E&P NOTE

Upper Jurassic updip stratigraphic trap and associated Smackover microbial and nearshore carbonate facies, eastern Gulf coastal plain

Ernest A. Mancini, William C. Parcell, Wayne M. Ahr, Victor O. Ramirez, Juan Carlos Llinás, and Milo Cameron

ABSTRACT

The development of Little Cedar Creek field in the eastern Gulf coastal plain of the United States has shown that the current exploration strategy used to find hydrocarbon-productive microbial and high-energy, nearshore carbonate facies in the Upper Jurassic Smackover Formation requires refinement to increase the probability of identifying and delineating these potential reservoir facies. In this field, the petroleum trap is a stratigraphic trap characterized by microbial boundstone and packstone and nearshore grainstone and packstone reservoirs that are underlain and overlain by lime mudstone and dolomudstone to wackestone and that grade into lime mudstone and dolomudstone near the depositional updip limit of the Smackover Formation. Reservoir rocks trend from southwest to northeast in the field area. The grainstone and packstone reservoir is thickest in the central part of the field. The boundstone reservoir is thickest in local buildups that are composed of thrombolites in the southern part of the field and is absent along the northern margin. These reservoir facies are interpreted to have accumulated in water depths of approximately 3 m (10 ft) and in 5 km (3 mi) of the paleoshoreline. In contrast to most other thrombolites identified in the Gulf coastal plain, these buildups did not grow directly on paleohighs associated with Paleozoic crystalline rocks. The characterization and modeling of the petroleum trap and reservoirs at Little Cedar Creek field provide new information for use in the formulation of strategies for exploration of other Upper Jurassic

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hydrocarbon productive microbial and related facies associated with stratigraphic traps in the Gulf coastal plain.

INTRODUCTION

Upper Jurassic (Oxfordian) Smackover microbial buildups are productive oil and gas reservoirs in the eastern Gulf coastal plain of the United States. The hydrocarbon reservoir potential of these carbonate facies was first recognized by Baria et al. (1982) and Crevello and Harris (1984). The sedimentary and reservoir characteristics of these deposits have been described by Markland (1992), Benson et al. (1996), Kopaska-Merkel (1998), Hart and Balch (2000), Parcell (2000), Mancini and Parcell (2001), and Llinás (2004). Mancini et al. (2004) published a discussion of the origin, development, and characteristics of thrombolites and of thrombolitic textures (microbial structure with a clotted internal fabric as described by Aitken, 1967, and Kennard and James, 1986). Geoscientists in search of oil and gas accumulations associated with microbial reservoirs have relied primarily on seismic reflection technology to identify pre-Smackover paleohighs for microbial buildups typically developed on Paleozoic paleotopographic features. This relationship made the buildups detectable through the use of seismic reflection techniques. Some 16 Smackover fields have been discovered and developed in the southwest Alabama area based on this strategy (Mancini et al., 2004). The best known of these fields are Appleton field (Markland, 1992; Mancini et al., 2000) and Vocation field (Powers, 1990; Llinás, 2004). To date, the combined oil production from microbial and associated facies in these fields totals 5 million bbl.

However, with the 1994 discovery and recent development of Smackover microbial and high-energy, nearshore reservoirs at Little Cedar Creek field in southwest Alabama (Figure 1), geoscientists now recognize that microbial buildups have developed in paleogeographic settings other than on Paleozoic basement paleohighs, including nearshore, shallow subtidal paleoenvironments along the updip margin of the Smackover deposition. Furthermore, the operator of the Little Cedar Creek field unit, Midroc Operating Company, has developed this field based on a thorough understanding of the regional geology of the area, refined subsurface interpretation, reservoir characterization, and detailed subsurface mapping using an integration of wire-line log and core data. Seismic reflection data have had limited use in the development of this field because of resolution issues related to the relative thinness of the reservoir intervals of 0–11 m (0–36 ft) at depths of 3353–3658 m (11,000–12,000 ft). According to the State Oil and Gas Board of Alabama (SOGBA), the unit operator predicts that primary recovery from the unitized field area will exceed 5 million bbl of oil, and that about 8 million bbl of oil will be recovered through primary and secondary operations for the unit (SOGBA Hearings, File Docket No. 9-29-04-4, 5, 6; 12-3-04-1; and 9-5-07-15, 2004 and 2007, personal

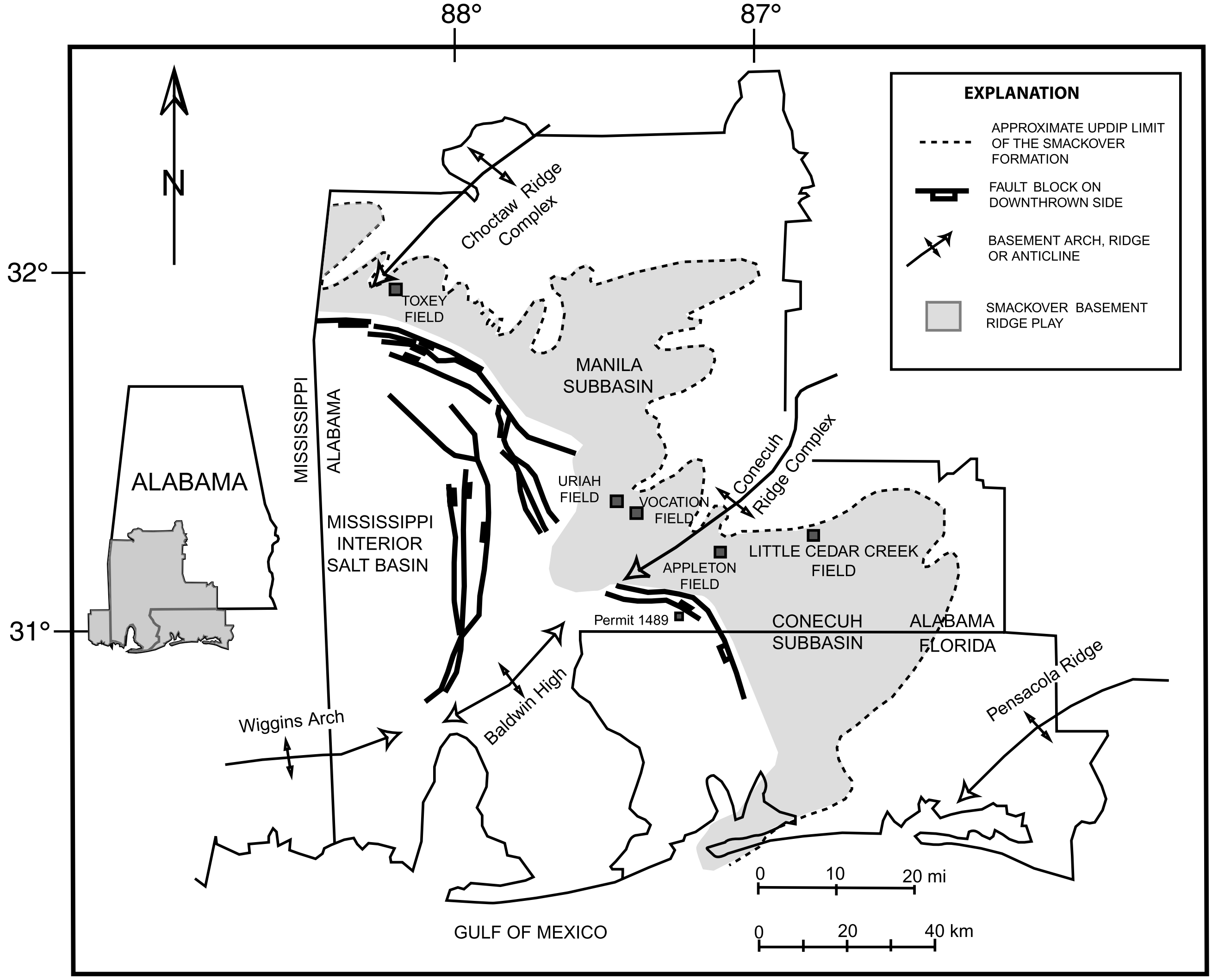


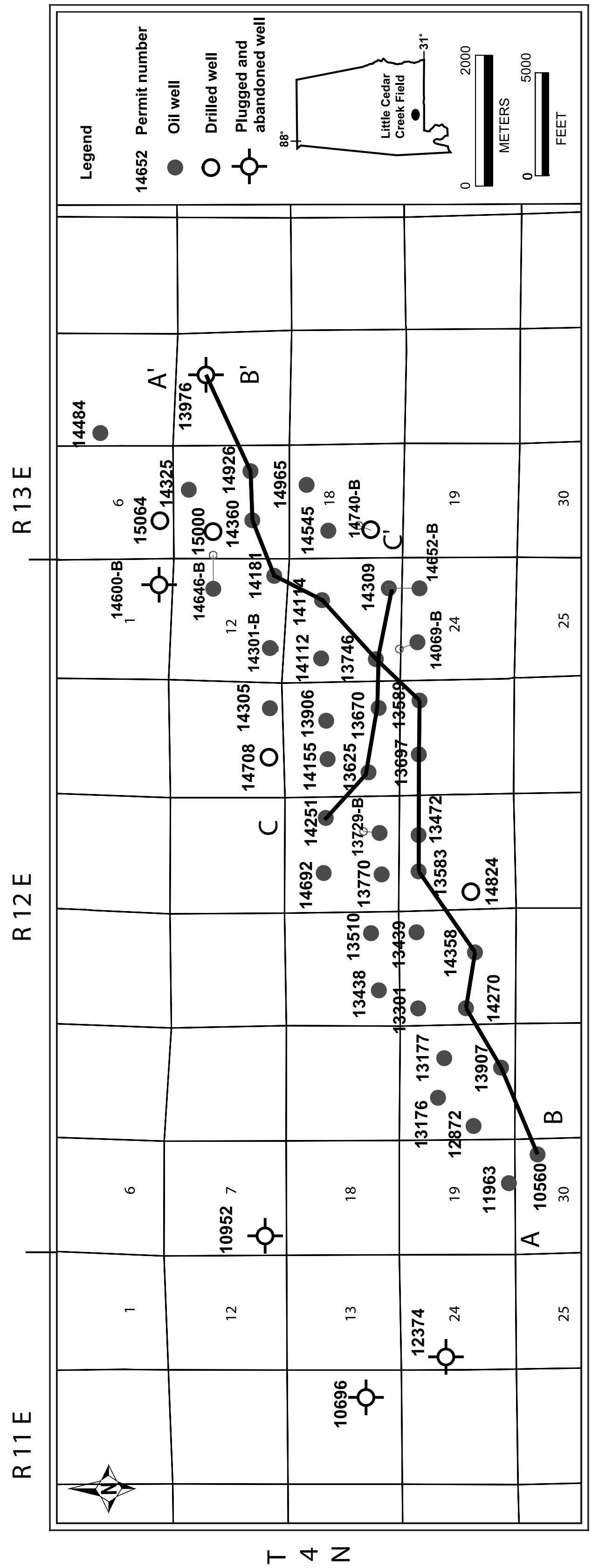
Figure 1. Location map showing major structural features and the approximate updip limit of the Smackover Formation in southwestern Alabama (modified from Mancini et al., 2004). Note the location of key Smackover fields, including the Little Cedar Creek field.

communication). Initial results from geological studies of the Little Cedar Creek field based on information from early drilling have been published by Heydari and Baria (2005) and Mancini et al. (2006).

