Upper Jurassic thrombolite reservoir play, northeastern Gulf of Mexico

Ernest A. Mancini, Juan Carlos Llinás, William C. Parcell, Marc Aurell, Beatriz Bádenas, Reinhold R. Leinfelder, and D. Joe Benson

ABSTRACT

In the northeastern Gulf of Mexico, Upper Jurassic Smackover inner ramp, shallow-water thrombolite buildups developed on paleotopographic features in the eastern part of the Mississippi Interior Salt basin and in the Manila and Conecuh subbasins. These thrombolites attained a thickness of 58 m (190 ft) and were present in an area of as much as 6.2 km^2 (2.4 mi^2). Although these buildups have been exploration targets for some 30 yr, new field discoveries continue to be made in this region. Thrombolites were best developed on a hard substrate during a rise in sea level under initial zero to low background sedimentation rates in low-energy and eurytopic paleoenvironments. Extensive microbial growth occurred in response to available accommodation space. The demise of the thrombolites corresponded to changes in the paleoenvironmental conditions associated with an overall regression of the sea. The keys to drilling successful wildcat wells in the thrombolite reservoir play are to (1) use three-dimensional seismic reflection technology to find paleohighs and to determine whether potential thrombolite reservoir facies occur on the crest and/or flanks of these features and are above the oil-water contact; (2) use the characteristics of thrombolite bioherms and reefs as observed in outcrop to develop a three-dimensional geologic model to reconstruct the growth of thrombolite buildups on paleohighs for improved targeting of the preferred dendroidal and chaotic thrombolite reservoir facies; and (3) use the evaporative pumping mechanism instead of the seepage reflux or mixing zone models as a means for assessing potential dolomitization of the thrombolite boundstone.

INTRODUCTION

Upper Jurassic microbial (formerly called blue-green algae or cyanobacteria) mounds in the northeastern Gulf of Mexico have been documented by numerous researchers (Baria et al., 1982; Crevello

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and Harris, 1984; Powers, 1990; Markland, 1992; Benson et al., 1996; Kopaska-Merkel, 1998, 2002; Parcell, 1999, 2000, 2002; Hart and Balch, 2000; Mancini et al., 2000; Mancini and Parcell, 2001; Llinás, 2002a, b). The thrombolite facies associated with these buildups are hydrocarbon productive from the Oxfordian Smackover Formation in numerous fields in the eastern Gulf coastal plain (Figure 1). A thrombolite is defined as a microbial structure characterized by a mesoscopic clotted internal fabric (Kennard and James, 1986). The most studied fields are Melvin field (Baria et al., 1982), Vocation field (Baria et al., 1982; Powers, 1990; Parcell, 2000; Llinás, 2002a, b), and Appleton field (Markland, 1992; Benson et al., 1996; Mancini and Benson, 1998; Hart and Balch, 2000; Mancini et al., 2000; Parcell, 2000). The reservoir facies at Appleton field consists mainly of microbial (thrombolite) boundstone (Benson et al., 1996; Mancini et al., 2000). Crevello and Harris (1984) reported that Smackover stromatolite (microbolite) mounds are primarily restricted to the eastern Gulf coastal plain. In addition, Dobson and Buffler (1997) identified Smackover mound-prone facies on seismic profiles for the northeastern Gulf of Mexico area as carbonate buildups. The basis for the restriction of microbial mound development to the northeastern Gulf of Mexico was postulated by Parcell (2003) to be the result of a combination of local substrate and basement relief elements, regional sedimentologic and water depth, energy and chemical conditions, and global oceanographic, climatic, and latitudinal factors that existed in this area during the Late Jurassic.

Although Upper Jurassic Smackover microbial buildups (Figure 2A) have been an exploration target in the northeastern Gulf of Mexico for more than 30 yr, new field discoveries continue to be made in this area, indicating that the origin and distribution of these buildups are not completely understood, and that the organosedimentary aspects of these deposits have not been adequately studied. However, the characteristics of Upper Jurassic thrombolite bioherms and reefs have been studied extensively in outcrop, especially in Portugal and Spain, by Leinfelder (1986, 1993), Fezer (1988), Ramalho (1988), Leinfelder et al. (1993a, b, 1994), Nose (1995), Schmid (1996), Aurell and Bádenas (1997), Bádenas (1999), and Leinfelder and Schmid (2000). The findings from these outcrop studies, which included such topics as the origin, composition, geometries, areal extent, and facies relationships affecting thrombolite bioherms and reefs, have not been widely applied to the Upper Jurassic thrombolite buildups in the Gulf of Mexico area, nor have the results of these outcrop studies been used effectively in the design of exploration strategies to identify and delineate potentially new hydrocarbon-bearing thrombolite buildups in the updip basement ridge play (Figure 1).

The updip basement ridge play is defined as the area between the updip limit of Smackover deposition and the regional peripheral fault trend (Mancini et al., 1991). The play is characterized by thin or absent Jurassic salt, and the hydrocarbon-bearing structures are related to pre-Jurassic paleotopographic features. Petroleum

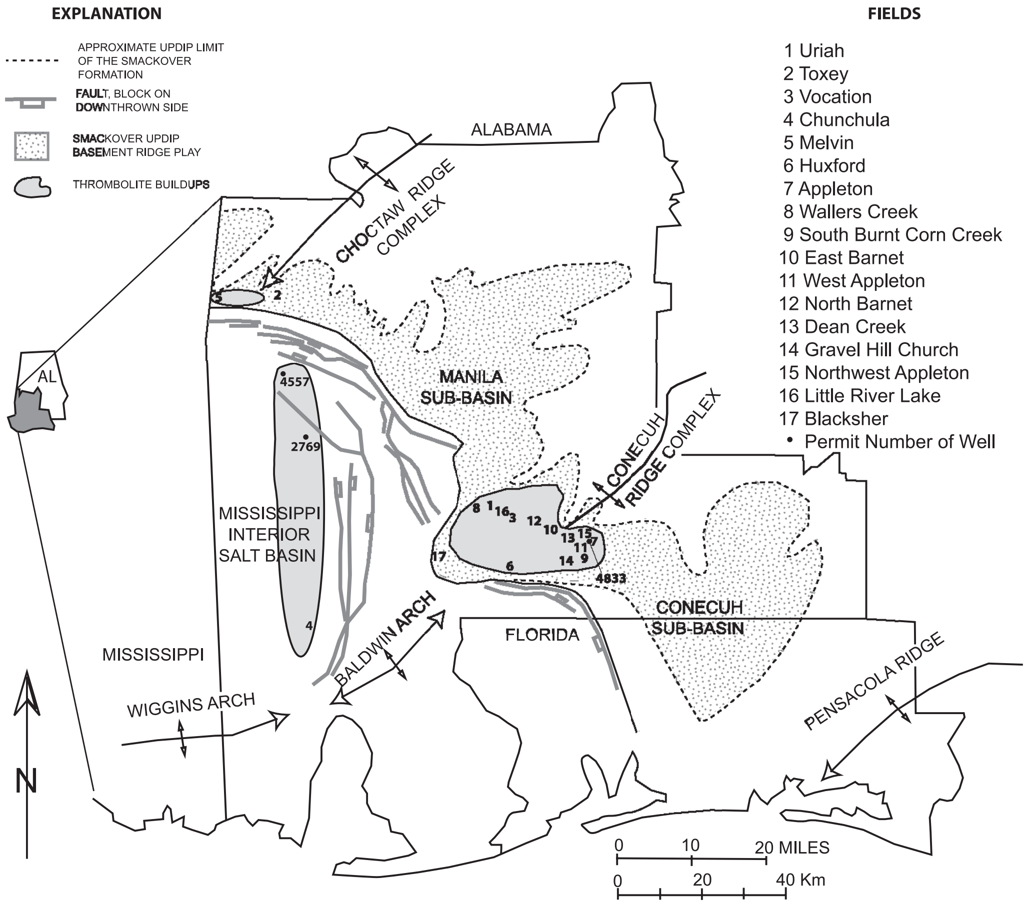


Figure 1. Location map showing major structural features, trend of the Smackover updip basement ridge play, distribution of major thrombolite buildups, and key oil fields with thrombolite and shoal facies in southwest Alabama.

traps are structural anticlines and faulted anticlines that are developed in association with Paleozoic crystalline basement paleohighs. Reservoir facies are shoreface and shoal grainstone and thrombolite boundstone. The source of the hydrocarbons found in these reservoirs is Smackover basinal lime mudstone, and the migration pathway of the oil is from the basin centers of the Manila and Conecuh subbasins updip, with entrapment in the paleohighs. The petroleum seal rocks are generally Buckner anhydrite beds (Kimmeridgian in age) that overlie the Smackover Formation (Figure 2A). The thrombolite reservoir play consists of those paleohighs on which thrombolite reservoir facies developed.

The purposes of this paper, therefore, are to (1) describe microbial (thrombolite) facies in general; (2) characterize known Smackover thrombolite buildups in the subsurface of the eastern Gulf coastal plain; (3) describe Upper Jurassic thrombolite bioherms and reefs in Portugal and Spain; (4) use the information from the characterization of thrombolite facies of Upper Jurassic buildups to better understand the origin, composition, geometries, areal extent, and facies relationships of these deposits; and (5) use this knowledge to design strategies to explore for new thrombolite buildups in the subsurface of the northeastern Gulf of Mexico.

CHARACTERISTICS OF MICROBES

According to Riding and Awramik (2000), microbes are abundant and widespread in carbonate and siliciclastic sediments. They are microscopic and include bacteria, algae, fungi, and protozoans. These organisms stabilize grains and provide sites for mineral nucleation; thus, they modify and create sediment. They range in geologic age from the Proterozoic to the present (Riding, 1991; Leinfelder and Schmid, 2000).

Microbolites are organosedimentary deposits that are a result of the activity of microbes. Microbial films can stabilize loose sediment, as well as initiate precipitation of calcareous crusts, and microbial coatings on sediment surfaces can serve to protect the sediment from erosion. Microbial mats and biofilms consist of microbial communities, primarily photosynthetic cyanobacteria, other chemosynthetic and anaerobic

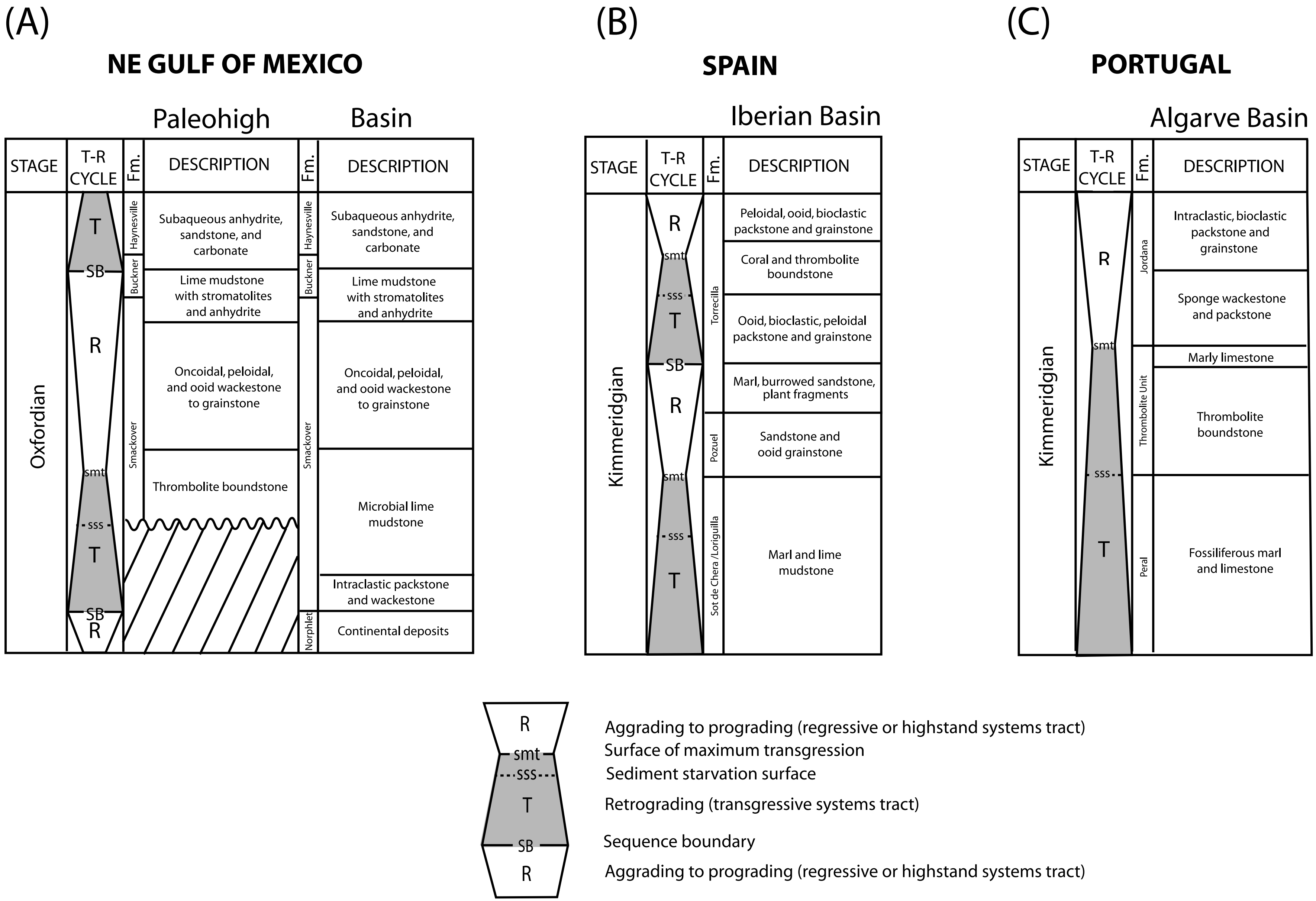


Figure 2. Comparison of Upper Jurassic stratigraphy for (A) the northeastern Gulf of Mexico, (B) Iberian basin, Spain, and (C) Algarve basin, Portugal (modified from Leinfelder et al., 1993a; Aurell and Bádenas, 1997; Mancini and Parcell, 2001).

microbes, and other encrusting organisms, such as foraminifera, that colonize a surface (Leinfelder et al., 1993b; Leinfelder et al., 1994; Stolz, 2000). There is interaction between the microbes, the colonized surface, and the surrounding environment. Slight changes in the physical environment, such as variations in the background sedimentation rate, may result in the sudden disappearance or modification of certain microbial fabrics (Schmid, 1996).

Stolz (2000) considered the microbial mats as complex biofilms and described the biofilms as consisting of micro-organisms and their extracellular products bound to solid surfaces. Biofilms are recognized from microbial mats in that they form on solid substrates such as rock. Beneath the surface layer of microbial mats, a layer of cyanobacteria is found (Stolz, 2000). Underlying this layer, there is a transition to anoxic conditions, where anoxygenic phototrophs occur. Heterogeneity is common in these distinct layers; therefore, Stolz (2000) described biofilms as masses of microcolonies in an extracellular polymeric matrix, which is honeycombed with water channels. The water channels and the associated convective flow facilitate nutrient delivery and waste removal.

