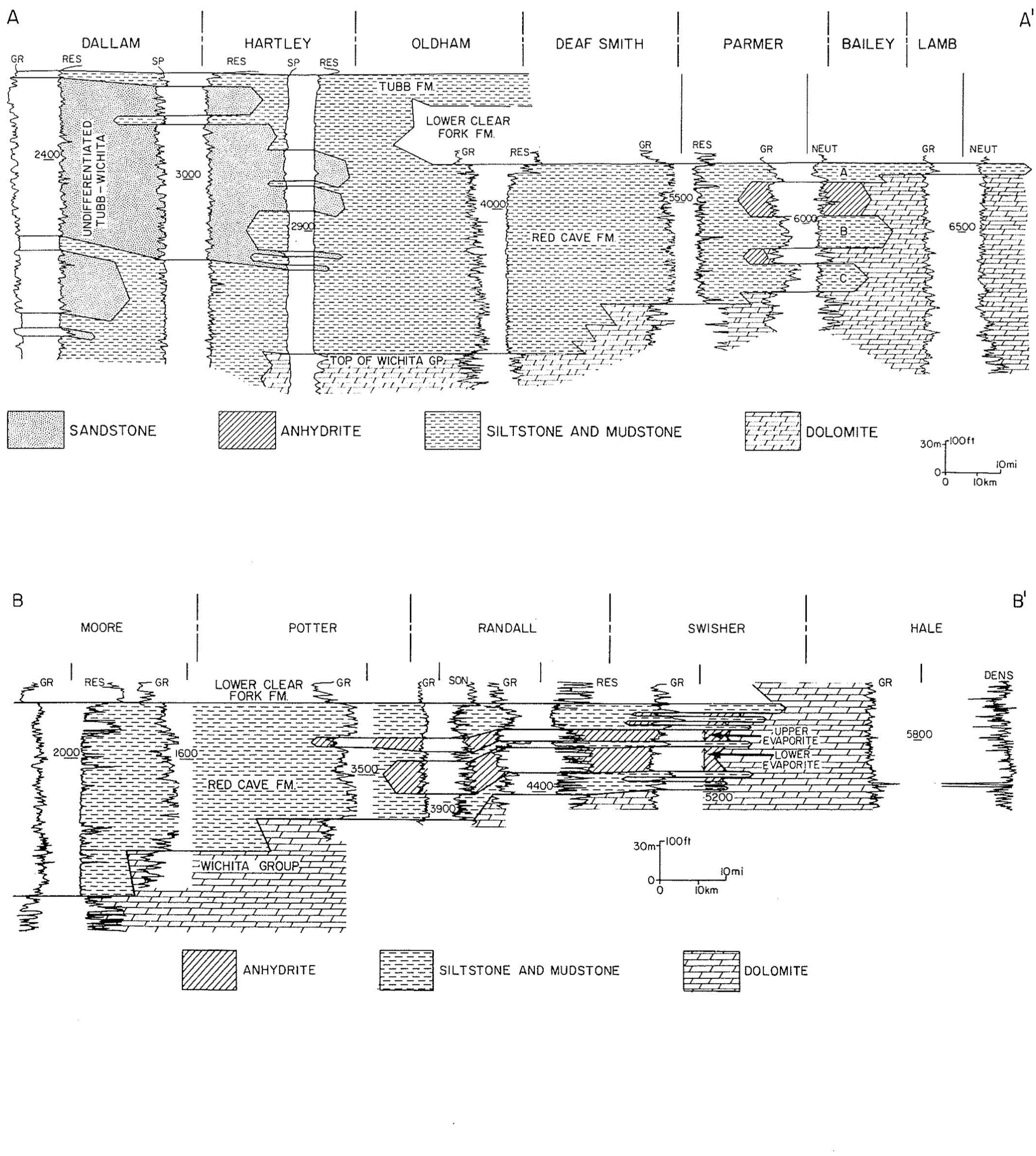


Figure 3. North-south cross sections A-A' and B-B' through the Red Cave Formation.

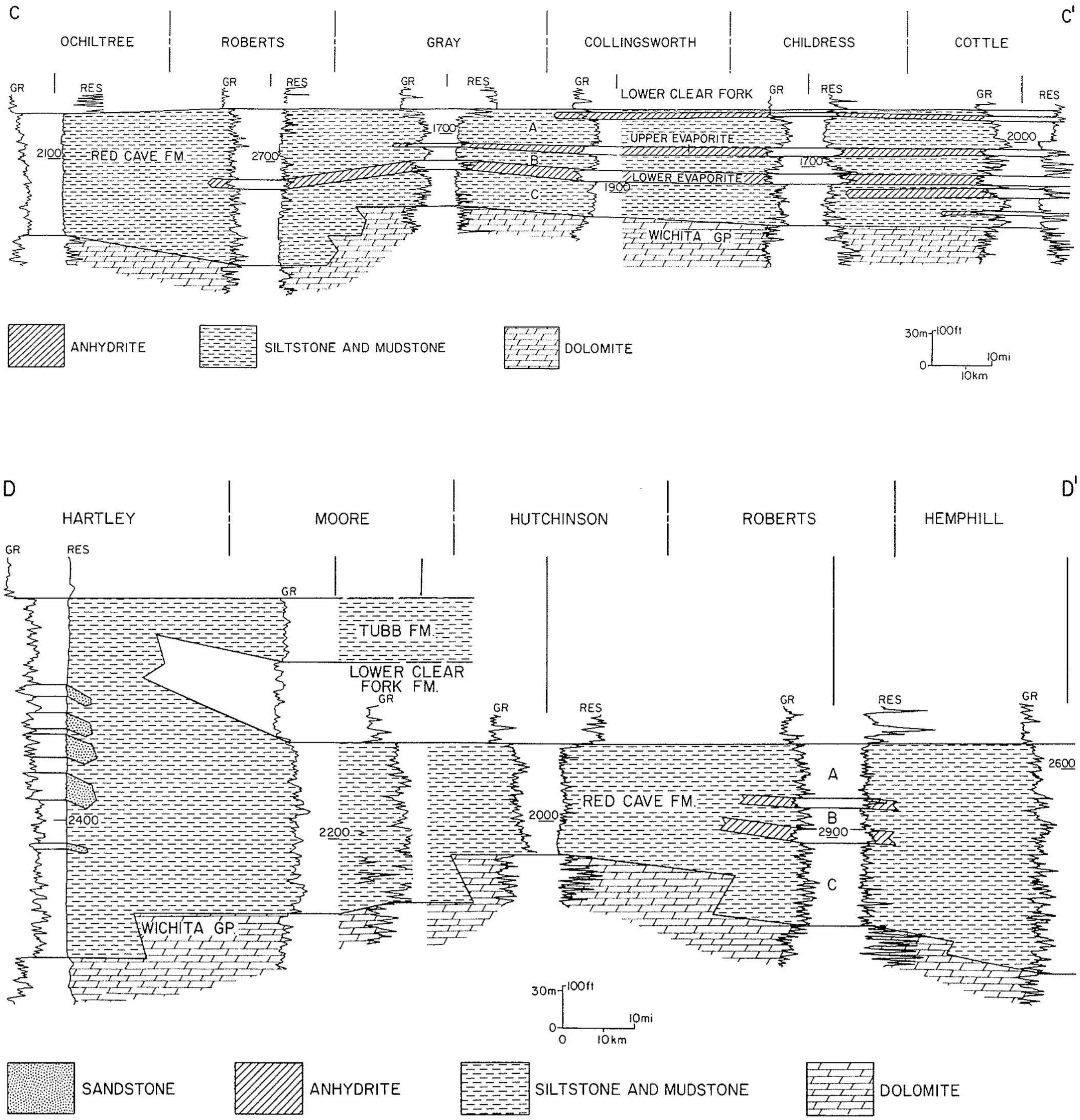
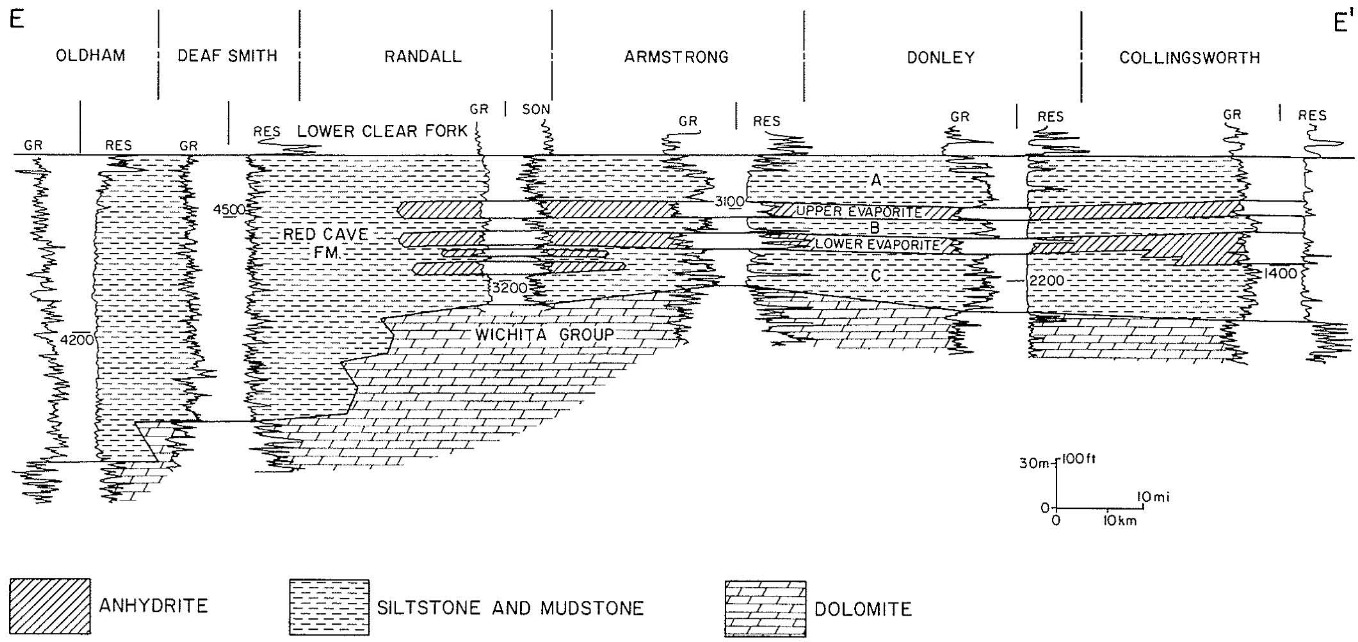


Figure 4. North-south and east-west cross sections C-C' and D-D' through the Red Cave Formation.