With the near completion of the development of the Little Cedar Creek field, the purpose of this article is to enhance the knowledge and advance the discussion regarding Smackover microbial and nearshore facies in the study area through reservoir and facies characterization and modeling and to discuss how the discovery and development of the Little Cedar Creek field have resulted in the refinement of the exploration and development strategies for microbial reservoir facies in the eastern Gulf coastal plain. This article builds on the work of Heydari and Baria (2005) and Mancini et al. (2006).

FIELD HISTORY

Little Cedar Creek field (Figure 2) in southwestern Alabama was discovered by Hunt Oil Company in 1994 with the drilling and testing of the 30-1 #1 Cedar Creek Land and Timber Company well (permit 10,560). The well tested from perforations at 3618–3622 m (11,870–11,883 ft) in the Upper Jurassic Smackover Formation (Figure 3) at 108 BOPD of 46° API oil. The SOGBA established the field in 1995. It was not until 2000 that a second well (permit 11,963) was drilled by the Midroc Operating Company and tested at 250 BOPD. These first two wells were not cored. In 2003, a third well (permit 12,872) was drilled, tested (365 BOPD), and cored by Midroc Operating Company. The description



and characterization of the rocks in this core provided evidence that the Smackover reservoirs in this field included thrombolites associated with the approximate updip limit of Smackover deposition, and that these deposits did not accumulate on a localized Paleozoic basement paleohigh. These findings differentiated the Little Cedar Creek field from other Smackover fields with hydrocarbon production from microbial facies. As of July 2007, 51 wells had been drilled in this field area, and 43 of the wells had been cored in the field area (Table 1).

Little Cedar Creek field was unitized in December 2004 (effective January 2005) for the purpose of pressure maintenance with some 15 wells in the unitized area. The initiation of pressure maintenance has been delayed until the established unit can be expanded field-wide. Waterflood and gas-injection studies have been conducted, and implementation of these operations is planned. As of July 2007, additional development had resulted in 37 producing wells in the field area with a cumulative production of 3.6 million bbl of oil and 3 bcf of gas.

PETROLEUM GEOLOGY

The hydrocarbon accumulation at Little Cedar Creek field has been described as a stratigraphic trap near the updip depositional limit of the Smackover Formation (SOGBA Hearings, File Docket No. 9-29-04-4, 5, 6 and 12-3-04-1, 2004, personal communication). The upper and lower reservoir facies are interbedded with three lime mudstone and dolomudstone to wackestone units that encase these reservoirs vertically and laterally (Figure 4). To the northeast and updip in well permit 13,976, the Smackover section consists of lime mudstone and dolomudstone that represent a lateral facies change critical in the formation of the updip seal for this stratigraphic trap (Mancini et al., 2006). Structural maps prepared on top of the Norphlet Formation, the Smackover transgressive subtidal lime mudstone and dolomudstone to wackestone, the Smackover deeper water subtidal lime mudstone, and the Smackover Formation show no indication of structural closure (Figures 5, 6).

Figure 2. Field map for Little Cedar Creek field area. Note the line of section for the structural cross section AA′ and for the stratigraphic cross sections BB′ and CC′. See Figure 1 for latitude and longitude coordinates for the field.

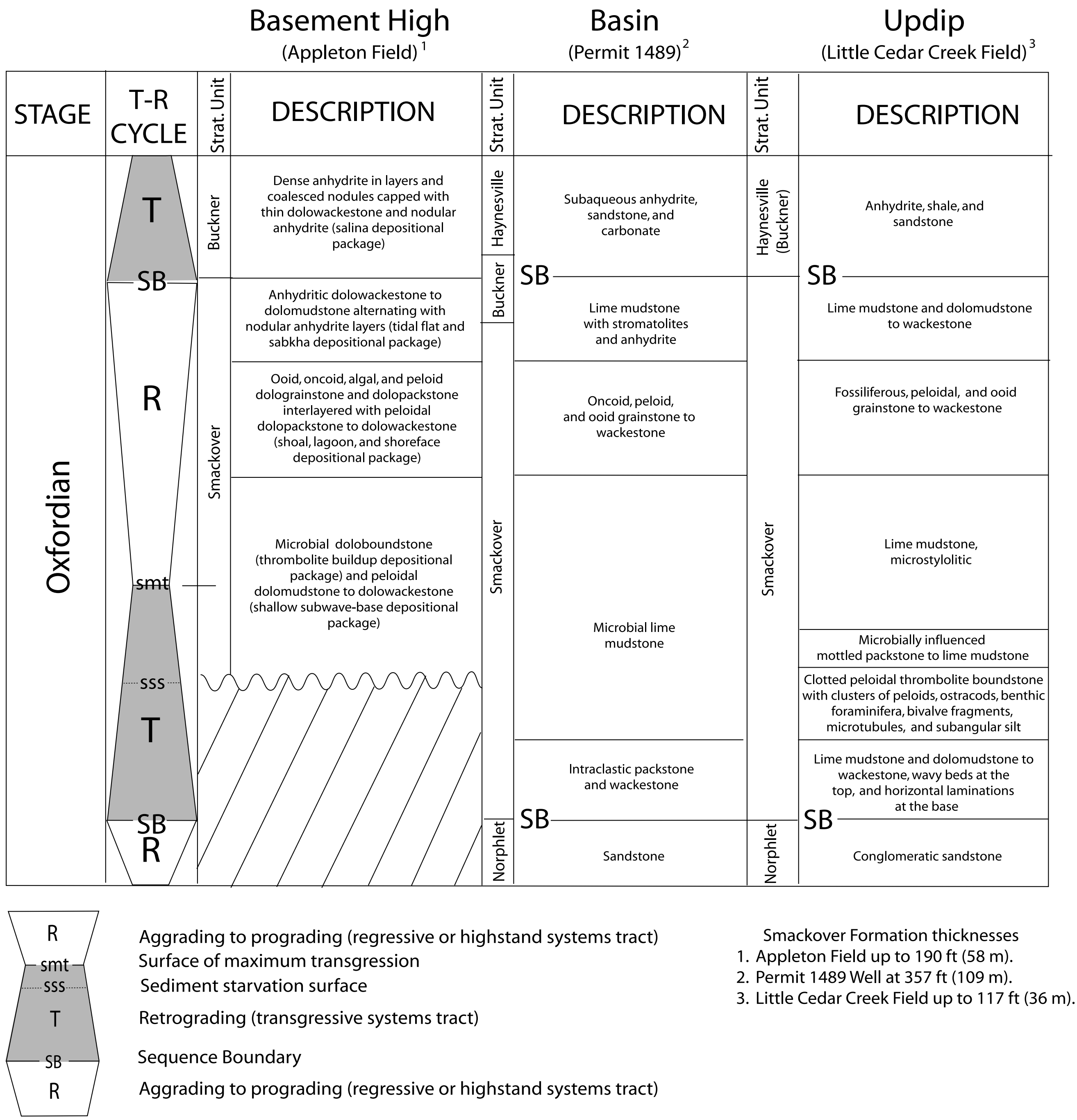


Figure 3. Comparison of Upper Jurassic (Oxfordian) Smackover sequence stratigraphy for a pre-Smackover paleohigh such as the Appleton field; the central area of the Conecuh subbasin as seen in the Exxon #1 Huxford well (permit 1489); and Little Cedar Creek field (modified from Mancini et al., 2004). Note the interpretation that the Smackover section of 18–36 m (58–117 ft) is approximately time equivalent to the Smackover section of 107–122 m (350–400 ft) in the central part of the Conecuh subbasin. See Figure 1 for the location of well permit 1489 and the location of Appleton and Little Cedar Creek fields.