Microbial structures characterized by a mesoscopic clotted internal fabric are called thrombolites (Aitken, 1967; Kennard and James, 1986). The clots are interpreted as primary features produced by calcified microbes. Thrombolites are interpreted as microcolonies of coccoid-dominated calcimicrobes, such as *Girvanella* and *Renalcis* (Kennard and James, 1986). The clotted fabric is primarily a microbial feature and not a disrupted or modified laminated fabric; however, the clotted fabric can be enhanced by physical damage in high-energy conditions and by bioerosion. Calcium carbonate precipitation can be facilitated by an increase in carbonate alkalinity according to Knorre and Krumbein (2000). Increased carbonate alkalinity can be induced by microbes as a by-product of physiological activities (Knorre and Krumbein, 2000). Thus, cyanobacterial photosynthesis can promote carbonate precipitation of micrite (Golubic et al., 2000). In-situ microbial calcification has been associated commonly with thrombolites, whereas agglutination of allochthonous grains has been associated with stromatolites (Kennard and James, 1986). However, both organosedimentary deposits have been reported to be produced by either process in Miocene strata (Braga et al., 1995). Sediment trapping can be accomplished by thrombolites, and calcification can be achieved by stromatolites. Episodic sediment trapping has been shown to produce a fabric with either an uneven pattern of accretion, favoring a clotted fabric, or an even pattern of accretion, favoring a laminated fabric (Braga et al., 1995). Leiolites (microbial structureless or dense macrofabric) formed where a steady uniform supply of well-sorted sediment was provided to the area colonized by the microbes (Braga et al., 1995).

MICROBIAL AND THROMBOLITE CLASSIFICATION

Key papers in the development of a classification for microbial and thrombolite structures are as follows. Aitken (1967) proposed a field classification for cryptalgal biolithites, which included oncolites, stromatolites, thrombolites, and crytalgalaminates. Cryptalgal was defined as sedimentary rocks or structures originating through sediment-binding and/or carbonate-precipitating activities of nonskeletal algae. Aitken (1967) used the term thrombolite to describe cryptalgal structures related to stromatolites (as defined by Kalkowsky, 1908) that lacked lamination and were characterized by a macroscopic clotted fabric.

Kennard and James (1986) proposed a tripartite field classification of lower Paleozoic microbial structures based on the dominant type of constructive mesoscopic constituents. The three end members were stromatolites, thrombolites, and undifferentiated microbial boundstone. Stromatolites were described as laminated organosedimentary structures built by episodic sediment-trapping, sediment-binding, and/or carbonate-precipitating activity of microbial communities. Thrombolites were described by Kennard and James (1986) as lacking lamination and characterized by a mesoscopic clotted fabric. Thrombolites were recognized to have a distinct internal structure consisting of clots separated by patches of mud and sand-size sediment or calcite cement. The individual clots or mesoclots were described as typically dark in color and having a micritic, microcrystalline structure.

Braga et al. (1995) used a classification of laminated (stromatolite), clotted (thrombolite), and structureless and dense (leiolite) to describe the macrofabric of late Miocene microbial biostromes and bioherms. They recognized that stromatolitic lamination can form by regular episodic accretion, involving particle trapping, microbial growth, and/or precipitation. The lamination was described as the primary feature. Thrombolites can form by microbial calcification and/or agglutination of particles (Braga et al., 1995). The clots of the thrombolites were recognized as either the primary features produced by calcified microbes or the results of alterations or disturbances of stromatolite fabrics. Thus, Braga et al. (1995) believed that stromatolites and thrombolites in the late Miocene were basically formed by similar combined processes of agglutination of sediment grains together with microbial calcification.

Schmid (1996) and Leinfelder and Schmid (2000) recognized three basic fabrics of Jurassic microbolites. Schmid (1996) uses the term microbolite instead of microbialite as per the recommendation of Riding (1991). The fabrics included stromatolites (laminated), thrombolites (clotted), and leiolites (unstructured). Using these basic fabric types, a tripartite classification of Upper Jurassic microbolites at the microscopic scale based on the end members of peloidal microstructure, laminated particle microstructure, and dense microstructure was proposed by Leinfelder et al. (1996) and Schmid (1996). Schmid (1996) published a compilation of growth forms at the macroscopic scale, which included bioherms, patch reefs, conical patch reefs, biostromes, isolated crusts, and oncoids, and at the mesoscopic scale, which included massive, columnar, dendroid, flat, platy, reticulate, hemispheroid, and basal cover crust.

Parcell (2000, 2002) used a classification of microbial facies to study Upper Jurassic microbolites in the subsurface. He used the following end members: thrombolite, stromatolite, and leiolite after Braga et al. (1995) and Schmid (1996). Parcell (2000, 2002) recognized five dominant calcimicrobe growth forms at the centimeter scale: laminated (layered) thrombolite (Figure 3A), reticulate (chaotic) thrombolite (Figure 3B), dendritic (dendroidal or branching) thrombolite (Figure 3C), encrusting stromatolite, and oncoidal cortices after Schmid (1996). The layered thrombolites were characterized by a clotted fabric that consists of dark-colored horizontal microbial laminae with abundant crypts (millimeter to centimeter scale) and were commonly bioturbated. The chaotic and dendroidal thrombolites were described as having a clotted fabric and a vertical growth component (stronger in the dendroidal form) and much interstitial sediment associated with these forms. The encrusting stromatolite form was recognized to lack a clotted fabric and represented essentially horizontal growth. Oncoids served as stable nucleation points for the development of the microbial oncoidal cortices.

This paper uses the classification of Upper Jurassic thrombolite fabrics (peloidal and micritic or dense) and growth forms (layered, chaotic, and dendroidal or branching) of Parcell (2000, 2002), which builds on the classifications of Aitken (1967), Kennard and James (1986), Braga et al. (1995), and Schmid (1996).

SUBSURFACE SMACKOVER THROMBOLITES

In the northeastern Gulf of Mexico, Upper Jurassic (Oxfordian) Smackover thrombolite buildups developed on paleotopographic features (Paleozoic basement paleohighs or Jurassic salt anticlines and ridges). Major basement ridges include the Choctaw Ridge complex (Melvin field), Conecuh Ridge complex (Vocation and Appleton fields), and the Wiggins arch (Mancini and Benson, 1980) (Figure 1). These paleotopographic highs interrupted the depositional surface of the inner portion of a Smackover distally steepened ramp setting. The Smackover carbonates accumulated during an overall eustatic rise in Jurassic sea level. Lower Smackover intertidal oncoidal and peloidal packstone and wackestone were deposited during the initial rise in sea level (Figure 2A). Middle Smackover subtidal microbial lime mudstone and peloidal wackestone accumulated as the rate of sea level rise and accommodation space increased. Upper Smackover shoal ooid, peloidal, and oncoidal grainstone, peloidal packstone, and intertidal lime mudstone were deposited as the rate of sea level rise and accommodation space decreased.

Baria et al. (1982) published an early description of Smackover buildups in the Gulf coastal plain (Arkansas to Florida). They report that nearly all the buildups found in the eastern part (Alabama and Florida) of the trend have been at the base of the upper Smackover interval. In the western part (Arkansas and Louisiana) of the trend, buildups occur in the upper Smackover interval. Typically, organosedimentary buildups in the eastern Gulf have depositional relief, are elongate features, have a thickness of 3–40 m (10–130 ft), and cover an area of some 8 km^2 (3 mi^2) (Crevello and Harris, 1984). These buildups have been described as stromatolitic algal mounds dominated by laminated stromatolites with pelleted thrombolite growth forms (Crevello and Harris, 1984). These mounds in the eastern Gulf consist of digitate and branching blue-green algae (cyanobacteria), *Tubiphytes*, and marine cements. By comparison, reefal buildups to the west have a more diverse coral-algal assemblage of corals (*Actinostrea*), skeletal algae (*Parachaetetes* and *Cayeuxia*), lithistid and hexactinellid sponges, bryozoans, and hydrozoans (Baria et al., 1982). The lack of corals in the eastern Gulf buildups is probably caused by adverse paleoenvironmental conditions, but their absence could be the result of the effects of intense dolomitization and dissolution.

Our work has focused on the microbolites, mainly thrombolites, in the eastern Gulf coastal plain. This effort

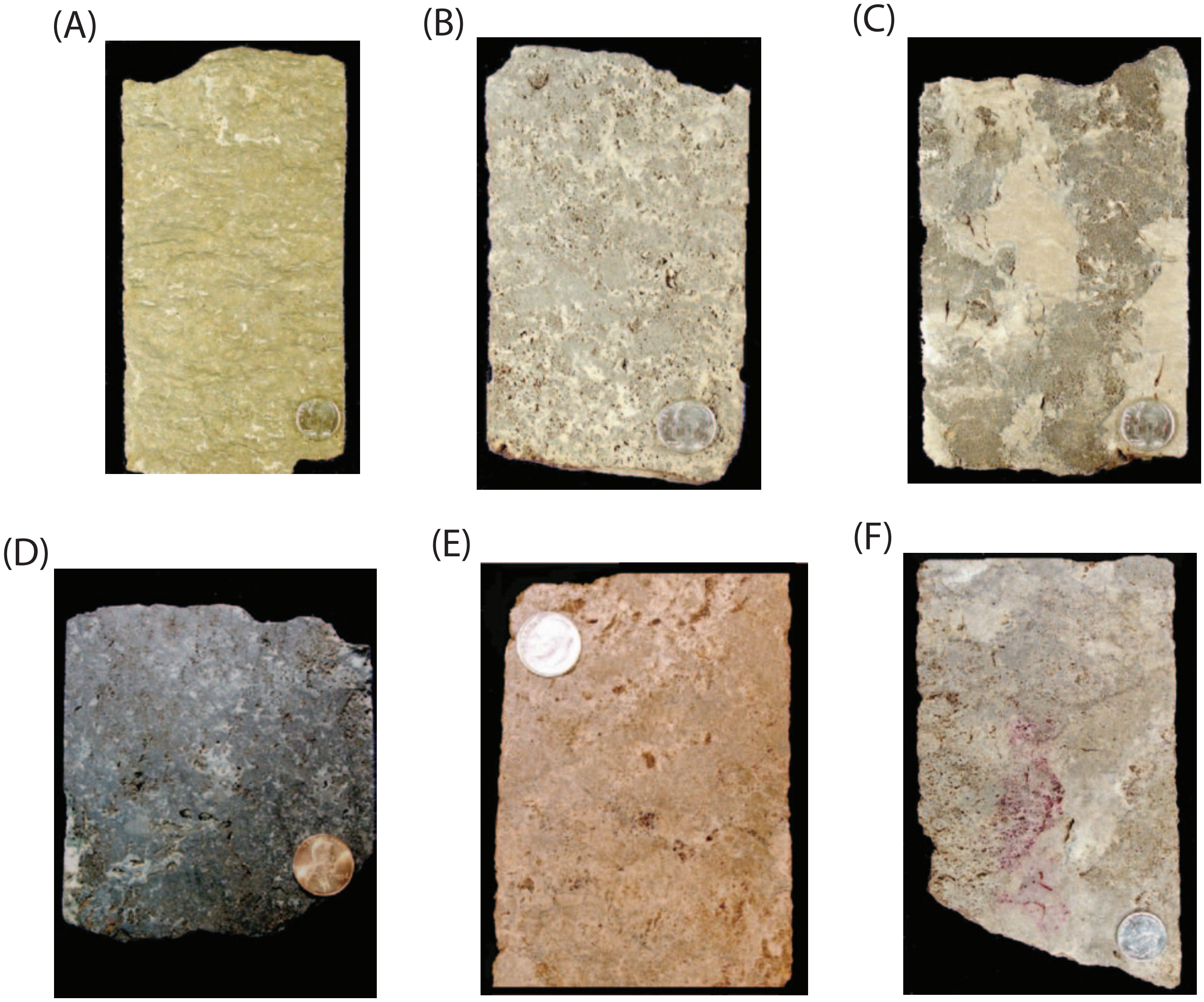


Figure 3. Core photographs of Smackover microbolite mesostructure. (A) Layered thrombolite, well permit 3986, depth 3969 m (13,021 ft), Appleton field; (B) chaotic thrombolite, well permit 4633-B, depth 3683 m (12,083 ft), Appleton field; (C) dendroidal thrombolite, well permit 3986, depth 3954 m (12,971 ft), Appleton field; (D) chaotic thrombolite, well permit 2935, depth 4308 m (14,135 ft), Vocation field; (E) chaotic thrombolite, well permit 11030-B, depth 4006 m (13,144 ft), Northwest Appleton field; and (F) chaotic thrombolite, well permit 4833, depth 3960 m (12,992 ft). See Figure 1 for location of oil fields.

builds on the initial work of Powers (1990), Markland (1992), and Benson et al. (1996). In this area, microbolites include basinal microbial laminates that occur in the middle Smackover section, lagoonal stromatolites and oncoidal cortices that generally are found in the upper part of the upper Smackover, and shallow-water (less than 10 m [~30 ft] in water depth) thrombolites that occur in the upper part of the middle Smackover section and the lower part of the upper Smackover section (Figure 2A). The basinal microbial laminates are the petroleum source rocks for Smackover hydrocarbons, including the Smackover oil discovered in the Upper Jurassic thrombolite reservoir play of the northeastern Gulf of Mexico (Claypool and Mancini, 1989). The thrombolites include layered (Figure 3A), chaotic (Figure 3B, D–F), and dendroidal (Figure 3C) growth forms. The microstructure of the thrombolite boundstone is peloidal and dense micrite.

Geographically, we have studied thrombolites occurring in the eastern part of the Mississippi Interior Salt basin, the Manila subbasin, and the Conecuh subbasin (Figure 1). In the Mississippi Interior Salt basin, thrombolite buildups developed on faulted Paleozoic basement blocks (Melvin field) (Baria et al., 1982) and on salt features (ridges and anticlines) along the eastern margin of the Mississippi Interior Salt basin (Kopaska-Merkel and Mann, 2000; Kopaska-Merkel, 2002). The 6-m (20-ft) thrombolite buildup at Melvin field

(Figure 1) is elongate and is about 1.6 km (1 mi) in length and 0.5 km (0.3 mi) in width. Serpulids, foraminifera, lithistid sponges, and red algae are common in the thrombolite-dominated boundstone (Baria et al., 1982). The boundstone has been highly leached and dolomitized and is underlain and overlain by lime mudstone. The microbial buildups associated with salt anticlines, such as that at Chunchula field and the salt ridge along the eastern margin of the Mississippi Interior Salt basin (well permits 2769 and 4557, Figure 1), consist of calcimicrobes, foraminifera, ostracods, bivalves, gastropods, echinoderms, and thalassinidean trace fossils in thrombolite-dominated doloboundstone and dolograinstone (Kopaska-Merkel, 2002). These microbial buildups attain a thickness of as much as 9 m (30 ft) and occur over a distance of 75 km (47 mi) on an elongate salt ridge (Figure 1) (Kopaska-Merkel, 2002). These buildups overlie subtidal peloidal wackestone and are overlain by lagoonal peloidal wackestone.