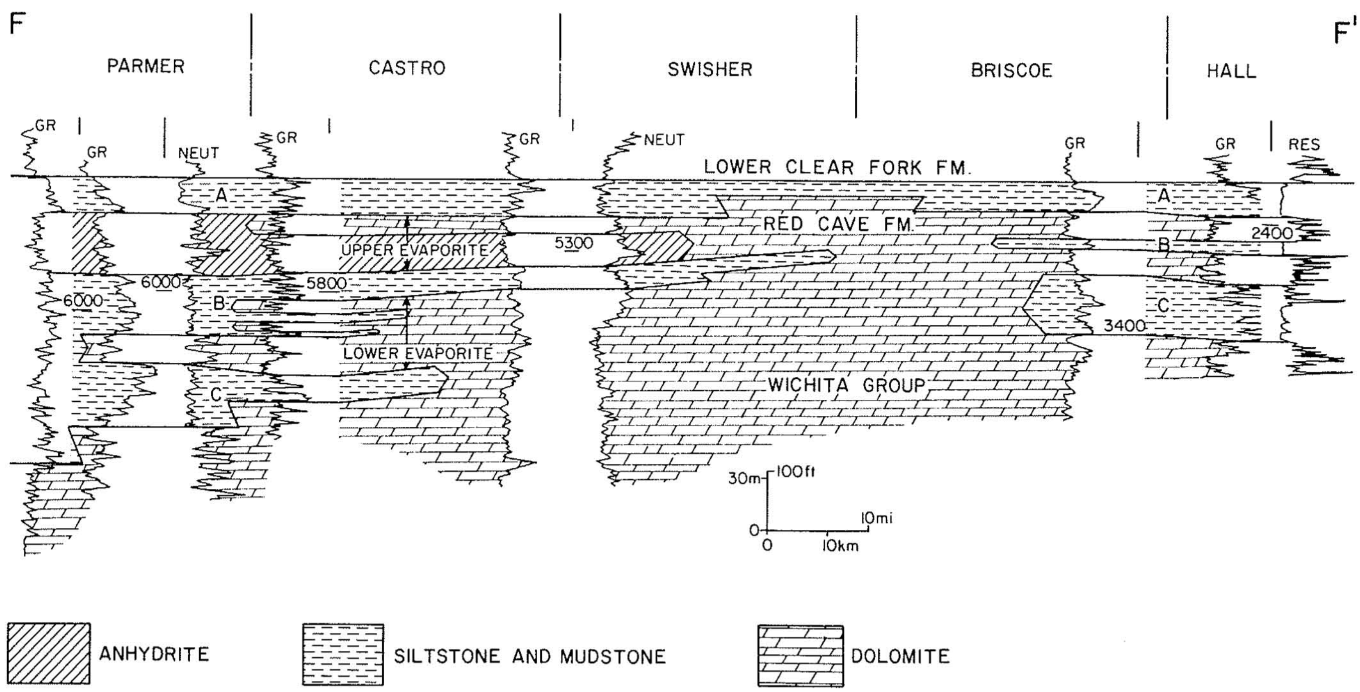


Figure 5. East-west cross sections E-E' and F-F'.

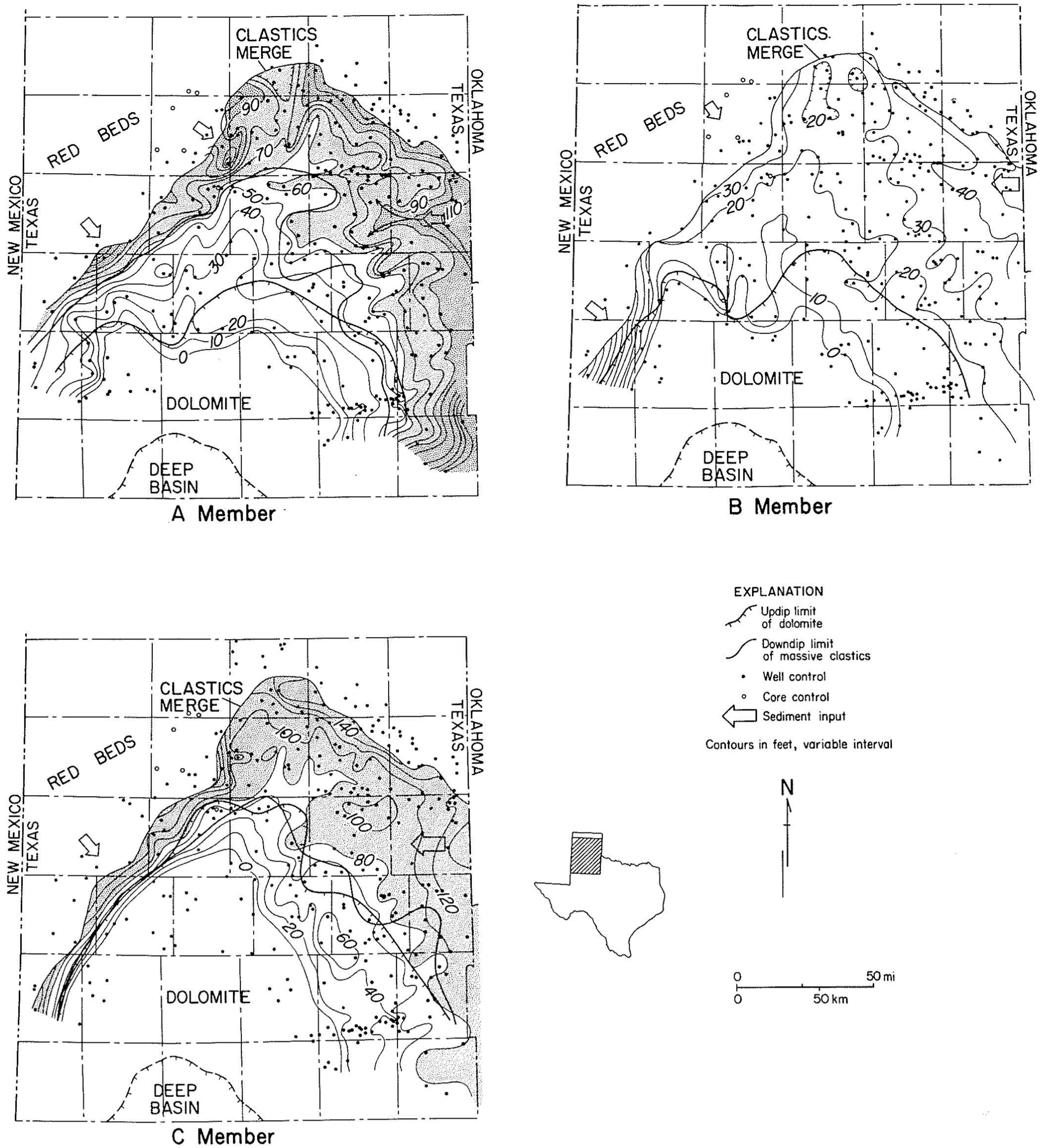


Figure 6. Net clastics isolith maps of A, B, and C clastic members of the Red Cave Formation. Unmapped areas north of the members are undifferentiated red beds of the Tubb-Wichita interval (see fig. 2). Stipple patterns accentuate the dip-oriented, southward thinning clastic units.

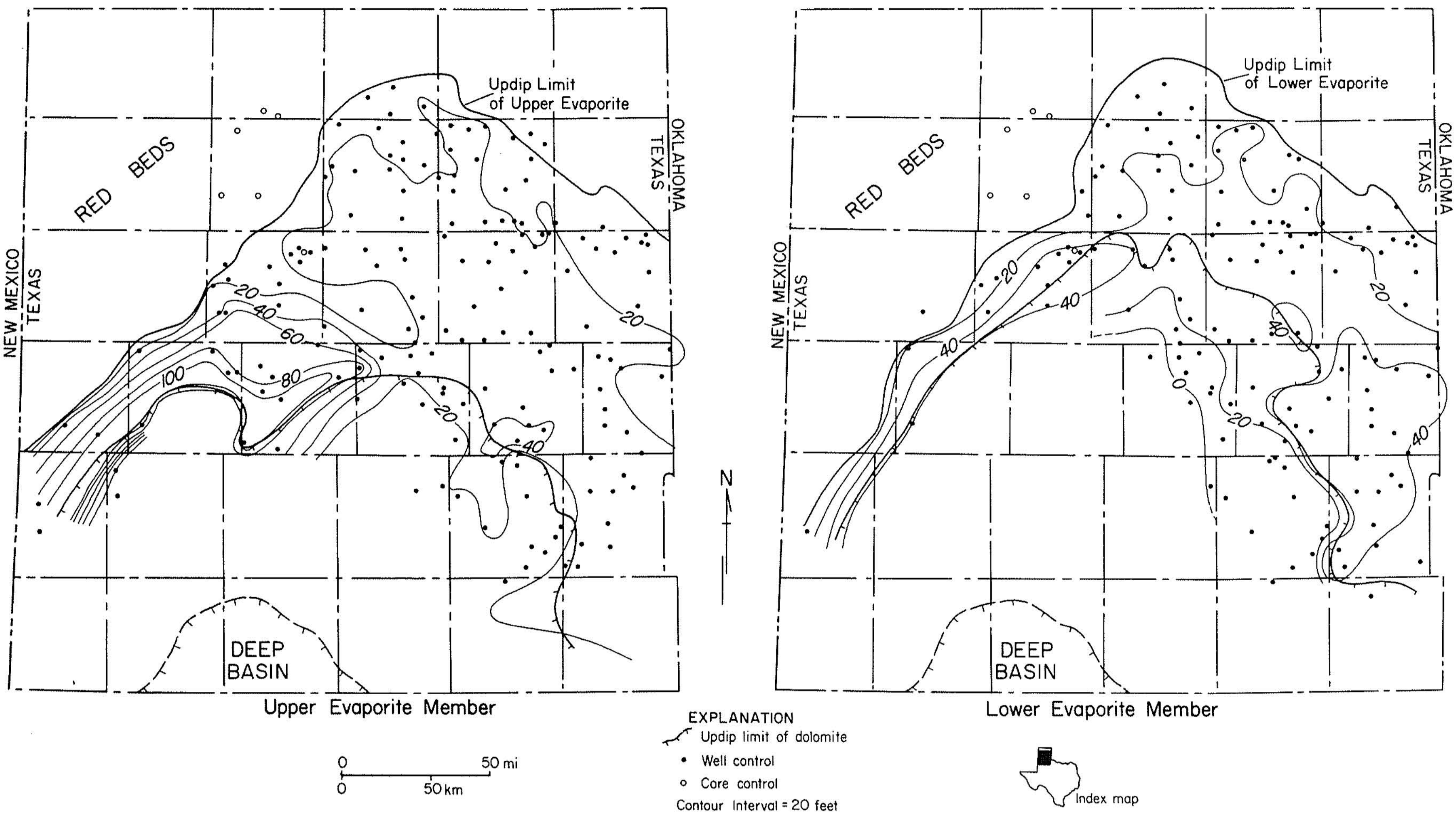


Figure 7. Net anhydrite isolith maps of the lower and upper evaporite members of the Red Cave Formation.

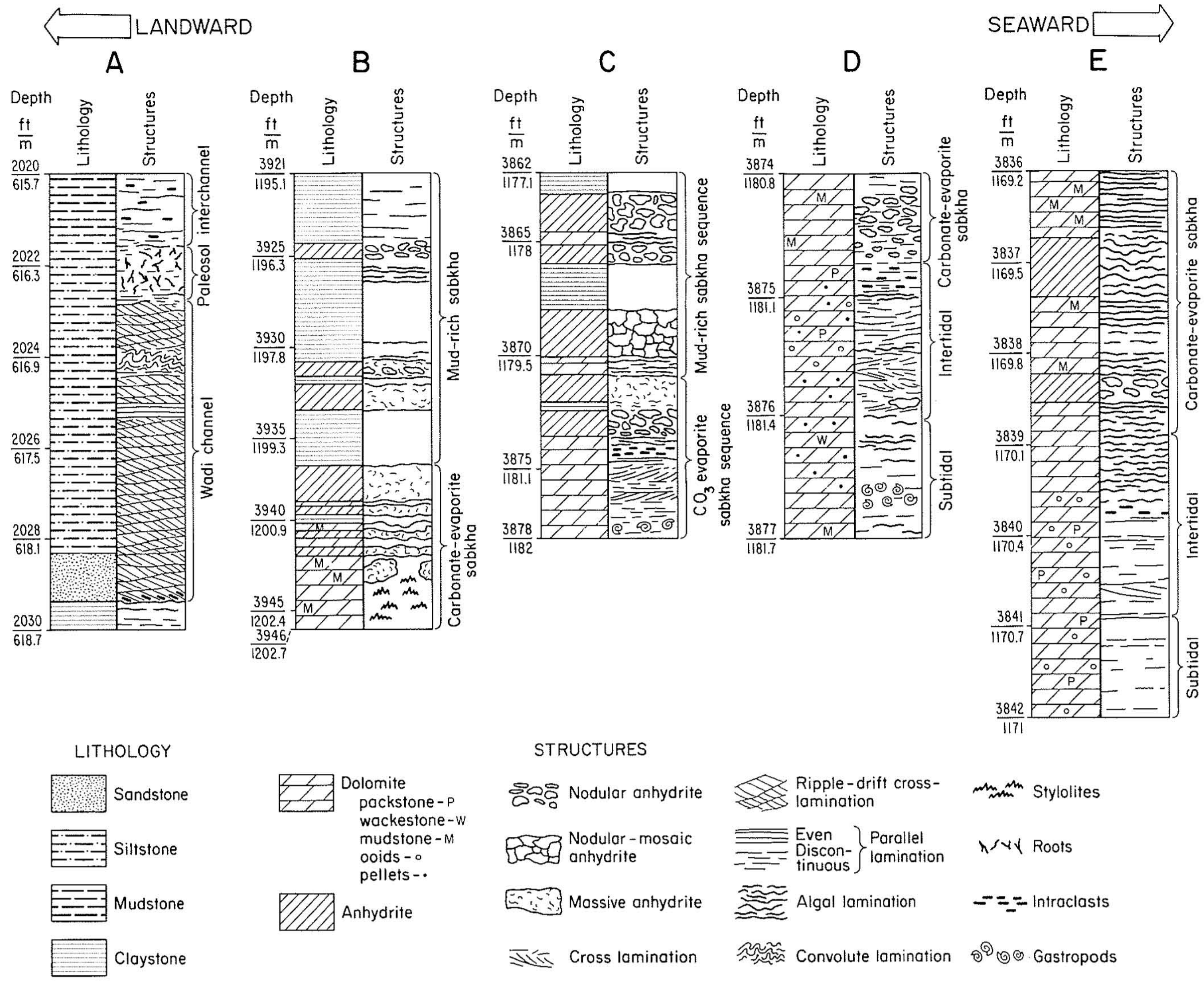


Figure 8. Sabkha and wadi plain facies sequences. Core A, Moore County, Maynard Oil Company, Sneed 3-6; Cores B, C, D, and E, Randall County, DOE/Gruy Federal, Inc., Rex W. White 1.