In the Little Cedar Creek field area, the Smackover Formation ranges from 18 to 36 m (58 to 117 ft) in thickness and is interpreted to be equivalent to the Smackover section of 107–122 m (350–400 ft) in more downdip locations in the Conecuh subbasin (Figure 3). Lower Smackover carbonates unconformably overlie Norphlet alluvial and fluvial facies (conglomeratic sandstone beds) in this field (Figures 7, 8I), and Haynesville (Buckner) lagoonal facies (argillaceous beds) or peritidal facies (sandstone deposits) disconformably overlie

Table 1. Wells in the Little Cedar Creek Field Area*

			Well Test			Production	
Permit	Well Name	Company	Oil (BOPD)	Gas (MCFD)	Perforations, m (ft)	Gas (mcf)	Oil (bbl)
10560	Cedar Creek Land and Timber Co. 30-1 1	Midroc Operating Co	108	49	3618–3622 (11,870–11,883)	1014	110,176
10696	Cedar Creek Land and Timber Co. 14-9 1	Hunt Oil Co.	NR**	NR	NR	NR	NR
10952	Cedar Creek Land and Timber Co. 7-13 1	Group 1 Ventures LLC	NR	NR	NR	NR	NR
11963[†]	Cedar Creek Land and Timber Co. 19-15	Midroc Operating Co	250	207	3614–3620; 3661–3664 (11,857–11,876; 12,010–12,020)	25,668	101,251
12374	Cedar Creek Land and Timber Co. 24-5	Midroc Operating Co.	NR	NR	NR	NR	NR
12872[†]	Cedar Creek Land and Timber Co. 20-12	Midroc Operating Co.	365	311	3605–3611 (11,826–11,846)	103,799	118,850
13176[†]	McCreary 20-6	Midroc Operating Co.	104	220	NR	34,340	51,400
13177[†]	Cedar Creek Land and Timber Co. 20-7	Midroc Operating Co.	240	240	3580–3585 (11,744–11,762)	119,093	122,153
13301[†]	Cedar Creek Land and Timber Co. 21-4	Midroc Operating Co.	242	210	3544–3552 (11,628–11,652)	127,154	151,498
13438[†]	Cedar Creek Land & Timber Co. 16-14	Midroc Operating Co.	235	270	3515–3520; 3527–3531 (11,532–11,550; 11,572–11,584)	6277	15,294
13439[†]	McCreary 21-1	Midroc Operating Co.	158	270	3520–3523; 3530–3532 (11,550–11,560; 11,583–11,588)	52,392	67,288
13472[†]	Pugh 22-2	Midroc Operating Co.	288	191	3519–3520 (11,544–11,550)	200,414	225,424
13510[†]	Cedar Creek Land and Timber Co. 16-16	Midroc Operating Co.	245	360	3514–3516; 3518–3520 (11,530–11,534; 11,543–11,548)	131,734	149,668
13583[†]	Pugh 22-3	Midroc Operating Co.	226	248	3506–3512; 3521–3523 (11,504–11,522; 11,552–11,558)	73,829	73,662
13589[†]	Sanders 23-1	Midroc Operating Co.	258	236	3498–3503 (11,478–11,494)	249,435	254,294
13625[†]	Price 14-12	Midroc Operating Co.	291	354	3481–3484; 3486–3489 (11,422–11,430; 11,438–11,448)	275,972	322,397
13670[†]	Tisdale 14-16	Midroc Operating Co	213	175	NR	154,454	160,419
13697[†]	Findley 23-3	Midroc Operating Co.	170	210	NR	160,958	175,151
13729-B[†]	Stuart 15-15	Midroc Operating Co.	405	325	NR	178,528	198,754
13770[†]	Overby 15-14	Midroc Operating Co.	155	183	3500–3507 (11,482–11,506)	60,923	62,172
13746[†]	Tisdale 13-13	Midroc Operating Co.	451	390	3458–3459; 3470–3474 (11,344–11,350; 11,383–11,398)	103,859	120,503
13906[†]	Horton 14-7	Midroc Operating Co.	250	236	3452–3460 (11,326–11,352)	75,042	98,422
13907[†]	Oliver 20-15	Midroc Operating Co.	138	20	NR	27,165	34,416
13976[†]	Craft-Mack 8-7 1	Skylar Exploration Co.	NR	NR	NR	NR	NR
14069-B	Tisdale 24-3	Midroc Operating Co.	384	355	3529–3542 (11,578–11,622)	175,452	186,962

14112[†]	Tisdale 13-5	Midroc Operating Co.	184	190	3433–3439; 3444–3452	71,851	87,292
					(11,264–11,282; 11,298–11,326)		
14114[†]	McCreary 13-1	Midroc Operating Co.	63	0	3453–3458 (11,328–11,345)	56,787	75,781
14155[†]	Whatley 14-6	Midroc Operating Co.	275	204	3448–3456 (11,312–11,340)	85,321	106,619
14181[†]	McCreary 12-16	Midroc Operating Co.	71.5	79	3433–3442 (11,262–11,292)	63,622	64,532
14216[†]	Cedar Creek Land and Timber Co. 15-10	Midroc Operating Co.	NR	NR	NR	NR	NR
14251[†]	Cedar Creek Land and Timber Co. 15-8	Midroc Operating Co.	184	138	3460–3466; 3470–3476	38,771	50,206
					(11,352–11,370; 11,386–11,404)		
14270[†]	Cedar Creek Land and Timber Co. 21-12	Midroc Operating Co.	171	160	3572–3579 (11,718–11,742)	6669	19,280
14301-B[†]	Horton 12-14	Midroc Operating Co.	153	167	3428–3432; 3436–3444	35,460	32,246
					(11,246–11,260; 11,274–11,300)		
14305[†]	Horton 11-16	Midroc Operating Co	307	251	3419–3425 (11,218–11,236)	43,425	50,879
14309[†]	McCreary 13-16 1	Midroc Operating Co.	364	401	3459–3472 (11,348–11,392)	42,211	44,124
14325	Craft-Mack 7-2 1	Skylar Exploration Co.	73	63	3365–3370; 3374–3384	24,665	25,754
					(11,040–11,056; 11,070–11,102)		
14358[†]	Cedar Creek Land and Timber Co. 21-10	Midroc Operating Co.	140	111	NR	31,590	43,306
14360[†]	McCreary 7-11	McCreary Operating	164	152	3406–3411; 3420–3427	42,425	59,104
					(11,174–11,192; 11,220–11,242)		
14484	Craft-Cedar Creek Land and Timber 5-5 1	Skylar Exploration Co.	NR	NR	3341–3344 (10,960–10,970)	0	427
14545[†]	McCreary 18-6 1	Midroc Operating Co.	418	406	3444–3456 (11,300–11,340)	64,296	69,966
14600-B	Craft-Evers 1-16 1	Skylar Exploration Co.	NR	NR	NR	NR	NR
14646-B[†]	McCreary 12-8	Midroc Operating Co.	220	203	NR	NR	NR
14652-B[†]	McCreary 24-1 1	Midroc Operating Co.	266	143	3530–3539 (1580–11,610)	26,906	19,342
14692[†]	Cedar Creek Land and Timber Co. 15-6 1	Midroc Operating Co.	37	28	3476–3480 (11,404–11,418)	2974	3542
14708[†]	Horton 11-14 1	Midroc Operating Co.	NR	NR	3425–3430 (11,238–11,252)	NR	NR
14740-B[†]	Harper 18-11	Midroc Operating Co.	NR	NR	3469–3480 (11,380–11,418)	NR	NR
14824[†]	Pugh 22-12	Midroc Operating Co.	NR	NR	3557–3558 (11,670–11,673)	NR	NR
14926[†]	McCreary 7-9	Midroc Operating Co.	450	405	NR	NR	NR
14965[†]	McCreary 18-2 1	Midroc Operating Co.	372	346	NR	NR	NR
15000[†]	McCreary 7-6	Midroc Operating Co.	308	0	NR	NR	NR
15064[†]	Horton 6-14	Midroc Operating Co.	NR	NR	NR	NR	NR
					Total	2,974,475	3,552,554

*Information from SOGBA as of January 2007.
**NR = not reported.
[†]Well with a corresponding core.

