Report of Investigations No. 112

SMACKOVER AND LOWER BUCKNER FORMATIONS, SOUTH TEXAS: Depositional Systems on a Jurassic Carbonate Ramp

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ABSTRACT

The Smackover and lower part of the Buckner Formations (Oxfordian) comprise a thick regressive sedimentary sequence deposited on a Jurassic carbonate ramp. Four major depositional systems are recognized: (1) basinal, (2) low-energy open shelf, (3) high-energy shoal, and (4) sabkha. Lithofacies boundaries within each system and between systems follow paleobathymetrical contours. High-energy grainstone facies were concentrated landward; muddy low-energy facies were deposited seaward.

Basinal facies are dominated by laminated carbonate mudstones, deposited from suspension, and irregularly laminated carbonate mudstones, the product of sediment reworking by oscillatory bottom currents. The outer-shelf facies is characterized by burrowed carbonate mudstones containing crustacean pellets and a pelagic fauna. The inner-shelf facies is composed of burrowed wackestones containing a benthic fauna. Burrowed oncolite and pellet packstones characterize the outer-shoal system, and crossbedded mixed-allochem, oolite-intraclast, and oolite grainstones compose the high-energy inner-shoal system. Increased sorting and decreased grain size within these facies suggest increasing energy levels landward even within the shoal system.

The sabkha system consists of cyclic subtidal to supratidal facies. Subtidal units are represented by burrowed gastropod and pellet wackestones and oolite wackestones to grainstones, whereas the intertidal zone is characterized by cross-laminated sandstones and algal-laminated dolomite mudstones. The supratidal facies consists of anhydrite nodules intercalated with carbonate and terrigenous mud, and siliciclastic sand and silt.

Depositional systems of the Yucatan Shelf of the Gulf of Mexico may be an approximate analog for those of the Smackover Formation. Smackover moderate-energy packstones may have originated in stabilized grainflats, whereas Smackover grainstones were deposited in mobile sand waves, shoals, spits, spillover lobes, beaches, and eolian dunes. Depositional environments of the Trucial Coast of the Persian Gulf are in part analogous to the Buckner sabkha system. Subtidal units of the lower part of the Buckner Formation were deposited in coastal lagoons, tidal-channel deltas, spits, and beaches. Intertidal facies include sediment deposited in sand flats and algal mat zones. Supratidal facies are characterized by anhydrite nodules.

During Late Jurassic (Oxfordian) time a carbonate ramp controlled deposition in the Gulf Coast region. The Smackover Formation, which was deposited on the ramp, is characterized by low-energy basinal deposits composed of parallel-laminated carbonate mudstones overlain by high-energy grainstone deposits (Newkirk, 1971). The lower part of the Buckner Formation, a coastal sabkha system, prograded over the grainstones.

The Smackover Formation is economically significant throughout the Gulf Coast region (Collins, 1980). Hydrocarbons are produced from both structural and stratigraphic traps in this formation from the East Texas Basin to the Florida Panhandle. Fields have also been discovered in the stratigraphically equivalent Zuloaga Formation of Mexico (Stabler, 1976). In South Texas, however, the Smackover Formation is virtually untested. Drilling density, approximately one well per 2,000 km^2 (775 mi^2) in pre-Cretaceous rocks, indicates that South Texas is truly a petroleum frontier region (Newkirk, 1971).

PURPOSE

Detailed facies patterns and depositional histories have been documented for the Smackover and lower part of the Buckner Formations in nearly all areas of the Gulf Coast Basin, including Arkansas (Becher and Moore, 1976), Louisiana (Bishop, 1968, 1971; Croft and others, 1980), Mississippi (Badon, 1974; Wakelyn, 1977), Alabama (Mancini and Benson, 1980),

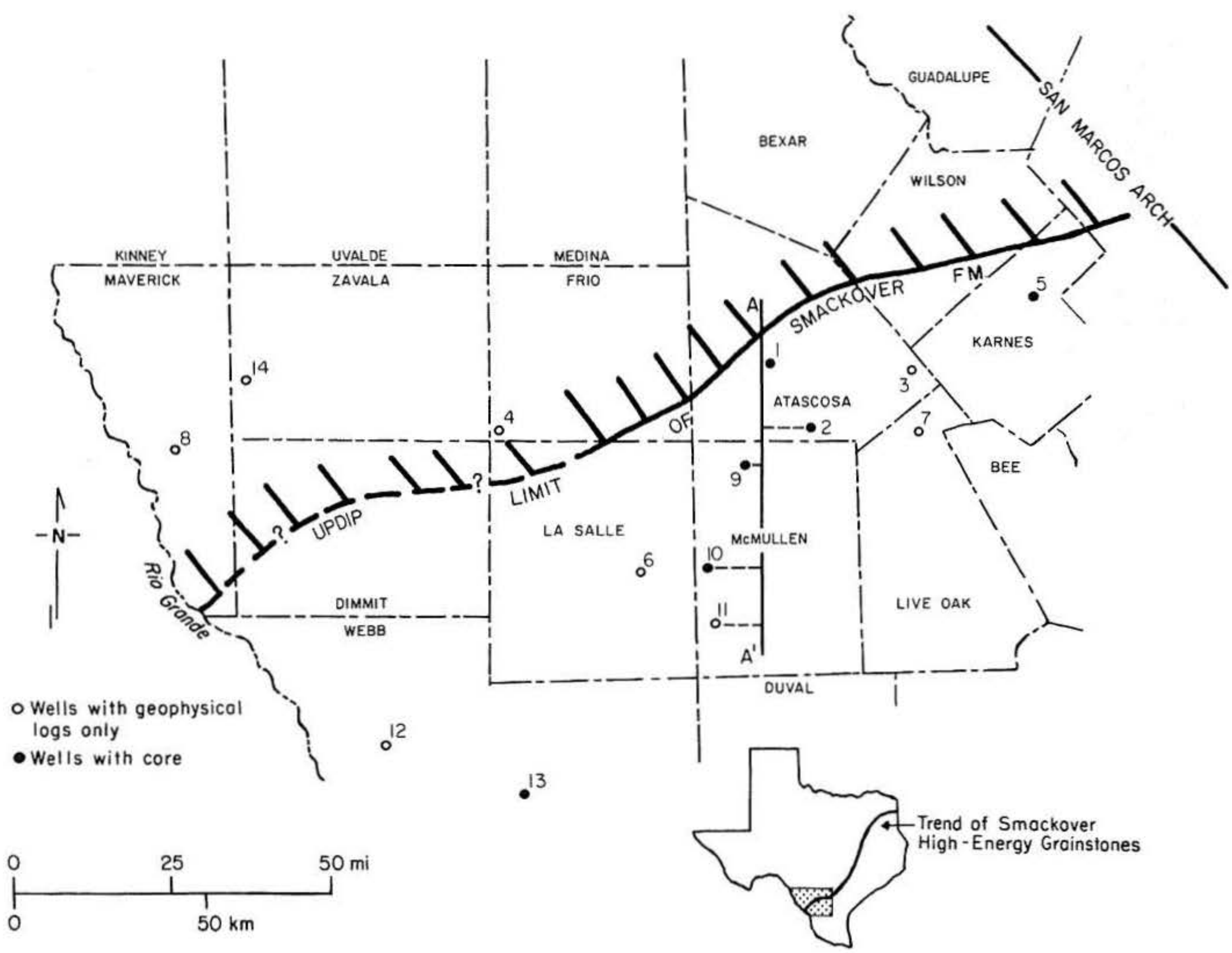

Figure 1. Index map of South Texas study area showing wells that penetrated the Buckner and Smackover Formations. For section A-A', see figure 4; see appendix for well names.

Florida (Ottmann and others, 1973; Sigsby, 1976), northeastern Texas (Dickinson, 1969), and northeastern Mexico (Oivanki, 1973). Only in South Texas have the Smackover and lower part of the Buckner Formations not been described.

This investigation describes the lithofacies, depositional environments, and depositional history of the Smackover and lower part of the Buckner Formations in South Texas. The South Texas area is bounded on the northeast by the San Marcos Arch, on the southwest by the Rio Grande, on the northwest by the subcrop of Jurassic rocks, and on the southeast by the absence of downdip control (fig. 1).

METHODS

Only 11 wells penetrate into or through the Smackover Formation in South Texas (fig. 1, appendix). Three additional wells were drilled into the overlying Buckner Formation. Geophysical logs of these 14 wells served as the initial data base for this investigation. However, Smackover and Buckner cores from five of these wells in Atascosa, Karnes, and McMullen Counties constitute the principal data source. Cores were thoroughly described according to lithology, color, allochem constituents, fabric, texture, and sedimentary structures. Comparison with the characteristics of modern carbonate sediments and environments was the basis for our interpretations. Petrographic analysis of about 190 thin sections augmented core analysis and enabled more accurate visual estimates of allochem percentages. Facies are named according to the textural terminology of Dunham (1962). Anhydrite textures are described according to the classification of Maiklem and others (1969).

REGIONAL GEOLOGIC SETTING

STRATIGRAPHIC FRAMEWORK

The regional Jurassic stratigraphy of the Gulf Coast region (fig. 2) has been delineated by Imlay (1943, 1980), Swain (1949), and Dickinson (1968). Throughout this region Jurassic strata are restricted to the subsurface. Each formation terminates progressively farther updip than the preceding formation, indicating coastal onlap (fig. 3). In South Texas the Werner Formation has yet to be penetrated.

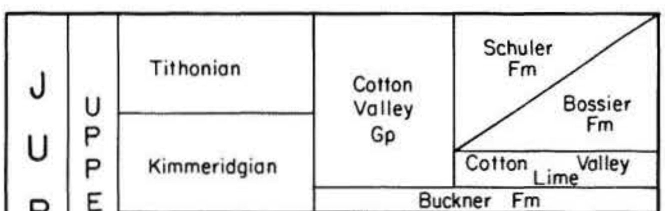

Figure 2. Generalized Jurassic stratigraphic nomenclature, Texas Gulf Coast (from Dickinson, 1968).

Evaporites of the Louann Formation are thickest in South Texas in a small isolated basin centered in southern Webb County (Martin, 1977). Updip of this basin, salt was encountered in four wells and cored in one well (appendix). The salt, a coarse-crystalline halite, contains minor amounts of anhydrite inclusions. Some samples are clear and transparent, but most are cloudy, white to light gray, and crudely laminated because of abundant inclusions of micrite.

The Louann Salt is overlain unconformably by the Norphlet Formation. The major depocenter of the Norphlet Formation lies in eastern Mississippi and Alabama where it is interpreted to have been deposited in braided stream, floodplain, fan-delta, and beach shoreface environments (Newkirk, 1971; Sigsby, 1976). An upper member, the Denkman Sandstone, is believed to be an eolianite (Hartman, 1968; Tyrell, 1972). Away from the major source of these siliciclastics, the Appalachian Mountains, the Norphlet Formation rarely exceeds 30 m (100 ft), indicating a lack of any other major terrigenous sources (Newkirk, 1971).

The Norphlet Formation in South Texas (fig. 4) does not exceed 6 m (19 ft) in thickness where cored and probably never exceeds 10 m (33 ft). The unit is in sharp contact with the underlying salt. The formation is typified by interbedded gray shales, algal-laminated dolomite, and anhydrite overlain by gray, fine- to medium-grained, micaceous sandstone (fig. 5). These lithofacies were probably deposited in a tidal-flat environment. Bioturbated,

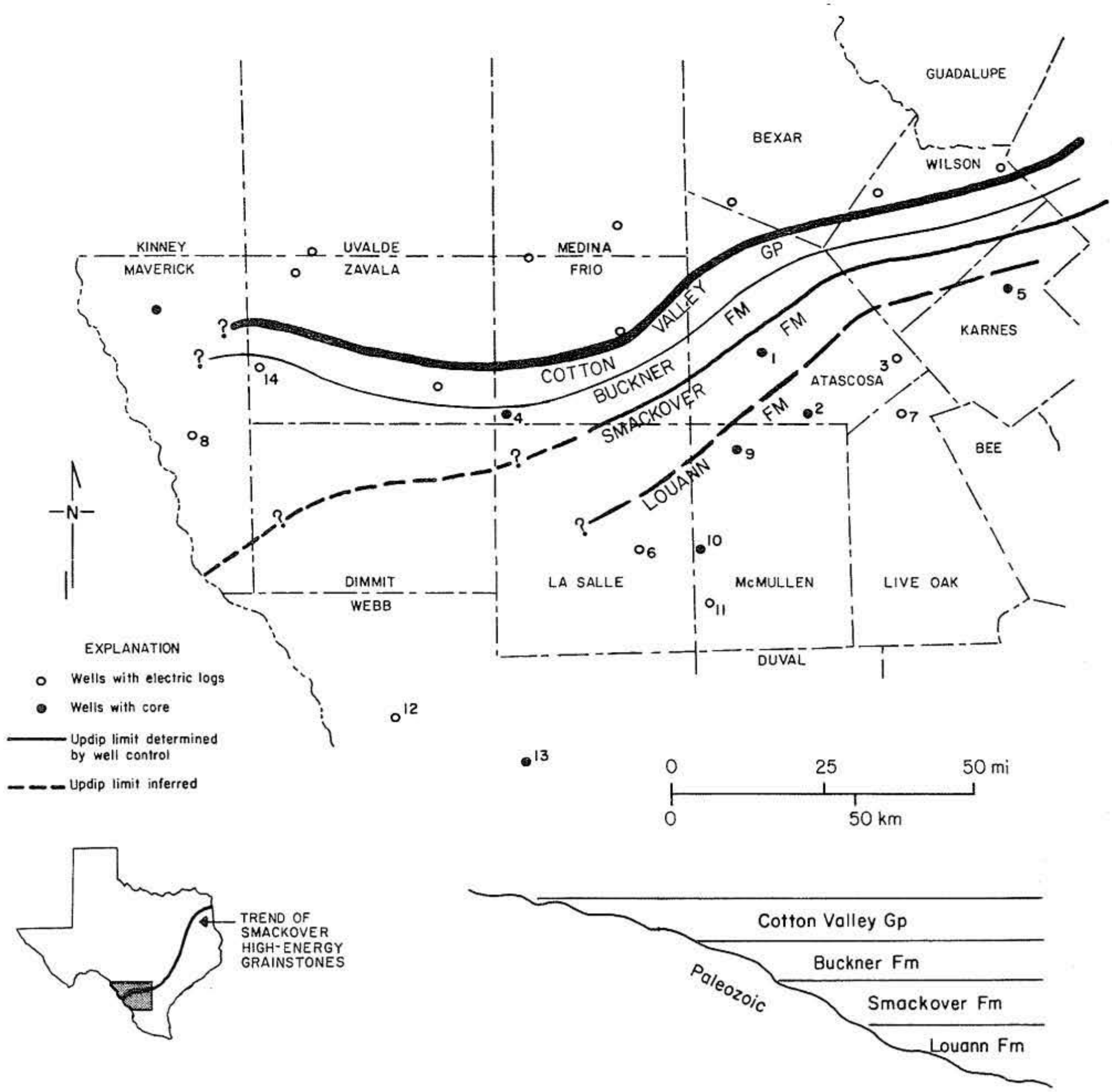

Figure 3. Coastal onlap (updip limits) exhibited by Jurassic strata, South Texas. See appendix for well names.

sandy red shales, interpreted as coastal- or wadi-plain deposits, also occur.

The Smackover Formation unconformably overlies the Norphlet Formation (Newkirk, 1971). In South Texas, the basal Smackover contact is sharp. A high percentage of siliciclastic sand is common within the basal few feet of the Smackover lime mudstones, although no evidence of erosion of the Norphlet Formation has been observed.

Throughout the Gulf Coast region the lower part of the Smackover Formation consists of carbonate mudstones deposited in a low-energy environment (fig. 5). These are dark colored, argillaceous, dense, and finely laminated, and are interpreted as a deep-water, euxinic deposit (Dickinson, 1969). A middle part of the formation, recognized in northeastern Texas (Dickinson, 1969), consists of pelleted skeletal carbonate mudstones deposited offshore but in shallower water than the underlying laminated mudstones.

The upper part of the Smackover Formation is uniform throughout the Gulf Coast region (fig. 5). It consists of a progradational shoaling-upward sequence of open-shelf pelleted micrite facies, mixed-allochem facies, high-energy shoal facies (generally an oolite grainstone), and lagoonal carbonate mudstone and dolomite facies. These facies are arranged in concentric belts (fig. 6) that apparently follow paleobathymetric contours

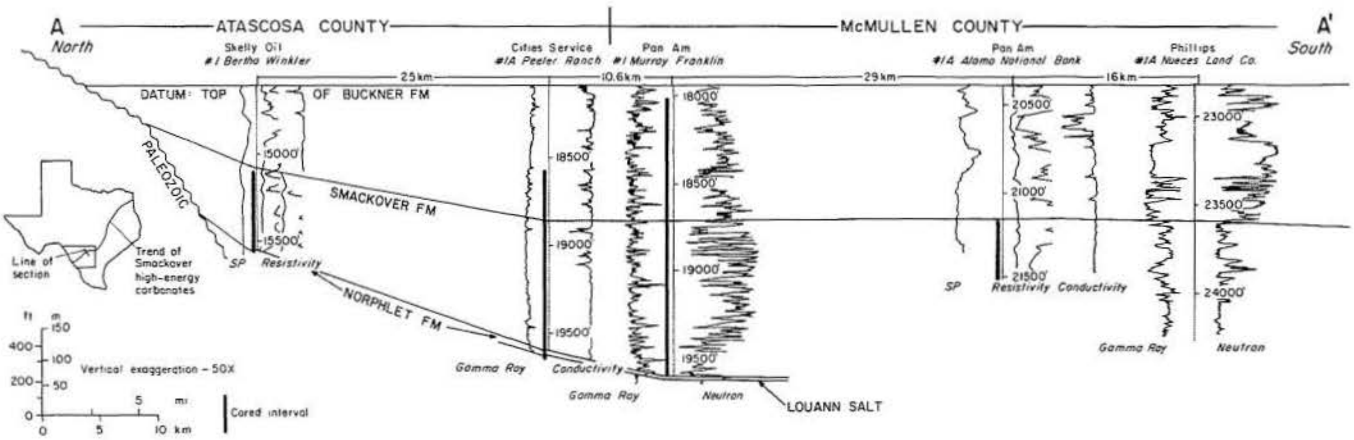

Figure 4. Regional dip section A-A', Upper Jurassic (Oxfordian) strata, South Texas. Datum is top of Buckner Formation. For line of section, see figure 1.