organic-rich clay laminae that may suggest the former presence of subtidal algal mats. In deposits younger than middle Paleozoic, prolific browsing and burrowing activity in lower intertidal zones have homogenized sediments so that the signature of intertidal deposition is recorded only within middle and upper intertidal sediments (James, 1977). However, where salinities increased significantly, gastropods, which are primarily grazers, were not abundant and thus allowed mats to grow into subtidal zones. Because marine evaporites are abundant and fossils are rare in Red Cave carbonates, elevated salinity is inferred; thus, conditions favorable for growth and preservation of lower subtidal algal mats may have been established.

Rocks of the inner shelf system are most common in the southern half of the Palo Duro Basin (figs. 6 and 7) outside the subcrop area of clastics belonging to the Red Cave Formation; however, thin carbonate beds extend northward at least into Randall County. This indicates that depositional relief was very low, so that minor subsidence of sabkhas to the north and extremely small eustatic sea level changes could have affected large areas of the Panhandle. Evidence of periodic rapid transgressions includes thin subtidal carbonate strata that overlie supratidal facies.

For the lower and upper evaporite members, the boundary between inner shelf and sabkha environments is generally defined by the updip transition from carbonate- to anhydrite-rich facies. The boundary in each clastic member occurs near their downdip pinchouts.

Sabkha Systems

A wide coastal and continental sabkha was present north of the inner shelf environment and was dominated by deposition of carbonate or terrigenous mud and interstitial precipitation of sulfates. Carbonate-evaporite sabkha environments were periodically covered by fluvially introduced, terrigenous red mud derived from updip (depositional) fluvial systems. Thus, two contrasting styles of sabkha sedimentation developed--a carbonate-evaporite sabkha system, exemplified by the lower and upper evaporite members (fig. 7), and a mud-rich sabkha system, represented by clastic members designated A, B, and C (fig. 6).

Carbonate-evaporite sabkhas

Facies of the lower and upper evaporite members form vertical sequences that commonly begin with subtidal inner shelf dolomite overlain by intertidal oolitic or pellet packstone and grainstone, followed by supratidal or sabkha dolomitic mudstone and various types of anhydrite (fig. 8, cores B, C, D, and E). These facies sequences are thought to record progradation of sabkha environments over intertidal-subtidal shelf deposits.

Intertidal oolitic and pellet grainstones (fig. 9a) are tan to brown, medium to coarse grained, and commonly bear intraclasts, fenestral fabrics, and abundant current structures (large-scale cross-lamination in sets up to several inches thick, and parallel lamination). Sedimentary textures and structures indicate a wave- or current-agitated shoreline.

Supratidal facies include dolomitic mudstone, pellet packstone, and intraclastic packstone. Wispy, black, organic-rich laminae and wavy to crenulated, dolomite-anhydrite laminae (fig. 9b) occur in these rocks and are interpreted as algal mat remains. Gypsum was probably precipitated in voids beneath algal mats on the sabkha surface. Similar relationships were reported from modern intertidal to supratidal facies of the Trucial Coast (Bathurst, 1971; Illing and others, 1965; Schneider, 1975), Shark Bay, Australia (Davies, 1970), and Laguna Madre, Texas (Brown and others, 1977; and Miller, 1975). Intraclastic debris in Red Cave dolomites probably records storm deposition across supratidal flats and in shallow channels (Davies, 1970; Shinn and others, 1969; and Wilson, 1975).

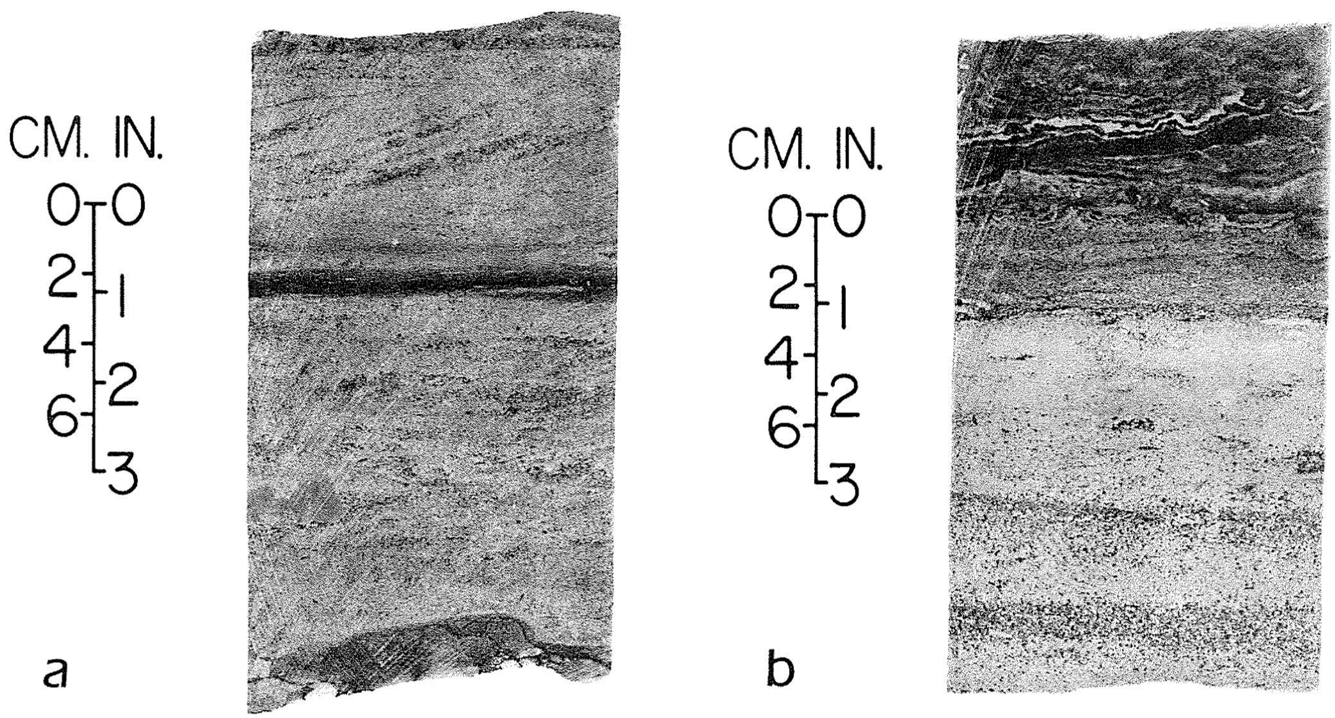


Figure 9. Bedding features in Red Cave cores: (a) cross-laminated, oolite packstone, 3,875.5 ft (1.181 m); (b) wavy, laminated dolomite and anhydrite, 3,840 ft (1170.4 m).

Supratidal dolomite (fig. 9 c, d) is overlain by and intercalated with blue to gray, or pinkish anhydrite, characterized by structures ranging from isolated nodules within supratidal carbonates, to nodular mosaic, laminated, and massive (classification after Maiklem and others, 1969).

Recent sabkha sequences are normally topped by nodular anhydrite and erosional upper surfaces. Kinsman (in Bathurst, 1971) and Shearman (1978) revealed that displacive diagenetic growth of gypsum and anhydrite in supratidal sediments of the Trucial Coast has raised the sabkha surface as much as 1 to 3 ft (0.3 to 1 m). Sediment at the surface is exposed to subaerial weathering and erosion. Shearman (1978) reported that the tops of anhydrite nodules are sometimes planed off, and the upper parts of contorted layers of anhydrite are truncated. Erosional surfaces such as these may have been recognized in Red Cave sabkha sequences. Irregular upper surfaces of nodular anhydrite are overlain by crenulated laminae of mudcracked dolomite and red mudstone. Abundant, small dolomite intraclasts covering the upper surfaces (fig. 10a), suggest subaerial exposure and erosion of these strata.

Figure 7 shows that the greatest concentrations of anhydrite occur in arcuate bands that are bounded on their southern sides by inner shelf carbonate facies. Wadi-plain red beds form their northern, or landward borders. Isopachous patterns and

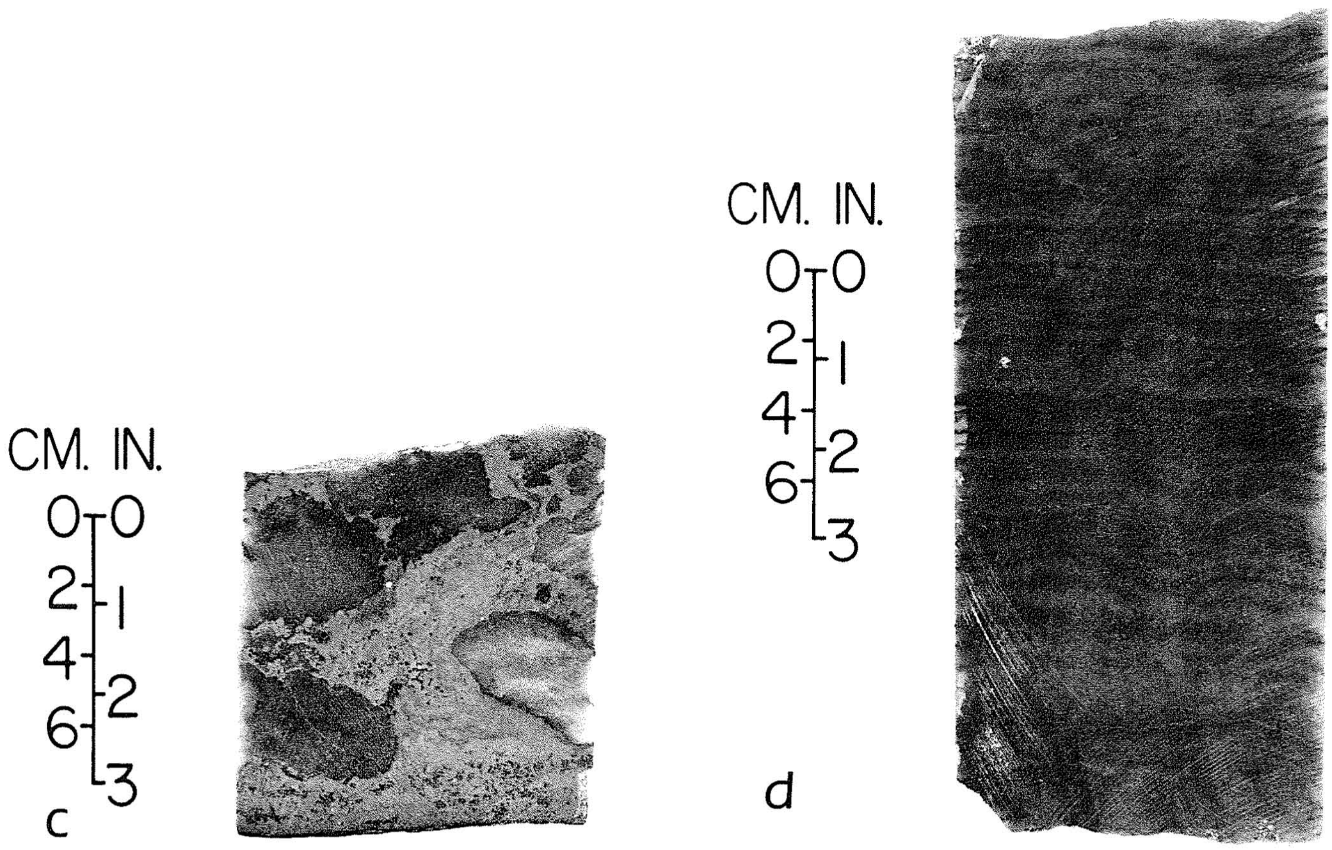


Figure 9. Bedding features in Red Cave cores: (c) nodular anhydrite, 3,955 ft (1,205 m); (d) laminated anhydrite, 3,858 ft (1,176 m). All cores from DOE/Gruy Federal, Inc., Rex White 1.

distribution of carbonate and evaporite facies suggest that at their greatest development coastal carbonate-evaporite sabkhas ranged from approximately 20 to 80 mi (32 to 130 km) wide.