The thrombolite buildups in the Manila and Conecuh subbasins occur along the northwestern and southeastern flanks of the Conecuh Ridge (Figure 1). In the Manila subbasin, thrombolite-dominated buildups developed on the flanks of Paleozoic basement paleohighs (Vocation field) (Baria et al., 1982; Llinás, 2002a, b; 2003). The 58-m (190-ft) thrombolite buildup at Vocation field was developed over an area of 1.8 km^2 (0.7 mi^2) (Figure 4A). The thrombolite facies is characterized by a regular pattern of lower gamma-ray values and higher porosity values as determined from density and neutron porosity curves (Figure 5A). Calcimicrobes, red algae, foraminifera, sponges, echinoids, and bivalves are common in the thrombolite boundstone (Baria et al., 1982). The Vocation thrombolite buildup overlies Paleozoic igneous and metamorphic rocks and is overlain by shoreface and shoal ooid grainstone and lagoonal peloidal wackestone (Figure 6A). Lateral facies are subtidal lime mudstone (Table 1). The buildup is only developed on the northeastern flank or leeward side of the Vocation paleohigh (Figures 4A, 6). In the Conecuh subbasin, thrombolite buildups developed on the crests and flanks of Paleozoic crystalline basement paleohighs (Appleton field, Figure 7), northwest Appleton field, west Appleton field, and Dean Creek field) (Benson et al., 1996; Kopaska-Merkel, 1998; Mancini et al., 2000). The 45-m (148-ft) thrombolite buildup in the Appleton field–Northwest Appleton field area covers 6.2 km^2 (2.4 mi^2) (Figure 4B). The thrombolite facies is characterized by gamma-ray, density-porosity, and neutron porosity well-log signatures (Figure 5B) similar to the thrombolite facies at Vocation field. Calcimicrobes, foraminifera, sponges, skeletal algae, bivalves, gastropods, and echinoids are common in the thrombolite boundstone (Benson et al., 1996; Kopaska-Merkel, 1998). The Appleton buildup overlies Paleozoic igneous and metamorphic rocks and is overlain by shoal and shoreface oncoidal and ooid grainstone (Figure 7A). Lateral facies are subtidal lime mudstone.

MICROBIAL BUILDUPS IN OUTCROP

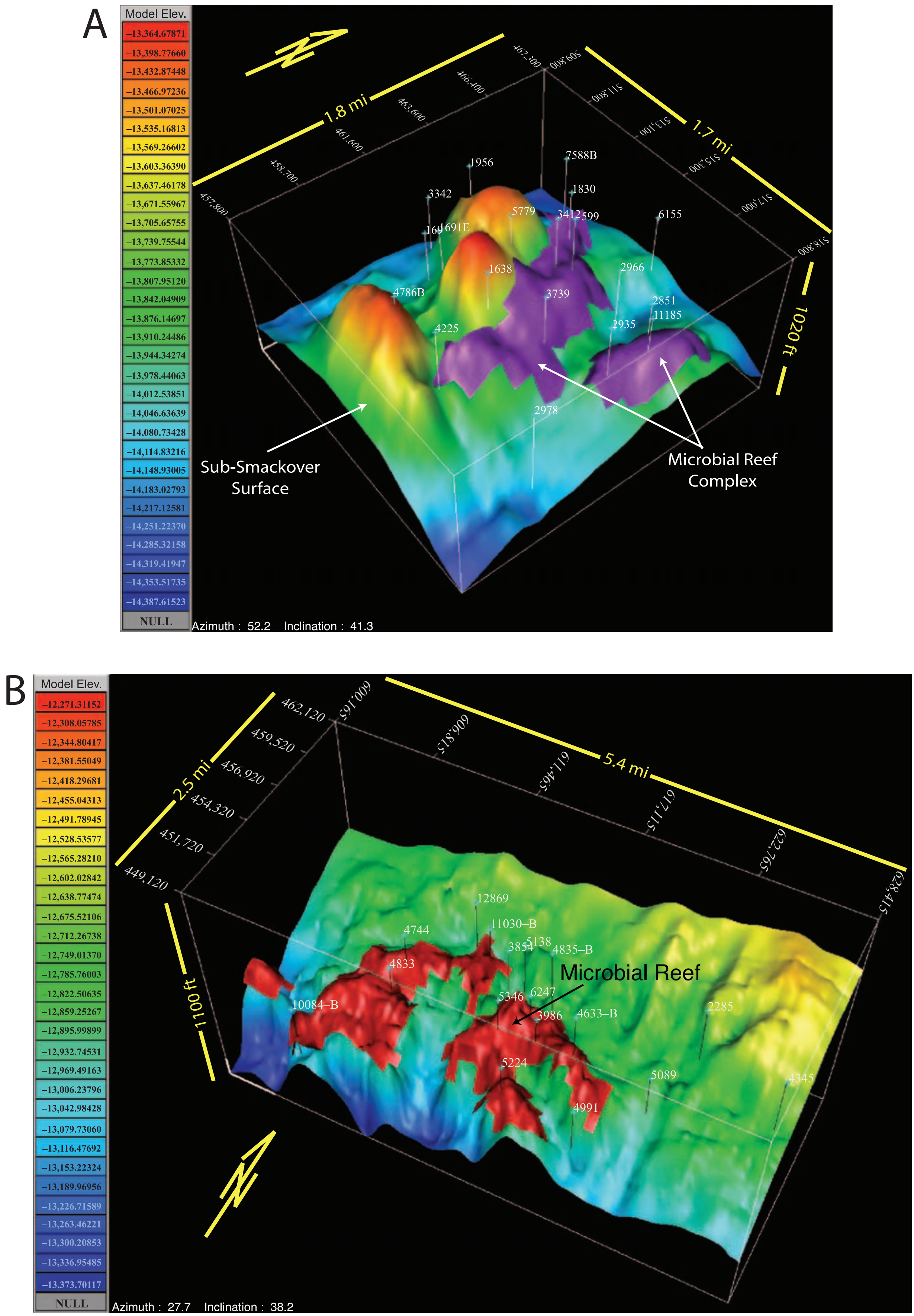
In studying microbial buildups in outcrop in France, Portugal, Spain, and Italy, the surface exposures in Portugal and Spain were found to be the best analogs for the thrombolite buildups in the Gulf of Mexico.

Spain

The Upper Jurassic (Kimmeridgian to lower Tithonian) outcrops of the Jabaloyas, Tormón, and Arroyo Cerezo area (Figure 8A) are located southeast of Teruel in northeastern Spain (Fezer, 1988; Leinfelder et al., 1993b, 1994; Nose, 1995; Aurell and Bádenas, 1997; Bádenas, 1999). They occur around the Sierra de Abarracín in the southeastern part of the Iberian chain, and the pinnacle reefs observed in these outcrops were developed in marginal areas of the Iberian basin (Aurell and Bádenas, 1997). Late Jurassic marine sedimentation in this basin occurred in a carbonate ramp setting (Bádenas, 1999). The carbonate ramp was open to the Tethys Sea to the east, but during major flooding episodes, connection with the Boreal realm was possible (Aurell and Bádenas, 1997). The stratigraphic section for the area (Figure 2B) is modified from Aurell and Bádenas (1997).

The thrombolite and coral buildups in Spain have been described as pinnacle reefs by Aurell and Bádenas (1997) and Bádenas (1999). They described these deposits in the field to be as follows. The pinnacle reefs have a height/width ratio of approximately 1 and have

Figure 4. A three-dimensional view of oil fields producing from Smackover thrombolite reservoirs: (A) Vocation field paleohigh showing the spatial distribution of the thrombolite buildups to the north and northeast of the main crest of the basement high (modified from Llinás, 2003) and (B) Appleton composite paleohigh, including Appleton field, Northwest Appleton field, and an area west of Appleton field, showing the spatial distribution of the thrombolite buildups on the crest and flanks of the crystalline basement high.


A
Model Elev.
1.8 mi
1.7 mi
1020 ft
Sub-Smackover Surface
Microbial Reef Complex
Azimuth : 52.2 Inclination : 41.3
B
Model Elev.
2.5 mi
5.4 mi
1100 ft
Microbial Reef
Azimuth : 27.7 Inclination : 38.2

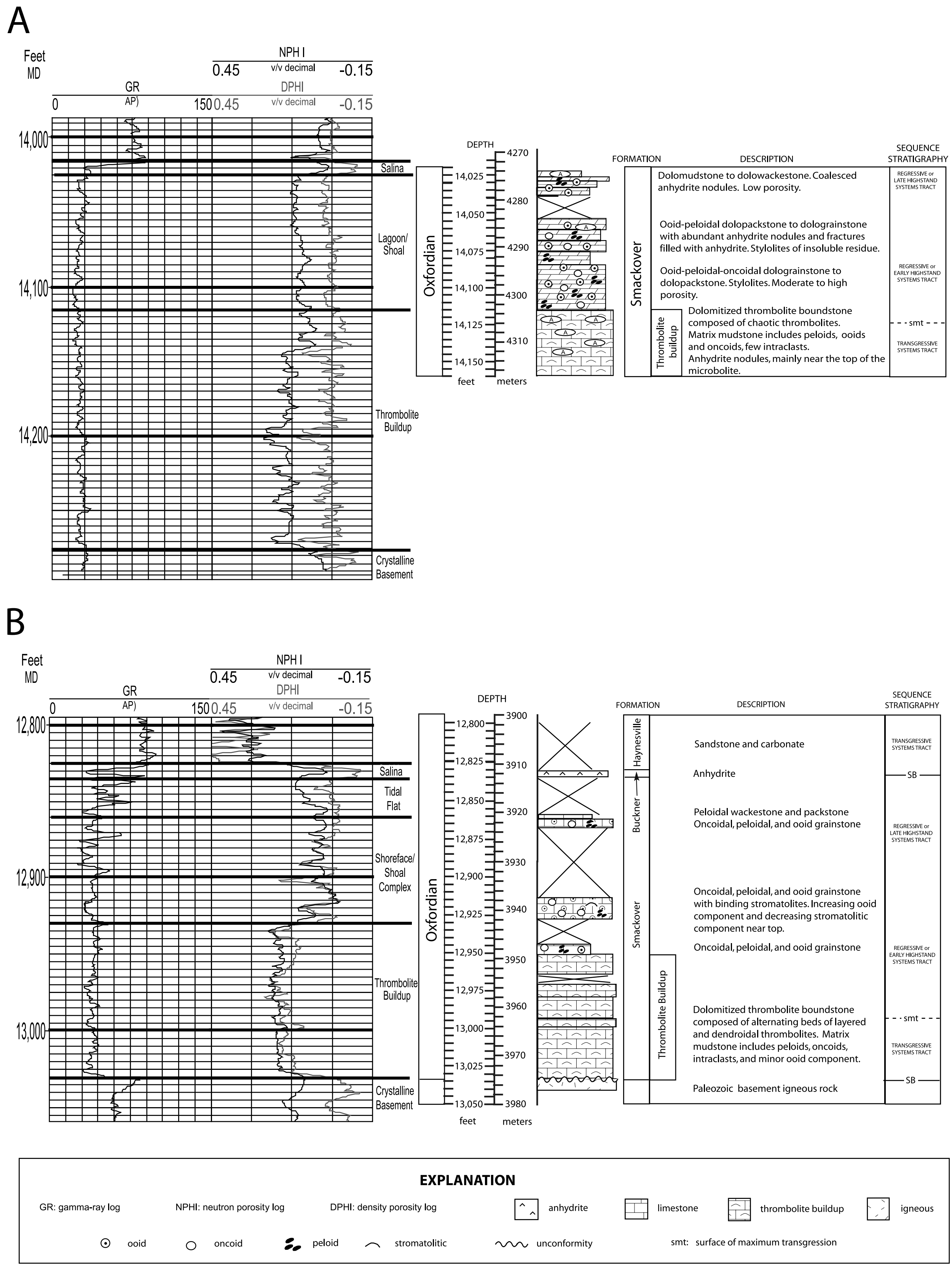


Figure 5. Correlation between core description and well-log response: (A) well permit 2935, Vocation field. The cored interval includes the upper 13.7 m (45 ft) of the thrombolite buildup and (B) well permit 4633-B, Appleton field. The cored interval includes the entire thrombolite buildup.

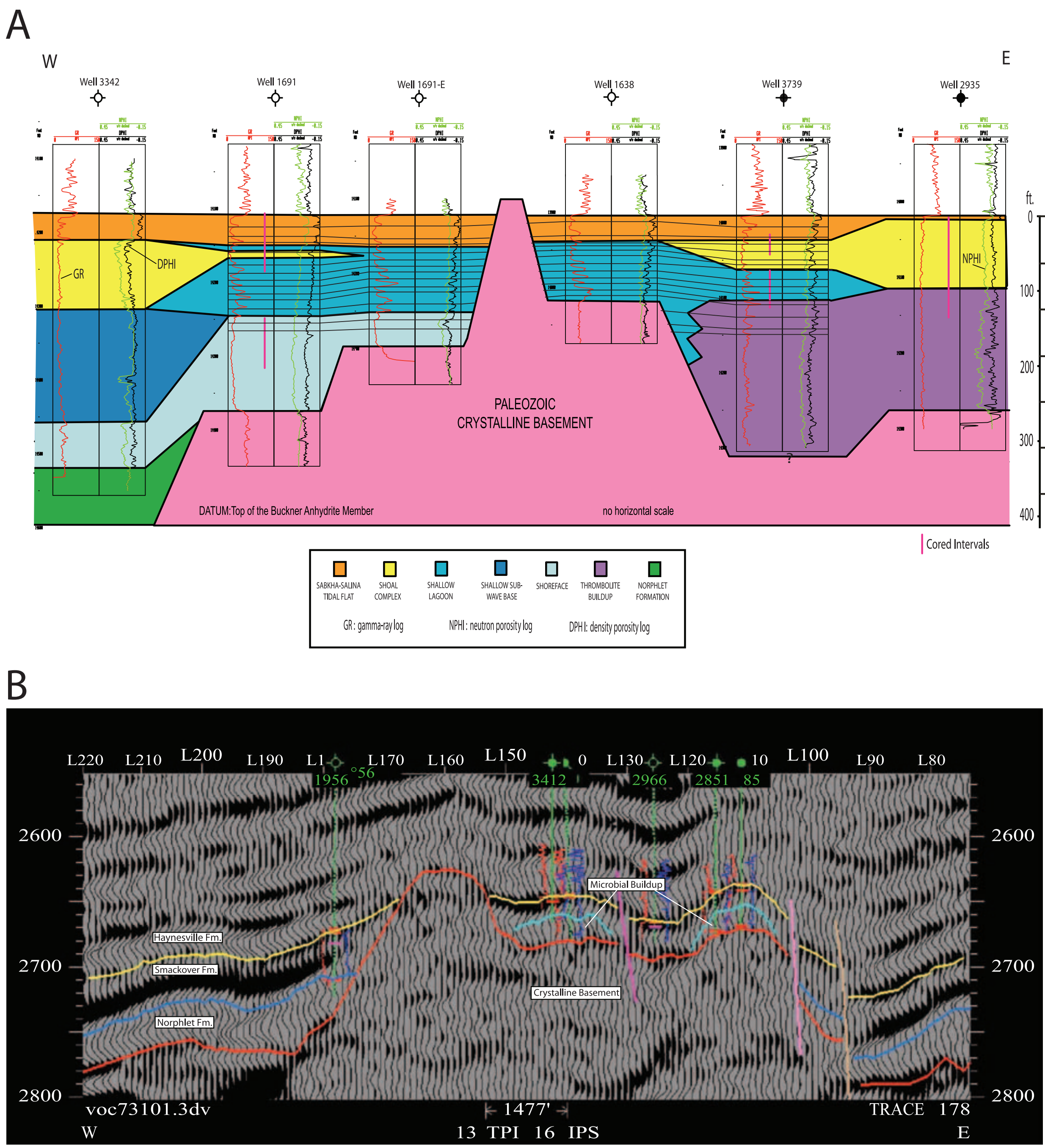


Figure 6. (A) West-east stratigraphic well-log cross section illustrating the lateral and vertical variation in the depositional facies identified in the Smackover and Buckner interval in the Vocation field area (modified from Llinás, 2002a) and (B) seismic profile illustrating trend of thrombolite buildup and crystalline basement paleohigh in the Vocation field area (modified from Llinás, 2002b).