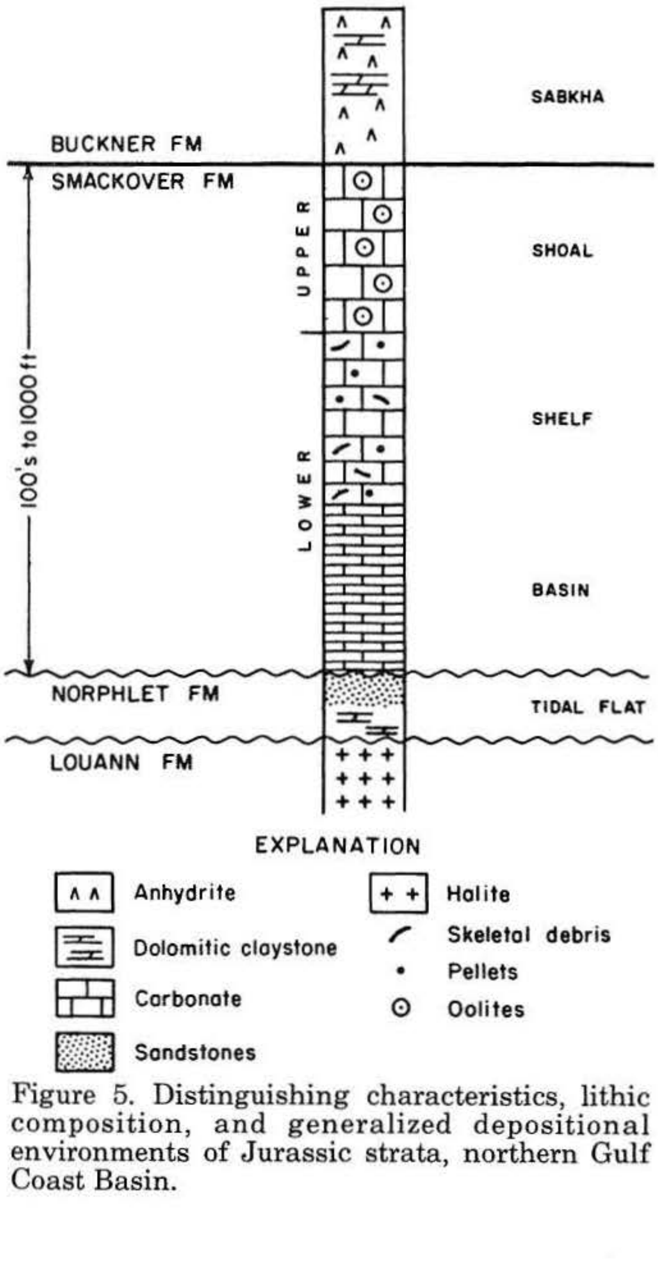

Figure 5. Distinguishing characteristics, lithic composition, and generalized depositional environments of Jurassic strata, northern Gulf Coast Basin.

(Bishop, 1968; Ahr, 1973). Oivanki (1973) recognized similar depositional facies and patterns in the outcropping Zuloaga Formation (Smackover equivalent) in northeastern Mexico. In the Jay Field area of Florida and Alabama (Ottmann and others, 1973; Sigsby, 1976), the high-energy Smackover facies is a pellet grainstone; oolites are absent east of Mississippi (Newkirk, 1971). Influx of siliciclastic sediment from the southern Appalachian Mountains has also resulted in the deposition of some quartz sandstone during Smackover time. These siliciclastic sandstones are common in the high-energy Smackover facies of eastern Louisiana and Mississippi (Newkirk, 1971).

Deposition of many high-energy grainstones in the upper part of the Smackover Formation may have been controlled by syndepositional growth of salt structures (Fowler, 1964; Hughes, 1968; Bishop, 1973; Ferns and York, 1979), although not all authors agree (Badon, 1974). In addition, enhancement and preservation of porosity in grainstones appear to have been controlled in part by diagenesis (Sigsby, 1976; Becher and Moore, 1976; Moore and Druckman, 1981; Loucks and Budd, 1981).

The Smackover Formation in South Texas pinches out in the deep subsurface against subjacent Paleozoic rocks of the Ouachita Fold Belt (fig. 4). The top of the Smackover Formation ranges from 4,600 to 7,190 m (15,087 to 23,585 ft) in depth. The formation is wedge-shaped and thickens seaward to 320 m (1,050 ft). The top of the Smackover Formation in South Texas is difficult to determine on all the available geophysical logs because deep burial, high temperatures, and abnormal pressures greatly inhibit the response and reliability of the logging tool.

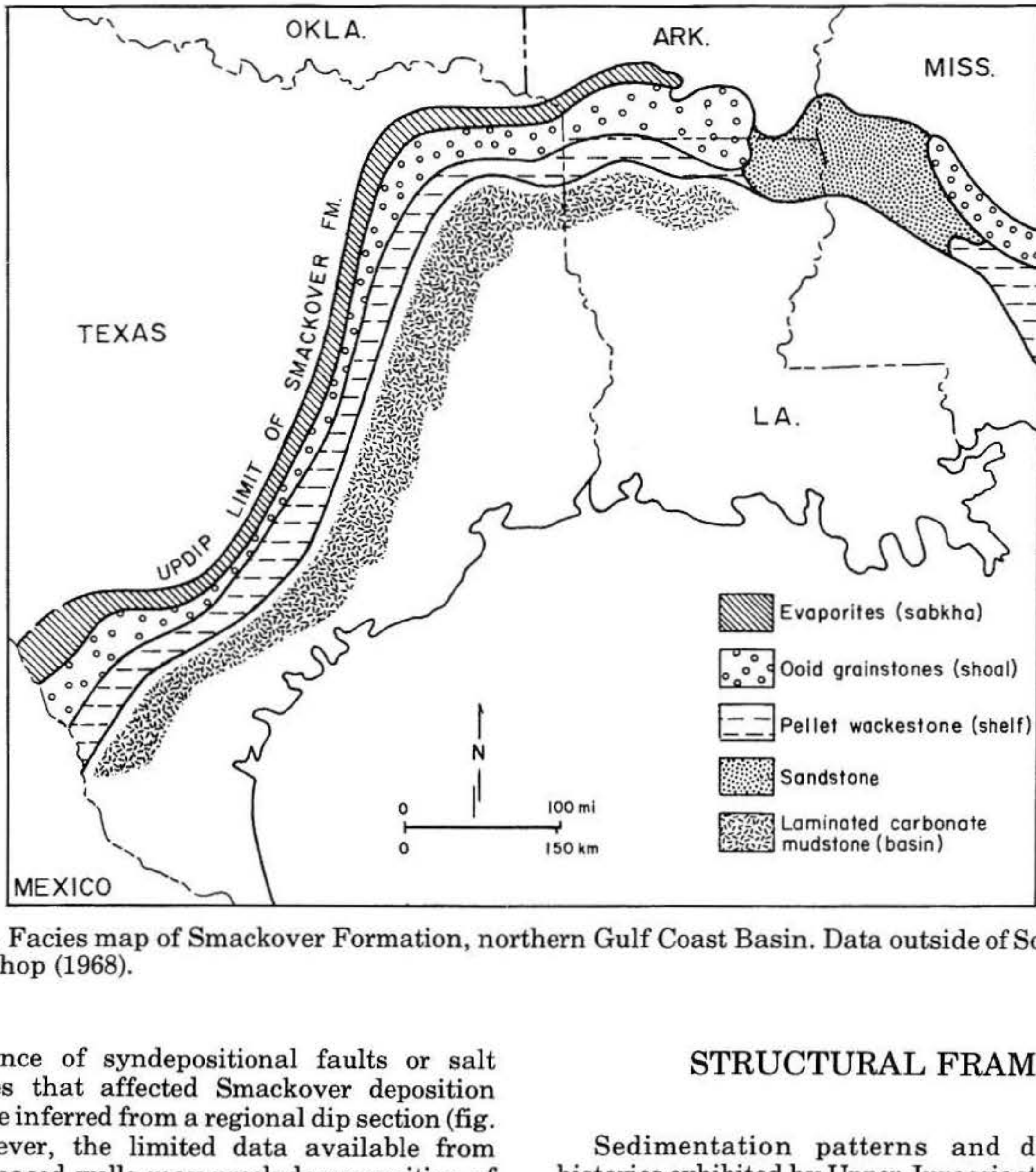

Figure 6. Facies map of Smackover Formation, northern Gulf Coast Basin. Data outside of South Texas from Bishop (1968).

Evidence of syndepositional faults or salt structures that affected Smackover deposition cannot be inferred from a regional dip section (fig. 4). However, the limited data available from widely spaced wells may preclude recognition of such features.

Regionally, the Buckner Formation conformably overlies the Smackover Formation. In South Texas, the Buckner thickens seaward from 150 to over 320 m (490 to 1,050 ft) (fig. 4). The lower part of the formation consists of anhydrite in a dolomitic and argillaceous matrix and associated carbonate grainstones (fig. 5). Farther upward in the section there is a decrease in anhydrite and carbonate with a concomitant increase in siliciclastic sandstone and red shale. The sandstones and red shales also become more abundant updip. Downdip, burrowed skeletal and pellet wackestones, indicative of open-marine sedimentation, become increasingly more abundant. These facies typify the Buckner Formation throughout the Gulf Coast region (Newkirk, 1971).

STRUCTURAL FRAMEWORK

Sedimentation patterns and diagenetic histories exhibited by Upper Jurassic strata in the Gulf Coast Basin were highly influenced by the tectonics of the evolving basin. The structural pattern of the northern Gulf Coast Basin (fig. 7) was summarized by Martin (1977). The basin was markedly stable, characterized by simple gravity tectonics (tensional), subsidence, growth faulting, and salt diapirism. The latter three processes affected only the sedimentary prism and were not the products of major crustal events (Martin, 1977).

An extensive system of grabens and half-grabens (down-to-the-coast faults), termed "peripheral fault zones," surrounds the inner margin of the Gulf Coast Basin from South Texas to northwestern Florida (fig. 7). Within this zone are three genetically different systems of faults and grabens (Martin, 1977): (1) a Triassic to Early

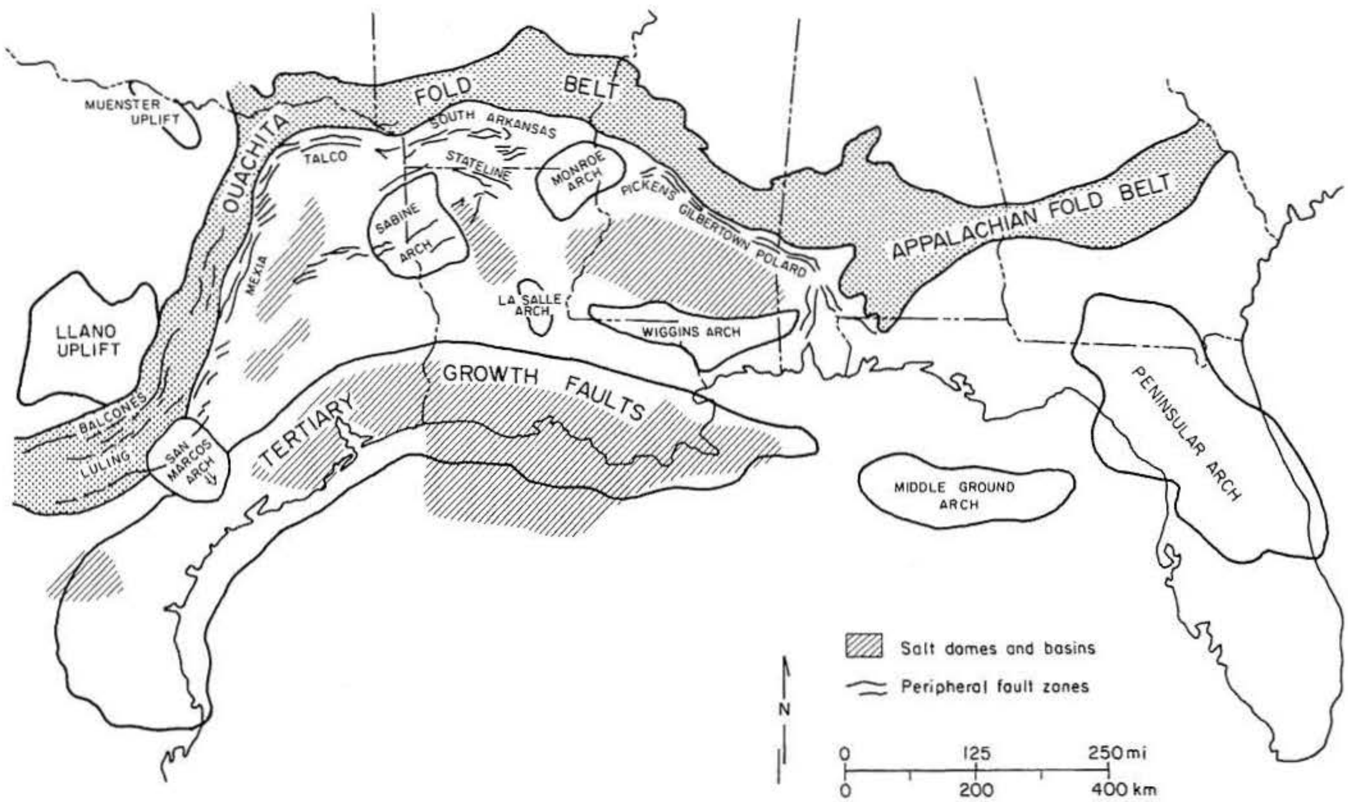

Figure 7. Structural framework, northern Gulf Coast Basin (from Martin, 1977).

Jurassic subsurface graben system along the innermost coastal plain, (2) a Late Jurassic to Miocene graben system coincident with the updip edge of the Louann Salt (Mexia, Talco, South Arkansas, Pickens, and Gilbertown Systems), and (3) a Late Cretaceous to Early Tertiary arcuate system of en echelon faults (such as the Luling and Balcones Faults).

From South Texas to western Alabama a series of interior salt basins is outlined by the peripheral faults to the north; each basin is separated from another by a series of uplifts and arches (fig. 7). Each salt basin is predominantly filled with Mesozoic sediments, and is characterized by abundant salt-associated anticlinal and domal structures.

The second peripheral fault zone is the most pronounced structural system of the Gulf Coast (Martin, 1977). The faults cut Upper Jurassic to Miocene rocks (Murray, 1961), yet faulting has affected deposition of the Smackover and Buckner Formations (Fowler, 1964; Hughes, 1968; Bishop, 1973), suggesting a long history of displacement. Faults are closely associated with the updip limit of the Louann Salt (Martin, 1977). Most authors attributed the faults to salt flowage (Bornhauser, 1958; Hughes, 1968), whereas others explained them as late-stage structural adjustments along basement faults initiated during rifting (Walper and Rowett, 1972).

This second system of peripheral faults and salt flowage structures in the salt basins immediately downdip is an important drilling target in the éxploration of the Smackover Formation throughout the Gulf Coast region (Collins, 1980). Limited exploration in South Texas has precluded adequate documentation of such structures in that area. However, faults cutting the Jurassic section and some salt anticlinal structures have been reported (J. J. Amoruso, personal communication, 1981). Thus, it appears that localized structural control of deposition of the Smackover Formation in South Texas probably exists. Consequently, seismic delineation of these structures and the application of successful Smackover exploration strategies used in the northern Gulf Coast area will guide initial exploration of the trend in South Texas. To date, wells in South Texas have penetrated the Smackover primarily along the third system of peripheral faults (Luling fault zone, Karnes and Atascosa troughs).

FACIES AND DEPOSITIONAL SYSTEMS

Sedimentary facies of the Smackover (table 1) and lower part of the Buckner (table 2) Formations were deposited in sedimentary environments within four major depositional systems: (1) basinal, (2) low-energy carbonate shelf, (3) high-energy shoal, and (4) sabkha (figs. 8 and 9). Each depositional system exhibits distinct facies assemblages and vertical sequences that are analogous to sediments of similar modern depositional environments.

Table 1. Smackover facies and characteristics.

Facies	*Composition*	*Characteristic sedimentary structures*	*Fauna*	*Other features*	*Environment*
Organic-rich, parallel-laminated, carbonate mudstone and siltstone	Alternating laminae of carbonate mud and siliciclastic silt, sand, clay, and pyrite	Uniform parallel laminae, thickness commonly less than 1 mm, but up to 5 mm	—	Carbonate mud recrystallized to microspar; anhydrite nodules, soft-sediment faults, some dolomitization (Cities Service No. 1A Peeler Ranch)	Deep basin
Organic-rich, irregularly laminated carbonate mudstone and siltstone	As above, except percent of carbonate mud increases	Subparallel to irregular laminae (wavy and lenticular flaser bedding?)	—	As above; also thin, isolated laminae of cross-laminated grainstone and packstone	Shallow basin
Wispy-laminated, fossil-bearing, crustacean-pellet carbonate mudstone	Carbonate mud with pellets of *Favreina* sp.; minor pyrite and siliciclastic silt in the wispy laminae	Wispy, irregular laminae; small, pencil-sized burrows	Thin-shelled pelagic bivalves with fragments of arthropods, foraminifers, echinoderms, and rare gastropods	Carbonate mud recrystallized to microspar; few anhydrite nodules (Skelly No. 1 Winkler); dolomitization updip	Outer shelf
Burrowed skeletal and pellet wackestone	Carbonate mud with pellets and fossils, rare intraclasts, oolites, oncolites or rhodolites; siliciclastic silt and pyrite in wispy laminae	Burrows common and variable in size; wispy laminae rare and widely spaced	Thick-shelled mollusks, including oysters, gastropods, and other bivalves, dominant; also foraminifers, fragments of echinoderms and arthropods, and rare worm tubes and green algae	Carbonate mud recrystallized to microspar; selective dolomitization of allochems and burrows; some cross-laminated grainstones; stylolites common; locally complete dolomitization with intercrystalline porosity (Skelly No. 1 Winkler)	Inner shelf
Pellet packstone	Nearly all pellets, with some siliciclastic silt	Abundant burrows	Mollusk, arthropod, and echinoderm debris	Partial to complete dolomitization; stylolites	Outer-shoal stabilized grainflats
Oncolite packstone	Oncolites (20-60%, avg. 45%); pellets (20-70%, avg. 40%); oolites, quartz sand, and uncoated skeletal debris (each up to 10%)	As above	As above	As above	Outer-shoal stabilized grainflats
Pellet grainstone	Up to 90% pellets with some skeletal debris	Cross-laminated, becoming parallel laminated upward and burrowed at the top	Mostly mollusk fragments	Occurs only in Cities Service No.1A Peeler Ranch; complete dolomitization	Inner shoal

Table 1 (con.)

Facies	*Composition*	*Characteristic sedimentary structures*	*Fauna*	*Other features*	*Environment*
Oncolitic, mixed-allochem grainstone	Oncolites (20-50%), pellets (20-40%), oolites (up to 20%), intraclasts, rhodolites and quartz sand (up to 10%)	Parallel laminae, low-angle cross-laminae, wispy laminae, and abundant burrows	Mollusk and echinoderm debris	—	Inner shoal
Oolitic mixed-allochem grainstone	Oolites (20-50%), pellets (20-40%), oncolites (up to 20%), intraclasts, rhodolites, and quartz sand (up to 10%)	As above, but with fewer burrows and better laminae	As above	Micritized grains	Inner shoal
Intraclast grainstone	Intraclasts (up to 50%), oolites (up to 30%) with pellets, quartz pebbles, and skeletal debris (each up to 10%)	Cross-laminae	Echinoderm and large oyster fragments	Micritized grains common; maximum observed grain size 6 cm; rhodolite grain size 0.7 to 2.0 mm	Inner shoal
Oolite-intraclast grainstone	Intraclasts and oolites (each about 40%) with pellets and skeletal debris	Cross and parallel laminae	As above	Some dolomitization between grains	Inner shoal
Oolitic quartz-arenite	Quartz sand (50-60%); with oolites, intraclasts, pellets and skeletal debris in decreasing order of abundance	Cross-laminae, burrows only at the bottom of this facies	Mollusk debris	Dolomitization variable but always greater than in adjacent facies	Inner shoal
Oolite grainstone	Oolites (50-80%, avg. 60%), pellets (10-40%, avg. 25%), intraclasts and skeletal debris (together up to 30%, avg. 15%), some quartz sand	Cross and parallel laminae, structureless or rare burrows	Mollusk and echinoderm fragments	Variable amounts of dolomitization, most occurring updip; oolites range in size from 0.1-0.6 mm, avg. 0.2-0.3 mm; rhodolites less than 1.2 mm; grains micritized	Inner shoal

BASINAL SYSTEM

The lower part of the Smackover Formation is composed of laminae of dark brown to black organic-rich carbonate mudstone alternating with laminae of pyrite and siliciclastic silt or sand. The sequence is interpreted to have been deposited in a low-energy basin. These dark-colored rocks are characterized by the absence of fauna or bioturbation, suggesting a euxinic environment. Sedimentary structures permit the subdivision of the section into two facies (fig. 10): a uniformly parallel-laminated facies (fig. 11a), and an overlying, irregularly laminated facies (figs. 11b, c). The basal facies is inferred to have been deposited in the deeper parts of the basin below the influence of wave-generated oscillatory currents. The upper facies originated in a slightly shallower basinal setting characterized by weak, intermittent wave-generated currents.