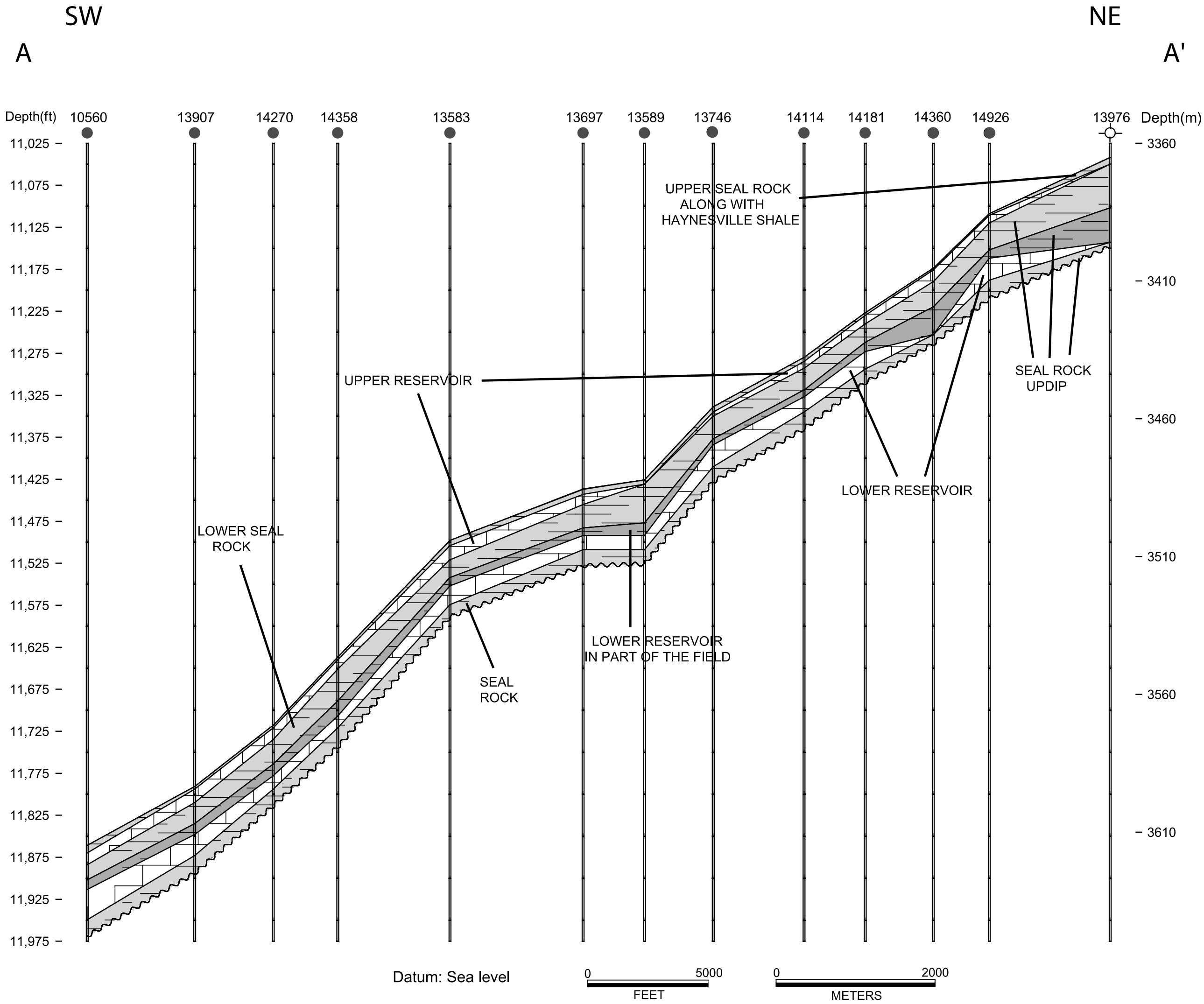


Figure 4. Structural cross section AA′, illustrating elevation changes in the Little Cedar Creek field area in a southwest-to-northeast direction. Note the facies change in the northeastern part of the field (well permit 13976) where the upper grainstone and packstone and lower boundstone reservoir facies transition to lime mudstone and dolomudstone to wackestone (top seal for the upper reservoir) and lime mudstone and microbially influenced lime mudstone (top seal for the lower reservoir) seal facies. These Smackover peritidal and deeper water subtidal facies along with the Haynesville peritidal argillaceous beds and Smackover subtidal transgressive lime mudstone and dolomudstone to wackestone provide the updip seal for this stratigraphic trap. See Figure 2 for the line of cross section.

upper Smackover carbonates (Figures 7, 8B). The lower Haynesville (Buckner) section includes sabkha anhydrite (Figure 8A), pebbly sandstone (Figure 8B), and argillaceous beds. Petrographic microfacies analysis, in conjunction with meso- and macroscale core description and the study of wire-line logs, has defined six major Smackover facies in the field area (Mancini et al., 2006) (Table 2). These facies include, in descending order, (1) peritidal lime mudstone and dolomudstone to wackestone (vertical and lateral seal rock) (Figure 8B); (2) shallow subtidal, nearshore grainstone to wackestone (upper reservoir) (Figures 8C, 9A); (3) deeper water, subtidal lime mudstone (vertical and lateral seal rock) (Figures 8D, 9B); (4) subtidal, microbially influenced lime mudstone to packstone (lower reservoir in the field and probable lateral seal rock to the northeast of the field) (Figures 8E, 9C); (5) subtidal thrombolite boundstone (lower reservoir) (Figures 8F, G; 9D, E); and (6) transgressive subtidal lime mudstone and dolomudstone to wackestone (lateral seal rock) (Figures 8H,

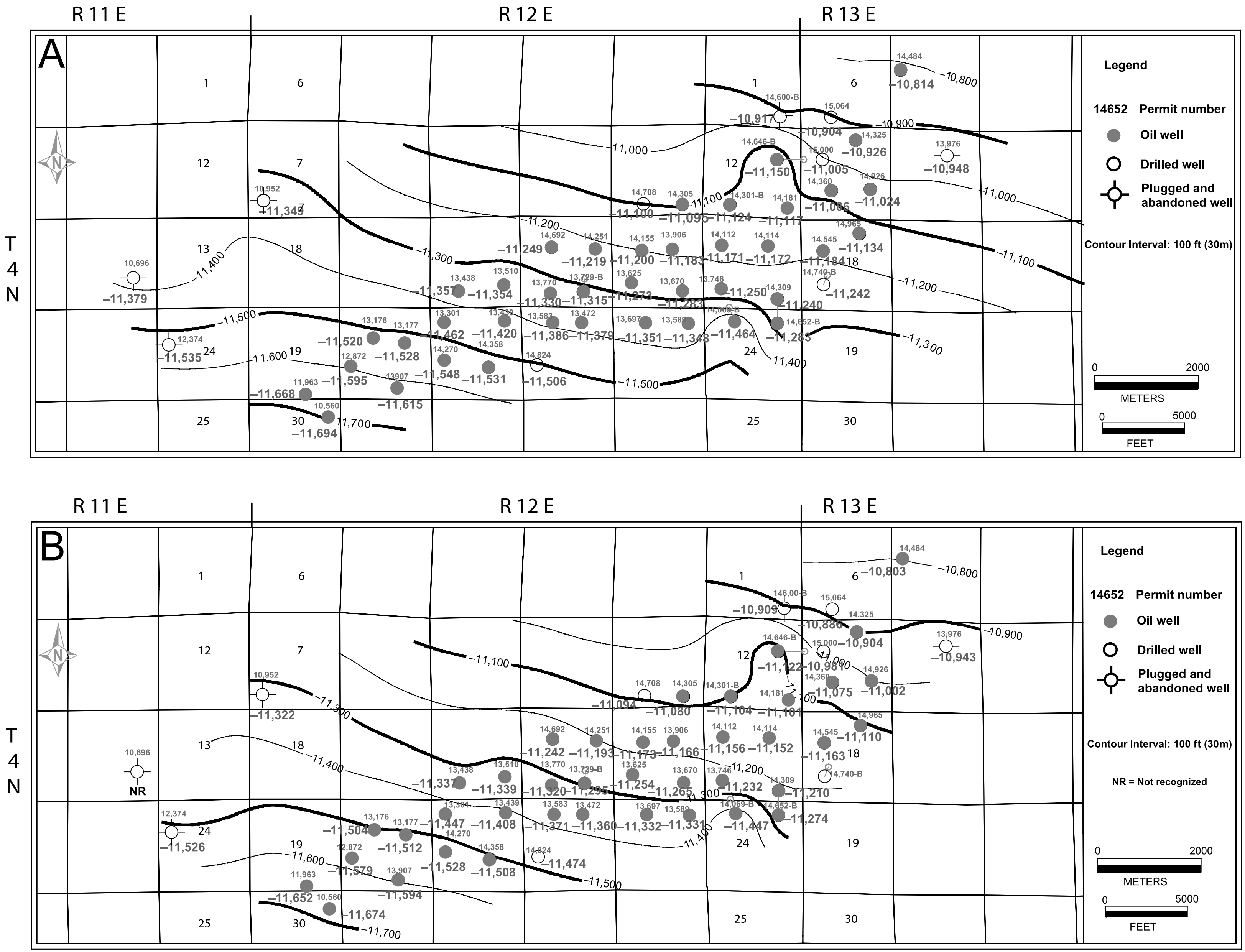


Figure 5. Structure maps: (A) on top of the Norphlet Formation and (B) on top of the Smackover transgressive subtidal lime mudstone and dolomudstone to wackestone in the Little Cedar Creek field area illustrating the absence of structural closure in the field.

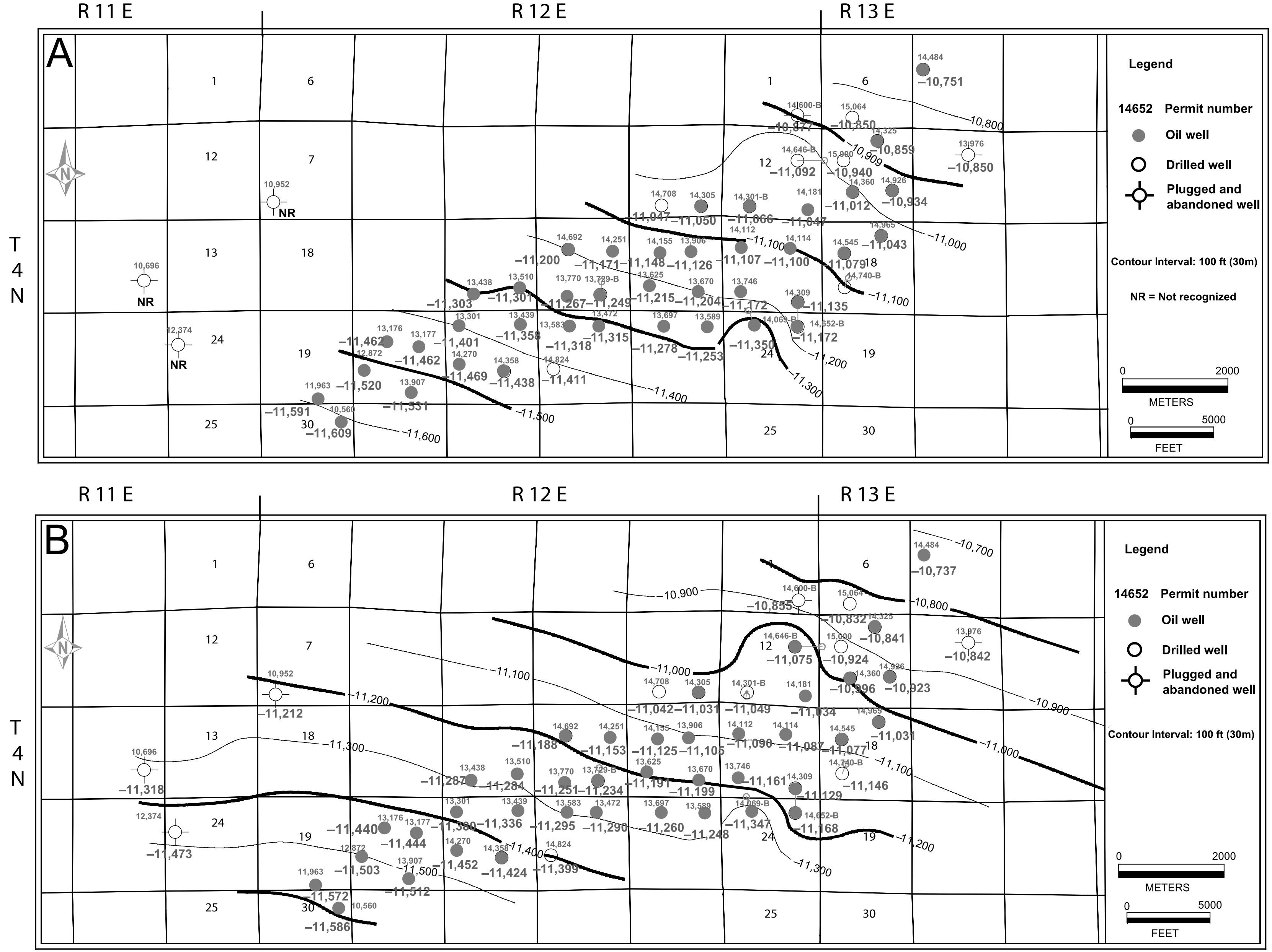


Figure 6. Structure maps: (A) on top of the Smackover deeper water, subtidal lime mudstone and (B) on top of the Smackover Formation in the Little Cedar Creek field area illustrating the absence of structural closure in the field.