very steep slopes greater than 45°. These buildups can attain a thickness of 16 m (52 ft). These coral-thrombolite and thrombolite-coral reefs occur as irregularly spaced, cylindrical to conical shaped buildups on a continuous ramp gradient of 15 km (9.4 mi) in a middle carbonate ramp setting (10–50 m [~30–160 ft] in water depth) (Figure 8B). The reefs are classified as coral-thrombolite, where the thrombolite content is equal to or less than 40% (Figure 9A, B), and thrombolite-coral, where the thrombolite content is greater than 40% (Figure 9C, D). Two types of internal cavities occur: cavities resulting from the growth of colonial corals and microbial crusts and cavities originating from bioerosion and boring. The internal

Table 1. Characteristics of Thrombolite Buildups

Parameter	Smackover Formation	Outcrop
Thickness	as much as 58 m (190 ft)	as much as 30 m (98 ft)
Areal extent	as much as 6.2 km^2 (2.4 mi^2)	as much as 2.3 km^2 (0.9 mi^2)
Sequence stratigraphy	late transgressive and regressive-early highstand systems tracts	late transgressive and regressive-early highstand systems tracts
Underlying facies	Paleozoic basement, localized cemented packstone-grainstone	localized cemented packstone-grainstone
Overlying facies	grainstone, packstone, wackestone	grainstone, packstone
Lateral facies	lime mudstone, wackestone	wackestone, packstone
Origin	shallow water, inner ramp	deeper water, middle to outer ramp
Environmental conditions	hard substrate, low background sedimentation, sea level rise, low energy, elevated water temperature, restricted circulation, fluctuating salinities, low oxygen levels, nutrient supply(?)	hard substrate, low background sedimentation, sea level rise, low-moderate energy, fluctuating oxygen and nutrient contents

sediment filling the cavities consists mostly of silty mudstone and wackestone. Bivalves, gastropods, and echinoids are common in the reef facies.

The coral-thrombolite reefs have been described as coral-chaetetid-stromatoporoid-microbial reefs (Leinfelder et al., 1994; Nose, 1995). Solenoporarean algae and sponges are present, and corals include massive, hemispherical, and branching forms (Nose, 1995). The dominant taxa are *Thamnasteria* and *Microsolena* (Fezer, 1988; Nose, 1995).

The microbial crusts consist of a dense micrite to peloidal composition (Aurell and Bádenas, 1997). The fabric is primarily clotted with a domal morphology. *Tubiphytes*, serpulids, and bryozoans are common (Bádenas, 1999).

Associated reef facies include prereef ooid, peloidal and bioclastic packstone and grainstone (Figure 9C); interreef skeletal wackestone and peloidal packstone (Figure 9C, D); and postreef ooid and bioclastic grainstone and packstone (Figure 9A, D) in middle-ramp areas (Aurell and Bádenas, 1997). The facies distribution overall shows a retrogradational stacking pattern in the lower part of the section and a progradational stacking pattern in the upper part (Bádenas, 1999). The reef and postreef facies have high petroleum reservoir potential.

Reef growth is initiated on a cemented and encrusted surface (sediment starvation surface). Reef growth occurred chiefly during a time of sea level rise (Aurell and Bádenas, 1997). A surface of maximum transgression (marine flooding surface) separates the transgressive deposits from the regressive or highstand deposits in the pinnacle reefs (Figure 9B, D). During sea level highstand conditions, the relative proportion of thrombolites to corals decreased (Figure 9C, D), and the growth of the reef eventually was diminished (Bádenas, 1999). Coral-thrombolite reefs are more common in the proximal portion of the middle-ramp setting (Figure 9A, B), whereas thrombolite-coral reefs of as much as 12 m (39 ft) in height developed in the distal portion of this middle-ramp setting (Figure 9D) (Aurell and Bádenas, 1997).

Portugal

Thrombolite buildups occur in the Algarve basin in Portugal. The discussion regarding outcrops in southern Portugal is from Ramalho (1988), Leinfelder et al. (1993a, b), and Mancini and Parcell (2001).

The eastern part of the Algarve basin of Portugal has been interpreted as the northern shelf of the western Tethyan Ocean (Leinfelder et al., 1993a). Tectonic events, as described by Wilson (1989), Leinfelder et al. (1993a), and Leinfelder and Wilson (1998) are as follows: Triassic to Callovian rifting and thermal subsidence, middle Oxfordian to early Berriasian ocean rifting and ocean spreading, Valanginian to early Aptian rifting, and late Aptian to Campanian ocean spreading. Sedimentation in the Algarve basin began with an initial graben rift phase that resulted in the deposition of Upper Triassic and Lower Jurassic red beds, volcanics, and evaporites. Shallow-water and hemipelagic carbonates and muds accumulated in the Early to Middle Jurassic. The Callovian to Oxfordian transition

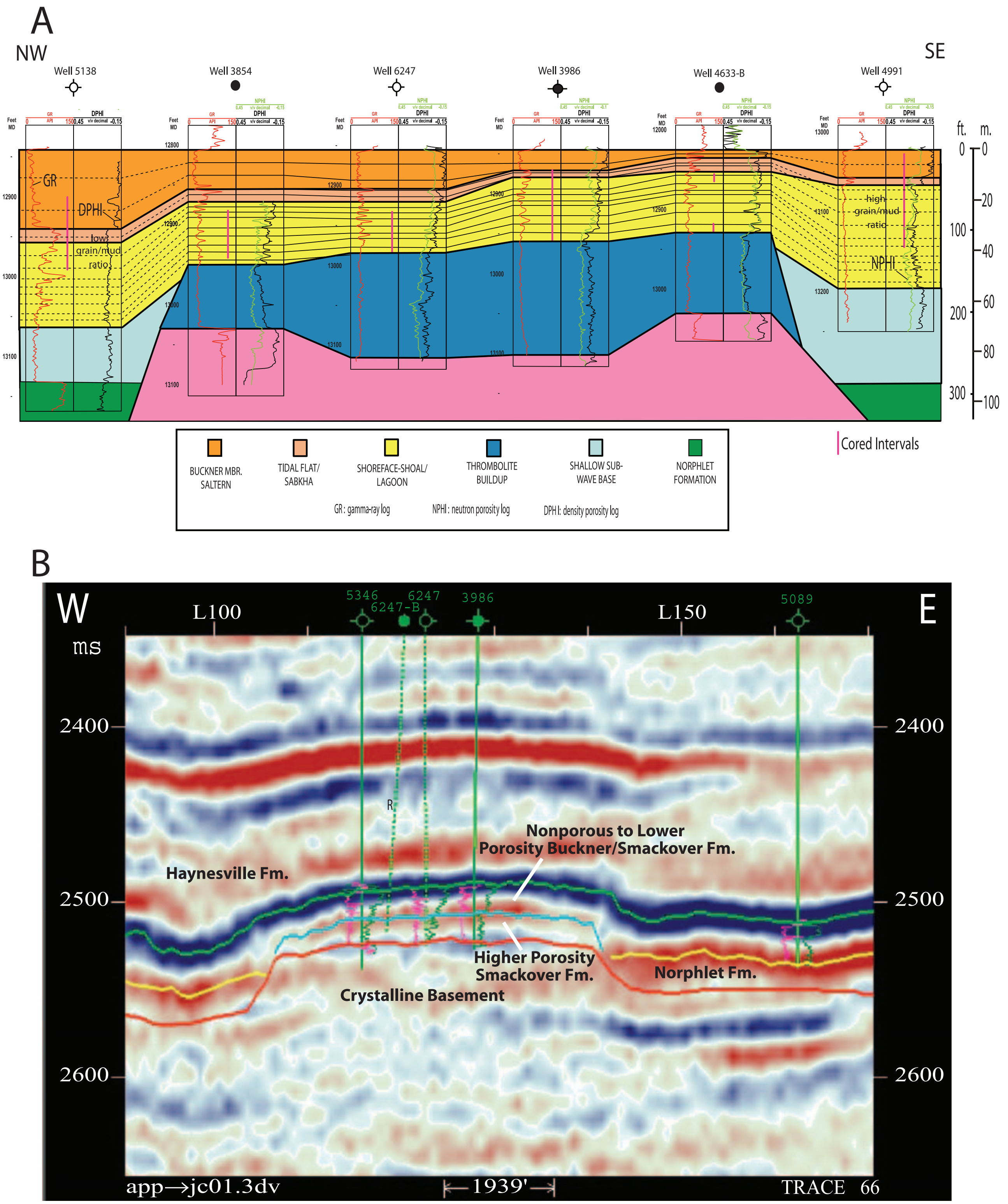


Figure 7. (A) Northwest-southeast stratigraphic well-log cross section illustrating the lateral and vertical variation of depositional facies identified in the Smackover and Buckner interval in the Appleton field area and (B) seismic profile illustrating trend of thrombolite buildup and crystalline basement paleohigh in the Appleton field area.

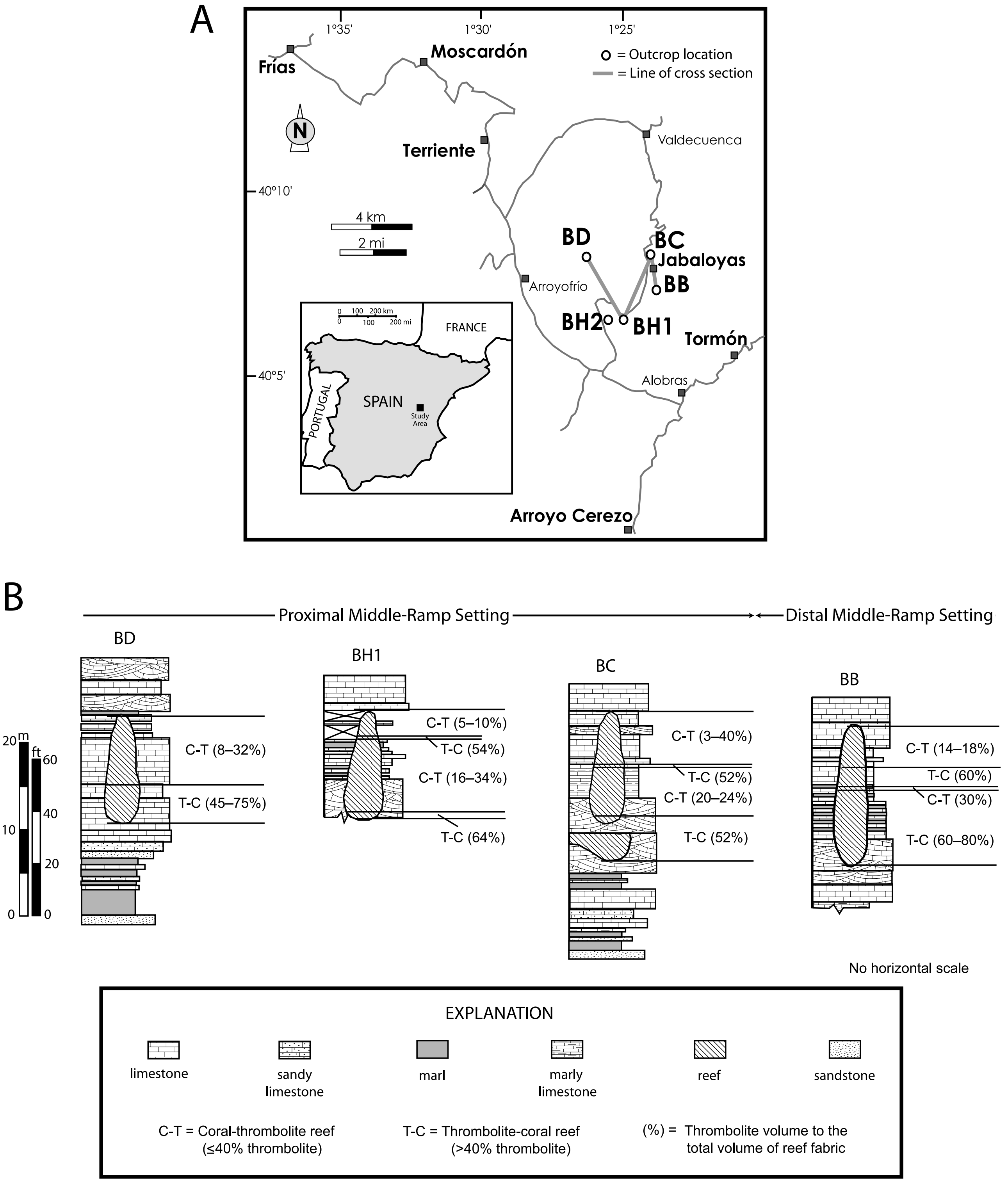


Figure 8. (A) Location of the key pinnacle reef outcrops studied in the Sierra de Albarracín. BD = Barranco del Diablo, BC = Barranco de la Canaleja, BB = Barranco de las Balsillas, BH1 and BH2 = Barranco de la Hoz (modified from Aurell and Bádenas, 1997). (B) Stratigraphic cross section illustrating the lateral and vertical variation of depositional facies, including faunal changes, in the pinnacle reefs in the Upper Jurassic Torrecilla Formation in the Jabaloyas area, northeastern Spain (modified from Aurell and Bádenas, 1997). The percentage of thrombolites in the pinnacle reefs was calculated based on thin-section point-counting by Bádenas (1999).