The term "basin," as used herein, implies only relative depth of water. No structural configuration or analogy to the modern Gulf Coast Basin is

Table 2. Lower Buckner facies and characteristics.

Facies	*Composition*	*Characteristic sedimentary structures*	*Fauna*	*Other features*	*Environment*
Oolite packstone and wackestone	Oolites, pellets, minor intraclasts, skeletal debris, and quartz sand in carbonate mud matrix	Wispy laminae and abundant burrows	Mollusk fragments, mostly gastropod	Partial to complete dolomitization	Subtidal
Oolite grainstone	As above, but without carbonate mud	Cross-laminae, parallel laminae, and some burrows	As above	As above	Tidal-delta sand bars, inlets, spits, and beaches
Gastropod and pellet wackestone	Carbonate mud, skeletal debris, pellets, siliciclastic silt and sand, some oolites	Abundant burrows	Gastropods and rare bivalves	As above	Lagoonal
Laminated dolomite mudstone	Carbonate mud	Algal laminae, some mudcracks, and rip-up clasts	—	—	Intertidal
Laminated siliciclastic sandstone and siltstone	Siliciclastic sand and silt: argillaceous, micaceous, and dolomitic or calcitic cements	Ripple-drift cross-laminae; parallel to irregular laminae; some slumped bedding, clay drapes, and scour surfaces	—	—	Intertidal
Argillaceous dolomite mudstone	Carbonate mud with lesser amounts of anhydrite, terrigenous mud, silt, and sand	Structureless or with distorted laminae; intercalated anhydrite abundant	—	Complete dolomitization	Sabkha
Green, dolomitic claystone	Terrigenous mud with silt and sand and lesser amounts of carbonate mud and anhydrite	As above	—	As above	Sabkha

intended. It is believed that the maximum water depth in the study area could not have exceeded the total observed thickness of the Smackover Formation, about 300 m (1,000 ft), and may well have been significantly less. The absence of a break in slope from shelf to basin suggests that the term "outermost ramp" may be synonymous with the term "basin" as used herein.

Two characteristics of both shallow- and deep-basin facies are soft-sediment deformation structures (fig. 11d) and isolated evaporite nodules. Both have been observed principally in the Cities Service No. 1A Peeler Ranch core. Slumping of soft sediment, probably stimulated by local slope instability or regional tectonic activity, has resulted in laminae sharply offset along normal microfaults by as much as 4 cm (1.5 inches) (fig. 11d). Micro-grabenlike structures also were observed. Offset laminae subsequently were draped by a continuous laminae of carbonate mud. Vertical fractures, now filled with coarse-crystalline calcite or dolomite, also terminate below the drapes and therefore are probably contemporaneous with the faults.

Small evaporite nodules (less than 2 cm [0.8 inch] in diameter) with coarse-crystalline dolomite or calcite or both surrounding coarse-crystalline anhydrite occur in some carbonate laminae. Unzoned nodules display very irregular, featherlike edges. Micrite inclusions are abundant in the coarse-crystalline calcite or dolomite, indicating a replacement origin for the outer rim. Whether the anhydrite grew displacively or by replacement is difficult to determine. The anhydrite contains no visible inclusions of micrite, yet no evidence of displacement of the carbonate mud has been observed. Growth of evaporite nodules within modern deep-sea sediments of the Atlantic

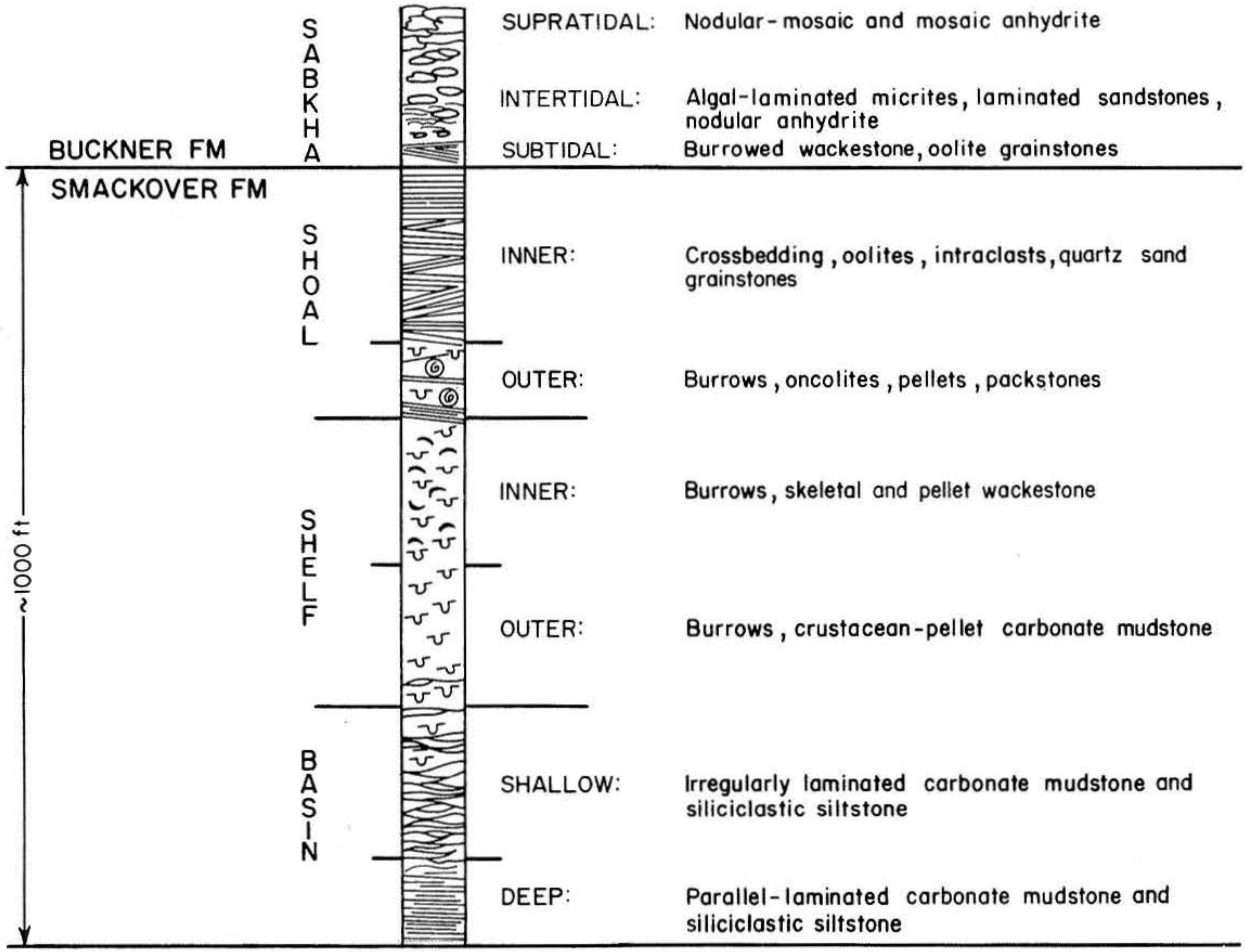

Figure 8. Idealized vertical section of Smackover and lower Buckner depositional systems and component facies based on inferred progradational model.

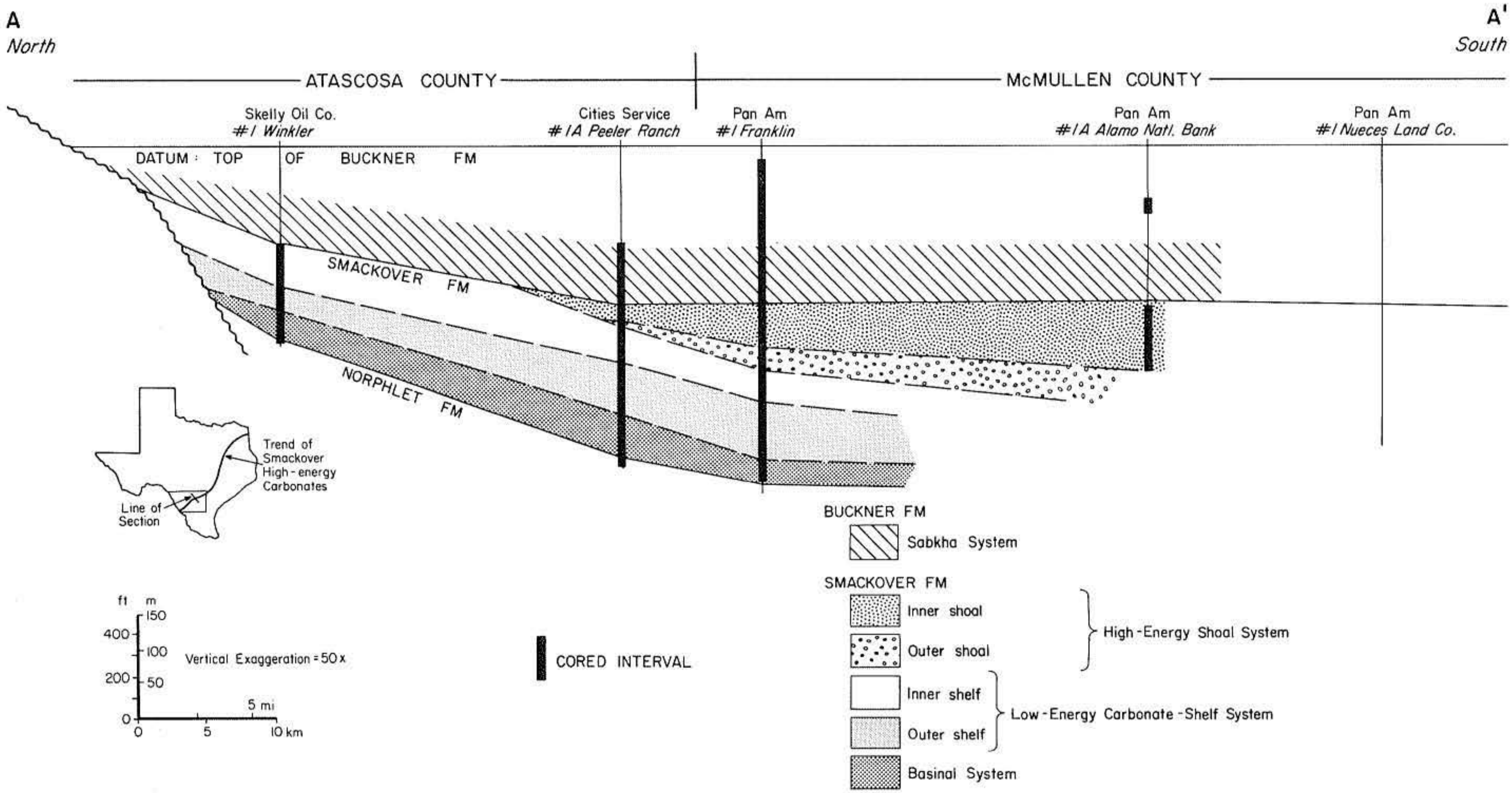

Figure 9. Generalized regional dip section, Smackover depositional systems and inferred paleoenvironments, South Texas. For line of section, see figure 1; for depth of core, see figure 4.

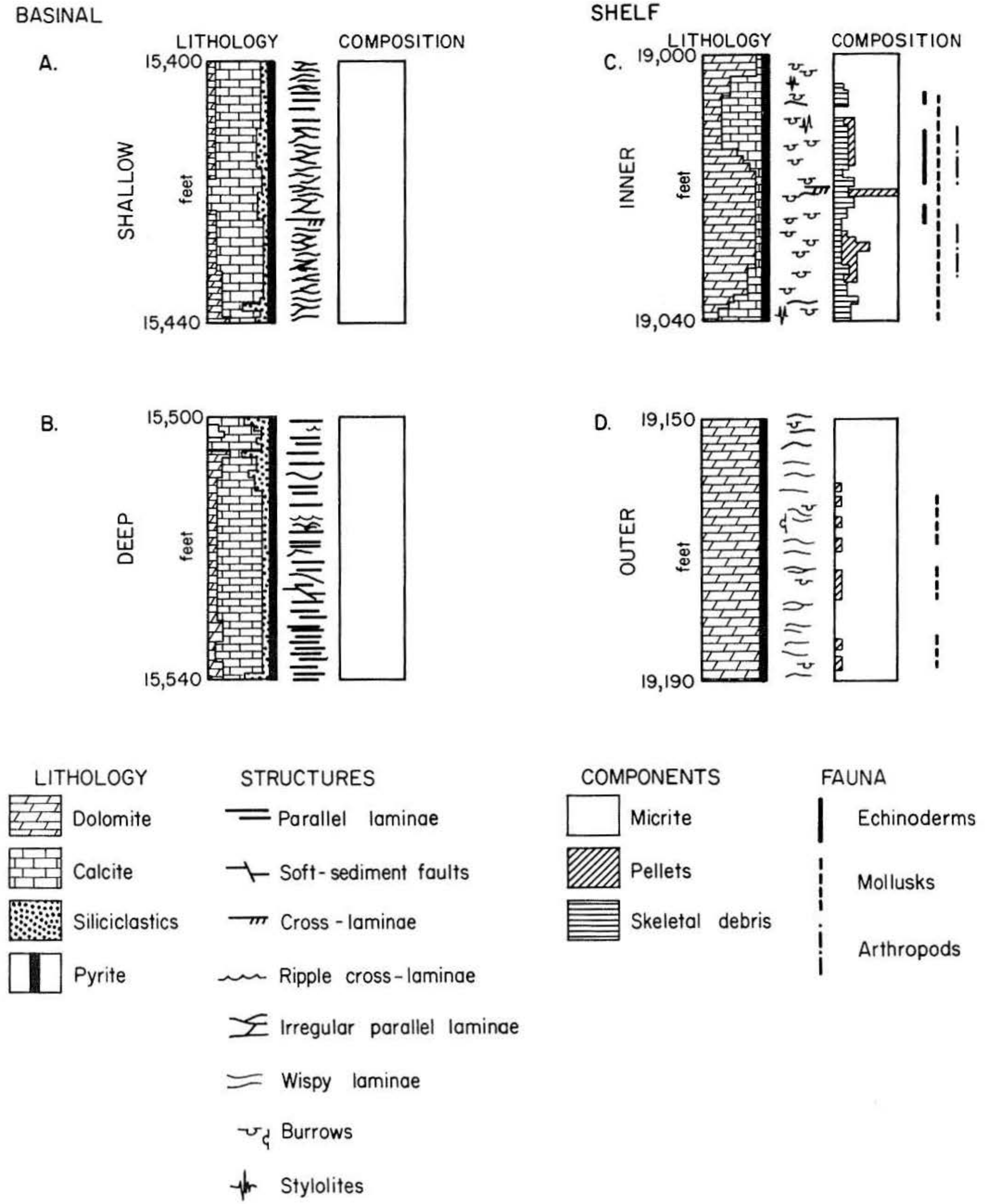

Figure 10. Vertical sequences of lithology, structures, constituents, and fauna within basinal and shelf systems, Smackover Formation. Sections A and B from Skelly No. 1 Winkler; sections C and D from Cities Service No. 1A Peeler Ranch.

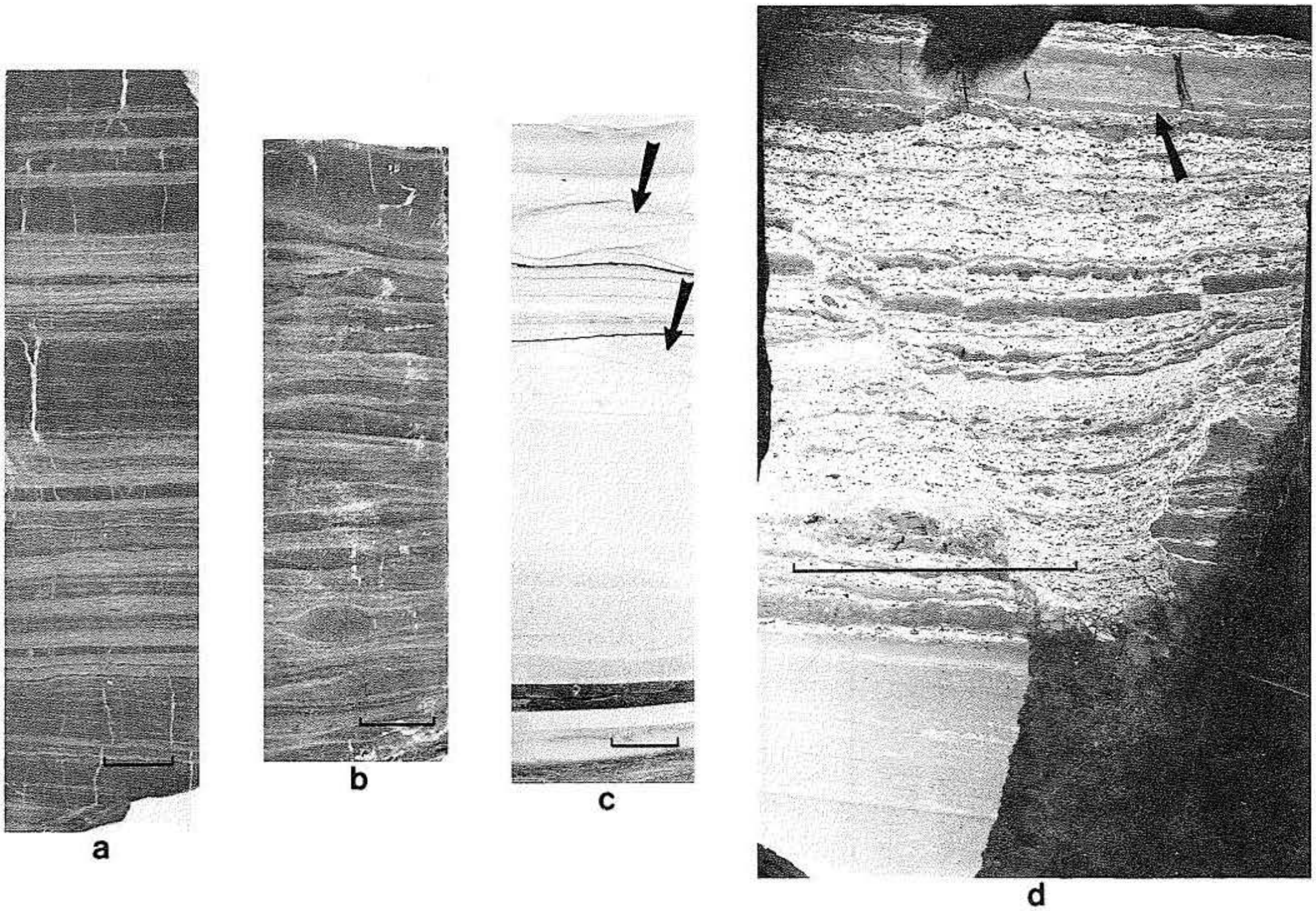

Figure 11. Facies and bedding features, basinal system. (a) Alternating organic-rich, parallel laminae of carbonate mudstone (dark) and pyritic siltstone (light); 4,735 m (15,531 ft). (b) Organic-rich, irregularly laminated carbonate mudstone containing subparallel and irregular flaserlike laminae alternating with pyritic siltstone drapes; 4,700 m (15,416 ft). (c) Ripple-drift cross-laminae (arrows) overlying parallel laminae in carbonate grainstone within mudstone facies; 5,802 m (19,031 ft). (d) Soft-sediment faulting in organic-rich, laminated facies. Thick carbonate mud laminae at the top of the figure (arrow) is not offset. Negative print of thin section; 5,945 m (19,500 ft). All scale bars are 1 cm. Cores a and b from Skelly No. 1 Winkler; cores c and d from Cities Service No. 1A Peeler Ranch.