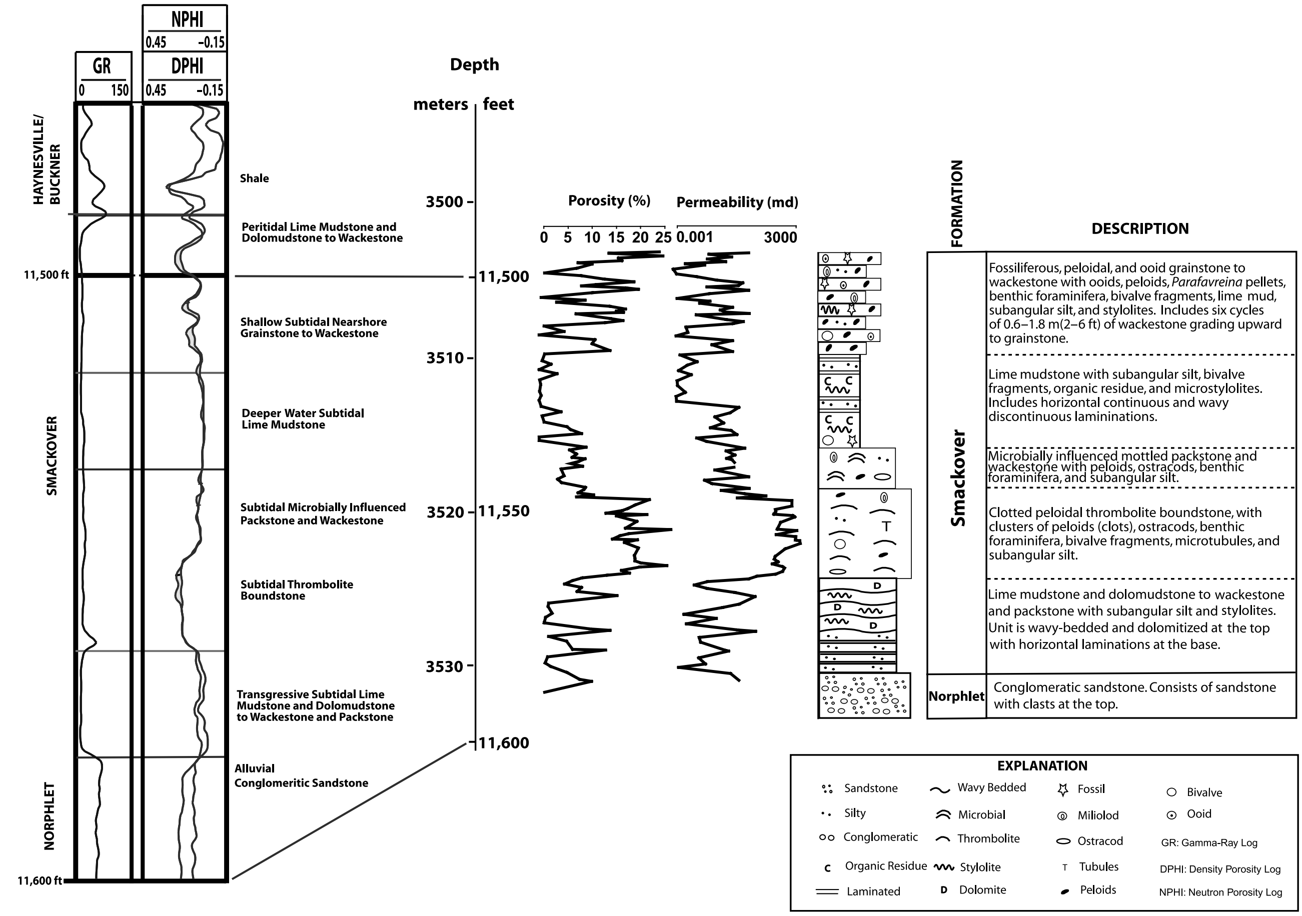


Figure 7. Correlation of wire-line log response, vertical trends in porosity and permeability, and core description for well permit 13472, Little Cedar Creek field (modified from Mancini et al., 2006). Grainstone and packstone constitute the upper reservoir and boundstone and packstone constitute the lower reservoir. The Smackover lime mudstone separating these two reservoirs and the argillaceous beds of the Haynesville (Buckner) and Smackover peritidal lime mudstone and dolomudstone to wackestone are the vertical seal rocks. See Figure 2 for the location of the well.

I; 9F). These facies accumulated in water depths of approximately 3 m (10 ft) and in 5 km (3 mi) of the paleoshoreline (Mancini et al., 2006) (Figures 1, 10).

Reservoir rock textures at the Little Cedar Creek field are similar to those described for Smackover fields that were produced from microbial buildups in southwestern Alabama (Mancini et al., 2004) (Figure 3), in that they include high-energy grainstone and packstone and microbial boundstone. However, these two reservoirs in the Little Cedar Creek field are separated vertically by an intervening deeper water subtidal lime mudstone. In other Smackover fields, the grainstone and packstone reservoir directly overlies the microbial boundstone reservoir (Mancini et al., 2004). The grainstone and packstone and microbial boundstone reservoir facies range in thickness from 0 to 6 m (0 to 20 ft) and 0 to 11 m (0 to 36 ft), respectively, in the Little Cedar Creek field (Table 2). The shallow subtidal nearshore grainstone and packstone reservoir is characterized by a southwest-to-northeast distribution with maximum development in the central part of the field area and is absent along the southern margin of the field (Figures 11, 12A). The boundstone reservoir exhibits a thickness trend characterized by local buildups of thrombolites in the southern part of the field area, and these buildups are absent along the northern margin of the field (Figures 11, 13B). In contrast, the distribution of these grainstone and packstone and microbial boundstone reservoir facies in other Smackover fields that are produced from microbial buildups is commonly continuous (Mancini et al., 2004).

Furthermore, the reservoirs at the Little Cedar Creek field are mainly limestone (Heydari and Baria, 2005), whereas the microbial boundstone and grainstone and packstone reservoirs in other described Smackover fields