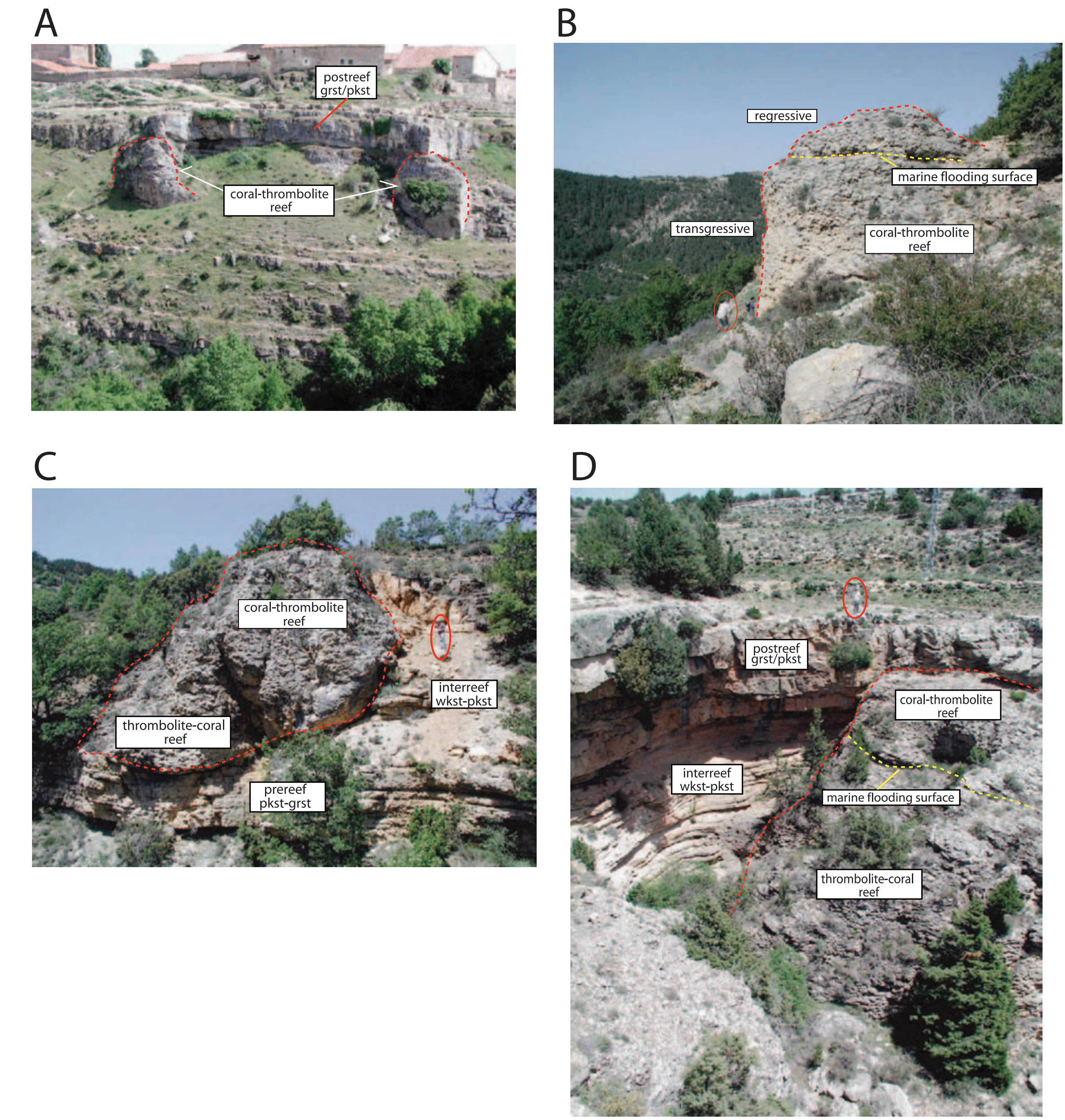
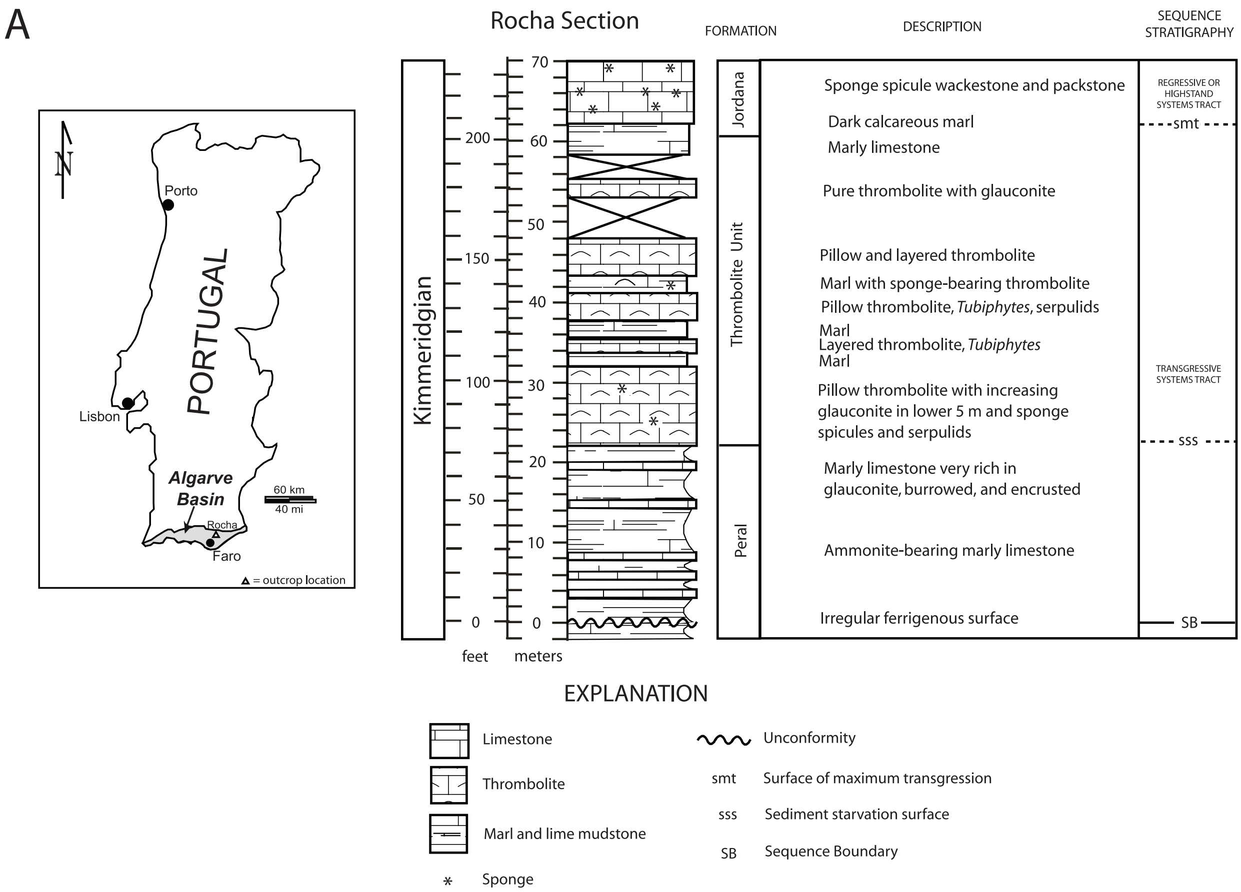


Figure 9. Outcrop photographs of middle-ramp pinnacle reefs and associated facies of the Torrecilla Formation: (A) Jabaloyas, illustrating postreef facies; (B) Barranco de la Hoz (BH1), illustrating the marine flooding surface affecting reef faunal composition and growth; (C) Barranco de la Hoz (BH2), illustrating prereef and interreef facies; and (D) Barranco de las Balsillas (BB), illustrating postreef and interreef facies, and the marine flooding surface affecting the pinnacle reef. See Figure 8A for location of the outcrops.

is marked by a subaerial unconformity in parts of this basin. Upper Jurassic sediments in the eastern Algarve basin consist of a mixed carbonate and siliciclastic shallowing-upward succession. The stratigraphic section for the area is modified from Leinfelder et al. (1993a) (Figure 2C).

At Rocha, Portugal, a thrombolite bioherm of 30 m (98 ft) in thickness (Table 1) occurs between the Peral and Jordana formations (Figure 10). This bioherm is described by Ramalho (1988) and Leinfelder et al. (1993a) as follows and has been interpreted by Leinfelder et al. (1993b), Schmid (1996), and Leinfelder



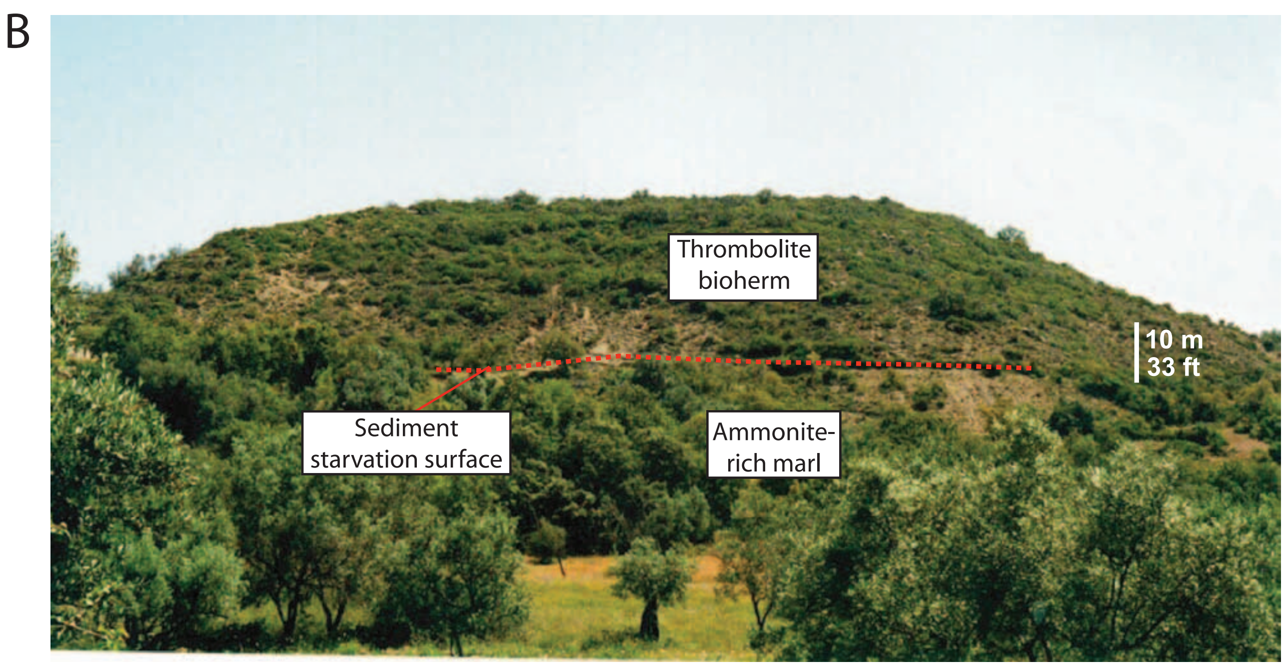


Figure 10. (A) Measured stratigraphic section of the Rocha thrombolite bioherm, Algarve basin (modified from Ramalho, 1988; Leinfelder et al, 1993a) and (B) outcrop photograph of the thrombolite bioherm at Rocha.

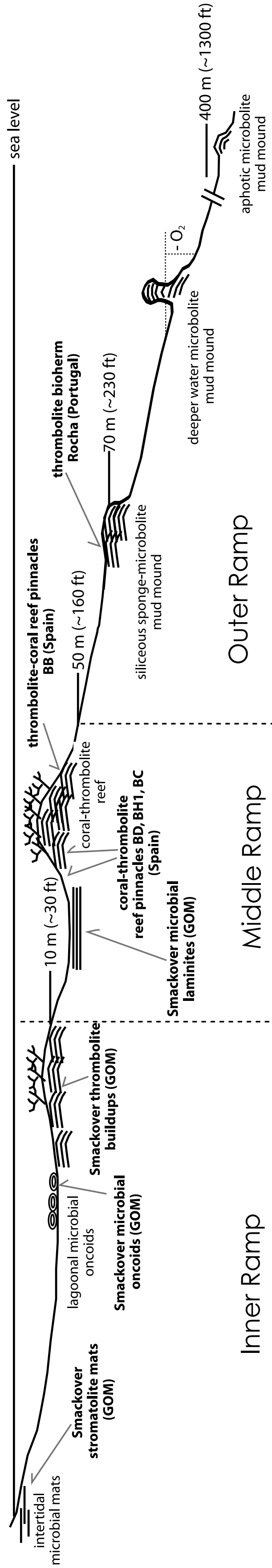


Figure 11. Generalized diagram illustrating the distribution of microbial buildups on a carbonate ramp (modified from Leinfelder, 1993b; Leinfelder and Schmid, 2000). Note the inner- to middle-ramp settings for Upper Jurassic Smackover microbial growth in the northeastern Gulf of Mexico (GOM), middle-ramp setting for the Upper Jurassic pinnacle reef development in northeastern Spain, and outer-ramp setting for Upper Jurassic thrombolite bioherm in Portugal.

(2001) to have formed in an outer-ramp setting at a water depth of approximately 70 m (230 ft) (Figure 11). The bioherm is underlain by the marly to micritic layers of the Peral Formation that contain abundant ammonites (transgressive systems tract deposits) (Figure 10A). The top of these beds (Peral) is characterized by a marly, encrusted limestone bed, rich in glauconite, bioclastic debris, and highly bioturbated with *Planolites* burrows. Cauliflower and pillow thrombolites containing glauconite constitute the majority of the bioherm (transgressive systems tract deposits). *Tubiphytes*, serpulids, and siliceous sponges occur throughout the bioherm with an interval rich in cup-shaped dictyid sponges in the middle part of the bioherm section. Layered thrombolite is common in the middle and near the lower part of the top of the section, reflecting changes in rates of sea level rise and water energy. The bioherm encompasses an area of 2.3 km^2 (0.9 mi^2). Regressive or highstand systems tract sponge spicule packstone and wackestone of the Jordana beds overlie the bioherm. The thrombolite bioherm facies have high petroleum reservoir potential.

CONTROLS ON MICROBIAL BUILDUP DEVELOPMENT

Although microbial buildups occur throughout the geologic record (Riding, 1991), microbolites were particularly abundant in the Late Jurassic in the northern Tethyan realm, where they occur in shallow- to deep-water settings (Leinfelder, 2001; Leinfelder et al., 2002). The increase in the abundance of thrombolite mounds in the Mesozoic shows correspondence with rises in global and regional sea level during this time (Leinfelder and Schmid, 2000). Such is the case with the Smackover buildups, which accumulated in the northern Tethyan realm in the Oxfordian during a rise in global sea level.