Mud-rich sabkhas

Mud-rich coastal sabkha facies are dominated by red to green, laminated or structureless mudstone and claystone overlying and interbedded with anhydrite and dolomite (fig. 8, cores B and C). Anhydrite structures are identical to those in carbonate-evaporite facies (fig. 10b).

In the northern Panhandle where evaporite facies pinch out into red beds, red siltstones cap progradational sabkha sequences. Many siltstones are probably eolian-reworked fluvial deposits. These rocks contain examples of wispy or poorly developed small-scale cross lamination similar to that produced by the migration of adhesion ripples. Glennie (1970, 1972) has shown that adhesion ripples commonly form on damp surfaces of modern sabkhas. As sand or silt is deposited on a moist surface by eolian processes, capillary rise of ground water dampens the newly deposited sediment and increases the opportunity for additional sediment to be deposited and adhere to the moist surface. Adhesion-rippled sandstones were also reported to occur in Upper Permian sabkha deposits of the Northwestern Shelf, New Mexico (Jacka and Franco, 1974).

Dip-oriented clastic isolith patterns (fig. 6) in the northwestern and northeastern Panhandle suggest that clastic sediment was transported by fluvial systems into sabkha environments. Because of infiltration and/or evaporation of water in ephemeral streams and probable low gradients, only silt and clay were carried into sabkhas. As modern examples, ephemeral streams flowing toward Willcox Playa in Arizona deposit coarse-grained sediment higher on the slopes, and only fine-grained sediment is carried onto the playa surface where it accumulates as "mud deltas" (Schreiber and others, 1972). Thus, facies patterns and inferred depositional processes suggest that Red Cave mud-rich sabkhas were slightly elevated platforms that spread across and smothered previously existing carbonate-evaporite sabkha surfaces.

Mud-rich coastal sabkhas probably passed landward into continental sabkhas and wadi plains. There is no sharp boundary separating these environments. Kinsman (1969) showed that Trucial Coast sabkhas grade inland without noticeable geomorphic discontinuity into continental sabkhas. For example, Sabkha Matti is contiguous with a coastal sabkha and extends 50 to 60 mi (80 to 95 km) inland from the Trucial Coast (Kinsman, 1969). During Leonardian time, continental sabkha terrain may have been

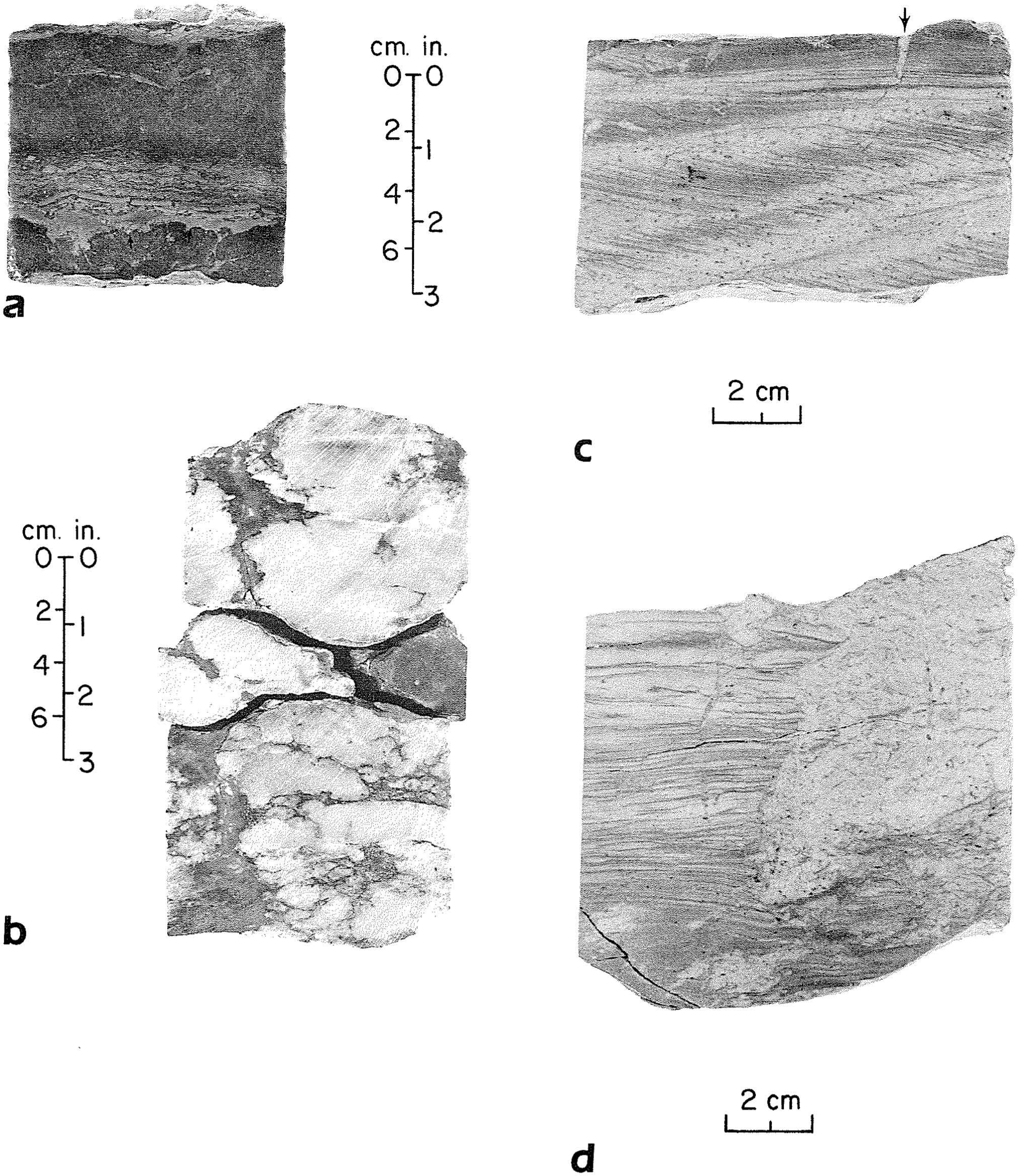


Figure 10. Bedding features in Red Cave cores; (a) upper surface (arrows) of sabkha anhydrite overlain by algal laminated, mudcracked dolomite with intraclasts, Potter County, USBM Bush A-6, 3,200 ft (975 m); (b) nodular anhydrite in red mudstone, Randall County, DOE/Gruy Federal, Inc., Rex White 1; 3,705 ft (1,129m) (c) ripple-drift, cross-laminated sandstone overlain by parallel-laminated, mudcracked (arrow) mudstone and siltstone, Potter County, D. O. Harrington, Bush A-1, 3,231 ft (985 m); (d) disturbed bedding in siltstone, Potter County, D. O. Harrington, Bush A-1, 3,261 ft (994 m).

present in remote, or isolated areas, and may be inferred where clastic isolith patterns in A, B, and C members are irregular, and cannot be described as either strike or dip oriented. This pattern is well illustrated by Red Cave B member (fig. 6) and suggests poorly defined internal drainage.

Continental sabkhas are equilibrium deflation-sedimentation surfaces that may develop in areas of low hinterland relief, small eolian sediment supply, and arid climate (Kinsman, 1969). The Red Cave Formation, especially its B member, across the northeastern Panhandle may have been deposited in such an environment. As shown by cross sections and facies maps, there are no significant quantities of evaporites or sandstone in this area; the Red Cave is mostly composed of red, fine-grained terrigenous sediments. It is relatively isolated from areas of marine influence and areas of major sand deposition. Furthermore, there is no evidence to suggest high relief in the vicinity.

Wadi Plain System

Most modern coastal and continental sabkhas are partially to wholly bounded by ephemeral stream plains, or wadi systems, and alluvial fans (Amiel and Friedman, 1971; Bull, 1972; Gavish, 1974; Glennie, 1970, 1972; Hardie and others, 1978; Kinsman, 1969; and Thompson, 1968). Modern wadi plain or distal fan deposits that interfinger with sabkha facies consist of water-laid sheetflood silt, clay, and minor eolian sand or silt. These sediments represent the suspended load of ephemeral, discontinuous braided streams or wadis (Glennie, 1970) that spread sediment in thin sheets across desert plains. Transportation of sediment is sporadic and abrupt (Glennie, 1972), usually corresponding to sudden rainstorms.

Sandstone and siltstone facies in the northwestern Panhandle interfinger in the southeast with Red Cave mudstone and carbonate-evaporite facies, and are interpreted as wadi plain deposits (figs. 3, 4, and 11). In Dallam County, coarse-grained, pink to red arkose is locally abundant. These sandstone units cannot be correlated between wells, which suggests that they are local and lenticular. Red Cave sandstones were probably transported into the Panhandle by small, braided ephemeral streams from a northwestern source in New Mexico. Granite terrains in Union County and north-central New Mexico were sources for most arkosic debris in the Sangre de Cristo Formation (Foster and others, 1972), which is partly coeval with the Red Cave Formation. The Sangre de Cristo Formation, therefore, can reasonably be interpreted to be the proximal fluvial facies of an extensive wadi plain system, the distal portions of which are observed in the northwestern Panhandle.

Distal deposits of the wadi plain system were observed in cores from Moore and Potter Counties (fig. 8, core A). These deposits consist of very fine grained sandstone and siltstone, with abundant ripple-drift cross-lamination (fig. 10c), recording deposition in small, braided, discontinuous fluvial channels. McKee (1965) reported that sands of the Colorado River in Arizona include abundant ripple-drift cross-lamination in areas where large spring floods annually overflow the channel banks and rapidly deposit sand out of suspension. Glennie (1972) observed that after mild rainstorms, water in desert wadi channels soaks into the sediment of the wadis, which causes the stream to reduce its discharge quickly (Harms and others, 1975), and thereby leads to the development of ripple-drift cross-lamination. In some Red Cave samples, ripple-drift cross-laminated sand is overlain by fine parallel laminae of silt and mud exhibiting desiccation cracks (fig. 10c). These mud-cracked laminae probably represent the last sediments deposited by waning currents after a flood episode. Other sandstone and siltstone strata are finely laminated but disrupted by burrow-like features and evidence of slumping or collapse (fig. 10d). Some siltstones and sandstones (fig. 12a) have abundant angular siltstone and mudstone clasts (0.5 to 1 cm diameter). These clasts probably represent silt and clay drapes deposited earlier on a wadi channel floor and subsequently ripped up by a sand-charged flow of water (Glennie, 1972). Although no direct evidence of eolian sedimentation was noted, it is likely that eolian processes have reworked some of the fluvial deposits.