Ocean and Mediterranean Sea has been documented by Robert and Chamley (1974), Siesser and Rogers (1976), and Brisken and Schreiber (1978).

Deep Basin

The alternating parallel laminae of the deep-basin facies (fig. 11a) are extremely thin (less than 1 mm) but some carbonate laminae are up to 5 mm thick. Carbonate laminae totally lack discernible allochems, and the carbonate mud typically is recrystallized to microspar (Folk, 1965). Dark carbonate mudstones containing millimeter-thick laminae are characteristic of deep-water, basinal deposition (Wilson, 1969). Neither the carbonate laminae nor the associated silt and pyrite laminae show any evidence of traction transport or reworking by currents, indicating that sediments settled below the effects of wave-generated bottom currents.

The sharp contrast in composition between the two types of alternating laminae, pyrite and siliciclastic versus carbonate (fig. 11a), indicates that they are derived from separate episodic events. Pyrite is the mineralized product of detrital organic matter; siliciclastic silt is probably of eolian origin. Detrital organic matter was probably deposited at relatively uniform but slow rates. Abundant pyrite in some laminae indicates long periods of no sediment influx except for occasional eolian dustfalls. Thus, pyrite and siliciclastic laminae represent starved-basin sedimentation (Wilson, 1975).

The carbonate laminae were derived from calcareous plankton, inorganic precipitation, or calcareous mud swept offshore from shallower muddy environments by tides and storms. However, only offshore transport of shallow-water-derived calcareous mud and inorganic precipitation can be considered episodic events. Sedimentation of significant amounts of calcareous plankton would have been continuous, resulting in a single type of laminae consisting of mixed carbonate, siliciclastic, and organic debris.

Offshore transport of carbonate mud by intermittent tidal and storm events has been documented in the Bahamas by Boardman (1978). Inorganic precipitation of carbonate mud from seawater (whitings) resulting from CO_2 loss due to seasonally high temperatures occurs in the Persian Gulf (Wells and Illing, 1964) and the Dead Sea (Friedman, 1965; Neev and Emery, 1967). Which mechanism produced the more significant contribution of carbonate mud to Smackover basinal sediments is unclear; both mechanisms are considered plausible.

Interpreting these carbonate laminae as seasonal varves may be erroneous. The number of storms affecting the Smackover sea from season to season and year to year probably varied. Likewise, whitings may not have occurred every summer. Thus, no regular seasonal pattern in laminations should be expected.

Shallow Basin

The parallel laminae of the lower basinal Smackover facies grade upward gradually into subparallel to irregular laminae of the upper basinal facies. Carbonate laminae continue to alternate with pyrite and siliciclastic silt. Carbonate laminae are much thicker here than in deep-basin facies. The pyrite and silt laminae are much thinner than in the deep-basin facies, normally no more than a few silt-grains thick (fig. 11b). Thin (less than 5 cm [2 inches]) cross-laminated grainstones and packstones are also intercalated with the carbonate mudstone (fig. 11c).

Laminae within this upper, shallow-basin facies resemble the wavy and lenticular flaser bedding described by Reineck and Wunderlich (1968). This suggests that silt-sized carbonate grains, probably pellets, were deposited by traction-transported, starved ripples, whereas the siliciclastic silt and pyrite were deposited as drapes. Wave-generated structures of similar appearance have been described by de Raaf and others (1977) from a lower Carboniferous siliciclastic marine sequence in Ireland. However, the inferred rippled carbonate laminae in the Smackover basinal facies is now microspar that exhibits no recognizable grains, even when examined under a scanning electron microscope. The only recognizable allochems are broken and abraded skeletal fragments and pellets that occur in thin and isolated grain-supported laminae. Nevertheless, the irregular laminae and the cross-laminated, grain-supported laminae probably indicate that weak intermittent wave-generated currents and downslope gravity currents affected bottom sediments and transported some allochems. Ripples caused by wave-generated currents have been reported as deep as 204 m (670 ft) on the modern high-energy Oregon shelf (Komar and others, 1972). Much of the Smackover shallow-basin carbonate mud originally was probably deposited from suspension but was subsequently reworked to form cross-laminae. The carbonate laminae are thicker in this facies (fig. 11b), perhaps because deposition occurred closer to a shallower water source of carbonate muds.

LOW-ENERGY CARBONATE SHELF SYSTEM

Wispy-laminated carbonate mudstone facies (fig. 10), characterized by in situ fauna and bioturbation, are interpreted as low-energy carbonate shelf deposits. In this paper, "shelf" is considered to be the top of a ramp or platform (Wilson, 1975). Shelf facies were undoubtedly influenced by the same intermittent wave-generated currents that affected the shallow-basin facies; however, biological activity on the shelf obliterated primary sedimentary structures. Both outer- and inner-shelf facies are recognized (fig. 10).

Outer Shelf

Wispy-laminated, fossiliferous, crustacean-pellet carbonate mudstone (fig. 12a) is gradational between the subjacent basinal facies and the suprajacent shallow inner-shelf facies. The wispy laminae consist of pyrite and siliciclastic silt concentrations. These laminae are very thin (one or two silt grains thick), and their abundance decreases upward. Crustacean pellets of *Favreina* sp. are abundant (fig. 12b). Fossils are rare and consist mostly of thin-shelled pelagic bivalves and arthropod fragments, minor foraminifers, and echinoderm fragments. Burrows are rare,

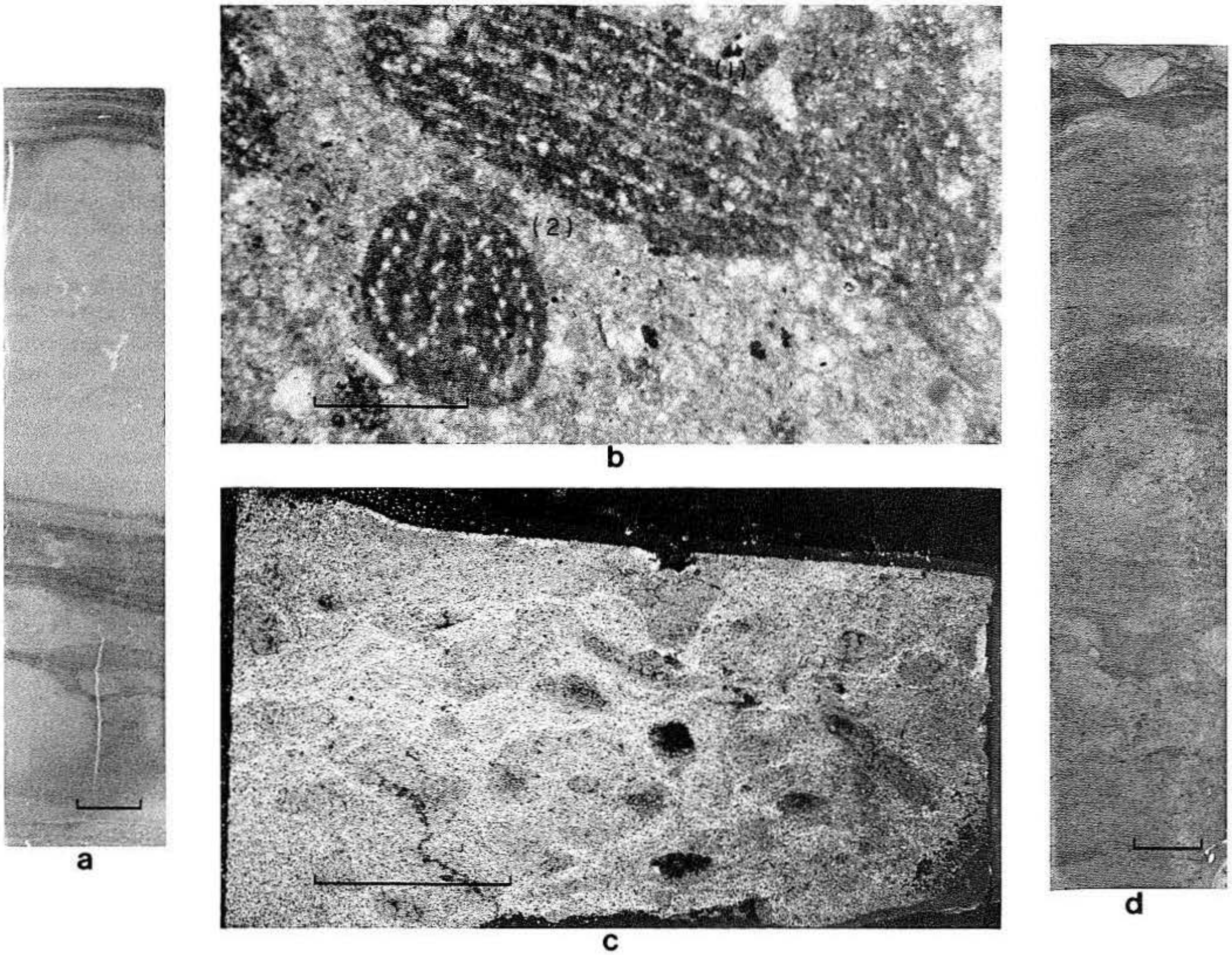

Figure 12. Facies, structures, and characteristic features, shelf system. (a) Wispy-laminated, fossil-bearing, crustacean-pellet carbonate mudstone of outer-shelf environment; 4,678 m (15,345 ft). (b) Photomicrograph of crustacean *Favreina* sp. pellet. Note characteristic longitudinal tubules in pellets (1) that form small circles in cross section (2); 5,895 m (19,337 ft). Scale bar equals 0.5 mm. (c) Small, pencil-sized burrows. Negative print of thin section; 5,799 m (19,023 ft). (d) Burrowed skeletal and pellet wackestone deposited in inner-shelf environment; 4,642 m (15,226 ft). Scale bars in a, c, and d equal 1 cm. Cores a and d from Skelly No. 1 Winkler; cores b and c from Cities Service No. 1A Peeler Ranch.

consisting of very small, pencil-sized structures (fig. 12c). Because *Favreina* pellets are commonly larger than the observed burrows, the crustacean responsible for the *Favreina* pellets was not the burrowing organism.

Inner Shelf

An increase in bioturbation, allochem variety, and allochem abundance, and a decrease in wispy laminae, crustacean pellets, and thin-shelled mollusks characterize the transition from outer-shelf to inner-shelf facies (fig. 10). The dominant facies deposited in this setting is a burrowed skeletal and pellet wackestone (fig. 12d). Wispy laminae are rare, and siliciclastic silt and sand generally occur only in downdip wells (Pan American, No. 1 Franklin and No. 1A Alamo National Bank). Burrows are variable in size and are also preferentially dolomitized. Some cross-laminated grainstones (less than 15 cm [6 inches] thick) probably represent deposition during storms.

Small (less than 0.2 mm) pellets are more common in this facies than the crustacean pellet, *Favreina* sp. Thick-shelled mollusks, including gastropods, oysters, and other bivalves, dominate the fauna. Echinoderms, foraminifers, and arthropods are also present. Worm tubes and an unknown green alga have been rarely observed. Other allochems include rare intraclasts, oolites, oncolites, and rhodolites.

This facies comprises the entire upper part of the Smackover Formation found in the updip Skelly No. 1 Winkler core (fig. 9). This suggests that either a lagoon or an embayment developed in the vicinity of this well when the high-energy shoal system developed farther seaward. Dominance of carbonate mudstone rather than wackestone in the Skelly No. 1 Winkler core may also indicate that the landward inner-shelf waters had more restricted circulation or salinity or both. Thus, there would be a decrease in faunal abundance.

HIGH-ENERGY SHOAL SYSTEM

Nine grain-supported facies compose the upper part of the Smackover Formation (table 1). These various lithofacies apparently were deposited in a variety of environments within a high-energy shoal system. Dominant processes affecting these environments were the physical reworking, sorting, and deposition of sand-size carbonate allochems, and development of coated grains, either by biological accretion (rhodolites and oncolites) or physical agitation (oolites). Other features of the shoal system that distinguish it from basin and shelf systems are (1) larger amounts of quartz sand, (2) decreased dolomitization, and (3) less pyrite.

It is impossible to determine the precise geometry of facies within this shoal system because of widely spaced wells. However, inferences about facies geometry can be made from the vertical sequences observed within each core. Thus, the shoal complex can be divided into two subsystems: an outer-shoal sequence of moderate-energy packstones and an inner-shoal sequence of high-energy grainstones (figs. 8 and 9).

Outer Shoal

Two lithofacies were recognized within the moderate-energy zone of the outer shoal (fig. 13): a pellet packstone overlain by an oncolite packstone (fig. 14a). Both facies are well burrowed. Although textures are variable, packstones are dominant. The combined thickness of these facies does not exceed 45 m (150 ft), and they are best developed in the Pan American No. 1 Franklin core (fig. 9).

Oncolites form when algae, dominantly blue-green algae, coat a grain (Logan and others, 1964). The algae trap sediment and precipitate micrite, forming concentric coatings (laminae) as the grains are periodically moved about on the seafloor (Logan and others, 1964; Bathurst, 1971). Gastropod, oyster, and other bivalve debris are the most common nuclei for coated grains in the Smackover Formation (fig. 14a). Pellets, quartz sand, or intraclasts also serve as oncolite nuclei. Oncolites range up to 1.2 cm (0.5 inch) in diameter, are round to oblong (fig. 14b), and display irregular growth bands conforming to the shape of the original core. A few oncolites are coated on only one side of the nucleus, suggesting that these grains were not continuously rolled about (Logan and others, 1964). Modern oncolites exist in moderate-energy subtidal to lower intertidal environments, normally in the lower shoreface near shoals or along the sides of large tidal channels (Wilson, 1975).

Inner Shoal

Oolites, intraclasts, rhodolites, oncolites, pellets, and quartz sand are components of the seven facies recognized within the inner-shoal complex. These facies, all of which are not present in a single well, represent a spectrum of high-energy conditions. In order of increasing energy of deposition the facies are: (1) pellet grainstone, (2) oncolitic mixed-allochem grainstone, (3) oolitic mixed-allochem grainstone, (4) intraclast grainstone, (5) oolite-intraclast grainstone, (6) oolitic quartzarenite, and (7) oolite grainstone.

Pellet Grainstone: The pellet grainstone facies (fig. 14c) was recognized only in the Cities Service No. 1A Peeler Ranch core. This facies overlies moderate-energy packstones and underlies oolite grainstone facies. It is cross-laminated at its base, becomes parallel-laminated upwards, and is burrowed at the top. A single shoaling-upward sequence is probably represented. Stabilization and bioturbation of the pellet grainstone facies occurred prior to deposition of the overlying oolite grainstone.

Mixed-Allochem Grainstones: The oncolitic and oolitic mixed-allochem grainstones (fig. 14d) are closely related. Both facies are best developed in the Pan American No. 1 Franklin core (fig. 13). Typically, the oncolitic mixed-allochem facies overlies the oncolite packstone and grades upward into the oolitic mixed-allochem grainstone, which in turn is overlain by an oolite grainstone. Very poor sorting and a variety of clast types

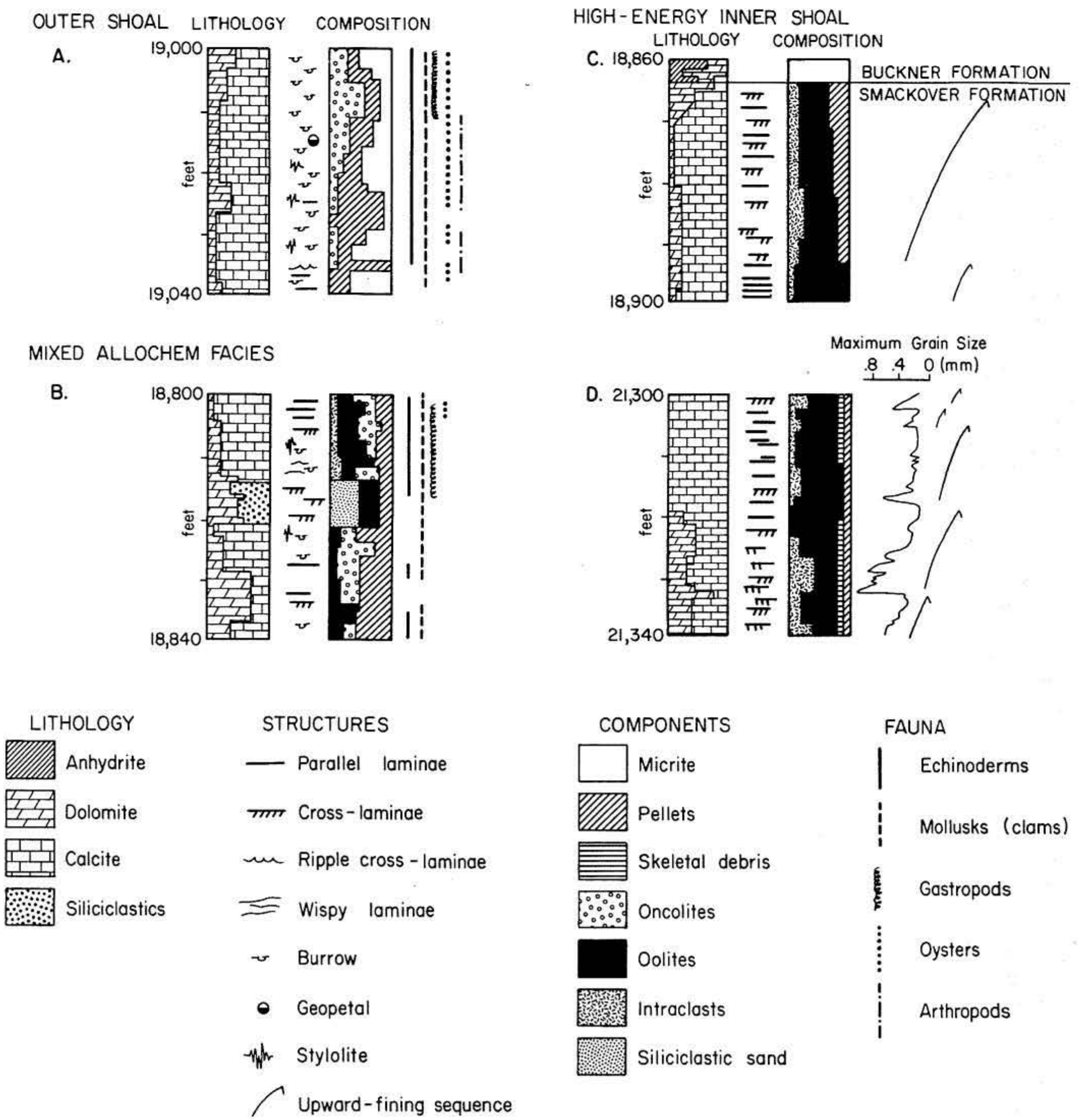

Figure 13. Vertical sequences of lithology, structures, constituents, and fauna within the high-energy shoal system. Sections A and B from Pan American No. 1 Franklin; section C from Cities Service No. 1A Peeler Ranch; and section D from Pan American No. 1A Alamo National Bank.