In western Europe (Portugal and Spain), bioherms of pure thrombolite occur in normal marine settings of greater than 70 m (230 ft) and as deep as 400 m (1300 ft) (Figure 11); however, pure thrombolite buildups can be found in shallower waters, in the area of coral growth, during times of sea level rise (Leinfelder and Schmid, 2000; Leinfelder, 2001). However, Smackover thrombolite buildups developed in shallower water environments (below wave base in settings of less than 10 m [~30 ft] in water depth). Clearly, bathymetry is not a limiting factor for thrombolite growth. In fact, Leinfelder et al. (1993b) have concluded that microbolites are eurytopic. That is, they are not restricted by water depth, salinity, temperature, light penetration, oxygen content, or nutrient supply. Pure thrombolites may occur where other reef organisms are excluded by some factor. However, in addition to being abundant in the northern Tethyan realm and during an overall rise in sea level, these opportunistic organisms require a hard substrate for nucleation, zero to low background sedimentation rate for initial growth, and low to moderate sedimentation rate for continued growth to support the calcification process (Leinfelder et al., 1993b). Smackover thrombolites nucleated on rockgrounds associated with Paleozoic basement paleohighs or sediment starvation surfaces (cemented shells and/or an encrusted substrate or hardground) associated with salt features. Although the rockgrounds are located near the Late Jurassic shoreline, the siliciclastic sediment influx essentially had ceased at this time. The initial growth of the thrombolites occurred when the rate of sea level rise began to slow and the amount of background sedimentation was low or zero (Figure 12A). Extensive microbial growth occurred in response to the available accommodation space (Figure 12B).

Thrombolite buildups were dominated by calcimicrobes (cyanobacteria and other heterotrophic bacteria) with encrusters (foraminifera *Tubiphytes*, algae, and metazoans) (Leinfelder et al., 1993b). Normal-marine (stenotopic) grazing mollusks were present, but their numbers are limited probably because of fluctuations in paleoenvironmental conditions, such as the periodic occurrence of low oxygen concentrations in slightly deeper waters or salinity fluctuations in shallower waters (Leinfelder et al., 1993b; Leinfelder 2001). Microbes, however, were capable of surviving dysaerobic or hyposaline and hypersaline conditions and were at least partly light independent, with some forms being aphotic (Dromart et al., 1994; Leinfelder and Schmid, 2000). Leinfelder et al. (1996) postulated that in successions of intercalated metazoan-thrombolite and pure thrombolite reefs, a fluctuation in oxygen content was the main limiting factor that favored the development of thrombolite mounds as opposed to the growth of coral or sponge reefs. Typically, microbial mats and their associated biofilms form on a hard substrate, form relief above the seafloor, and grow laterally over soft areas of the substrate by producing an extracellular polymeric matrix, which is then calcified and produces a bridge over the previous substrate surface (Leinfelder et al., 1993b; Mancini and Parcell, 2001; Parcell, 2003). Generally, with a continued reduction in the rate of sea level rise and resulting stabilization of paleoenvironmental conditions, metazoans such as corals colonized the area of thrombolite development, and the growth of the thrombolites was reduced (Leinfelder et al., 1993b). In the case with Smackover thrombolites, continued seawater evaporation and an increase in the shallowing of the depositional setting to above the wave base, which was related to the reduction in the accommodation space caused by the slowing of the rate of relative sea level rise and an increase in sedimentation rate, led to the demise of these organisms. Ooid shoals and upper shoreface deposits accumulated in this high-energy paleoenvironmental setting (Figure 12D). The relief and geographic location of the paleohighs had an effect on thrombolite growth and distribution. On low-relief paleohighs (submerged by the Smackover transgression), microbial crusts colonized the crests of these paleotopographic features as well as the flanks. On high-relief paleohighs (partially emergent throughout the Oxfordian), microbial crusts colonized only the flanks of these features. Thrombolites only developed on the leeward or northeastern side of the Vocation paleohigh because of the higher energy conditions on the windward side of this feature (Figure 12). Ooid upper shoreface deposits accumulated on the windward flank of this paleohigh.

PETROLEUM EXPLORATION STRATEGIES

Smackover oil was first discovered in 1967 in southwestern Alabama at Toxey field in shoal and shoreface grainstone facies deposited in association with a Paleozoic basement paleohigh related to the Choctaw Ridge complex (Figure 1). In 1970, Smackover oil was discovered at Uriah field in Smackover shoal and shoreface grainstone facies on a Paleozoic basement paleohigh related to the Conecuh Ridge complex, where microbial boundstone was penetrated in this field. Vocation field, which produces oil from thrombolite boundstone (Figure 3D) and shoal and shoreface grainstone facies, was discovered in 1971. It is located on a basement paleohigh (Figure 6) related to the Conecuh Ridge complex. Significant (total oil production near or greater than 1 million bbl) Smackover discoveries associated with basement paleohighs, in addition to Toxey field and Vocation field, followed and included Blacksher field (1980), Huxford field (1982), Appleton field (1983), Wallers Creek field (1985), South Burnt Corn Creek field (1987), East Barnett field (1988), West Appleton field (1988), North Barnett field (1991), Gravel Hill Church field (1995), and Little River Lake field (1998) (Figure 1). To date, some 54 Smackover oil

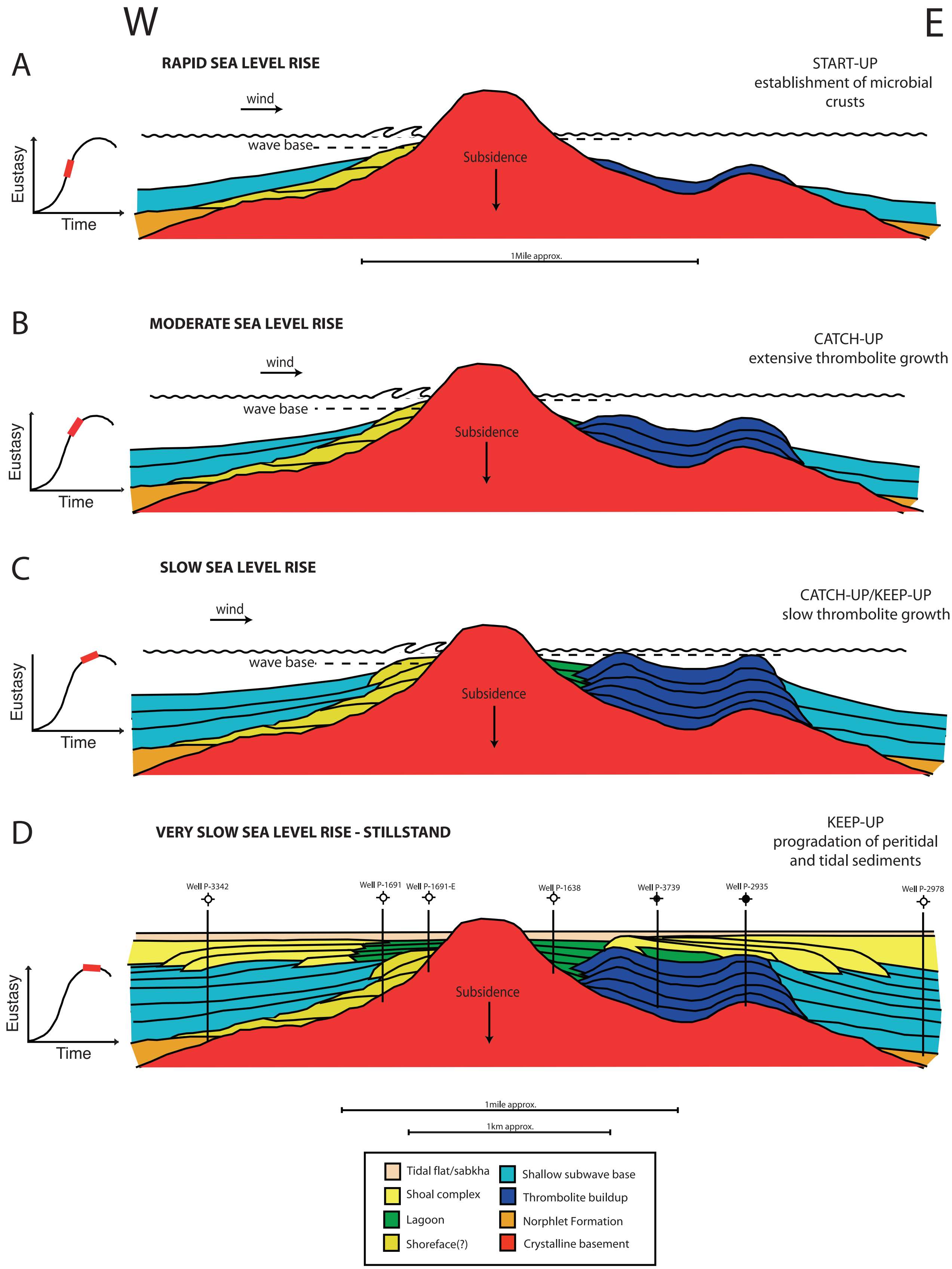


Figure 12. Evolution of thrombolite growth and associated facies on the high-relief structure at Vocation field (modified from Llinás, 2002b).

Table 2. Field Discoveries in the Smackover Updip Basement Ridge Play

Field	Discovery Date	Location (County)	Number of Wells	Total Production (BO)
Toxey	1967	Choctaw	7	2,004,390
Uriah	1970	Monroe	4	306,052
Vocation	1971	Monroe	8	2,260,179
Barnett	1975	Conecuh and Escambia	4	576,366
Melvin	1977	Choctaw	2	324,318
Blacksher	1980	Baldwin	5	2,386,343
Little River	1981	Baldwin and Monroe	2	127,958
Huxford	1982	Escambia	6	2,016,050
Appleton	1983	Escambia	6	2,689,489
South Vocation	1984	Monroe	2	76,739
Wallers Creek	1985	Monroe	2	987,247
Burnt Corn Creek	1986	Escambia	1	10,911
Hanberry Church	1987	Escambia	1	99,844
Wallace	1987	Escambia	2	11,164
South Burnt Corn Creek	1987	Escambia	3	997,050
Wild Fork Creek	1988	Escambia	2	963,079
East Barnett	1988	Conecuh and Escambia	4	1,600,250
Smiths Church	1988	Escambia	1	102,153
Palmers Crossroads	1988	Monroe	1	412,908
Broken Leg Creek	1988	Escambia	2	376,029
West Okatuppa Creek	1988	Choctaw	1	6,961
South Wild Fork Creek	1988	Escambia	1	22,836
West Appleton	1988	Escambia	3	1,293,890
Northwest Range	1988	Conecuh	2	230,290
East Huxford	1989	Escambia	1	246,433
Northeast Barnett	1989	Conecuh	2	510,973
North Smiths Church	1990	Escambia	1	15,212
North Wallers Creek	1990	Monroe	1	55,247
Robinson Creek	1990	Escambia	1	476,742
Mineola	1990	Monroe	1	610,896
East Corley Creek	1990	Conecuh	3	204,493
South Uriah	1990	Monroe	1	50,842
North Barnett	1991	Conecuh	2	1,134,953
South Dean Creek	1991	Escambia	1	212,352
Southwest Range	1992	Conecuh	2	71,374
Dean Creek	1992	Escambia	2	149,942
Big Spring Creek	1992	Escambia	1	372,325
Northwest Smiths Church	1992	Escambia	1	410,361
Canaan Church	1992	Escambia	2	820,433
Chitterling Creek	1992	Escambia	1	204,668
Baileys Creek	1994	Escambia	1	76,630
East Robinson Creek	1994	Escambia	1	24,900
Horseneck Creek	1994	Baldwin	1	154,148
Little Cedar Creek	1994	Conecuh	3	188,443
Northeast Melvin	1995	Choctaw	2	172,165
Gravel Hill Church	1995	Escambia	2	1,040,024
Narrow Gap Creek	1996	Escambia	1	196,574

Table 2. Continued

Field	Discovery Date	Location (County)	Number of Wells	Total Production (BO)
West Canaan Church	1996	Escambia	2	697,520
Northwest Appleton	1996	Escambia	1	592,924
South Gravel Hill Church	1996	Escambia	1	21,662
Southwest Canaan Church	1997	Escambia	2	608,552
Little River Lake	1998	Monroe	1	1,056,862
Juniper Creek	2001	Conecuh	1	20,547
North Robinson Creek	2001	Escambia	1	117,085

fields (Table 2) have been discovered in the updip basement ridge play. The most recent Smackover paleohigh discoveries were Juniper Creek and North Robinson Creek fields in 2001.

Delineation of paleotopographic anomalies (Figures 6B, 7B) using seismic reflection data was the key to detecting these paleohighs. However, because paleohighs were both emergent (high relief, Figure 6B) and submergent (low relief, Figure 7B) during Smackover carbonate accumulation, a critical element to the exploration strategy was the determination as to whether reservoir facies were developed on the crest and flanks of a particular paleohigh or restricted to the flanks of the feature.

With the advent of three-dimensional seismic reflection technology, the prediction as to whether Smackover facies were present on the crest and flanks or restricted to the flanks of a particular paleohigh has been highly improved. The current issue is the prediction of the type of facies present; that is, whether shoal and shoreface grainstone and/or thrombolite boundstone reservoir facies accumulated on a given targeted paleohigh (Figures 6A, 7A).

The Appleton paleohigh and associated Smackover facies provide a stratigraphic and structural model for the development of potential thrombolite reservoirs on the crest and flanks of a low-relief paleohigh (Figure 7). This model can be used to predict the hydrocarbon potential of other paleohighs in the thrombolite reservoir play. Figures 13–15 were prepared to demonstrate three scenarios involving the variables of present-day structural elevation and presence or absence of potential thrombolite facies.

The three-dimensional seismic interpretation for the paleohighs studied uses the criteria for seismic reflection horizon identification and mapping described by Hart and Balch (2000). The top of the Buckner and Smackover interval is identified as a high-amplitude peak or positive reflector (Figures 7B, 13) that formed as the wavelet traveled from shaly and sandy deposits of the middle part of the Haynesville Formation to the denser layers of anhydrite of the Buckner Anhydrite Member of the Haynesville Formation and of nonporous and lower porosity carbonate facies of the upper Smackover Formation. The acoustic impedance contrast between the upper nonporous and lower porosity Smackover facies and the underlying higher porosity Smackover thrombolite facies is great enough for a distinct seismic event identified as a high- to moderate-amplitude and moderate-frequency trough, corresponding to a negative reflection coefficient that is generated across this intraformational contact. The amplitude of the reflection depends on the petrophysical properties of the strata above the thrombolite. For example, the contrast in acoustic impedance between muddy lagoonal deposits and thrombolite facies is expected to be greater than between porous grainstone shoal deposits and thrombolite facies. Onstructure, the thrombolite facies overlies Paleozoic crystalline basement rocks. This unconformity corresponds to a transition from slow-velocity (porous, less dense) rocks to fast-velocity (nonporous, more dense) rocks that results in a positive reflection coefficient and is manifested as a peak in the seismic reflection data. Variations in amplitude for this reflector are the result of changes in thickness and lateral variations in the thrombolite facies.