Several thin intervals of finely and evenly laminated (varve-like) siltstone and mudstone (fig. 12b) suggest suspension settling of sedimentary particles in a standing body of water. Fine-grained sediment in modern desert basins is deposited from suspension in ephemeral playa lakes, flooded deflation hollows, and interchannel depressions (Blissenbach, 1954; Bull, 1972; Glennie, 1970; and Groat, 1972). Any of those geomorphic features may have existed and been periodically flooded on the Red Cave wadi plain. Small carbonate nodules in mudstone and siltstone, and dark, organic-rich root-like features in siltstones overlying wadi-channel-fill sequences are interpreted as paleosols (fig. 12c, d).

In summary, the abundance of lenticular sandstone units with sharp basal contacts and fining-upward sequences, topped by rooted, caliche-like zones, suggests deposition by fluvial processes in a wadi plain environment.

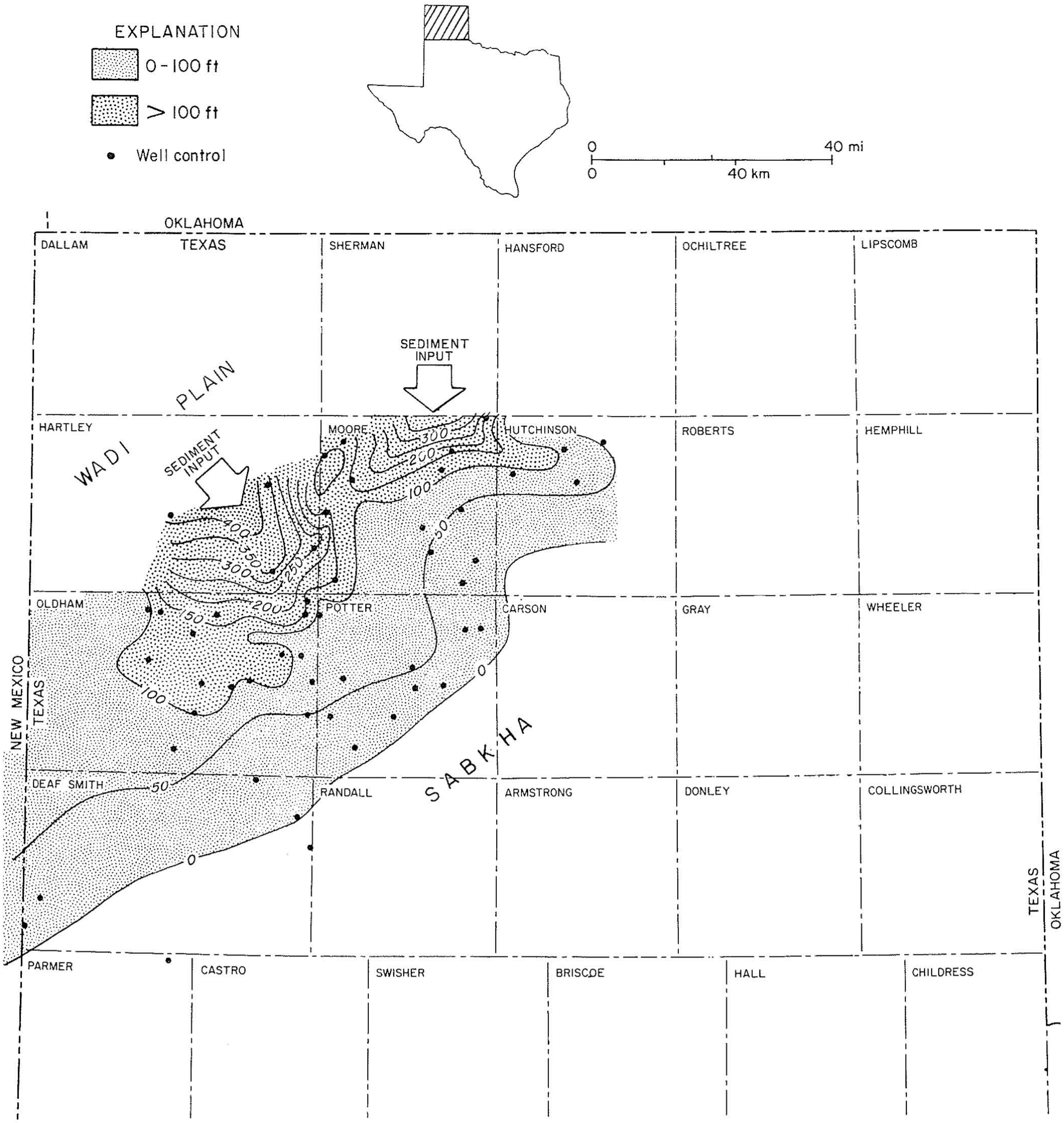


Figure 11. Net sandstone isolith map of Red Cave Formation. Map is based upon lithologic interpretation of gamma ray logs. Source terrain in New Mexico is implied by sandstone thickening northwestward.

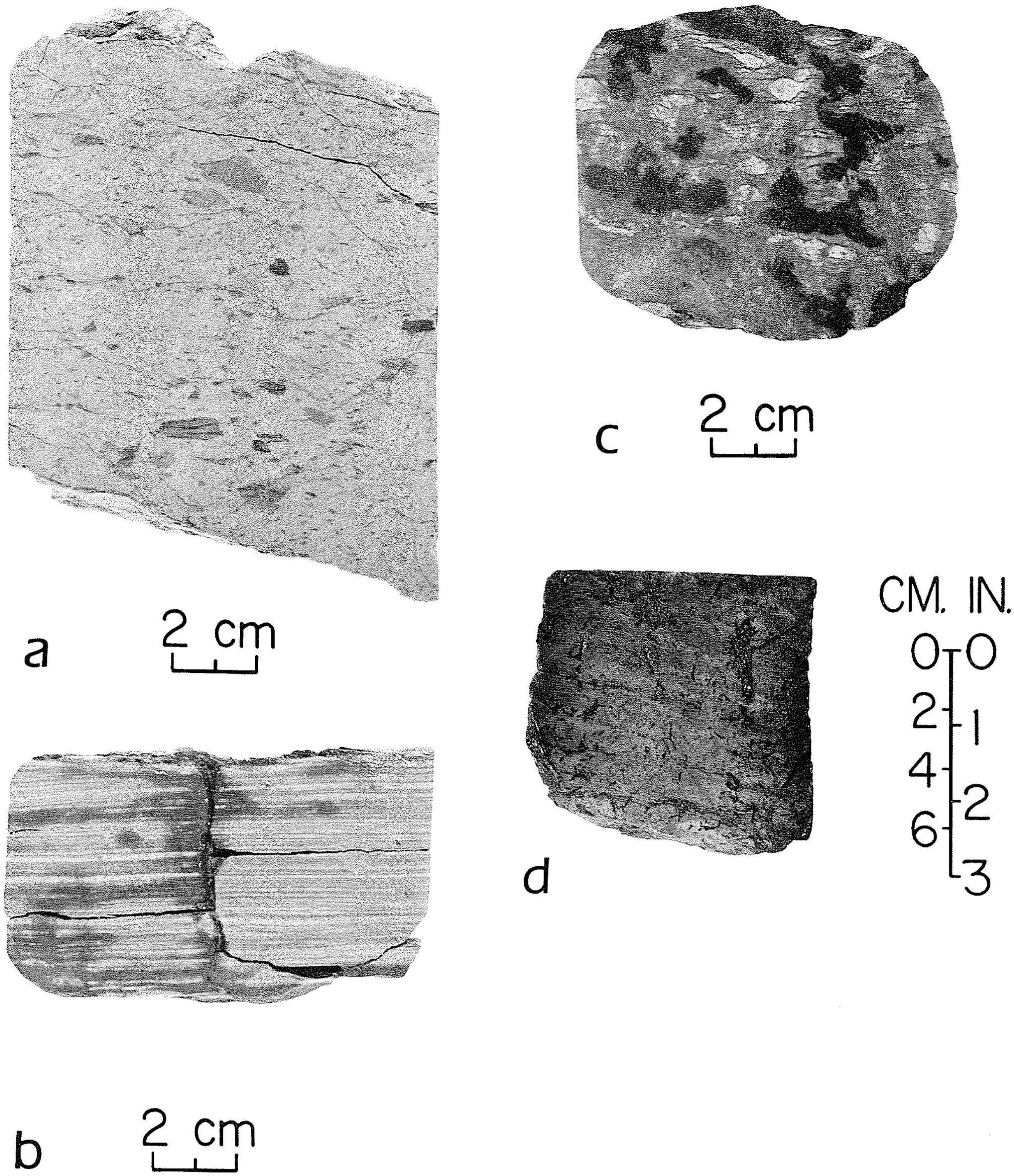


Figure 12. Bedding features in Red Cave cores; (a) angular intraclasts of siltstone and mudstone in sandstone, 3,299 ft (1,005 m); (b) evenly laminated siltstone and mudstone, 3,228 ft (984 m); (c) caliche-like, carbonate nodules in mudstone, 3,294 ft (1,004 m); (d) carbonaceous root-like structures in siltstone. Core samples a, b, and c are from Potter County, D. O. Harrington, Bush A-1, and sample d is from Moore County, Maynard Oil, Sneed 3-6.

DEPOSITIONAL MODEL

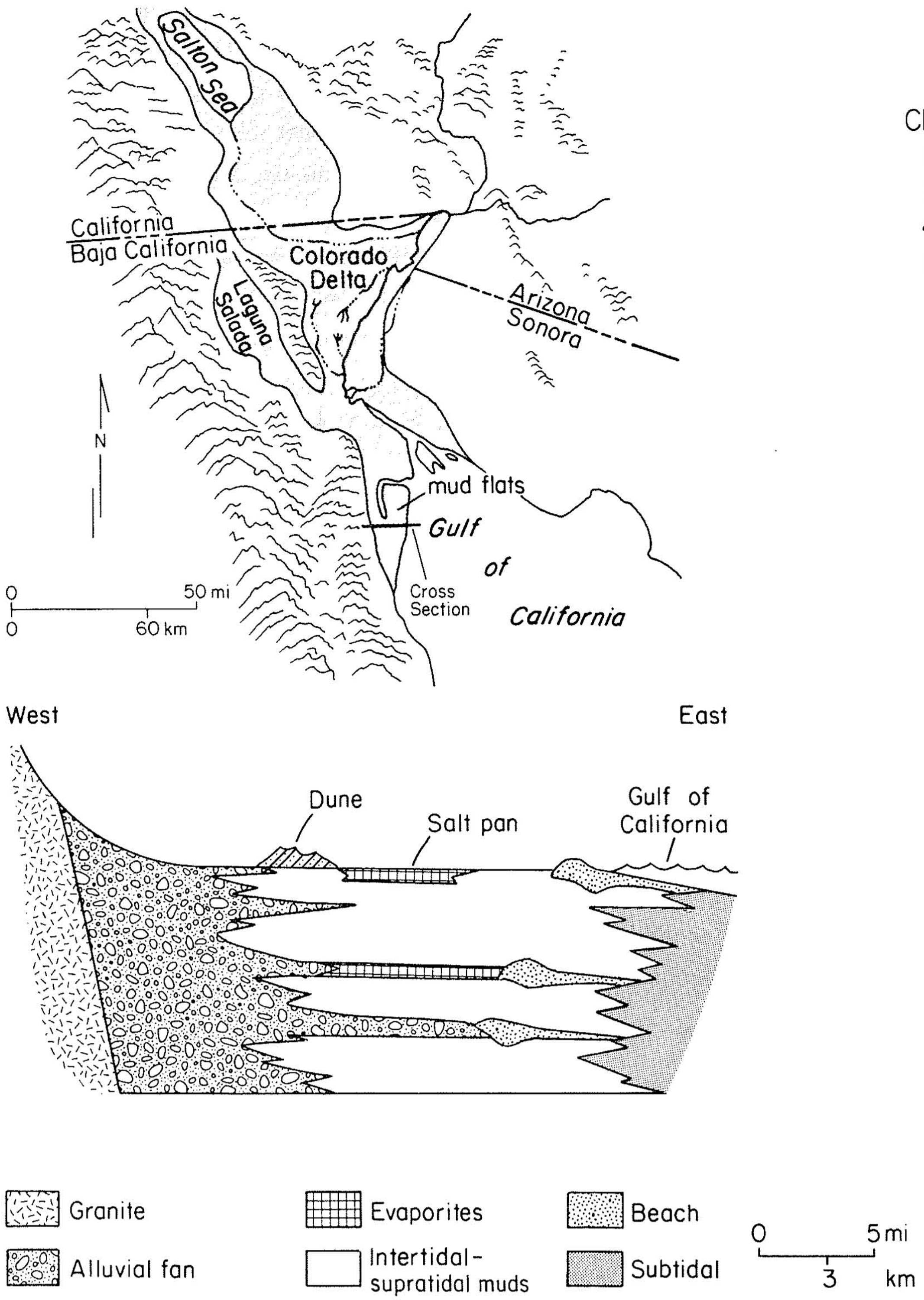
Mud-rich coastal to continental sabkhas and carbonate-evaporite coastal sabkhas prevailed in early Leonardian time. Terrigenous mudstone facies in the A, B, and C members were deposited in coastal to continental mud-rich sabkhas, and the lower and upper carbonate-evaporite members were deposited in coastal sabkhas. Variations in depositional style that are observable through time and in each stratigraphic member can be related to several modern sabkhas.