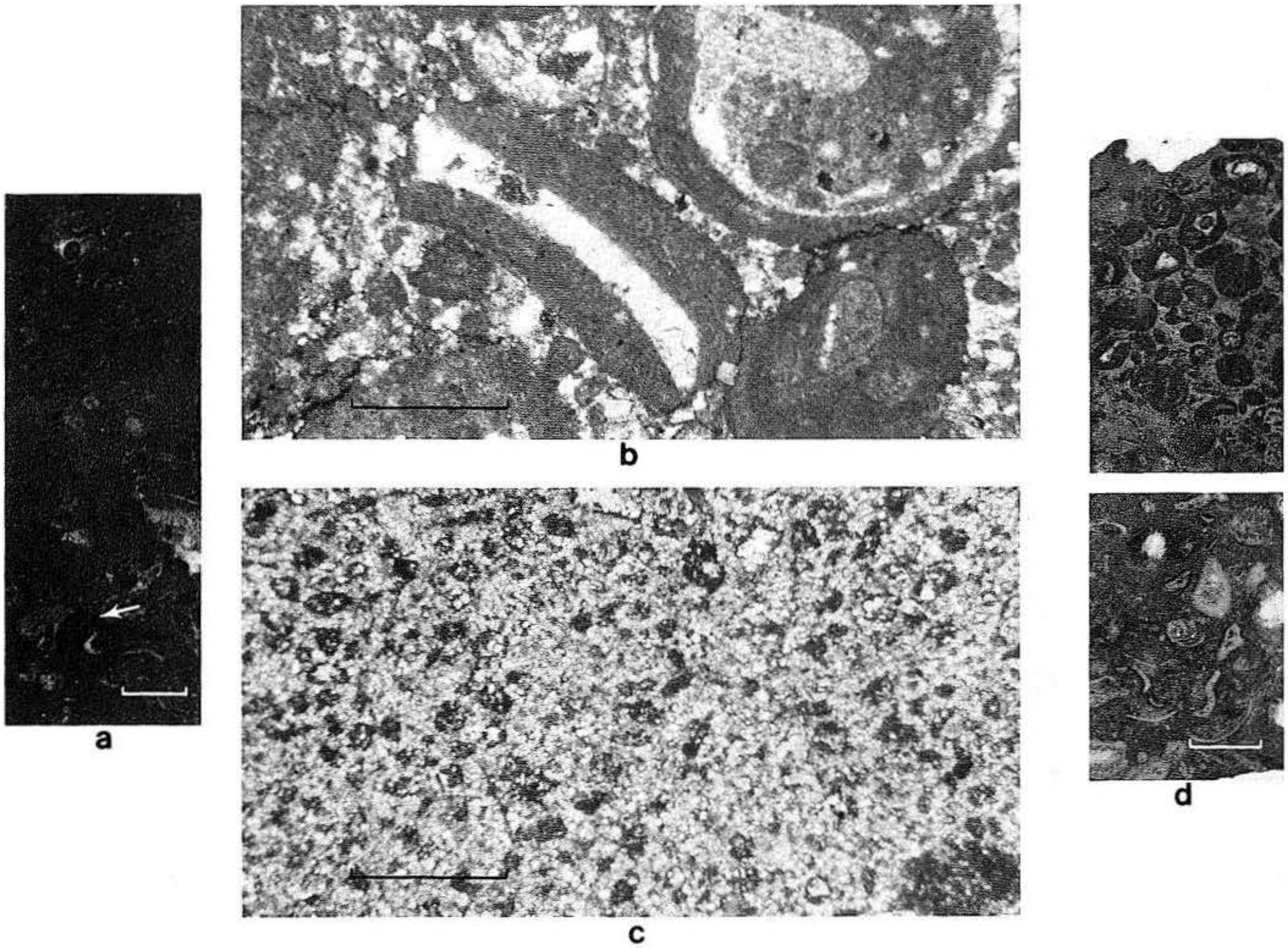

Figure 14. Textures and allochems of oncolite and pellet facies. (a) Oncolite packstone; note skeletal fragments in oncolite cores (arrow); 5,787 m (18,981 ft). (b) Photomicrograph of large oncolite grains; 5,789 m (18,989 ft). (c) Photomicrograph of dolomitized pellet grainstone; dark blobs are pellets; 5,776 m (18,946 ft). (d) Oncolitic mixed-allochem grainstone; 5,740 m (18,826 ft). Scale bars in a and d equal 1 cm; in b and c they equal 0.5 mm. Core c from Cities Service No. 1A Peeler Ranch; all others from Pan American No. 1 Franklin.

characterize these mixed-allochem grainstones. Both facies contain more burrows and carbonate mud than do other grainstone facies. Such features are indicative of sediment stabilization. Burrows, carbonate mud, and wispy laminae are more common in the oncolitic facies, whereas parallel and cross laminae are more abundant in oolitic facies, reflecting a slight increase in the level of depositional energy from the oncolitic to oolitic facies.

Oolitic Quartzarenite: The fine-grained submature oolitic quartzarenite (fig. 15a) is best developed in the Pan American No. 1 Alamo National Bank core. The quartzarenite is crossbedded (fig. 15b), an indication of deposition in a mobile sand shoal. Some laminae contain quartz pebbles (fig. 15c), indicating very strong currents. Burrows occur only at the base of this facies, typically within a single coset (fig. 15d), and may be escape structures made by organisms living in underlying carbonate sediment.

Intraclast, Oolite-Intraclast, and Oolite Grainstones: The remaining high-energy facies—oolite grainstone, oolite-intraclast grainstone, and intraclast grainstone—always occur together and dominate the upper part of the Smackover shoal system. Upward-fining sequences (fig. 13) of oolite-intraclast to oolite grainstones are repeated within all cores examined except the Skelly No. 1 Winkler. In the Pan American No. 1A Alamo

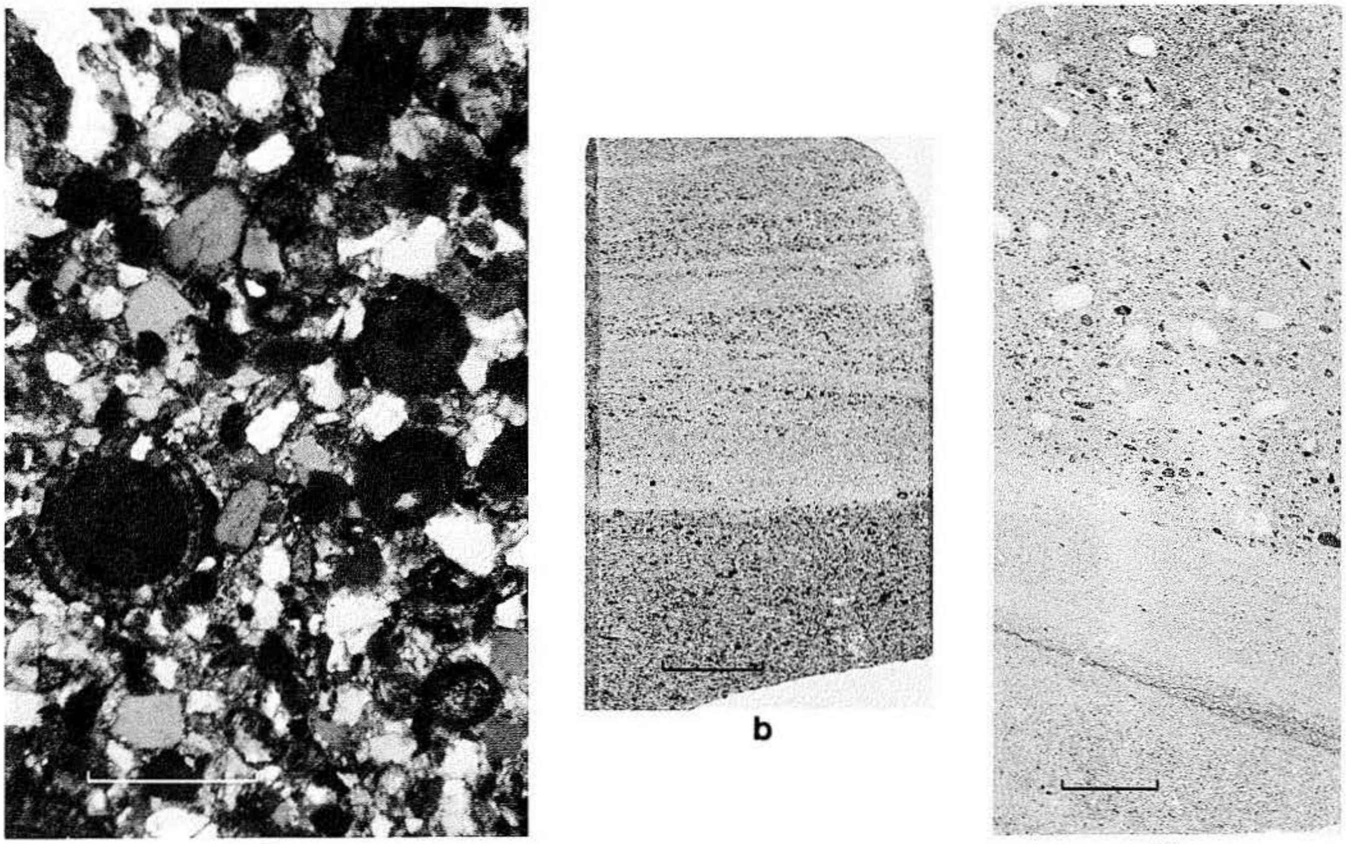

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Figure 15. Bedding structures of the fine-grained oolitic quartzarenite. (a) Photomicrograph of quartz grain and oolites, using polarized light; 6,483 m (21,263 ft). Scale bar equals 0.5 mm. (b) Cross-laminations; 6,546 m (21,472 ft). (c) Large quartz pebbles (white) and carbonate intraclasts (dark); 6,540 m (21,453 ft).

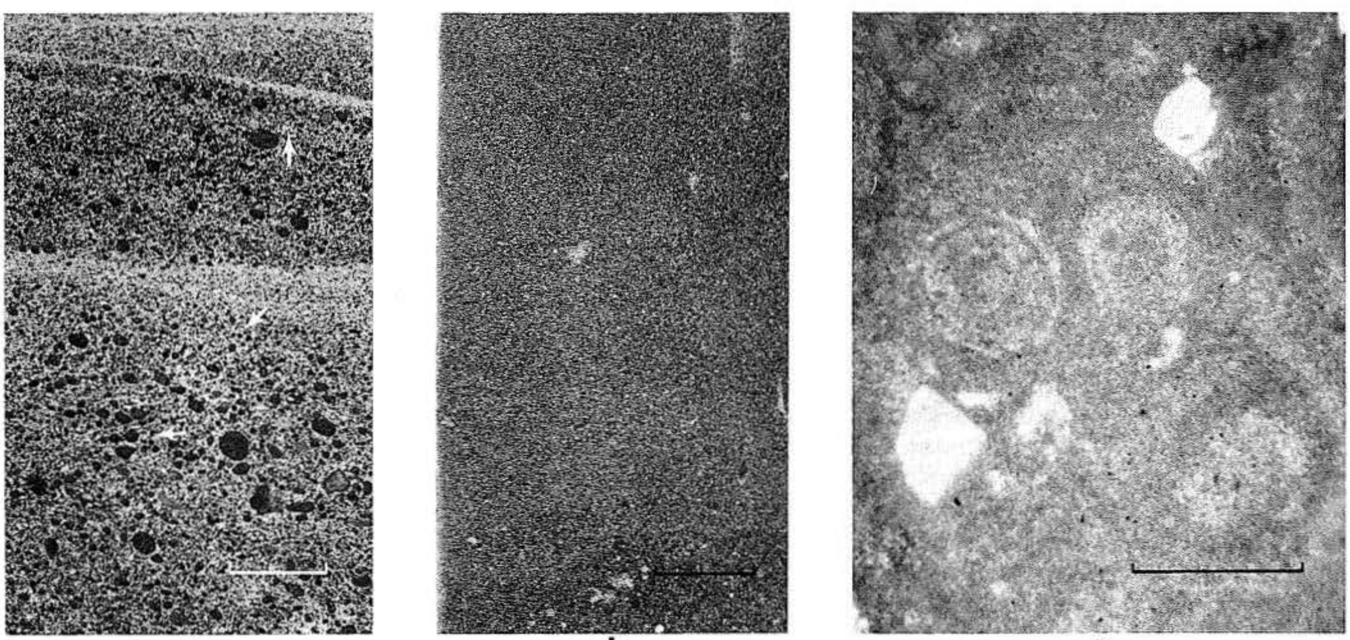

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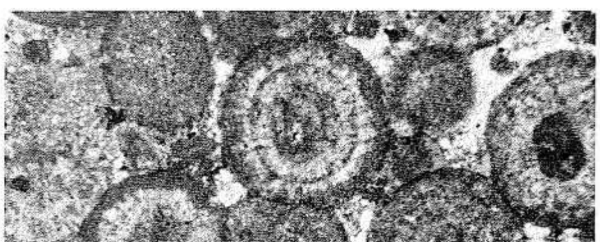
Figure 16. Oolite and intraclast grainstones, high-energy inner shoal. (a) Cross-laminated intraclast grainstone. Large clasts are probably rhodolites (arrows); 6,507 m (21,342 ft). (b) Well-sorted, structureless oolite grainstone; 6,519 m (21,383 ft). (c) Photomicrograph of abraded and rounded clast of oolites; 6,504 m (21,333 ft). (d) Photomicrograph of oolite grainstone facies containing uniform fine-grained oolites;

d

figure 15 (con.)

(d) Burrows within single coset; 6,552 m (21,492 ft). Scale bars in b, c, and d equal 2 cm; core from Pan American No. 1A Alamo National Bank.



d

figure 16 (con.)

6,477 m (21,244 ft). Scale bars in a and b equal 2 cm; in c and d they equal 0.5 mm. All core from Pan American No. 1A Alamo National Bank.

National Bank core, intraclast grainstone normally defines the base of each sequence, and an oolite-intraclast grainstone rather than an oolite grainstone caps the sequence (fig. 13).

Sedimentary structures also vary systematically within this facies sequence. The coarse-grained basal facies are cross-laminated (fig. 16a), whereas the fine-grained facies at the top of each sequence are parallel laminated or structureless (fig. 16b). Vertical changes in structures and grain sizes within these sequences indicate decreasing energy upward within each shoaling sequence.

The crossbedded intraclast grainstone (fig. 16a) commonly contains up to 50 percent intraclasts with a maximum grain size of 6 cm (2.4 inches). Included as intraclasts are large (0.7 to 2.0 mm), well-rounded rhodolites (Bosellini and Ginsburg, 1971), which are typical Smackover allochems throughout the Gulf Coast Basin (fig. 16a). Few concentric growth laminae are visible (fig. 16b); most were destroyed by micritization. Bosellini and Ginsburg (1971) reported that modern spheroidal rhodolites with dense concentric laminae and smooth surfaces are concentrated in high-energy settings, notably tidal channels. Most other Smackover intraclasts consist of abraded and rounded clasts of oolites (fig. 16c) that were cemented in submarine hardgrounds. Such hardgrounds are common on modern oolite shoals (Dravis, 1979; Harris, 1978).

The oolite-intraclast grainstone is crossbedded and poorly sorted, having a bimodal grain size (large intraclasts and small oolites). Like the intraclast grainstone, the intraclasts in this facies are well-rounded rhodolites and oolite clasts. Maximum clast size observed was 5 cm (2 inches), although most did not exceed 2 to 3 cm (about 1 inch).

The oolite grainstone facies (fig. 16b) is finer grained than other grainstones except the pellet grainstone facies. The oolites range in size from about 0.1 mm to 0.6 mm and average 0.2 to 0.3 mm in diameter (fig. 16d). This facies grades vertically into the oolite-intraclast grainstone and the oolitic sandstone facies. The close spatial association of this facies with the oolitic quartzarenite suggests that they formed under similar hydraulic conditions. Cross and parallel laminae are common, but the facies may appear structureless where only oolites are present (fig. 16b). Isolated escape burrows are also present.

Modern oolite shoals are composed of well-sorted oolite sands having coarse-grained intraclasts only in tidal channels or adjacent to hardgrounds (Ball, 1967; Dravis, 1977; Harris, 1979). Crossbedding is also typical of modern carbonate sand belts and tidal bars (Ball, 1967; Hine, 1977).

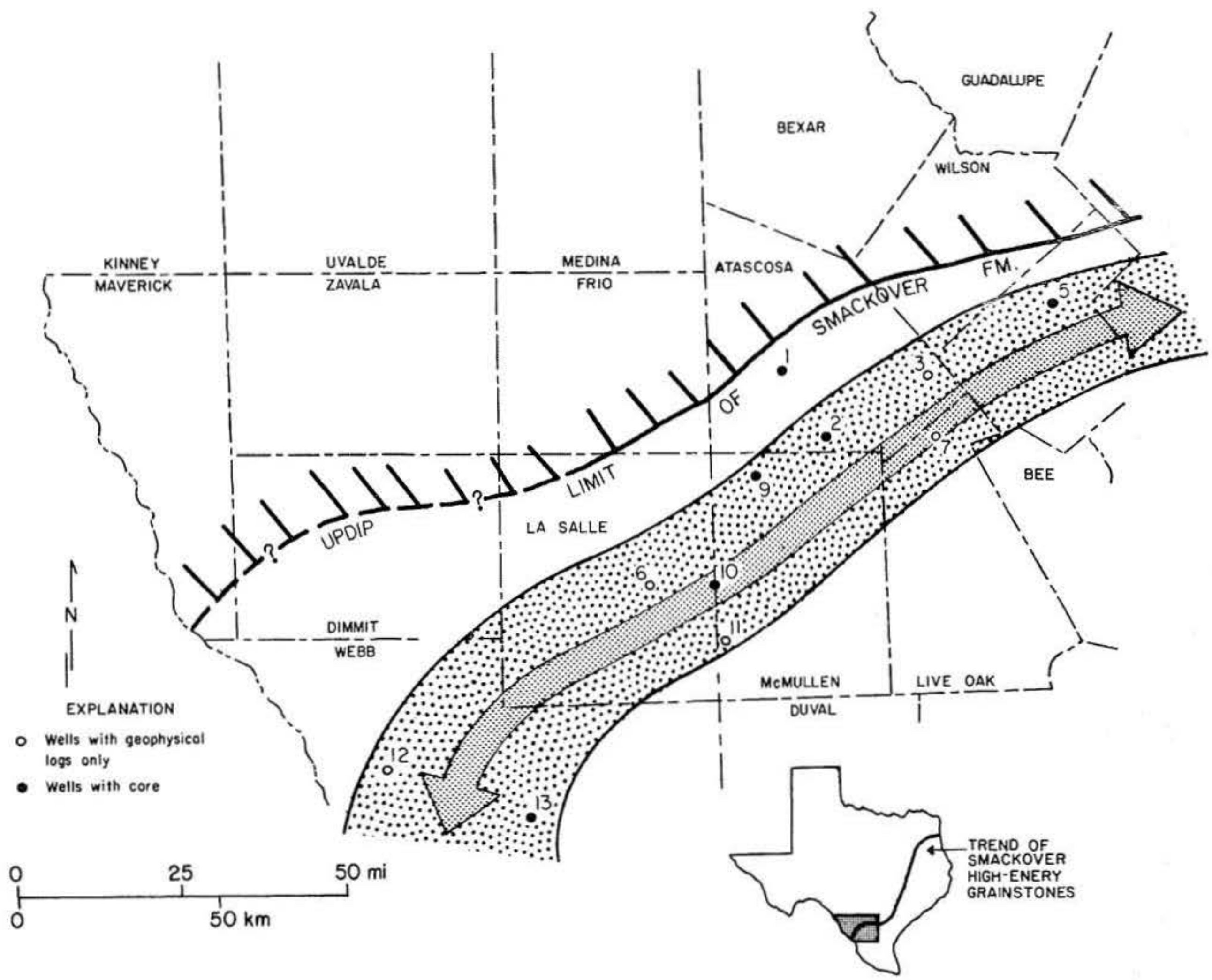


Figure 17. Postulated axis (stippled arrow) of maximum buildup, high-energy Smackover shoal system (stippled area). See appendix for well names.