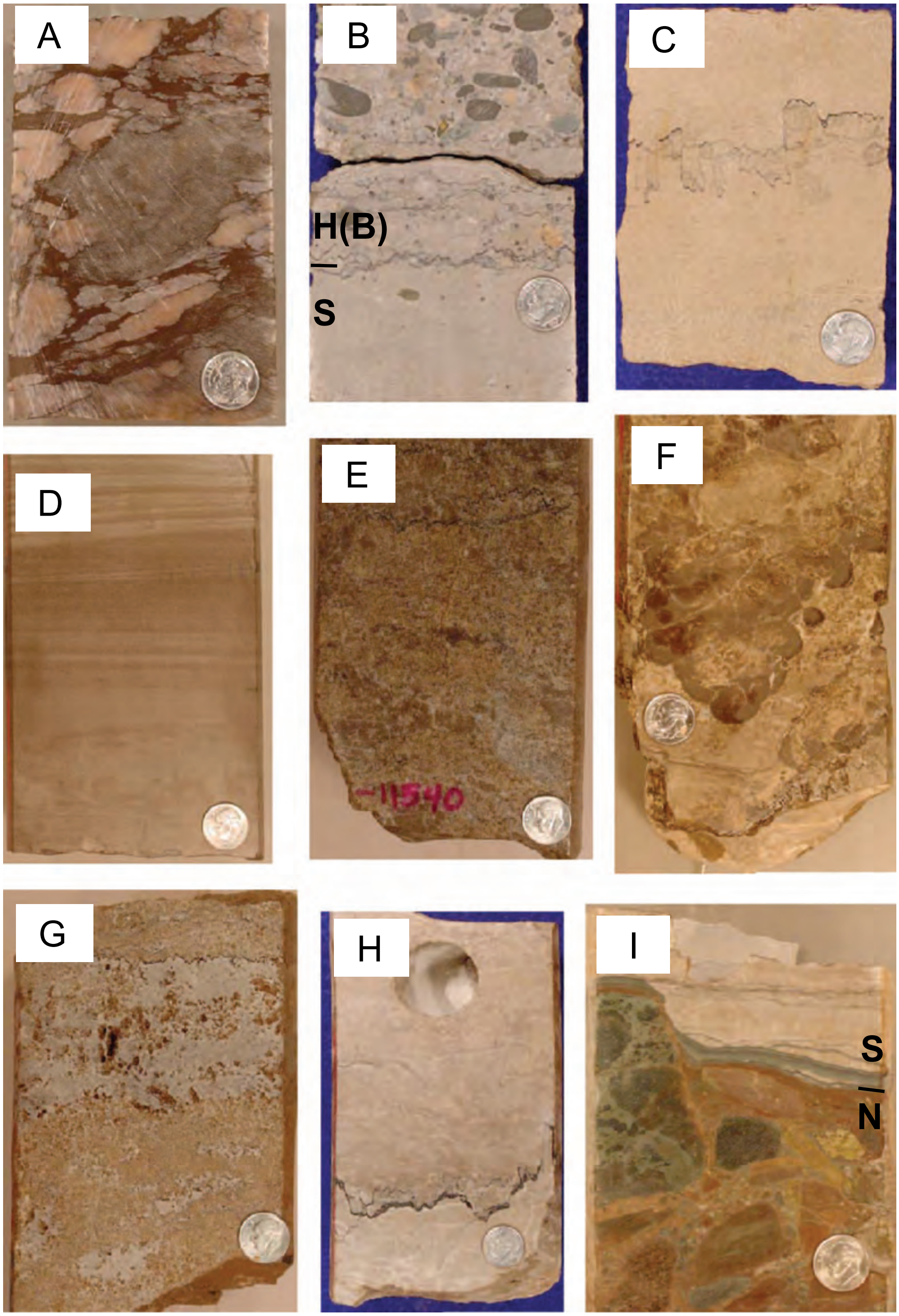


Figure 8. Core photographs of Haynesville, Smackover, and Norphlet facies in the Little Cedar Creek field area. (A) Haynesville (Buckner) anhydrite, well permit 14,251, depth 3457 m (11,341 ft); (B) contact of the upper Smackover lime mudstone and dolomudstone (S) with pebbly sandstone of the Haynesville (Buckner) (H/B), well permit 13,510, depth 3503 m (11,493 ft); (C) ooid grainstone, well permit 13,472, depth 3504 m (11,495 ft); (D) lime mudstone, well permit 13,438, depth 3531 m (11,584 ft); (E) microbially influenced packstone, well permit 13,472, depth 3517 m (11,540 ft); (F) thrombolite boundstone, well permit 14,181, depth 3439 m (11,282 ft); (G) leached thrombolite boundstone, well permit 12,872, depth 3621 m (11,881 ft); (H) wavy-bedded lime mudstone and dolomudstone to wackestone and packstone that underlies the thrombolite boundstone facies, well permit 13,472, depth 3523 m (11,560 ft); and (I) contact of the lower Smackover laminated lime mudstone and dolomudstone (S) with conglomeratic sandstone of the Norphlet Formation (N), well permit 14,305, depth 3438 m (11,279 ft). See Figure 2 for the location of the wells. Diameter of the coin is 18 mm.

in the Conecuh and Manila subbasins are pervasively dolomitized (Mancini et al., 2004). Porosity in the boundstone reservoir at the Little Cedar Creek field chiefly consists of vuggy pores (Figure 9E), and porosity in the nearshore grainstone and packstone reservoir mainly includes grain-moldic pore types (Figure 9A) (Mancini et al., 2006). The predominance of diagenetically modified pore types in the productive intervals

Table 2. Smackover Facies in the Little Cedar Creek Field Area

Environment	Lithology	Constituents	Porosity (%)	Permeability (md)	Thickness, m (ft)	Photograph Reference
Peritidal	Lime mudstone and dolomudstone to wackestone	Lime mud and subangular silt	3–4*	<0.02*	0.3–3.0 (1–10)	Figure 8B
Shallow subtidal nearshore	Grainstone to wackestone	Ooids, peloids, lime mud, bivalve fragments, and subangular silt	16.3**	7.6**	0–6.1 (0–20)	Figures 8C, 9A
Deeper water subtidal	Lime mudstone	Lime mud, bivalves, and subangular silt	0.1–4†	<0.01†	0.3–20.4 (1–67)	Figures 8D, 9B
Subtidal microbially influenced	Lime mudstone to packstone	Peloids, ostracods, foraminifera, and subangular silt	0.1–8†,††	<0.03–9.1†,††	0.3–10.4 (1–34)	Figures 8E, 9C
Subtidal thrombolite	Clotted (peloidal) boundstone	Peloids, ostracods, foraminifera, and subangular silt	10.8**	196**	0–11.0 (0–36)	Figures 8F, G; 9D, E
Transgressive subtidal	Lime mudstone and dolomudstone to wackestone	Lime mud and subangular silt	1–6†	<1.89†	1.8–9.8 (6–32)	Figures 8H, I; 9F

*Based on core analyses from well 12872.
**Based on analyses by field operator (SOGBA Hearings, File Docket No. 9-21-64-4, 5 6 and 12-3-64-4, 2004, personal communication).
†Based on core analyses from well 13472.
††Based on core analyses from well 13976.

at the Little Cedar Creek field illustrates the significance of postdepositional processes in the development of quality reservoirs. Heydari and Baria (2005) published core descriptions, petrographic information, and porosity and permeability data for 10 of the first wells drilled in the field area.

Haynesville (Buckner) anhydrite beds are present in the Little Cedar Creek field area, but these anhydrite beds are thin and discontinuous and do not directly overlie the Smackover reservoirs (Heydari and Baria, 2005; Mancini et al., 2006) (Figure 8A). The vertical seal rocks in this field include the Haynesville (Buckner) argillaceous beds and Smackover lime mudstone and dolomudstone to wackestone (Figure 7) that overlie the upper grainstone and packstone reservoir and the lime mudstone (Figure 8D) that overlies the lower boundstone and packstone reservoir. Reservoir pressure and fluid data indicate a lack of communication between the upper and the lower reservoirs in the Little Cedar Creek field (SOGBA Hearings, File Docket No. 9-29-04-4, 5, 6 and 12-3-04-1, 2004, personal communication).

Source rock analysis shows that the thermal alteration (thermal alteration index [TAI] of 2^- to 3) of the amorphous (microbial) and herbaceous kerogen contained in the Smackover beds may be sufficient for these beds to serve as source rocks. However, the low total organic carbon content (0.10–0.21) and the thinness of these beds are not adequate to generate a commercial amount of hydrocarbons (Table 3). Thus, the oil in this field probably migrated north into the region from the basin center area of the Conecuh subbasin (Mancini et al., 2006).

COMPARISON TO OTHER JURASSIC THROMBOLITES

In western Europe, Upper Jurassic microbial buildups consisting of calcimicrobes (cyanobacteria and other heterotrophic bacteria) and encrusters (foraminifera, algae, *Tubiphytes*, and metazoans) can be viewed in outcrop as mound-shaped features (bioherms) and as conical shaped features (pinnacles). The bioherms attain a thickness of 30 m (98 ft) and encompass an area of 2.3 km^2 (0.9 mi^2) in Portugal (Ramalho, 1988; Leinfelder et al., 1993a). The pinnacles reach a height of 16 m (52 ft) in Spain (Aurell and Bádenas, 1997; Bádenas, 1999). These buildups are interpreted to have developed in normal-marine environments on middle ramp settings of 10–30 m (33–98 ft) of water depth to outer ramp settings of 70–400 m (230–1312 ft) of water depth

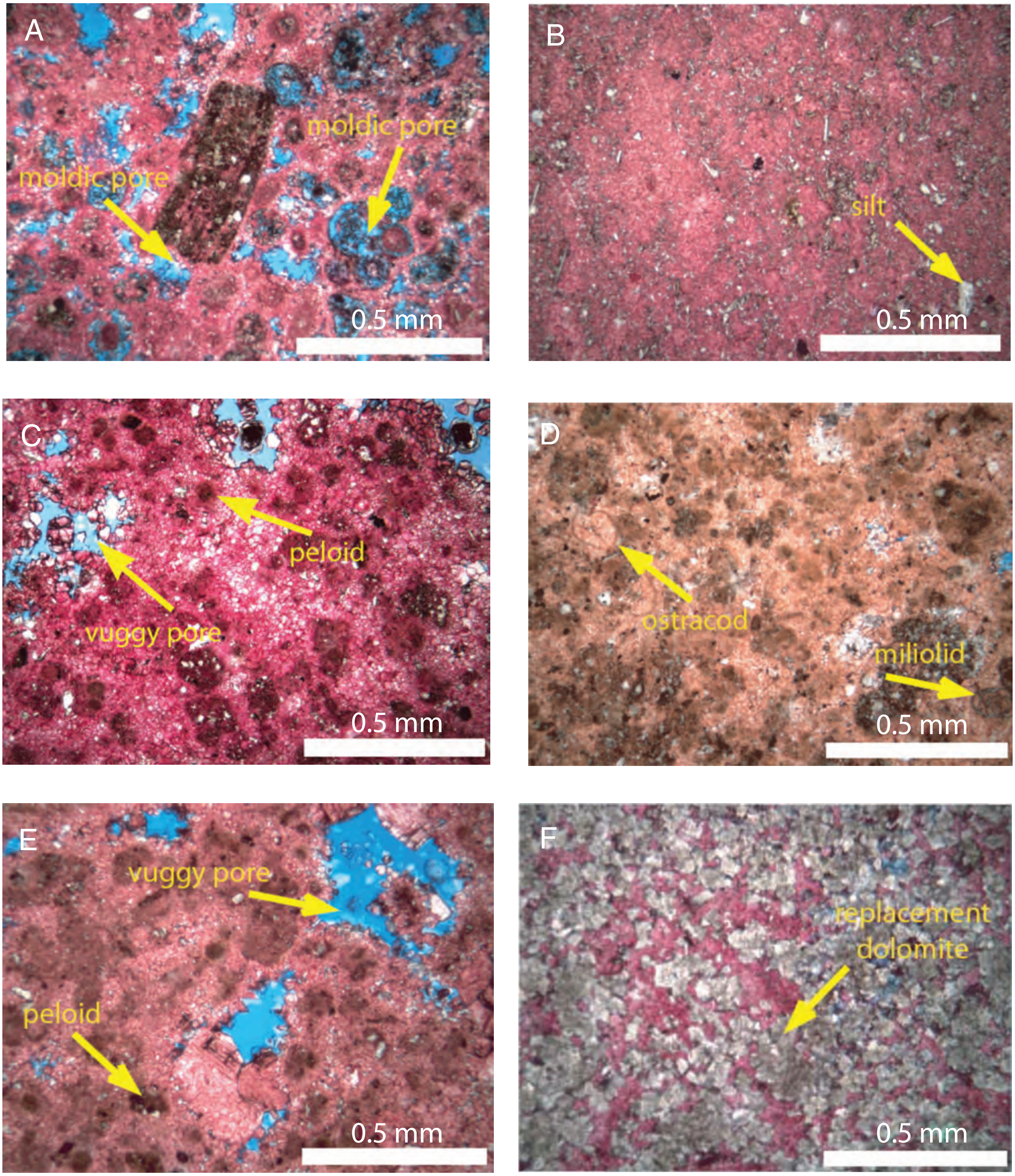


Figure 9. Photomicrographs of the Smackover facies. (A) Ooid grainstone showing moldic pores, well permit 13,472, depth 3504 m (11,495 ft); (B) lime mudstone showing siliciclastic silt content, well permit 13,472, depth 3516 m (11,532 ft); (C) microbially influenced packstone showing vuggy pores and peloids, well permit 13,472, depth 3518 m (11,542 ft); (D) peloidal boundstone showing microfossil content of this facies, well permit 13,439, depth 3532 m (11,589 ft); (E) leached boundstone showing vuggy pores and peloids, well permit 13,670, depth 3483 m (11,426 ft); and (F) lime mudstone to dolomudstone showing replacement dolomite, well permit 13,472, depth 3527 m (11,572 ft). See Figure 2 for the location of the wells.