Modern Analogs

It would be fortuitous, if not impossible, to find a well-described, modern depositional environment that exactly duplicates the ancient depositional settings of the Red Cave Formation. To derive comprehensive depositional models for the Red Cave depositional systems, pieces of information must be taken from several modern examples and related to ancient counterparts. For mud-rich sabkha sedimentation, coastal mud flats at the mouth of the Colorado River in Baja California, Mexico, and parts of Shark Bay and tidal flats in Western Australia are appropriate modern analogs. Carbonate-evaporite coastal sabkhas and inner shelf systems are comparable to progradational facies along the Trucial Coast of the Persian Gulf.

Coastal mud flats, Baja California, Mexico

Barren, reddish-brown, supratidal mud flats and salt pans occur on the northwestern side of the Gulf of California near the mouth of the Colorado River (fig. 13). The flats extend southward from the river mouth for approximately 37 mi (60 km) along the Baja coast (Thompson, 1968; Walker, 1967). Silt and clay composing the flats were supplied by the Colorado River and deposited by flood tidal currents. The mud flats grew seaward during the late stages of Holocene sea level rise largely because of the high rates of mud supply and low wave energy. Supratidal sediments comprise laminated reddish-brown silty clay and significant quantities of gypsum and halite (fig. 14). Kinsman (1969) and Butler (1970) report that small anhydrite nodules occur in landward parts of the sabkha mud flats. Laminae are commonly disrupted by evaporite precipitation and mudcracking. The coastal mud flats grade inland to large alluvial fans emerging from mountains; the highest and most inland parts of the mud flats are rarely flooded, and northwest of the active mud flats is a former tidal flat that is



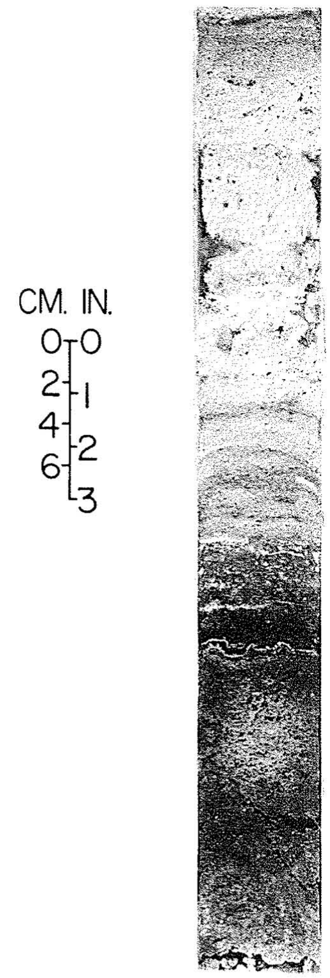


Figure 14. Plastic impregnated core of sabkha salt and gypsum overlying supratidal mud, Baja California mud flats.

Figure 13. Regional map of northern Gulf of California showing coastal mud flats near the mouth of the Colorado River, and schematic cross section through the mud flats. Modified from Thompson (1968) and Walker (1967).

now a playa, or continental sabkha. Laguna Salada (fig. 19) was cut off from the main Gulf during Recent progradation of the Colorado River delta (Meckel, 1975), and has occasionally received Colorado River floodwaters.

Although progradational mechanisms differ between the Red Cave mud-rich sabkhas and Baja California mud flats, there are striking similarities between facies of both. In both cases, facies belts include alluvial fan or wadi plain clastics that pass seaward into prograding mud-rich sabkhas. Furthermore, sediment texture and color are almost identical. Baja mud flats are almost devoid of channels, and channel-fill sequences have not been recognized in Red Cave sabkha facies.

However, different mechanisms of mud supply influenced the development of Baja coastal mud flats and Red Cave mud-rich sabkhas. In the Red Cave Formation, terrigenous sediment composing mud-rich sabkha facies was supplied by fluvial processes from updip wadi systems and reworked by wind and tidal processes to form progradational wedges. In contrast, Baja California mud flats receive very little sediment from updip alluvial fans. Most sediment is contributed along strike by the Colorado River delta and is accreted to the mud flats during tidal flooding.

Gladstone Embayment, Shark Bay, Western Australia

An ephemeral stream delta (Wooramel Delta) that has prograded onto a carbonate tidal-flat environment in Shark Bay, Western Australia (fig. 15) has created a mud-rich sabkha characterized by lithofacies resembling those of Red Cave mud-rich sabkha environments (Davies, 1970). The tidal flats in front of the delta in Gladstone Embayment are up to 2 mi (3 km) wide and consist of algal-laminated carbonate and gypsum-rich sediments that interfinger with red deltaic sand, silt, and mud. The Wooramel Delta now progrades into intertidal environments and is active only when the river floods. At other times the river bed is usually dry. As the river flows, sediment is deposited by two distributaries bounded by levees at the margins of the distributaries on the tidal flat.

The vertical succession of facies is subtidal to intertidal skeletal carbonate sands, upward through interlaminated deltaic silt and tidal-flat carbonate, and overlain by gypsum mush at the top (fig. 15). Nearly identical vertical sequences occur in the Red Cave Formation (fig. 8, cores B and C).

Trucial Coast, Persian Gulf

Lithofacies of modern sabkhas and lagoons along the Trucial Coast of the Persian Gulf (fig. 16) are quite similar to those that were deposited in Red Cave inner shelf and carbonate-evaporite sabkha environments (Bathurst, 1971; Purser, 1973; and Reading,

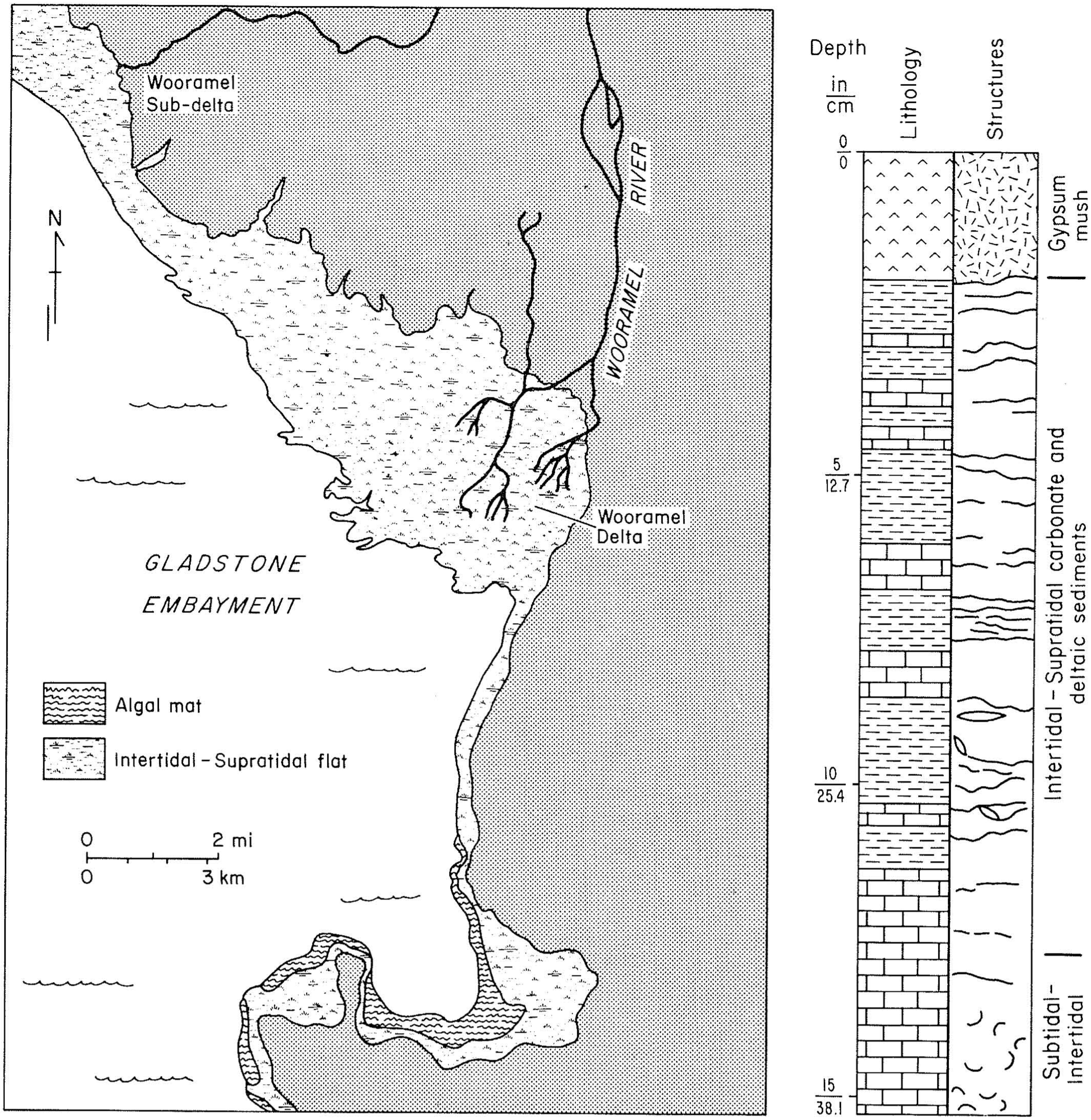


Figure 15. Regional setting and facies sequence through tidal flat and Wooramel delta in Gladstone Embayment, Shark Bay, Western Australia. Modified from Davies (1970).

1978). Lagoonal, subtidal sediments near Abu Dhabi include gray, muddy sand that is rich in peneroplid foraminifers and bivalves and is stabilized by sea grasses. This facies grades landward into a broad intertidal zone of fecal pellet sediment and well-developed algal mats. In upper intertidal areas, a wrinkled algal mat is underlain by gypsum precipitated from interstitial pore waters. Algal laminae are disrupted by gypsum growth.

Above the level of normal high tide is a broad salt flat, or sabkha, that consists of mixed eolian quartz sand, carbonate mud, and nodular anhydrite. The sabkha surface is flooded only when high offshore winds combine with high spring tides, causing shallow pools to form on the surface. These pools evaporate within 2 to 3 weeks, leaving an ephemeral crust of halite. Some halite is precipitated below the surface in higher parts of the sabkha.

The lateral gradation of environments and facies, from subtidal-intertidal through sabkha, is also repeated in vertical sequence. Progradation of the intertidal and supratidal or sabkha surface over subtidal environments has created a distinctive sedimentary sequence that is diagnostic of progradational, evaporite carbonate shorelines and can be closely compared to progradational, carbonate-shoreline facies sequences in the Red Cave Formation (fig. 8, cores D and E, and fig. 16).