By analogy, the intraclast grainstones in the Smackover Formation were deposited as lags in tidal channels, whereas the oolite and oolite-intraclast grainstones were deposited in active sand belts and tidal bars. These three facies reflect the highest depositional energy in the Smackover shoal system and dominate the Pan American No. 1A Alamo National Bank core where the grainstone sequence displays maximum thickness (fig. 9). Consequently, the axis of maximum buildup of the high-energy shoal system in South Texas trends approximately through the Alamo National Bank well and parallels the updip Smackover shoreline and paleobathymetric contours (fig. 17).

Facies inferred to reflect lesser energy levels are more common in the Cities Service No. 1A Peeler Ranch and Pan American No. 1 Franklin cores, behind the zone of maximum buildup where the shoal system is thinner. Lower energy grainstones and packstones also occur behind active shoals in modern carbonate environments, normally as stabilized grainflats (Harris, 1979). A similar depositional setting is inferred for the pellet and mixed-allochem grainstone facies of the Smackover shoal system. The greater abundance of burrows and carbonate mud in these facies supports such an interpretation.

SABKHA SYSTEM

During Buckner time a coastal sabkha, dominated by carbonate and/or siliciclastic

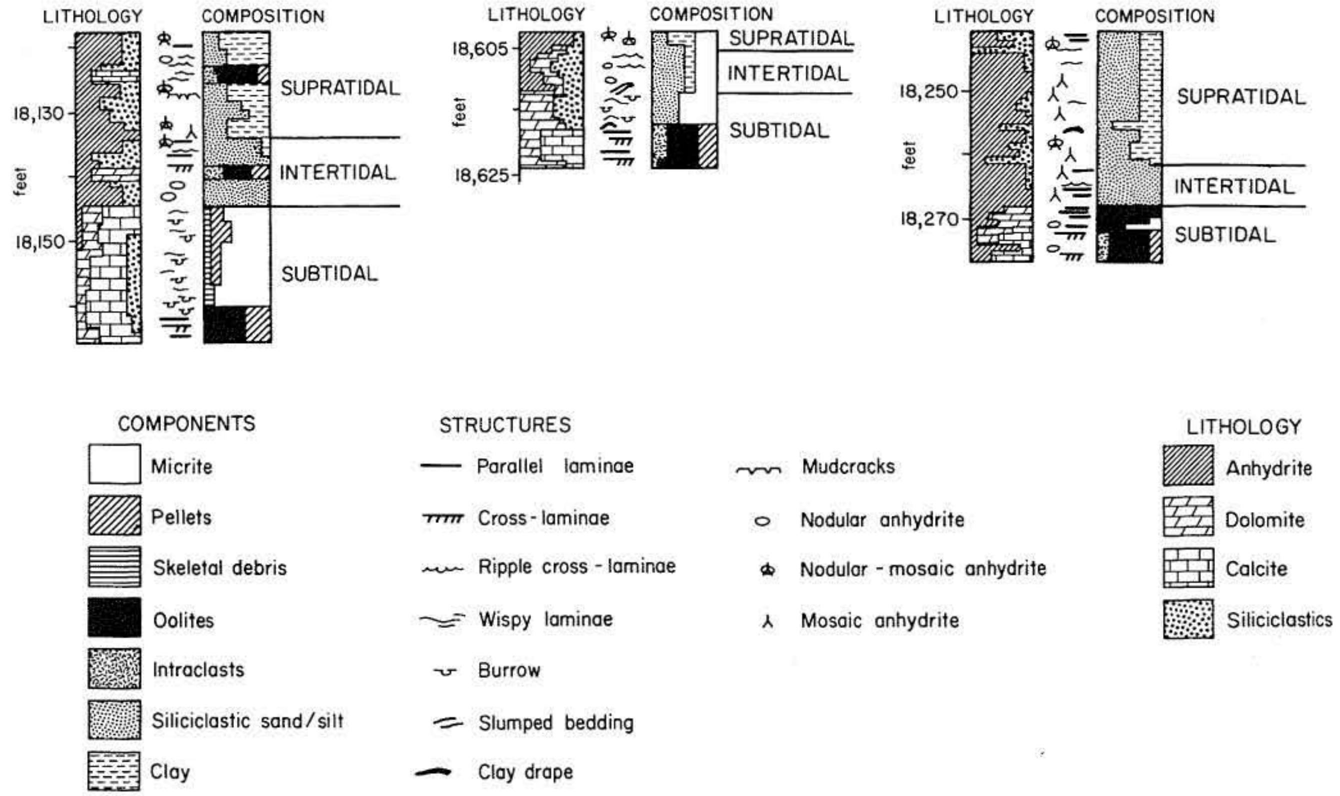


Figure 18. Vertical sequences of subtidal to supratidal deposits, Buckner sabkha system. All sections from Pan American No. 1 Franklin.

sediment and evaporites, prograded over the top of the Smackover Formation (figs. 8 and 9). Siliciclastic and carbonate sediments are thoroughly mixed, preventing distinction between a carbonate-dominated and siliciclastic-dominated sabkha. However, repeated vertical sequences of subtidal, intertidal, and supratidal facies are recognized (fig. 18).

Subtidal to lower intertidal facies are burrowed gastropod and pellet wackestone, oolite wackestone, oolite packstone, and oolite grainstone. Upper intertidal facies are laminated dolomite mudstone, laminated siliciclastic sandstone, and cross-laminated siliciclastic siltstone. The supratidal facies are argillaceous dolomite mudstone and green dolomitic claystone, both intercalated with various types of anhydrite.

Subtidal

The dark gray subtidal facies of the basal Buckner Formation contain allochems and textures similar to those of the underlying Smackover Formation. Oolite wackestone (fig. 19a) grades upward into oolite packstone (fig. 19b), which is overlain gradationally by oolite grainstone (fig. 19c). The wackestone and packstone facies are burrowed and exhibit wispy laminae. Together they are rarely more than 2.4 m (8 ft) thick. The grainstone facies is cross-laminated (large-scale sets up to 0.5 m [1.5 ft]) and commonly grades upward into parallel-laminated grainstones that may be burrowed. The oolite grainstone typically contains a coarse lag at its base, composed of reworked pebbles of supratidal anhydrite. The wackestone-to-grainstone sequence is interpreted to reflect deposition within tidal deltas and bars capped with tidal-inlet, spit, and beach facies. Channels probably connected restricted lagoons with the adjacent marine environment. Oolite grainstones are common in such settings along the Trucial Coast of the Persian Gulf (Bathurst, 1971; Loreau and Purser, 1973).

A facies believed to have been deposited within the lagoonal to lower intertidal environment is a dark-gray, burrowed gastropod and pellet wackestone (fig. 19d). Gastropods dominate the fauna, although some bivalves are also present. Such a monotypic fauna is typical of restricted, high-stress conditions. Browsing and burrowing

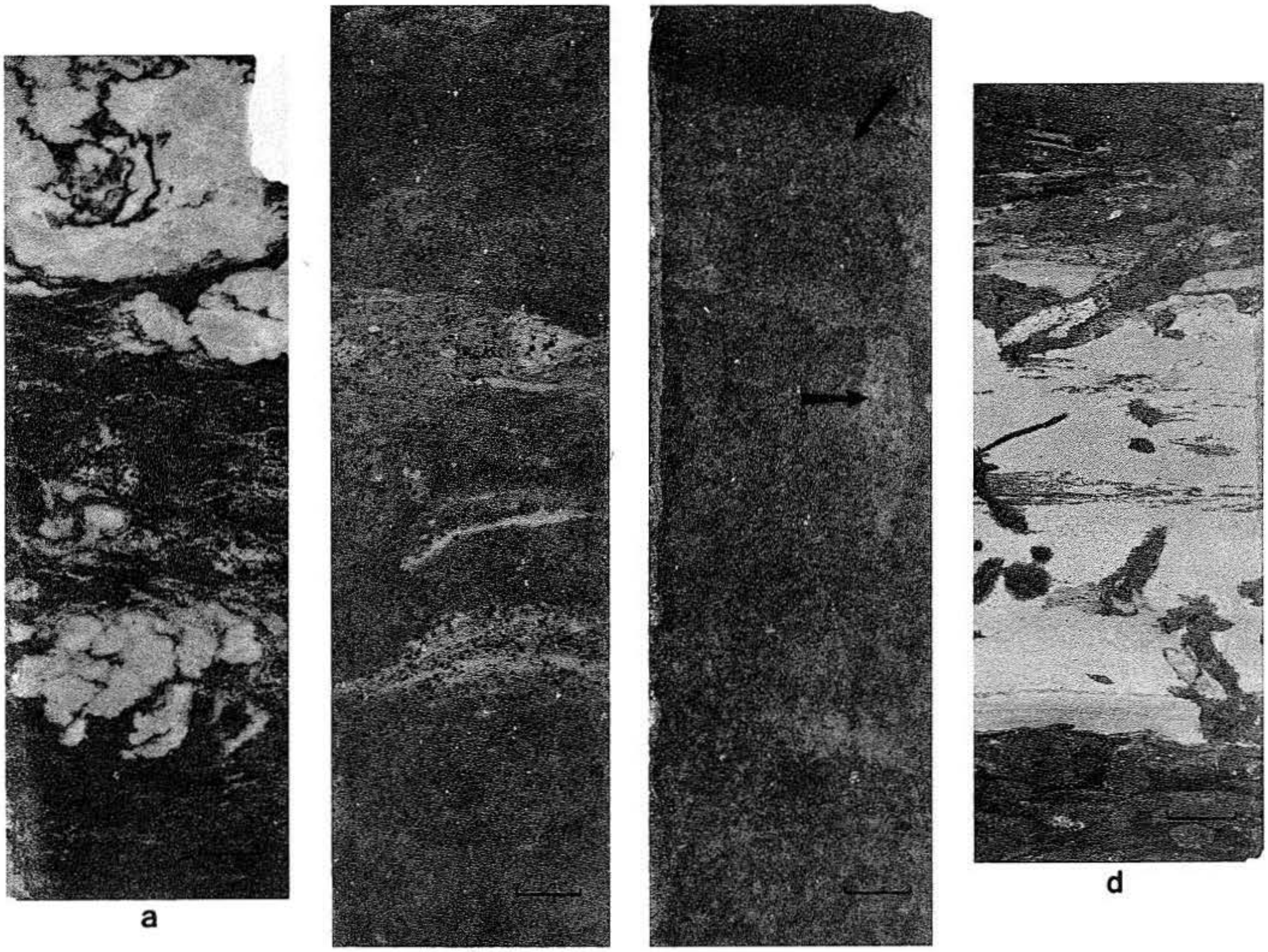


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Figure 19. Subtidal facies and structures, Buckner sabkha system. (a) Oolite wackestone containing nodular anhydrite (light gray); 5,561 m (18,241 ft). (b) Burrowed oolite packstone; 5,521 m (18,108 ft). (c) Oolite grainstone containing vague cross-laminae and possible escape burrow (arrows); 5,517 m (18,097 ft). (d) Burrowed gastropod and pellet wackestone (dark gray) containing a lens of sandstone (light gray) probably deposited during a storm; 5,552 m (18,210 ft). All scale bars equal 1 cm; all core from Pan American No. 1 Franklin.

organisms homogenized the sediment and destroyed the characteristic structures necessary to distinguish between the subtidal and lower intertidal zones (Shinn and others, 1969; Bathurst, 1971; Wilson, 1975). Some oolites and sandstone lenses are present, presumably deposited in the lagoon by strong storm tides. Most of these lenses were subsequently homogenized by burrowers (fig. 19d). This facies typically overlies the oolite grainstone, suggesting progradation of the lagoon over the beach or tidal delta. Where the oolite grainstone overlies the gastropod-pellet wackestone, reoccupation of a tidal delta, deposition of a storm washover, or the cessation of a progradational phase is indicated.

Intertidal

Intertidal deposits are thin, commonly less than 3 to 5 m (10 to 15 ft) thick. The laminated dolomite mudstone (fig. 20a) contains many thin, parallel, and crenulated laminae suggestive of algal-mat remains (Kendall and Skipwith, 1968; Bathurst, 1971). Mudcracks indicative of exposure, rip-up breccias, and thin (less than 5 cm [2 inches]) oolite laminae also occur within this facies. The breccias and oolites represent sediment deposited by storm washover and flooding of the intertidal zone (Shinn and others, 1969; Wilson, 1975). Most intertidal sediments are gray to dark gray, laminated siliciclastic sandstones

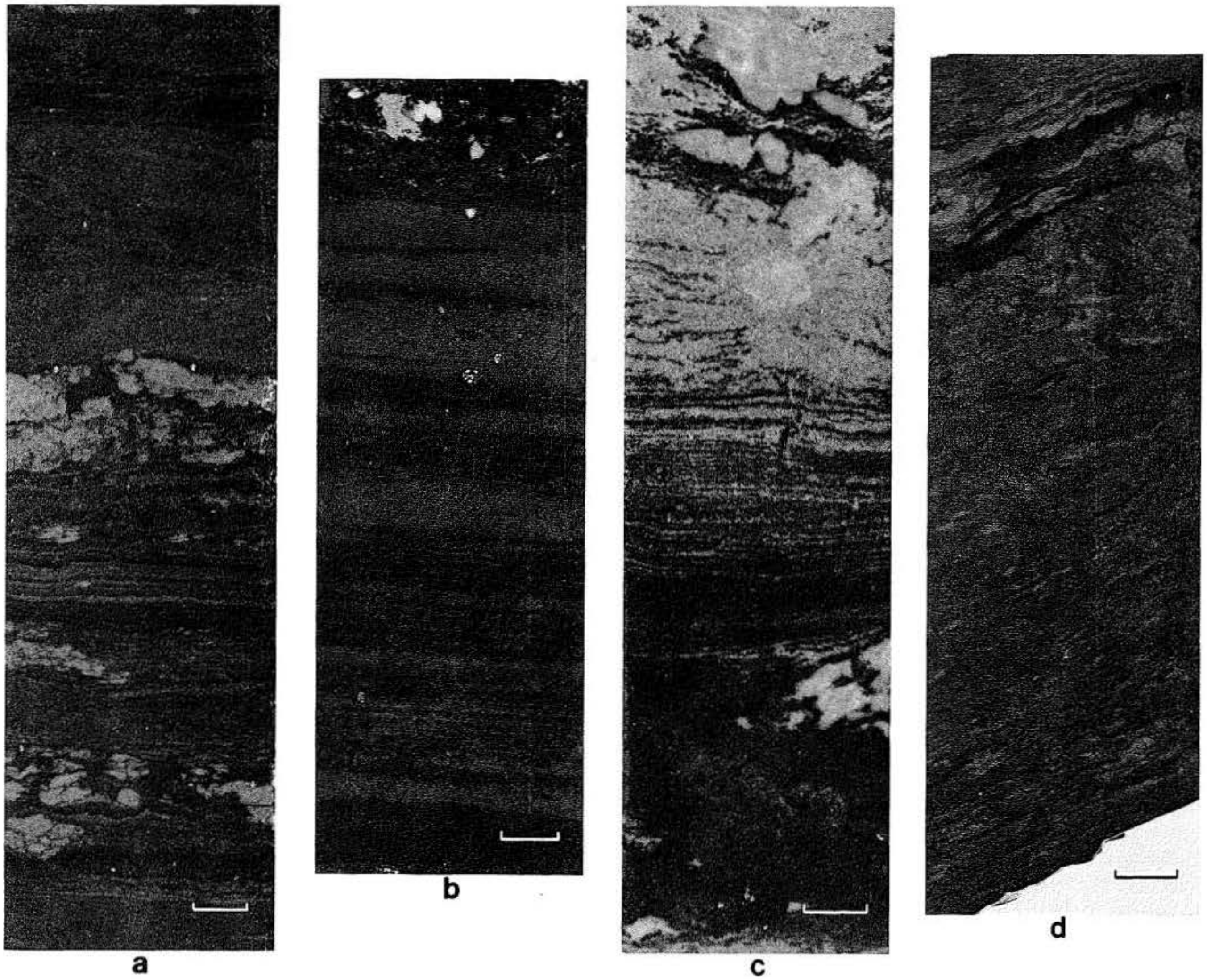


Figure 20. Intertidal facies and structures, Buckner sabkha system. (a) Laminated dolomite mudstone containing bedded nodular anhydrite (light gray). Crinkled laminae suggest algal mats; 5,540 m (18,171 ft). (b) Parallel-laminated siliciclastic sandstone; 5,709 m (18,725 ft). (c) Parallel to irregularly laminated siliciclastic sandstone containing nodular anhydrite; 5,544 m (18,186 ft). (d) Possible slumped bedding in intertidally deposited siliciclastic sandstone; 5,675 m (18,614 ft). All scale bars equal 1 cm; all core from Pan American No. 1 Franklin.

and siltstones. The sandstones are fine-grained submature subarkoses, sublitharenites, and litharenites. Sedimentary structures include ripple-drift cross-laminae, parallel and irregular laminae (fig. 20b, c), slumped beds (fig. 20d), scoured surfaces, and clay drapes, all typical of modern intertidal zones (Reineck, 1972; Reineck and Singh, 1975).

Supratidal

Supratidal facies are interlayered gray, argillaceous dolomite mudstone and green, dolomitic claystone. The original texture of both facies is interpreted to have been a mixture of carbonate, anhydrite, and terrigenous mud. Intercalated siliciclastic silt and sand were probably deposited by eolian processes (Bathurst, 1971). The dolomite mudstone and dolomitic claystone facies can be differentiated by the amount of carbonate or terrigenous mud components. Both facies are typically structureless or contain vague, distorted laminae (fig. 21a). Laminae composed of oolites, intraclasts, pellets, and fossils within these facies probably record deposition by storms that flooded across the supratidal flat (Shinn and others, 1969; Wilson, 1975).