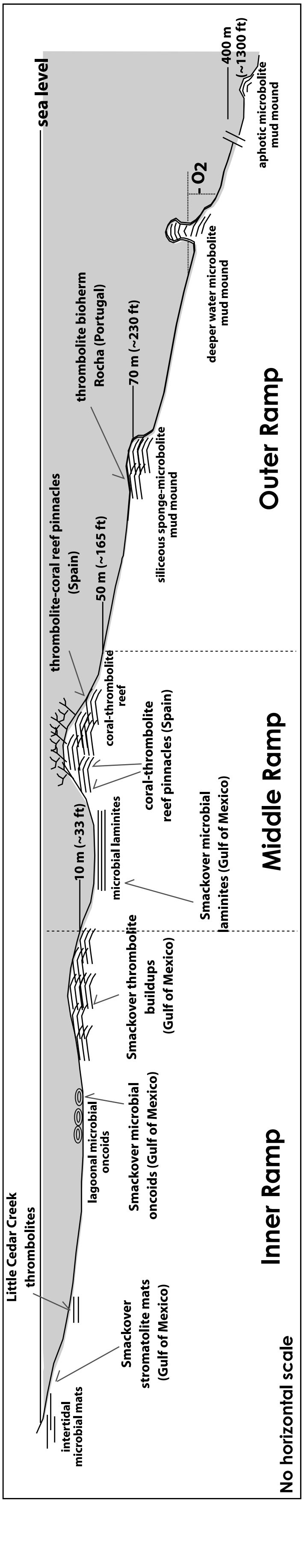


Figure 10. Generalized diagram illustrating the distribution of thrombolite and microbial buildups on a carbonate ramp (modified from Mancini et al., 2004). Note the nearshore inner ramp setting for the Upper Jurassic Smackover thrombolites at Little Cedar Creek field compared to the outer inner ramp setting for the Smackover thrombolites associated with paleohighs such as Appleton and Vocation fields.

(Aurell and Bádenas, 1997; Bádenas, 1999; Leinfelder and Schmid, 2000; Leinfelder, 2001) (Figure 10).

Thrombolites of these types initiate growth during an overall rise in sea level and have the ability to bridge over a soft substrate by producing a biofilm, which later becomes calcified (Leinfelder et al., 1993b). Leinfelder et al. (1993b) further concluded that microbolites are not necessarily limited by water depth, salinity, temperature, light penetration, oxygen content, and/or nutrient supply. They stated that microbolites require a hard substrate for nucleation, zero to low background sedimentation rates for initial growth, and low to moderate background sedimentation rates for continued growth.

Prior to the discovery and development of the Little Cedar Creek field, Smackover microbial buildups were interpreted to occur in shallow water in an inner ramp setting of less than 9 m (30 ft) of water depth and commonly developed on Paleozoic crystalline paleotopographic features (Table 4) (Mancini et al., 2004). These thrombolites attained a thickness of more than 58 m (190 ft) and covered an area of up to 6.2 km^2 (2.4 mi^2) (Mancini et al., 2004). These buildups are composed of calcimicrobes, red algae, foraminifera, sponges, echinoids, and bivalves (Baria et al., 1982; Kopaska-Merkel, 1998, 2002). They developed directly on elevated igneous and/or metamorphic basement rocks in a low-energy paleoenvironment under low background sedimentation rates and fluctuating environmental conditions. Cessation of microbial growth has been interpreted by Mancini et al. (2004) to be related to regressions of the Smackover sea. The buildups commonly were overlain by higher energy, nearshore facies. Microbial facies studied prior to the discovery of the Little Cedar Creek field consisted of highly leached and dolomitized rocks, indicating that depositional topography attained during the growth of these buildups made them susceptible to early diagenetic dissolution and dolomitization. Depositional porosity typically is a mixture of primary fenestral and shelter pores overprinted by dolomite intercrystalline and vuggy diagenetic pore types (Mancini et al., 2004).

The thrombolites at the Little Cedar Creek field developed farther up the depositional dip than other discovered microbolites in the eastern Gulf coastal plain. They were approximately within 5 km (3 mi) of the Smackover paleoshoreline (as inferred to be coincident with the present-day Smackover zero isopach line as recognized by seismic and wire-line log data), suggesting that microbial growth probably occurred in water depths of less than 3 m (10 ft) (Mancini et al., 2006). These thrombolites attained a thickness of more than 11 m

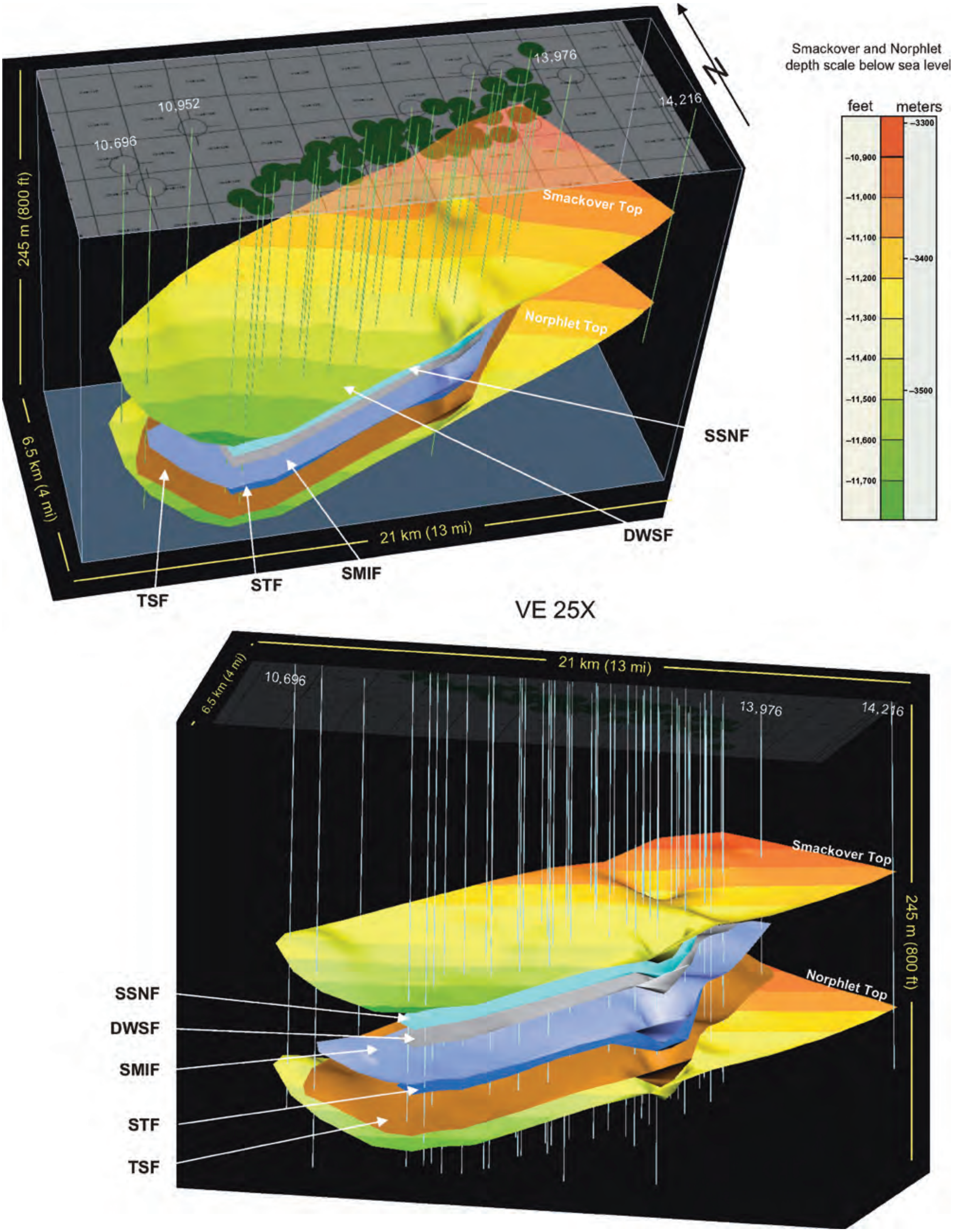


Figure 11. (A) Top view and (B) oblique view of a 3-D visualization of the geometry of the structure and stratigraphy and the facies distribution at the Little Cedar Creek field. TSF = transgressive subtidal facies; STF = subtidal thrombolite facies; SMIF = subtidal microbially influenced facies; DWSF = deeper water subtidal facies; SSNF = shallow subtidal nearshore facies. Peritidal facies are not shown.