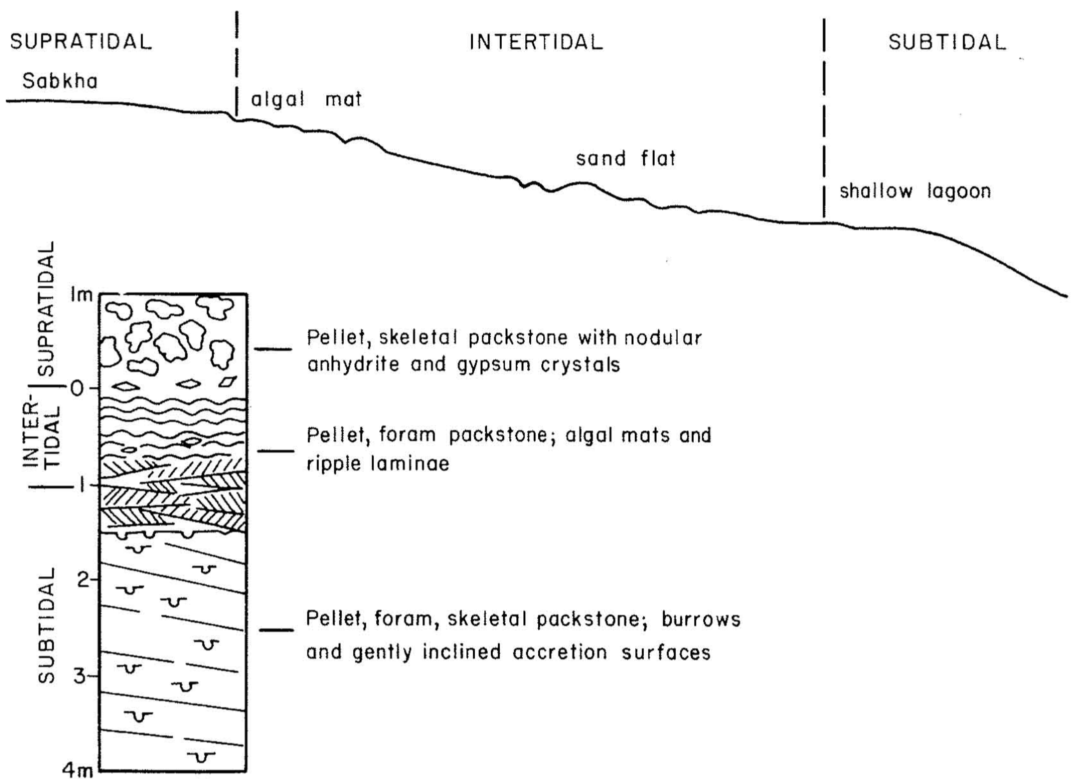


Figure 16. Profile through lagoon shoreline in Trucial Coast of the Persian Gulf and sabkha facies sequence. Modified from Purser (1973).

Red Cave Sabkha Models

Depositional models were developed to explain lateral and vertical facies relationships and to illustrate depositional mechanisms (figs. 17 and 18). These models illustrate first, the expected lateral facies changes and physical depositional systems (fig. 17), and second, variations recognized in carbonate-evaporite and mud-rich sabkha environments. For each sabkha type, carbonate-evaporite environments prograded seaward mainly as a result of deposition of fine-grained carbonate sediment in intertidal and supratidal zones from storm, wind, and spring tidal floodwaters. This process is similar to that responsible for extension or progradation of Trucial Coast sabkhas and tidal flats of Andros Island, Bahamas (Bathurst, 1971).

The principal difference between carbonate-evaporite and mud-rich sabkhas lies in the amounts of terrigenous sediment that were deposited on sabkha surfaces. The mud-rich sabkha model (fig. 18) proposes that most terrigenous sediment deposited on

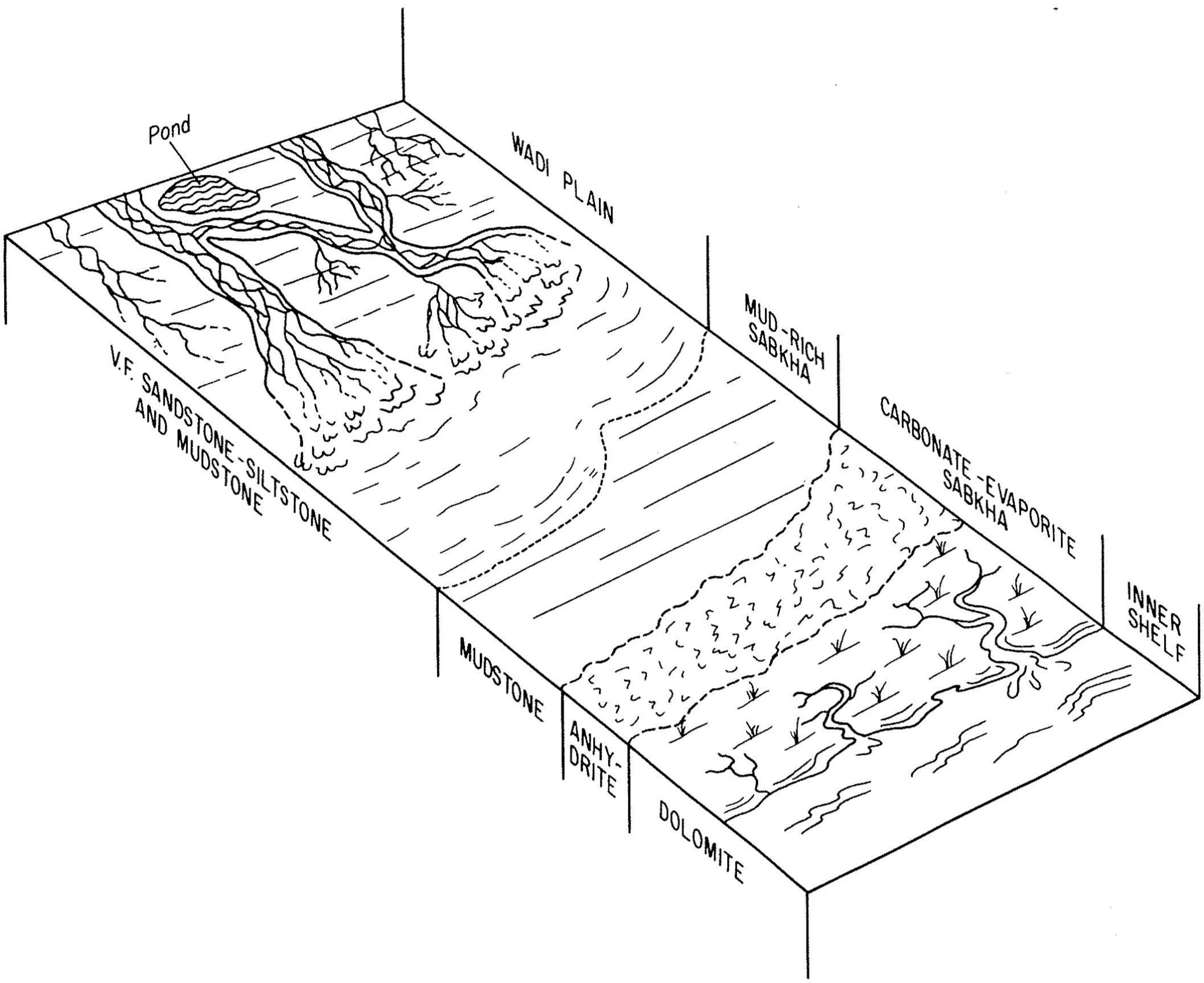


Figure 17. Composite depositional model for Red Cave carbonate, evaporite, and clastic facies.

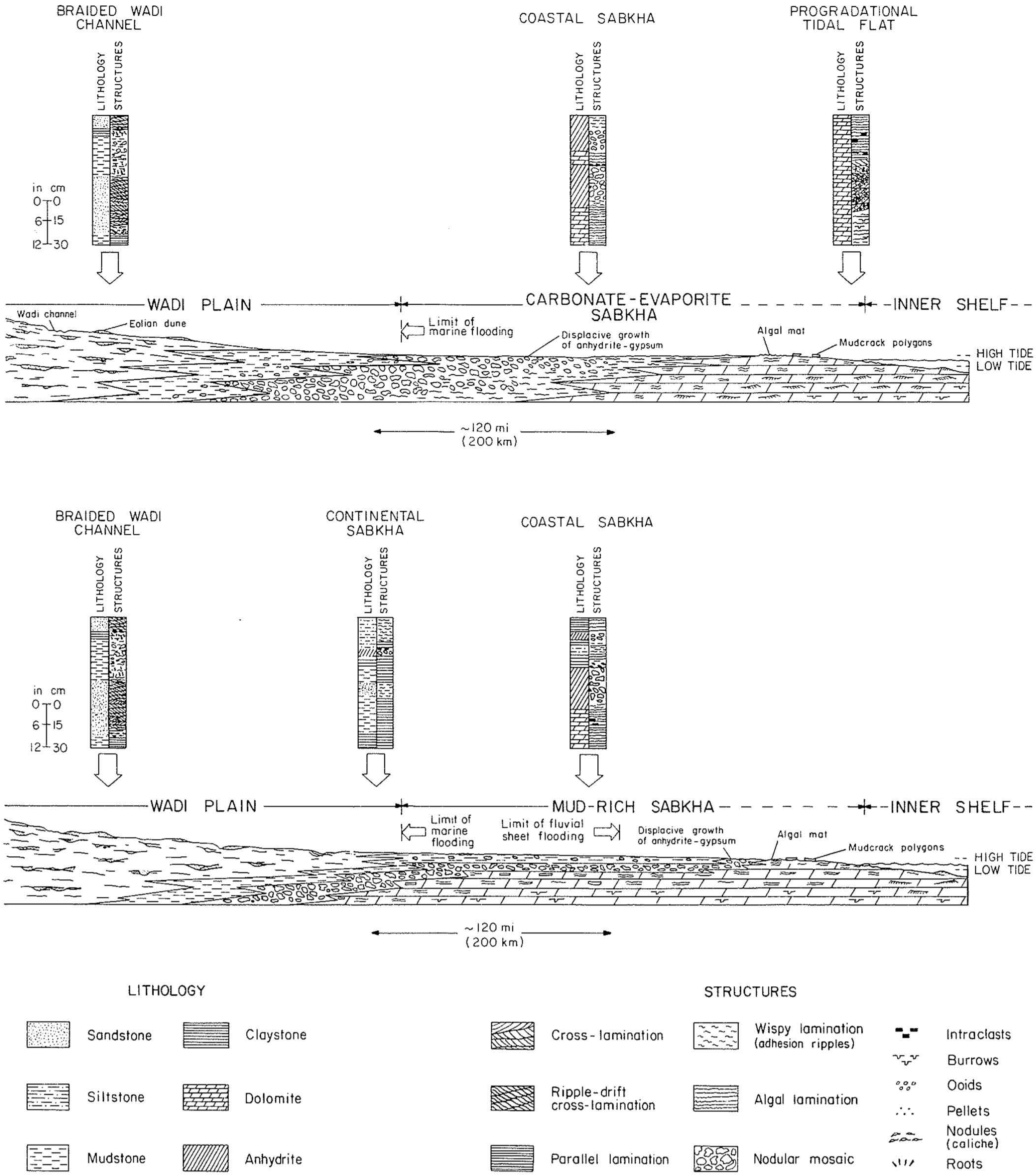


Figure 18. Facies relationships and sequences in (a) carbonate-evaporite sabkhas (upper diagram) represented by the lower and upper evaporite members, and (b) mud-rich sabkhas (lower diagram) represented by clastic members of the Red Cave Formation.