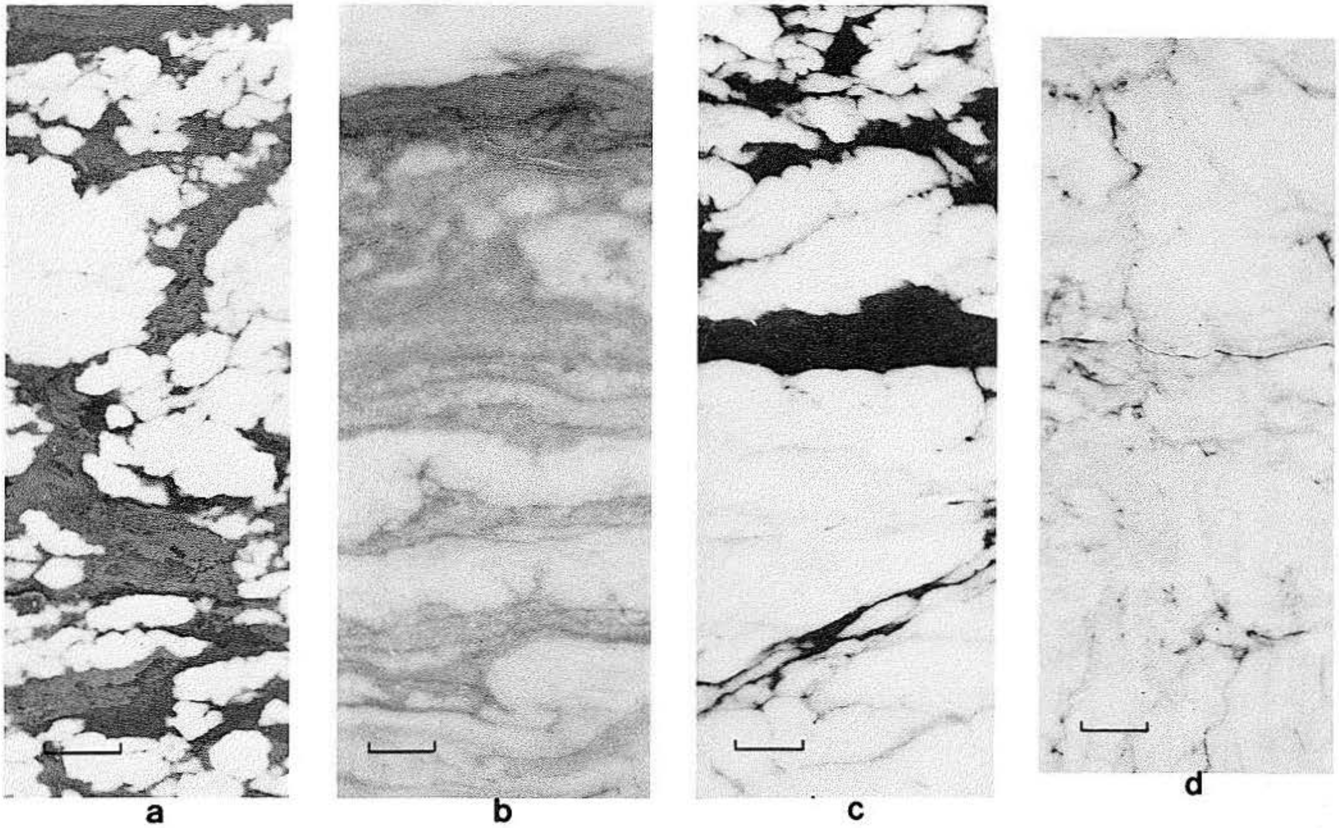


Figure 21. Anhydrite textures of supratidal facies, Buckner sabkha system. (a) Nodular anhydrite in green matrix of dolomitic claystone. Irregular laminae are typical and indicate displacement of sediment with growth of evaporites; 5,510 m (18,074 ft). (b) Ropy-bedded anhydrite in green dolomitic claystone matrix; 5,629 m (18,465 ft). (c) Nodular-mosaic anhydrite in dark gray dolomitized carbonate mudstone; 5,512 m (18,081 ft). (d) Mosaic to massive anhydrite; 5,528 m (18,132 ft). All scale bars equal 1 cm; all core from Pan American No. 1 Franklin.

The dominant characteristic of the supratidal facies is intercalated, white to gray anhydrite. Massive, mosaic, nodular-mosaic, nodular, and laminated textures are most common (fig. 21). These evaporites are interpreted to have precipitated as gypsum or anhydrite from interstitial fluids beneath the surface of the sabkha. A similar origin has been reported for modern evaporites of the Trucial Coast (Kinsman, 1966; Butler, 1969; Kendall and Skipwith, 1969; Shearman, 1978). Anhydrite with nodular and nodular-mosaic textures also occurs in subtidal and intertidal facies, but it is most abundant in supratidal facies. In subtidal and intertidal facies the evaporites probably precipitated when supratidal facies prograded over them (Shearman, 1978). Anhydrite abundance decreases downward from the top of each depositional cycle concomitant with a change in anhydrite textures from principally mosaic and nodular-mosaic to nodular. These changes reflect a decrease in precipitation downward from the near surface (fig. 18).

Lateral and vertical variations within the sabkha system are complex. Although the system is composed of repeated cycles of subtidal to supratidal deposits, the specific facies within these cycles vary. The thickness of each subtidal to supratidal cycle is also variable. Subtidal and intertidal facies are thicker and dominate cycles in the lower part of the Buckner Formation in the Pan American No. 1 Franklin core. In the upper part of the same core, the supratidal facies are three to six times thicker than all other facies, and subtidal facies are usually absent. Red, bioturbated siliciclastic sandstone and shale occur within the upper cycles and are interpreted to represent the seaward edge of a coastal- or wadi-plain system that interfingered with and prograded over the sabkha system.

MODERN ANALOGS

The Smackover and lower part of the Buckner Formations were deposited in basinal, shelf, shoal, and sabkha depositional systems. Vertical facies sequences within both formations can be related to modern depositional environments. A modern analog duplicating every Smackover and Buckner environment does not exist. Instead, we have developed a composite depositional model for these formations, based on two modern settings: the Yucatan Shelf of the Gulf of Mexico and the Trucial Coast of the Persian Gulf.

Yucatan Shelf

The western Yucatan Shelf, which slopes uniformly from the mainland beach to the Campeche Scarp (fig. 22), is typical of modern carbonate ramp systems. The entire shelf is exposed to ocean waves and currents accompanied by winnowing of sediment to reported depths of 100 m (360 ft) (Sellwood, 1978).

Distribution of facies on the Yucatan Shelf is complicated by a mixture of modern sediments in equilibrium with the present depositional setting and relict sediments associated with the Holocene flooding of the shelf. Logan and others (1969), however, found that variations in grain size and composition of modern surface sediments parallel bathymetry and reflect deposition on a ramp (Ahr, 1973). Sediments on the western inner shelf consist of a thin veneer of coarse-grained mollusk sands. Coral reefs, which developed during the last Holocene sea-level rise, are essentially relict features, although they still flourish today. Below the 90-m (300-ft) isobath, pelagic oozes dominate the sediment and slowly dilute the relict carbonate sands.

These relict sediments also typify ramp facies (Ahr, 1973). Facies patterns (fig. 22), developed during the early Holocene sea-level rise from about -90 to -55 m (-300 to -180 ft), follow bathymetric contours and consist of offshore pelagic oozes that grade landward into ooid-pellet-intraclast sands.

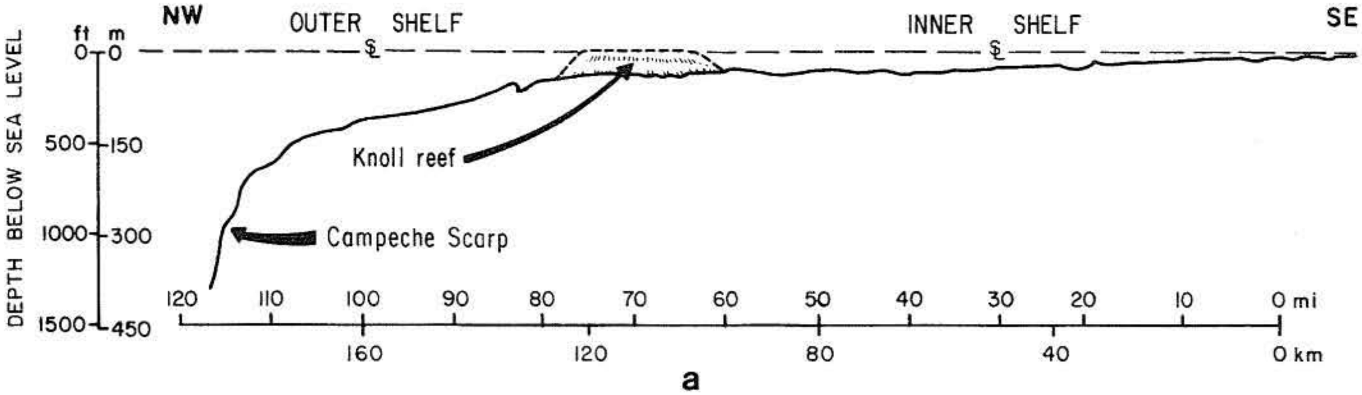
Ward and Brady (1973) and Ward (1976) describe the geometry and distribution of the nearshore, high-energy carbonate sands (fig. 23) on the eastern Yucatan Shelf. Oolite and skeletal sand and gravel are deposited in large mobile sand waves, stabilized sand banks, beaches, spits, spillover lobes, and eolian dunes. Textural belts parallel the shoreline; the best-sorted sands lie along the beach-dune trend and sorting decreases seaward. The stabilized sands are muddy and poorly sorted, and bedding is presumably destroyed by bioturbation. Active sand waves, composed of oolites with minor intraclasts (Harms and others, 1976), are rippled and contain steep crossbeds.

Although the thin sediment veneer and relict sediments preclude direct comparison of the Yucatan Shelf with the Smackover Formation, striking similarities exist between facies patterns and inferred processes: high-energy sand facies occur landward and muddier facies seaward, reflecting increasing depositional energy up the ramp. Open-ocean waves influence the sediments and winnow some of the pelagic oozes. The carbonate sands of the eastern Yucatan Shelf and the grainstones of the Smackover Formation are composed of identical allochems and contain many similar primary depositional features: variations in sorting, rippled and crossbedded mobile sands, and burrowed, stabilized muddy sands. Finally, the width of the Smackover shoal system, about 32 km (20 mi), is nearly identical to that of the western Yucatan Shelf blanket sands and is not significantly greater than the width (12 km [7.5 mi]) of the high-energy carbonate sands of the eastern Yucatan Shelf.

Differences between the modern Yucatan Shelf and the ancient Smackover ramp include (1) the origin of the carbonate mud and (2) the vertical sequences and thickness exhibited by grainstone belts. Yucatan muds are derived from planktonic coccoliths and calcareous foraminifers; there is little production of lime mud by other means (Logan and others, 1969). Although calcareous plankton existed in the Jurassic, Smackover carbonate muds probably originated either from destruction of calcareous green algae, or from inorganic chemical precipitate (whitings). Thickness of the Smackover grainstones resulted from rapid subsidence, a factor that has not influenced the sand veneer (less than 4.5 m [15 ft] thick) that has accumulated on the stable Yucatan Shelf. In addition, vertical sequences displayed by Smackover grainstones have not been reworked into a veneer of blanket sands as have the transgressive sands of the western Yucatan Shelf.

Trucial Coast, Persian Gulf

Lithofacies of the sabkha system of the lower part of the Buckner Formation are comparable to the modern sabkha, lagoons, and tidal passes along the Trucial Coast of the Persian Gulf. The lateral and vertical gradation of Trucial Coast environments and facies from subtidal to supratidal (fig. 24) has been studied by many



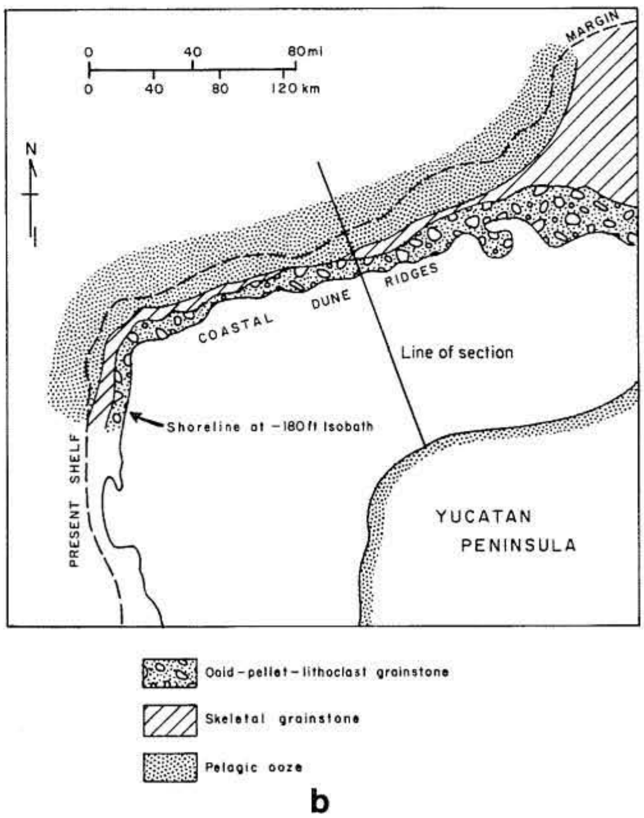


Figure 22. (above) (a) Profile of modern western Yucatan Shelf showing uniformly sloping surface. Line of section plotted on facies map below. (b) Facies map of relict Holocene sediment deposited on Yucatan Shelf during early Holocene time. Both a and b show characteristic features of carbonate ramp model (see table 3). Modified from Logan and others (1969).

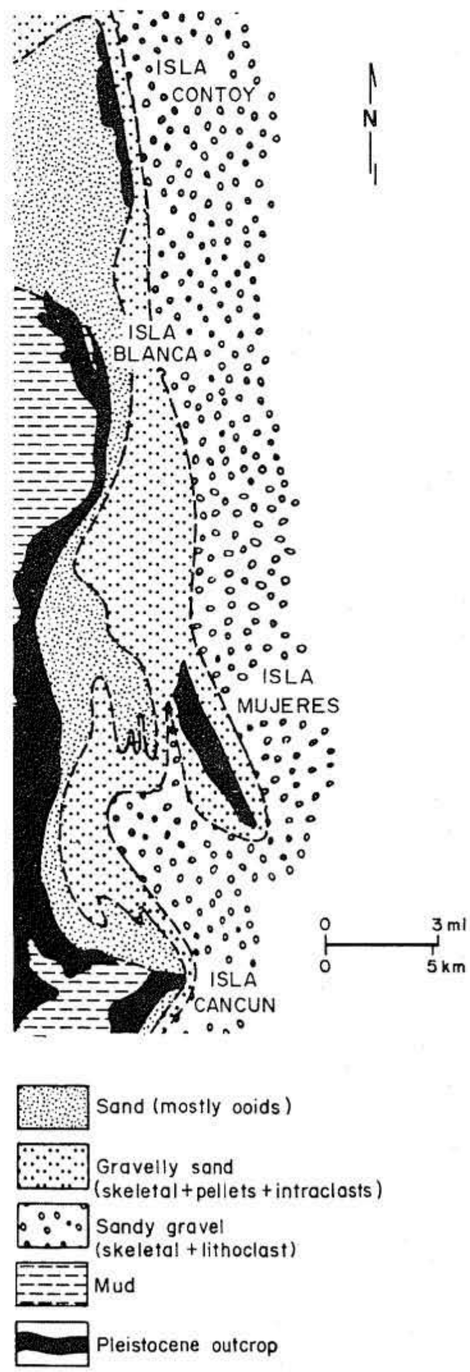


Figure 23. (right) Facies map of high-energy carbonate sands, eastern Yucatan Shelf (from Ward and Brady, 1973).

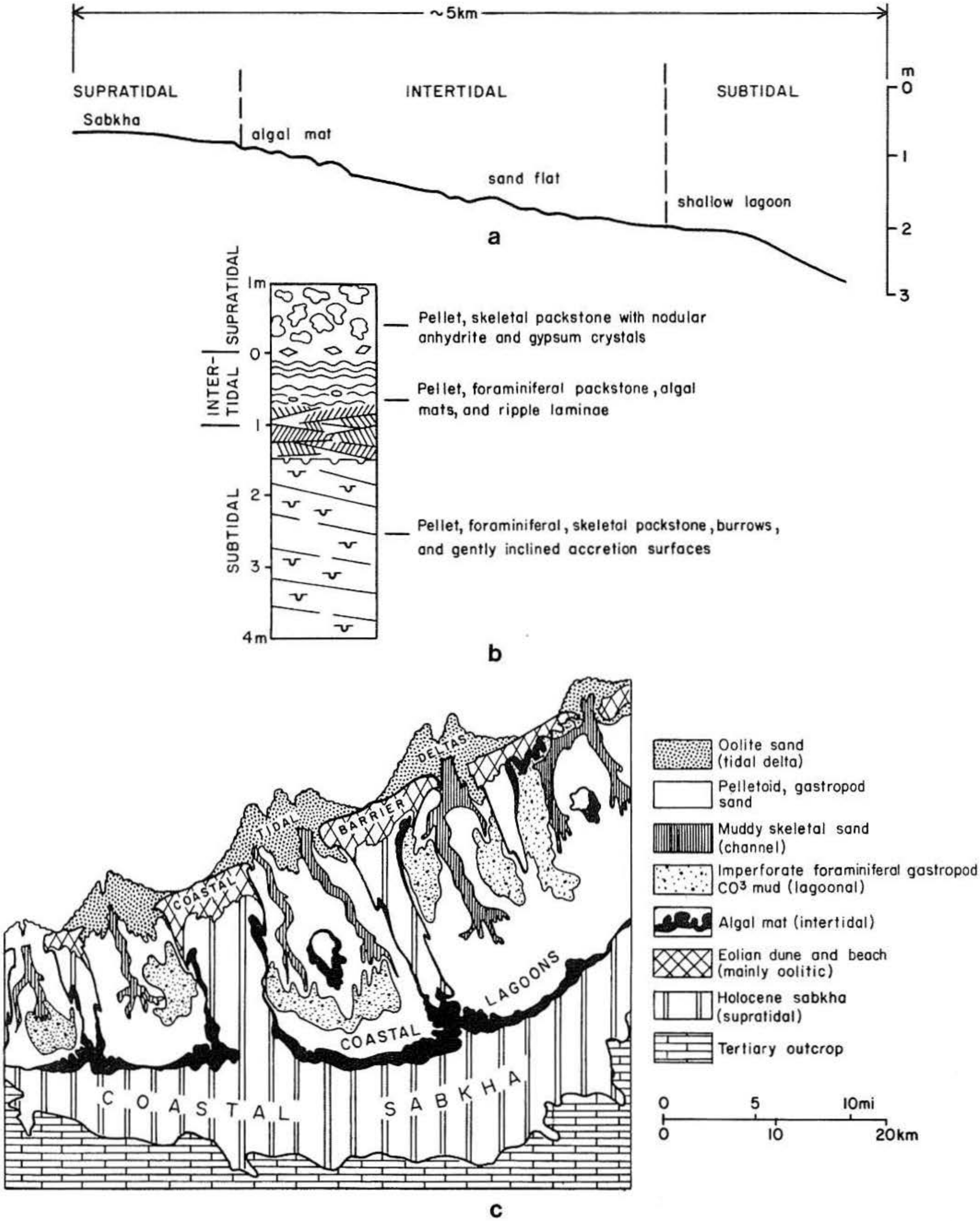


Figure 24. Bathymetric profile (a), facies sequence (b), and schematic map (c) of coastal lagoons and sabkhas, Trucial Coast, Persian Gulf. Modified from Purser and Evans (1973).