Figure 13 compares the Appleton thrombolite buildup over a low-relief paleohigh to a potential thrombolite buildup over a low-relief paleohigh to the northwest of the Appleton feature. Figure 13A shows a mounded geometry configuration for the top of the thrombolite reflector at Appleton field, and this geometry is also characteristic of this reflector over the crest of the paleohigh northwest of Appleton field. This feature was drilled in 1996 and penetrated a total of 38.4 m (126 ft) of thrombolite facies (Figure 13B). The discovery

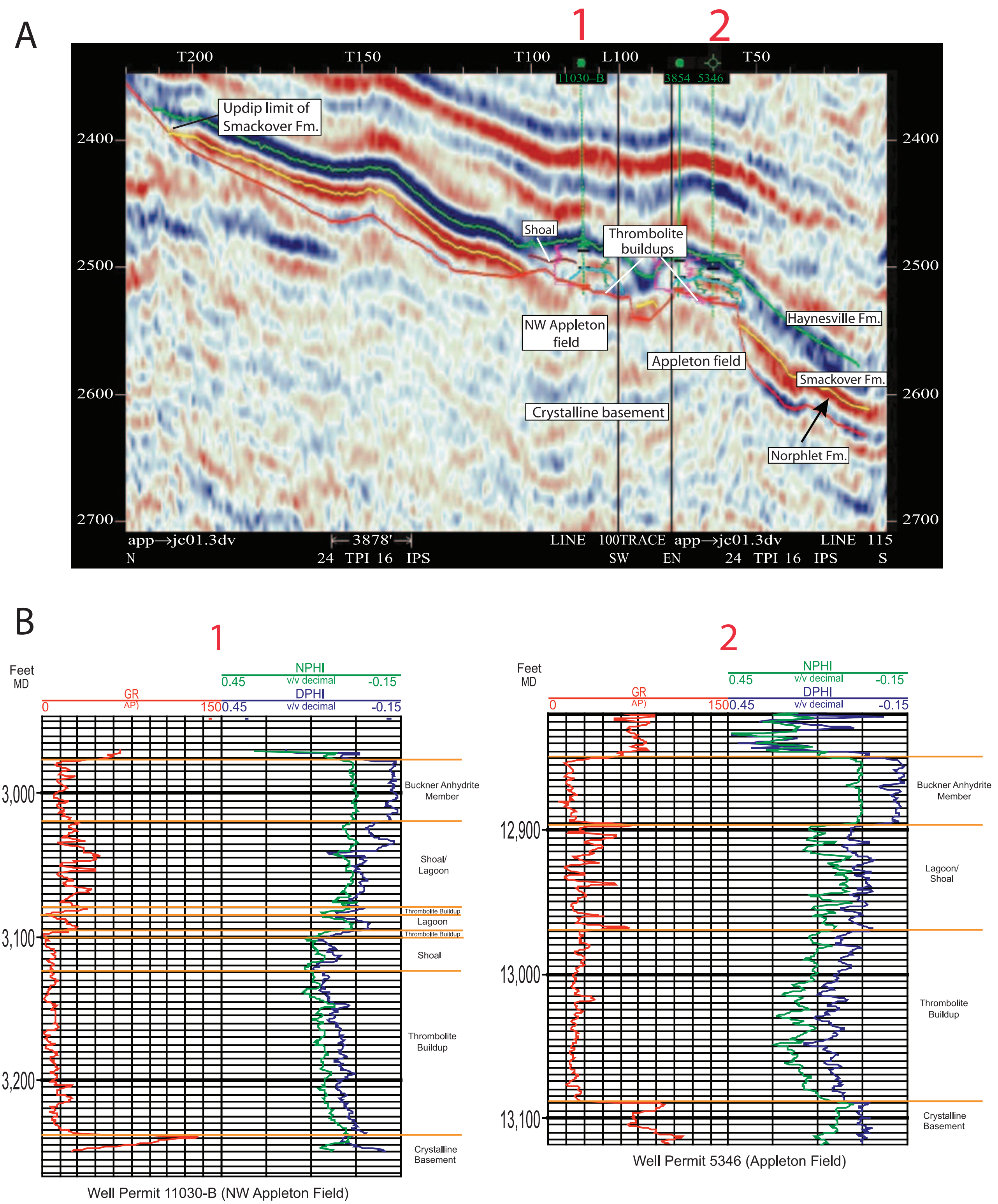


Figure 13. (A) Seismic profile oriented in an approximate dip direction showing the thrombolite buildups on the Appleton and Northwest Appleton paleohighs. Note the termination of Smackover and the underlying Norphlet strata against basement (updip depositional limit of these formations) and (B) representative well logs from wells in these fields illustrating the characteristic regular pattern of lower gamma-ray (GR) values coupled with relative high neutron (NPHI) and density (DPHI) porosity values for the thrombolite facies (well permits 11030-B and 5346).

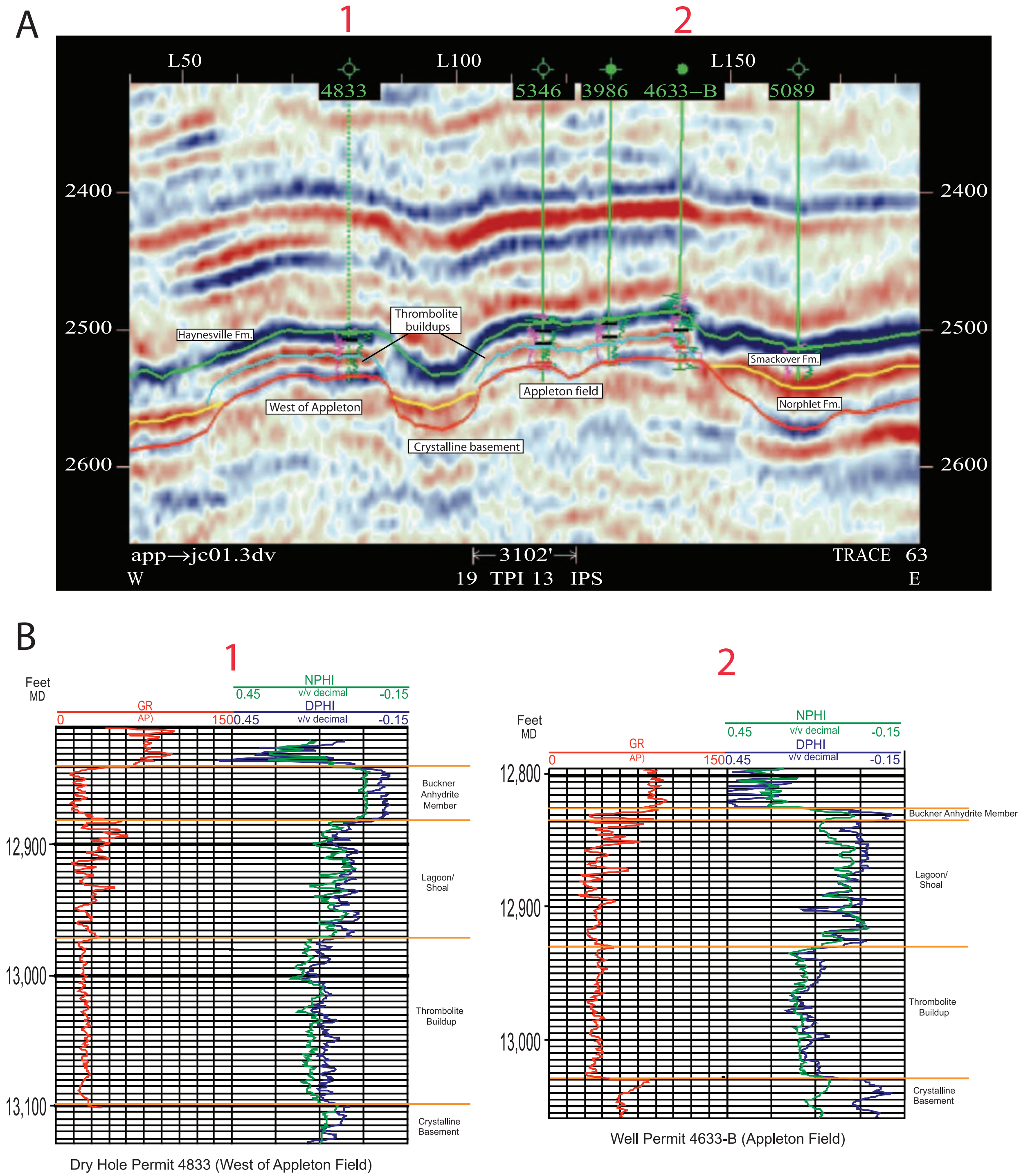


Figure 14. (A) Seismic profile oriented in an approximate strike direction showing the thrombolite buildups on the Appleton paleohigh and on a paleohigh west of Appleton field and (B) representative logs from wells for these areas illustrating the characteristic regular pattern of lower gamma-ray (GR) values coupled with relative high density (DPHI) and neutron (NPHI) porosity values for the thrombolite facies (dry-hole permit 4833 and well permit 4633B).

well tested 264 BOPD and led to the establishment of the Northwest Appleton field, which has produced 592,924 bbl of oil. The presence of the thrombolite boundstone reservoir at Northwest Appleton field was confirmed by core study (Figure 3E). The well-log curves from 4000- to 4035-m (13,124- to 13,238-ft) depths (and thin intervals above this section) for the discovery well also are consistent with a thrombolite

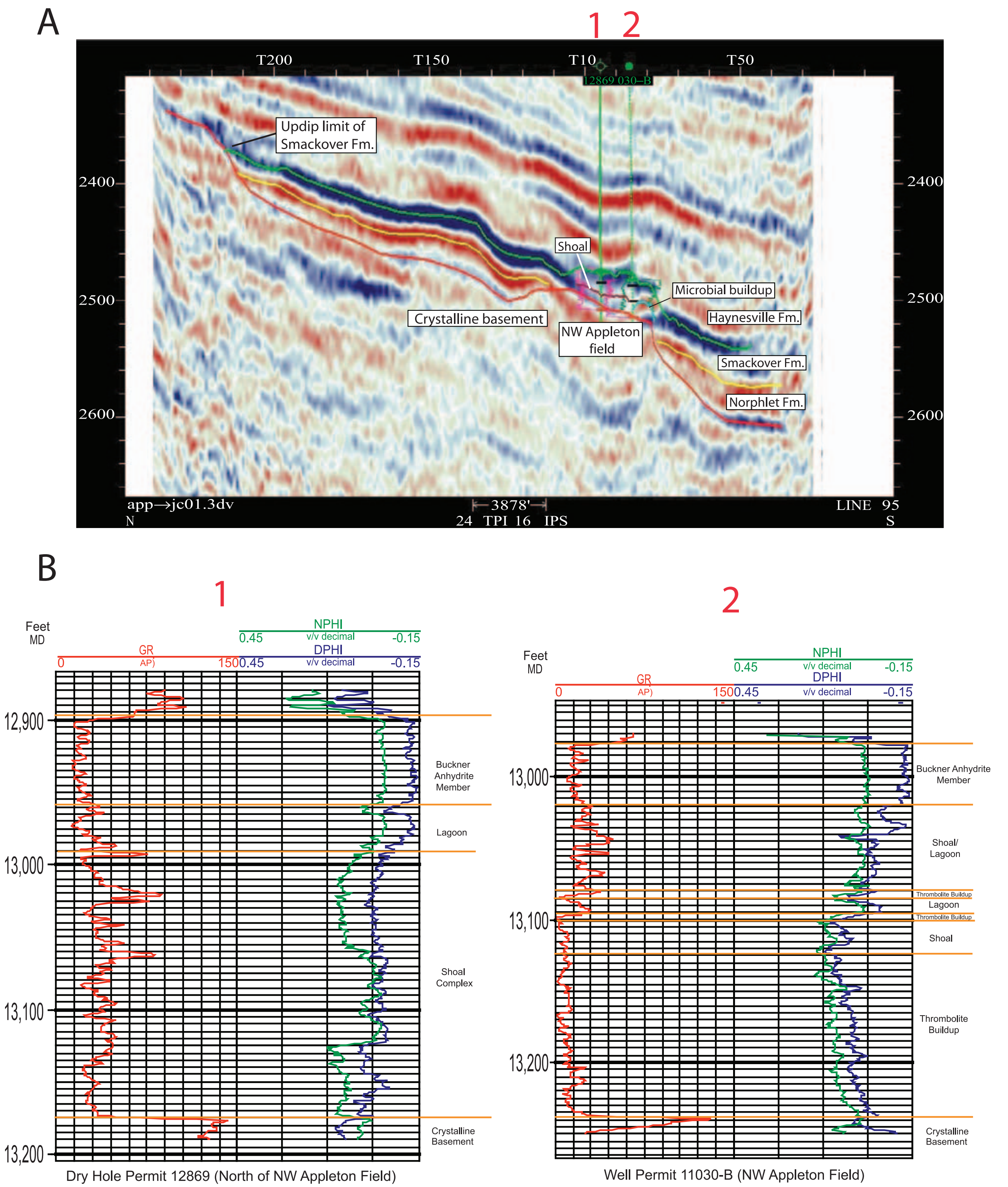


Figure 15. (A) Seismic profile oriented in an approximate dip direction showing the Northwest Appleton paleohigh where thrombolite facies developed on the southern part of this basement high. To the north of Northwest Appleton field on this paleohigh, the strong reflector that identifies the thrombolite buildup is replaced by a fuzzy low-amplitude reflector and (B) representative logs from wells for these areas. Notice that the dry-hole permit 12869, located in the area north of Northwest Appleton, shows an irregular pattern of relatively high gamma-ray (GR) values and lower density (DPHI) and neutron (NPHI) porosities, which may indicate the presence of shoal and lagoon facies.

facies. In this case, well-log signatures are characterized by a regular pattern of lower gamma-ray values and higher porosity values, as determined by density and neutron porosity curves (Figure 13B).

Figure 14 compares the Appleton field thrombolite buildup to a potential thrombolite buildup over a low-relief paleohigh to the west of the Appleton field feature. Figure 14A shows a mounded geometry configuration for the top of the thrombolite reflector for this area. This feature was drilled in 1986 and penetrated 39 m (128 ft) of the thrombolite facies, as determined from the well-log signature and core study from dry-hole permit 4833 (Figure 3F). The gamma-ray log curve, characterized by a regular pattern of lower values, from 3954- to 3993-m (12,972- to 13,100-ft) depth for this dry hole is consistent with a thrombolite facies (Figure 14B). The high porosity values as determined by density and neutron porosity curves indicate that the thrombolite facies has reservoir potential in this area. However, as seen from the seismic data (Figure 14A), the basement paleohigh is structurally lower today than the Appleton field paleohigh, thus resulting in the drilling of a dry hole. The top of the thrombolite buildup is 34.4 m (113 ft) higher in well permit 4633-B (Appleton field) than in the dry-hole permit 4833 (structure to the west of Appleton field). Well permit 4633-B from Appleton field has produced 1.16 million bbl of oil.