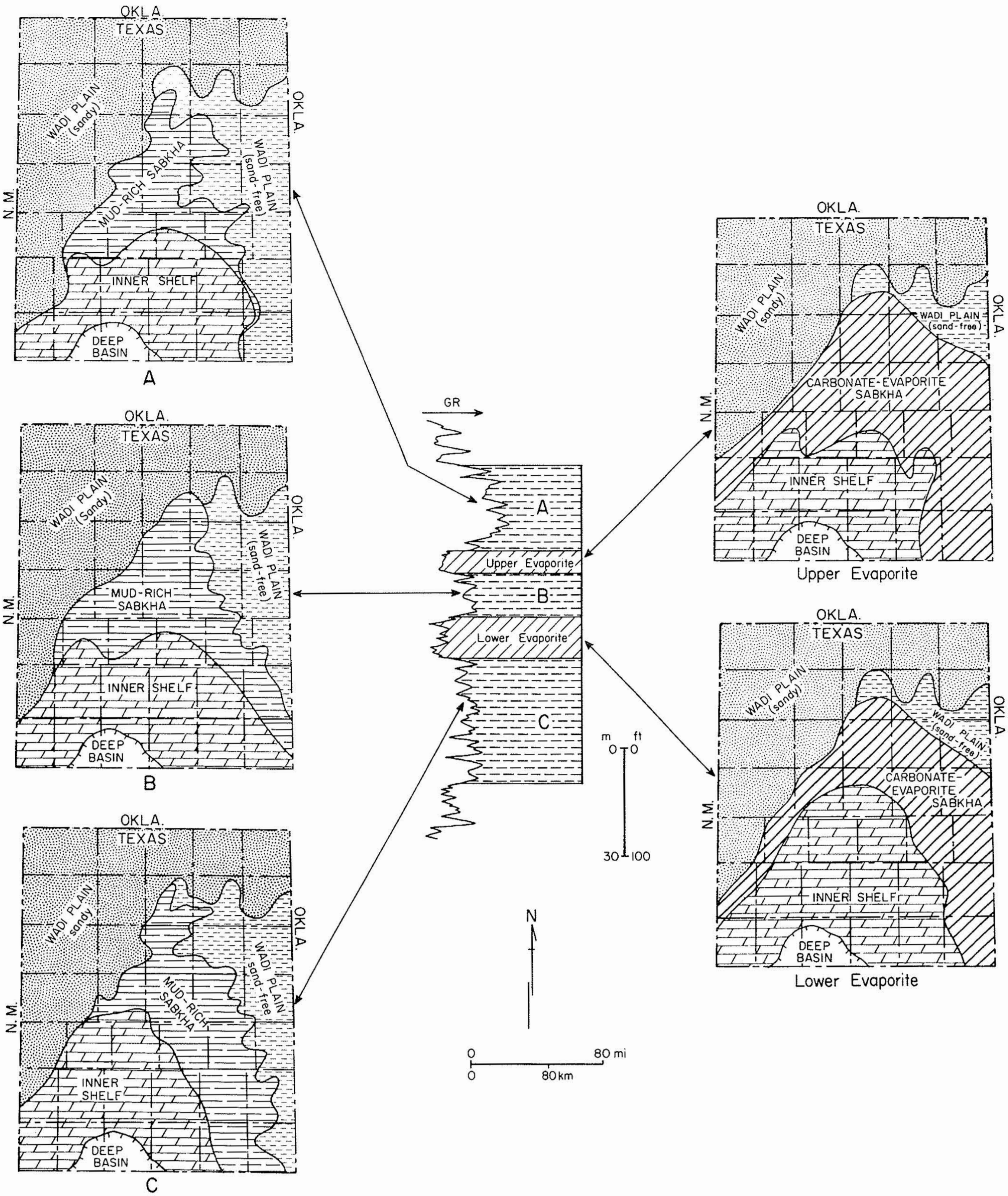


Figure 19. Paleogeography of the Red Cave Formation. Cyclic clastic and carbonate-evaporite facies reflect alternating styles of sabkha deposition that were brought on by the periodic availability and supply of clastics to sabkha environments.

the sabkha was first carried there by fluvial sheetflood from the mouths of wadi channels near the distal margins of the wadi plain. Subsequently, some of the sediment may have been slightly reworked by marine floodwaters to form an extensive mud flat across the sabkha surface. Additional terrigenous sediment may have been transported northeastward along strike from the margins of the wadi plain by storm and spring tidal floodwaters. The distance that mud-rich sabkhas could prograde over a previously built carbonate-evaporite sabkha surface was largely limited by the amount of sediment supplied from updip by wadi plain systems, and by marine floodwater reworking of sediment. Progradation of mud-rich sabkhas created facies sequences capped by red to green mud (fig. 18) that thickens landward (north).

The carbonate-evaporite sabkha model lacks significant input of terrigenous sediment; therefore, sabkha lithofacies consist almost wholly of dolomite and anhydrite (fig. 18). Shoreline progradation required deposition by storm, wind, and spring tidal flooding processes.

DEPOSITIONAL HISTORY

Red Cave stratigraphic members are cyclical, and the progradational, or downdip, (depositional) limits of each clastic member (A, B, C) increased through time (figs. 3 and 5). Member B prograded farther south than member C, and member A prograded farther than B and C. This southerly migration is also reflected in shifting facies of wadi plain and mud-rich sabkha environments. However, progradation was twice interrupted by regional termination or reduction of clastic sediment supply, resulting in deposition of the lower and upper evaporite members.

Mechanisms and underlying causes of cyclic sedimentation over wide shelves built to sea level have been discussed by many authors (Coogan, 1972; Duff and others, 1967; Merriam, 1964; and Wilson, 1975). Some of the hypotheses include one or several combinations of the following (Wilson, 1975):

(1) intra- and extra-basinal tectonic controls;

(2) eustatic sea-level changes caused by tectonics or glaciation;

(3) climatic changes that control development of reefs or carbonate banks causing restricted circulation and more evaporitic conditions;

(4) climatic changes that control supply of terrigenous clastics, and

(5) sedimentological controls such as delta-lobe shifting.

According to Wilson (1975), prevailing views have favored an eustatic mechanism to explain shelf cycles because they occur in areas of variable tectonic activity.

Certainly there was minimal relief across Red Cave sabkhas so that eustatic sea-level changes of the slightest magnitude could have affected vast areas. However, since the relative supply of clastics by fluvial systems through time apparently controlled the transitions from mud-rich to mud-poor sabkha sedimentation, giving rise to the large-scale cycles (clastic versus evaporite members), it is difficult to call upon eustatic sea-level changes to explain cyclicity in this case. The vast majority of Red Cave strata, including carbonate-evaporite and clastic members, was deposited above mean sea level; thus, it is unlikely that sea-level changes could have affected sabkha sedimentation to create the observed cyclic relationships. Perhaps it is more appropriate to call upon continuous and steady subsidence and sediment compaction (permitting minor transgressions) in concert with repetitive progradation of environments and some mechanism that controlled the supply of terrigenous clastics, such as extra-basinal tectonics in source areas, climatic changes, and sedimentological controls.

Although Red Cave stratigraphic members are composed of regressive, diachronously deposited facies, boundaries between sedimentary cycles may closely approximate time lines. Thus, each of the regional clastic-evaporite isolith maps of Red Cave members (figs. 6 and 7) was modified to illustrate regional paleogeography through time (fig. 19). Sabkha facies belts in each of the five members are consistently about 60 mi (95 km) wide, which is taken to represent the maximum width of sabkha environments during Red Cave deposition. Although sabkhas were up to 60 mi (95 km) wide at their maximum development, that does not mean that tidal flooding reached 60 mi (95 km) inland. Progradation of sabkha environments probably caused earliest formed sabkha surfaces to become gradually isolated from marine flooding through time. A similar pattern of sabkha isolation from marine flooding, and hence transformation to a continental sabkha, is documented from the coastal mud flats of Baja, Mexico (Meckel, 1975, and Thompson, 1968), discussed above. Isolated mud flats occur 12 mi (20 km) from the mean shoreline, and Laguna Salada, once a marine tidal flat, is currently 70 mi (115 km) from the open Gulf of California. Along the Trucial Coast, coastal and laterally contiguous continental sabkhas extend 50 to 60 mi (80 to 95 km) inland; however, the inland limit of marine flooding is only about 6 mi (10 km).

CONCLUSIONS

Traditionally, subsurface lithofacies mapping has been successfully used to delineate depositional trends and regional environments of deposition in facies such as those deposited in fluvial-deltaic, barrier-bar, shelf-margin, and submarine-fan systems.

In this study, regional-subsurface distributions of red-bed and anhydrite-dolomite facies, in conjunction with a sedimentological analysis of cores and detailed examination of recognizable depositional sequences, were useful for determining the presence, lateral extent, and evolution of Permian coastal sabkha systems.

Subsurface stratigraphic analysis of the Red Cave Formation resulted in recognition of (1) an inner shelf carbonate system, (2) two kinds of coastal sabkhas--a carbonate-evaporite sabkha system, and a mud-rich sabkha system, and (3) a wadi plain system composed of desert-alluvial and eolian red beds. Sedimentary features in lithofacies of each system are comparable in many ways to recent counterparts. Wadi-plain red beds and mud-rich sabkha facies of the Red Cave Formation are similar to alluvial-fan and coastal mud-flat deposits in the northwestern Gulf of California, and ephemeral-stream deltaic and tidal-flat sediments in Gladstone Embayment, Western Australia. Carbonate-evaporite facies and depositional sequences of the Trucial Coast sabkhas are modern analogs of those of the Red Cave Formation.

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APPENDIX 1
Well Logs Used in Cross Sections

Cross Section County	BEG Number	Company	Well Name
A-A'			
Dallam	1	Shell	Simms #1-2
Dallam	42	F.W.A. Drilling	Johnson #1
Hartley	58	E. J. Athens	Houghton Ranch #1
Oldham	69	Pan American	D. Whaley #1
Parmer	2	Gulf	Kelliehor #A-1
Parmer	10	Sunray	Kimbrough #1
Lamb	43	Pacific Western	D. L. Brown #1-B
B-B'			
Moore	9	Shamrock Oil & Gas	T. J. Nunley et al. #4
Moore	46	Colorado Interstate Gas	Masterson #A-36
Potter	41	Asarco	W D W #1-29
Randall	-	DOE/Gruy Federal, Inc.	Rex H. White #1
Randall	19	Frankfort Oil	Grogan #1
Swisher	7	H. L. Hunt	Bivins #1
Hale	8	Permian Basin	Shipp #1
C-C'			
Ochiltree	22	Sun Oil	Elliott #3-A
Roberts	33	Phillips	Cowan #1-C
Gray	49	Phillips	Morse #5
Collingsworth	20	Roden Oil	Dwyer #1
Childress	16	U.S. Corps Eng.	Jonah Creek #1
Cottle	36	Shell	Williford #1
D-D'			
Hartley	91	Texas-Gulf Prod.	Matador #1
Moore	50	Sinclair	Masterson #1
Moore	46	Colorado Interstate Gas	Masterson #A-36
Hutchinson	45	A. E. Hermann Corp.	Scott #5
Roberts	44	Gulf Oil Corp.	J. P. Osborne #2
Hemphill	35	Phillips Petroleum	Bowers #D-1
E-E'			
Oldham	69	Pan American	D. Whaley #1
Deaf Smith	2	Frankfort Oil	Allison-Hayes #1
Randall	-	DOE/Gruy Federal, Inc.	Rex H. White #1
Armstrong	6	Nebo Oil	Thom Bugbee #1
Donley	6	Jake L. Hamon	Hommell #1
Collingsworth	9	Hi-Plains Prod.	Williams #2
F-F'			
Parmer	8	Texaco	Owen Patton #1
Parmer	10	Sunray Oil	Kimbrough #1
Castro	12	Austral Oil	A. H. Warre #1
Swisher	9	Humble	A. B. Nanny #1
Briscoe	23	Amerada	Hamilton #1
Hall	21	Sinclair Oil	Annie Hughes #2

APPENDIX 2
Cores Examined in This Study

County	Company	Well Name
Moore	Maynard Oil Co.	Sneed 3-6
Moore	Colorado Interstate Gas	Masterson 2-R
Potter	Colorado Interstate Gas	Bivins 55R
Potter	USBM	Bush A-6
Potter	D. D. Harrington	Bush A-1
Randall	DOE/Gruy Federal, Inc.	Rex H. White #1