Table 3. Comparison of the ramp and rimmed shelf models of modern carbonate environments (modified from Ahr [1973], and Ginsburg and James [1974]).

Ramp model	*Rimmed shelf model*
Modern examples: Yucatan Shelf, Sahul Shelf, and the western Persian Gulf	Modern examples: South Florida Shelf, Bahama Banks, Belize Shelf, and Great Barrier Reef (Queensland Shelf)
*(1) Flat surface with low-angle slopes and no significant break in slope	(1) Nearly non-sloping platforms having irregular bathymetry out to the sharp slope break that marks the shelf margin
*(2) Concentric facies belts that follow bathymetric contours	(2) Facies tracts governed by local topography, having grainstones and boundstones on the highs and muddier sediments in the lows
*(3) Grainstones *updip* passing into pelagic mudstones downdip having no distinct shelf-margin facies	(3) Muddy sediments *updip* passing into grainstone and boundstones at the shelf margin
*(4) Monotonous wedge-shaped deposits thickening seaward except where modified by local structural control	(4) Detrital carbonate units gradually thickening downdip having shelf-margin boundstones locally thicker than detrital facies
*(5) Absence of a continuous reef trend; however, patch reefs may be present locally	(5) Continuous reef trends having patch reefs locally behind the shelf margin

*Characteristics of the Smackover Formation, South Texas

workers and summarized by Bathurst (1971), Purser (1973), Till (1978), and Kendall (1979). Tidal deltas and oolitic sand bars occur seaward of the subtidal lagoonal sediments. Tidal currents flow in and out of the protected lagoons through channels floored with muddy skeletal sands. Lagoonal sediments include gray, muddy skeletal sands and lesser amounts of fossiliferous lime muds. Benthic foraminifers and gastropods dominate the fauna. Gastropods thoroughly bioturbate the sediment and destroy all algal mats up to the upper intertidal zone.

Intertidal sediments consist of fecal-pellet mud and well-developed algal mats deposited in a broad zone. In the upper reaches of the intertidal zone the mats are wrinkled and underlain by gypsum crystals. There is no evidence of extensive desiccation and exposure in either the upper intertidal or supratidal zones. The supratidal zone, a broad salt flat or sabkha, is a deflation surface whose sediment consists of eolian quartz sand, carbonate mud, and nodular anhydrite. This zone rarely floods. Anhydrite precipitates within the sediment, displacing the carbonate-mud and quartz-sand matrix.

Although the overall facies tract and progradational sequence of the Trucial Coast resemble the inferred lower Buckner sabkha system, differences do exist. Most Buckner subtidal lagoonal sediments are muddier than those of the Trucial Coast. Sandstones, absent on the Trucial Coast, are the predominant intertidal facies in the Buckner Formation. These sandstones correspond to the lower intertidal, rippled carbonate sands deposited along the Trucial Coast (fig. 24). These Buckner sandstones indicate that terrigenous sediment was supplied by updip, fluvial processes, a feature absent along the Trucial Coast. Abundance of terrigenous clay in the Buckner supratidal facies also suggests fluvial input to the sabkha system.

SMACKOVER MODEL

Based on the modern Yucatan Shelf and Trucial Coast analogs, a schematic model of the depositional environments of the Smackover and lower part of the Buckner Formations was constructed (fig. 25). This model illustrates the lateral facies tract and the physical relationships between depositional environments. The ramp model of Ahr (1973), which serves as the prototype (table 3), depicts (1) a seaward-thickening wedge of sediment, (2) concentric facies belts that apparently follow paleobathymetric contours, (3) no continuous reef trend, and (4) grainstones and packstones facies updip and muddier facies downdip.

Environments in the Buckner sabkha system included ponds, lagoons, tidal deltas and channels, intertidal flats, salt flats, beaches, and eolian dunes. The high-energy Smackover shoal system was dominated by mobile sand shoals but also included stabilized sand shoals, tidal bars and channels, and accretionary shoreface deposits. Locally, muddy lagoons separated the shoal and sabkba systems.

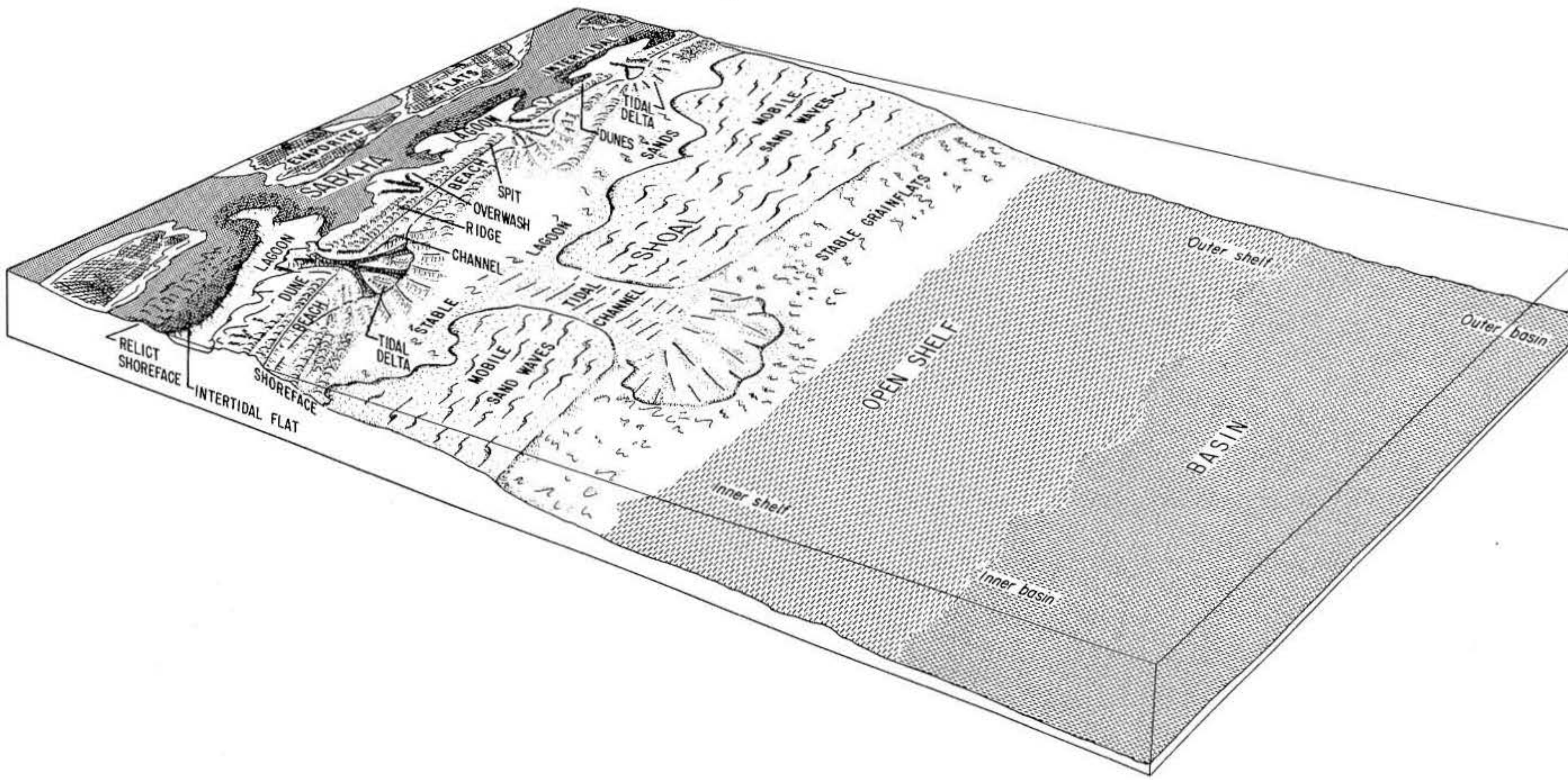


Figure 25. Depositional model, Smackover and lower Buckner basinal shelf, shoal, and sabkha systems, South Texas.

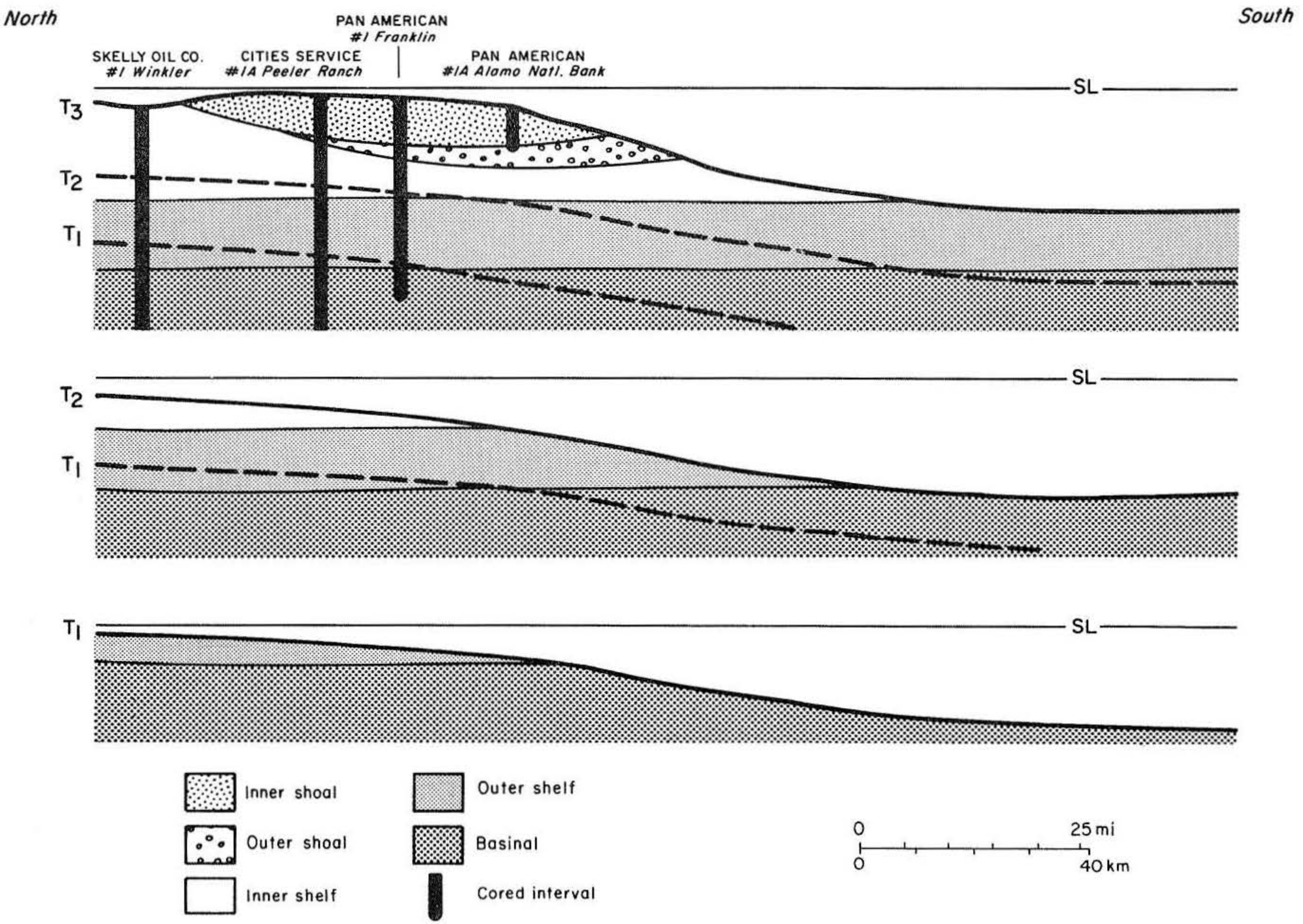


Figure 26. Interpreted evolution of deposition in the Smackover basin from a low-energy ramp setting (T_1) to a high-energy ramp setting (T_3). Compare uppermost schematic to figure 9. No vertical scale.

Immediately seaward was a grainflat where poorly sorted, burrowed oncolite packstone was deposited. Open-shelf sediments were deposited below the zone of shoaling waters; burrowed wackestones of the inner shelf graded into the carbonate mudstones of the outer shelf, which in turn graded into those of the basinal system. Energy levels decreased as water depths increased, resulting only in deposition from suspension in the deepest parts of the basin.

BASIN EVOLUTION

Facies interpreted as having been deposited in basinal and shelf settings occur stratigraphically below and updip of the grainstones deposited in the high-energy shoal system (fig. 9). This relationship suggests that the early Smackover basin was characterized by very low-energy conditions in which only facies associated with shelf and basinal systems were deposited (fig. 26). Through time the Smackover basin evolved to higher energy conditions and the shoal system developed. Whether changes in relative sea level, the physiographic nature of the basin, or some other feature caused this trend to develop is unknown. The Smackover model (fig. 25) and its correspondence to the Yucatan Shelf and Trucial Coast is only valid for late Smackover time; a low-energy ramp model applies to early Smackover time.

CONCLUSIONS

Lithofacies of the Jurassic Smackover and lower part of the Buckner Formations in South Texas were deposited on a rapidly subsiding carbonate ramp. Depositional environments ranged from supratidal sabkha to very low-energy, euxinic basin. Following a rapid transgression over Norphlet tidal-flat sediments, these basinal to sabkha environments slowly prograded seaward during Smackover and early Buckner time, producing a thick vertical sequence of regressive facies. Only a single major progradational sequence, represented by the entire Smackover and lower part of the Buckner Formations, was deposited. This extremely thick sequence, the product of slow seaward progradation of the facies tract, demonstrates that the rate of vertical accumulation (aggradation) of sediment far exceeded the rate of progradation because of relatively rapid subsidence.

Cyclic sedimentation can be inhibited by (1) rapid and continuous subsidence, (2) lack of climatic or sedimentological changes, or (3) lack of eustatic sea-level changes (Wilson, 1975). The absence of cyclicity in the Smackover carbonates indicates continuous subsidence and relatively static climatic and sedimentological conditions. Only within the sabkha system of the lower part of the Buckner Formation was sedimentation cyclic (repeated subtidal to supratidal sequences). These cycles, however, were deposited at or slightly above mean sea level and thus were more sensitive to subtle changes, especially in eustatic sea level, sediment supply, or sediment compaction.

The resultant spatial arrangement of ramp lithofacies indicates that Smackover and lower Buckner strata are characterized by (1) concentric facies belts that apparently follow paleobathymetric contours and (2) grainstone facies updip and carbonate mudstone facies downdip, reflecting downslope decreases in depositional energies. Each depositional system is composed of one or more lithofacies, the product of unique biological or physical processes:

(a) Smackover basinal system: No evidence of biological activity or an in situ fauna was observed in basinally deposited facies. Deposition from suspension produced alternating, uniformly parallel laminae of organic-rich carbonate mudstone and siliciclastic silt in the deepest parts of the basin. In slightly shallower, yet still euxinic settings, the sediment was reworked by weak, wave-generated oscillatory currents, producing irregularly laminated carbonate mudstones with siliciclastic siltstone drapes.

(b) Smackover shelf system: In contrast to the basinal system, the shelf was characterized by its in situ fauna and biological processes. Evidence of physical processes is rare. Wispy-laminated, crustacean-pellet carbonate mudstone containing a pelagic fauna was deposited on the outer shelf. In shallower waters of the inner shelf, a burrowed skeletal and pellet wackestone containing a benthic fauna was deposited.

(c) Smackover shoal system: Burrowed packstones composed of oncolites and pellets were deposited in a moderate-energy setting on stabilized grainflats between areas of low-energy shelf wackestone and the high-energy cross-bedded grainstones deposited in the inner shoal system. Physical reworking, sorting and deposition of sand-sized allochems, and development of coated grains (oolites and rhodolites) were dominant processes in the inner shoal system. A continuous spectrum of increasing depositional energies is documented by grain composition and sediment sorting in vertically arranged facies. Oncolitic mixed-allochem grainstones are the most poorly sorted, coarse-grained, and variable inner shoal lithofacies. Oolite grainstone is the best sorted, finest grained, and most homogeneous lithofacies. Grainstones of the inner shoal system were deposited in active sand shoals, spits, spillover lobes, beaches, and eolian dunes. The Yucatan Shelf of the Gulf of Mexico is a modern analog.

(d) Buckner sabkha system: A coastal sabkha, characterized by precipitation of evaporites and analogous in part to the modern Trucial Coast of the Persian Gulf, prograded over the Smackover lithofacies. Subtidal to supratidal facies were deposited in tidal lagoons, channels, shoals, spits, beaches, intertidal sandflats, algal mats, exposed salt flats, and sabkha surfaces. Carbonate sediment was derived from the subtidal environment, but the presence of siliciclastic sands and clays indicates some fluvial input into the system. Intercalated nodular anhydrites were not restricted to the supratidal facies but also precipitated in subtidal and intertidal facies as the sabkha prograded seaward.

The facies pattern of the Smackover and the lower part of the Buckner Formations in South Texas resembles that of the Smackover and lower part of the Buckner Formations throughout the Gulf Coast region, in particular in northeastern Texas, Louisiana, and Arkansas (Bishop, 1968; Dickinson, 1968). Thus, petroleum exploration models developed for the northern Gulf Coast Basin can be directly applied to South Texas.

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APPENDIX: SOUTH TEXAS SMACKOVER AND BUCKNER WELLS

Well	Cored interval (ft)	Cored unit	Formation at total depth
Atascosa County 1. Skelly Oil Co. No. 1 Bertha Winkler	15,107-15,565	NRPL, SMKV	NRPL
2. Cities Service Co. No. 1A Peeler Ranch	18,574-19,629	SLT, NRPL, SMKV	SLT
3. Shell Oil Co. No. 1 Peter Urbanczyk	—	—	SMKV?
Frio County 4. Pan American Petroleum Corp. No. 1 Lena Buerger	16,000-16,064	BKNR	BKNR/PLZ
Karnes County 5. Shell Oil Co. No. 1A Ben Pawelek	17,712-17,728	SMKV	SLT
La Salle County 6. Pan American Petroleum Corp. No. 1 A. M. Foerster	—	—	SLT
Live Oak County 7. Cities Service Co. No. 1A Schultze	—	—	SMKV?
Maverick County 8. Continental Oil Co. No. 1 Halsell FDT	—	—	BKNR
McMullen County 9. Pan American Petroleum Corp. No. 1 Murray Franklin	18,010-19,590	SMKV, BKNR	SLT
10. Pan American Petroleum Corp. No. 1A Alamo National Bank	20,648-20,720 21,176-21,517	SMKV, BKNR	SMKV
11. Phillips Petroleum Co. No. 1A Nueces Land Co.	—	—	SMKV
Webb County 12. Pan American Petroleum Corp. No. 1 Rosa Benavides	—	—	SLT
13. Humble Oil and Refining Co. No. 1 Carlos Y. Benavides	18,846-18,896	SMKV	SMKV
Zavala County 14. Shell Oil Co. No. 1 H. C. Plumley	—	—	BKNR

Formation Abbreviations:
BKNR Buckner
SMKV Smackover
NRPL Norphlet
SLT Louann Salt
PLZ Paleozoic