Figure 15 compares the Northwest Appleton field thrombolite buildup to a potential buildup north of the Northwest Appleton field. The seismic data indicate that the high-amplitude trough, as seen in the seismic data from Northwest Appleton field, is replaced by a fuzzy low-amplitude reflector in this area, suggesting that the thrombolite facies is absent (Figure 15A). The apparent absence of the thrombolite facies in this area is confirmed by the gamma-ray log curve for dry-hole permit 12869 (Figure 15B). The gamma-ray pattern in this well from 3959- to 4016-m (12,990- to 13,175-ft) depth suggests that shoal and lagoon facies, instead of thrombolite facies, overlie the Northwest Appleton field paleohigh to the north. The gamma-ray curve for this interval is irregular instead of regular, and it has higher values than the pattern for the thrombolite facies in this area. The porosity values, as indicated from the density and neutron porosity curves, are relatively lower, indicating that the Smackover shoal and lagoon facies has little reservoir potential in this area. Wave and/or current activity and/or sediment influx were probably too high in this area to support thrombolite development. Although no core data are available to confirm this interpretation, well cuttings from dry-hole permit 12869 support this conclusion.

Although the primary control on reservoir architecture and geographic distribution of Smackover reservoirs is the fabric and texture of the depositional facies, diagenesis (chiefly dolomitization) is a significant factor that preserves and enhances reservoir quality. At Appleton field, the shoal grainstone and thrombolite boundstone are the reservoir facies, whereas tidal packstone and lagoonal wackestone are nonreservoir facies. The reservoir quality of the thrombolite boundstone facies is greater than the quality of the shoal grainstone facies (Mancini et al., 2000). In addition, the reservoir quality of the dendroidal (Figure 3C) and chaotic (Figure 3B, D–F) thrombolite boundstone is greater than the layered thrombolite bindstone (Figure 3A), because the dendroidal and chaotic thrombolites produce high lateral and vertical pore interconnectivity because of their vertical and horizontal branching growth pattern (Mancini and Parcell, 2001).

Porosity in the thrombolite boundstone facies is a mixture of primary shelter and fenestral porosity overprinted by secondary dolomite intercrystalline and vuggy porosity (Figure 16). The higher reservoir quality of the dendroidal (Figure 16B) and chaotic (Figure 16C, D) thrombolite boundstone is attributed to the higher permeability and greater interconnectivity of this facies because of the nature of the pore system (pore topology and geometry and pore-throat size distribution) instead of the amount of porosity. Pore-throat size distribution is one of the important factors determining permeability because the smallest pore throats are the bottlenecks that determine the rate at which fluids pass through a rock (Kopaska-Merkel, 1991; Ahr and Hammel, 1999). The intercrystalline- and vuggy-dominated pore system of the dolomitized and leached boundstone is characterized by a higher percentage of large-sized pores ($>10{,}000\ \mu m^2$ in size) having larger pore throats.

The exploration challenge, therefore, in drilling a successful wildcat well in the Upper Jurassic thrombolite reservoir play in the northeastern Gulf of Mexico is to identify and delineate low-relief basement paleohighs associated with dendroidal thrombolite boundstone that has been dolomitized and occurs above the oil-water contact. As mentioned previously, the use of three-dimensional seismic data provide for the imaging of low-relief structures that are characterized by thrombolite development on their crest and flanks and that have sufficient present-day structural relief so the thrombolite buildup rests above the oil-water contact. Use of the characteristics of thrombolites, as observed in

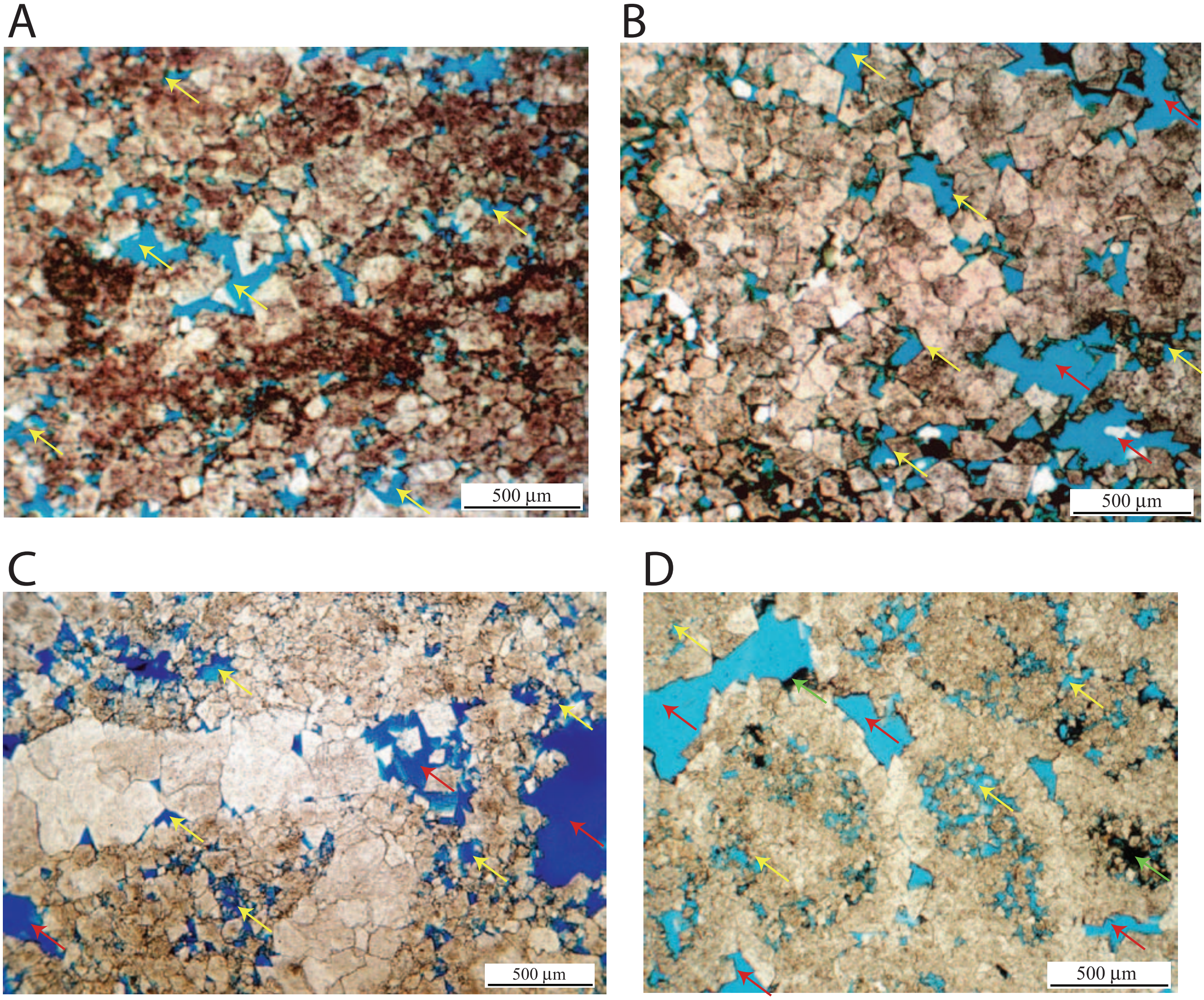


Figure 16. Photomicrographs of Smackover thrombolite facies from Appleton, Vocation, and Northwest Appleton fields showing the intense degree of dolomitization and the resulting development of effective dolomite intercrystalline (yellow arrows) and vuggy (red arrows) porosity that acted to improve reservoir connectivity of (A) layered thrombolite, well permit 4633-B, depth 3969 m (13,022 ft), Appleton field; (B) dendroidal thrombolite, well permit 3986, depth 3953 m (12,970 ft), Appleton field; (C) chaotic thrombolite, well permit 2935, depth 4305 m (14,124 ft), Vocation field; and (D) chaotic thrombolite, well permit 11030-B, depth 4005 m (13,139 ft), Northwest Appleton field. Notice that in the last photomicrograph, the presence of dead oil residue is partially filling the pore space (green arrows).

outcrop and as seen from past subsurface studies, has the potential to facilitate the formulation of an effective exploration strategy for determining whether dendroidal thrombolite facies are associated with the structure. Low-relief basement paleohighs that are geographically located updip or near the Jurassic paleoshoreline have been shown to be features that are conducive for thrombolite colonization and growth (Benson et al., 1996; Mancini and Parcell, 2001; Llinás 2002b). These paleohighs were submergent during Smackover deposition, and they provided the hard substrate required for microbial crust nucleation. The paleohighs acted as barriers that disperse ocean currents and waves, providing a paleoenvironment on their leeward sides that is characterized by abnormal marine conditions in oxygen, salinity, temperature, and/or nutrient supply, which acted to exclude stenotopic marine metazoans (corals) and to support the growth of the eurytopic and opportunistic thrombolites. Stratigraphically, thrombolite development was optimal during overall transgression of the Smackover seas. The Smackover maximum transgression event (1) approximates the greatest rate of sea level rise during the Oxfordian, (2) is related to the maximum sediment starvation in the basin, which corresponds to zero to minimum terrigenous sediment influx from Jurassic highlands into the basin, and (3) is associated with the creation of the greatest accommodation space. These factors all contributed to optimal shallow-water thrombolite development, but excluded other reefal organisms because of the fluctuation in paleoenvironmental conditions in this nearshore setting. After microbial crust colonization in a low-energy paleoenvironment, a slightly elevated background sedimentation rate would favor dendroidal thrombolite growth in that area. Schmid (1996) reported that Upper Jurassic microbolites developed dendroidal growth forms as a reaction to slightly elevated sedimentation rates in low-energy paleoenvironments. In the Smackover Formation, an alternation of thrombolite growth forms from layered to dendroidal or chaotic is common. This alternation is probably the result of moderate changes in energy level and sedimentation rate in the depositional setting.

With three-dimensional seismic and three-dimensional geologic modeling technologies available for the reliable prediction of petroleum trap development and of reservoir depositional facies, the major exploration uncertainty remaining is how to determine whether the thrombolite boundstone has been dolomitized. Fortunately, as reported by Benson and Mancini (1999), Mancini et al. (2000), and Llinás (2002b), dolomitization is a very common agent of diagenesis in the onshore areas of the northeastern Gulf of Mexico. Dolomitization in this area has been interpreted as a relatively early diagenetic event, with paleotopography, fluctuations in sea level, and climate being critical factors to this diagenetic process (Benson and Mancini, 1999). The arid climate, the elevation of paleotopographic features, the restrictive nature of ocean circulation caused by barriers, the decrease in the rate of sea level rise, and the overall paleoenvironmental conditions in the nearshore areas of the northeastern Gulf of Mexico during the latest Oxfordian into the Kimmeridgian were conducive for dolomitization. Although seepage reflux and mixing zone diagenetic processes are mechanisms for the formation of Smackover dolostone, Benson and Mancini (1999) favored the evaporative pumping mechanism of Saller and Moore (1986) to explain the movement of hypersaline, marine-derived waters through Smackover lime sediments soon after deposition in updip areas of the eastern Gulf coastal plain. This mechanism is attractive because it explains very early perhaps even syndepositional dolomitization and would predict dolomitization of thrombolite facies on any paleohigh having sufficient depositional relief to stand above sea level for a period during sediment deposition. However, because of the intense and extensive dolomitization of Smackover carbonates in the northeastern Gulf of Mexico, several processes, including seepage (brine) reflux, mixing zone (shallow burial mixed water), and evaporative pumping, probably have altered Smackover deposits in this area (Prather, 1992).

CONCLUSIONS

1. Although Upper Jurassic microbial buildups have been exploration targets in the northeastern Gulf of Mexico for more than 30 yr, new field discoveries continue to be made in this area, indicating that the origin and distribution of these microbolites are not completely understood.
2. Microbolites form mounds that are organosedimentary buildups consisting of microbial mats comprised of complex calcimicrobe communities associated with biofilms that form on solid substrates or stabilize loose sediment through agglutination or calcification.
3. Microbolites consist of stromatolites (laminated mesostructure), thrombolites (clotted mesostructure), and leiolites (structureless to dense mesostructure). Thrombolites have the capability to grow and produce depositional relief above the seafloor, creating mounds.
4. Thrombolite buildups dominated by calcimicrobes and encrusters were abundant in the Late Jurassic in the northern Tethyan realm, including the Gulf of Mexico and western Europe, because of local, regional, and global paleoenvironmental conditions. Microbolites apparently were not restricted by water depth, temperature, salinity, light penetration, oxygen content, or nutrient supply. Stratigraphically, thrombolites were best developed during an overall marine transgression under initial zero to low background sedimentation rates and in low-energy and eurytopic depositional settings. Thrombolites nucleated on rockgrounds or on sediment starvation surfaces (encrusted or hardgrounds) that formed prior to a decrease in the rate of sea level rise. Extensive microbial growth followed but was limited by the available accommodation space. The demise of the thrombolites corresponded to changes in the paleoenvironmental conditions associated with an overall regression of the sea.
5. In the northeastern Gulf of Mexico, Oxfordian Smackover inner ramp, shallow-water thrombolite buildups grew on the crests and/or flanks of

paleotopographic highs formed by basement paleohighs or salt anticlines or ridges. These opportunistic thrombolites dominated by calcimicrobes attained a thickness of 58 m (190 ft) and covered an area of as much as 6.2 km^2 (2.4 mi^2). The chief reservoir facies are dendroidal (branching) and chaotic thrombolites.

6. By studying Kimmeridgian thrombolite pinnacle reefs and bioherms as preserved in outcrop in Spain and Portugal, the geometries, areal extents, and facies relationships of thrombolites can be better characterized. These middle- to outer-ramp (deeper water) thrombolites dominated by calcimicrobes with *Tubiphytes*, serpulids, and siliceous sponges attained a thickness of 30 m (98 ft) and covered an area of as much as 2.3 km^2 (0.9 mi^2).
7. The exploration challenge in drilling a successful wildcat well in the Upper Jurassic thrombolite reservoir play in the northeastern Gulf of Mexico is to identify and delineate low-relief crystalline basement paleohighs associated with dendroidal and chaotic thrombolite dolomitized boundstone, which have sufficient present-day structural relief so the thrombolite facies rests above the oil-water contact. The use of three-dimensional seismic data provides for the imaging of low-relief structures characterized by thrombolite development. The use of the characteristics of thrombolites, as observed in outcrop and as seen from past subsurface studies, has the potential to facilitate the formulation of an effective exploration strategy through three-dimensional geologic modeling for determining whether dendroidal and chaotic thrombolite facies are associated with the structure. A major uncertainty in exploration is the dolomitization of the thrombolite boundstone. This risk is reduced with the knowledge that Late Jurassic paleoenvironmental conditions in updip areas of the northeastern Gulf of Mexico were conducive for dolomitization through an evaporative pumping mechanism that acted to move hypersaline, marine-derived waters through carbonate sediments deposited on paleohighs having sufficient depositional relief above sea level for a period during sediment deposition.

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