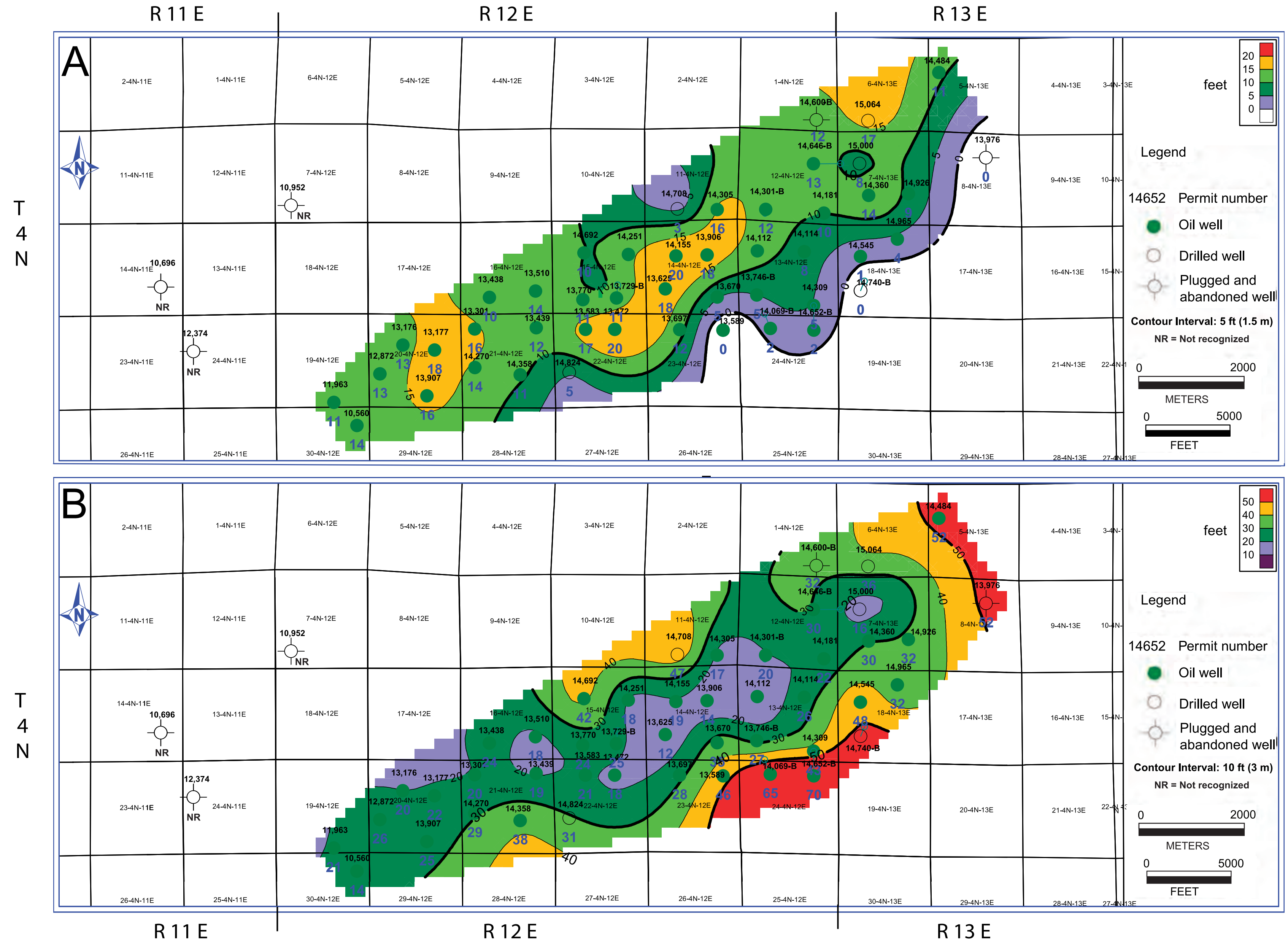


Figure 12. Isopach maps of the (A) shallow subtidal nearshore facies and (B) deeper water subtidal facies in the Little Cedar Creek field area. Note that the shallow subtidal nearshore facies thins or is absent along the southern margin of the field and that this unit attains maximum thickness in the central part of the field in three distinct carbonate bodies oriented parallel with the overall southwest to northeast trend of this facies. The deeper water subtidal lime mudstone facies occurs throughout the field area.

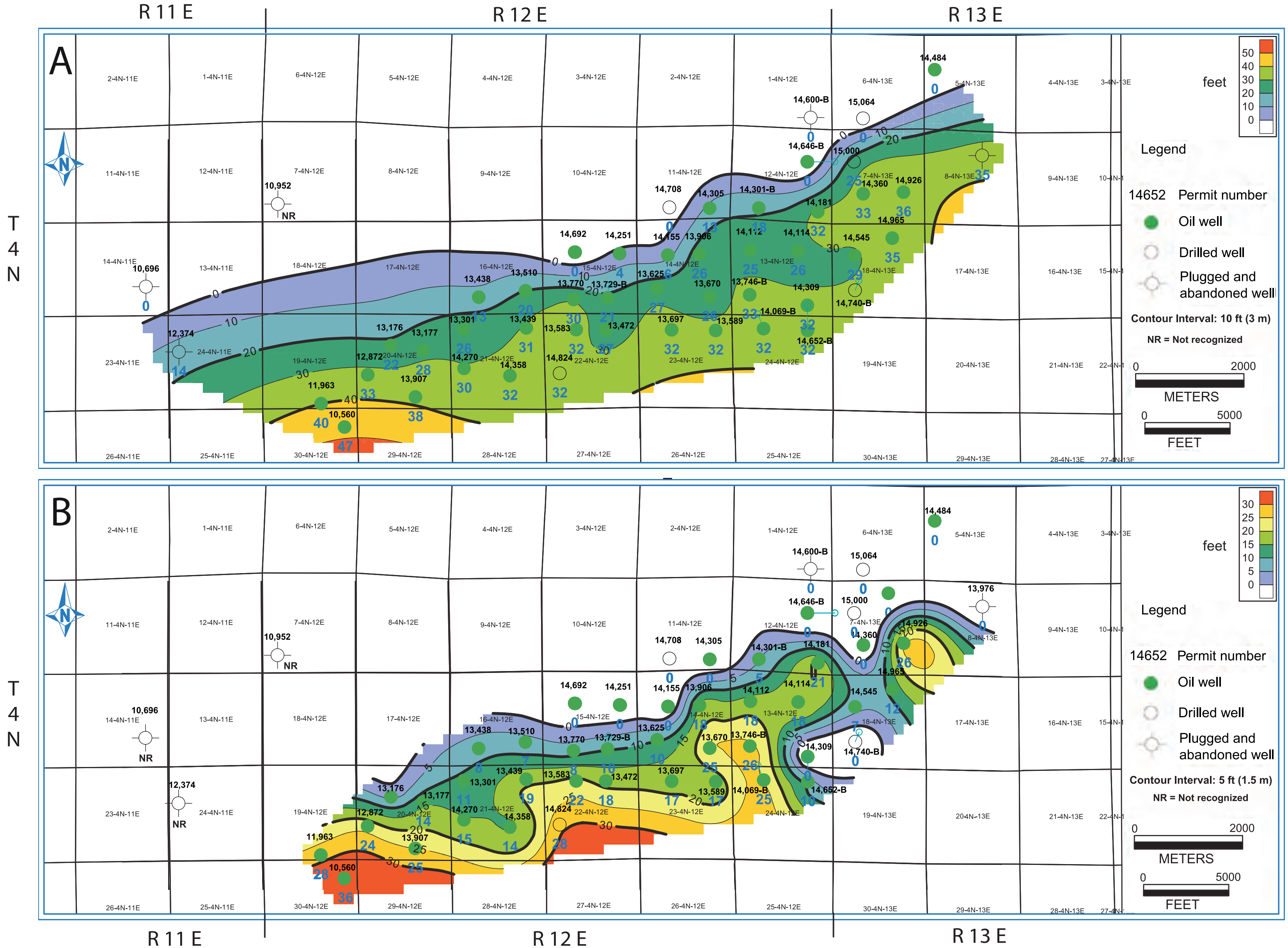


Figure 13. Isopach maps of the (A) subtidal microbially influenced facies and (B) subtidal thrombolite facies in the Little Cedar Creek field area. Note that the subtidal thrombolite facies is absent along the northern part of the field and is thickest in the southern part of the field as four buildups. The microbially influenced packstone to lime mudstone facies occurs throughout the field area.

Table 3. Visual Kerogen Assessment of Smackover Facies at Little Cedar Creek Field

Permit	Depth, m (ft)	Facies	TOC (%)*	OMT**	TAI†
13589	3503 (11,493)	Transgressive lime mudstone	0.12	Am-H††	2^{-} to 2
13583	3524 (11,563)	Thrombolite boundstone	0.21	H-W‡	2
13438	3531 (11,584)	Deeper subtidal lime mudstone	0.17	Am	3^{-} to 3
13301	3547 (11,638)	Nearshore grainstone	0.10	Am	2^{-} to 2

*TOC = total organic carbon.
**OMT = organic matter type.
†TAI = thermal alteration index (scale of 1–5, with subdivisions of minus (−) and plus (+).
††Am = amorphous; H = herbaceous.
‡W = woody.

(36 ft) and occurred over an area of up to 13 km^2 (5 mi^2), with individual buildups covering an area of 2 km^2 (0.8 mi^2) (Figure 13B). The thrombolites consist of clotted peloidal boundstone and include a microfauna of benthic foraminifera, ostracods, bivalves, and microtubules (Mancini et al., 2006).

The distribution of the thrombolite buildups in the field area suggests that their depositional trend follows a subtle pattern. These buildups are absent along the northern margin of the field, and they attain maximum thickness in the southern part of the field (Figure 13B). Furthermore, three thrombolite buildups occur in the southwestern to south-central part of the field separated from a buildup in the southeastern part of the field (Figures 13B, 14). Stratigraphic cross section CC′ illustrates the facies relationships associated with a thrombolite buildup in the south-central part of the field (Figure 15).

The subtle pattern in the depositional trend of the thrombolite facies may be related to antecedent topography on the eroded surface of the Norphlet Formation (Figures 14, 15). In the field area, Norphlet deposits include mainly the alluvial-fan and plain and braided stream deposits (Mancini et al., 1985). Therefore, the Norphlet paleotopography that resulted from variations in alluvial and fluvial depositional facies combined with postdepositional processes may have influenced the development of the thrombolite buildups. However, no subtle features are evident on the structure map drawn on top of the Norphlet Formation (Figure 5A), nor was any such relief observed on the structure map constructed on top of the transgressive subtidal facies that directly underlies the thrombolite facies (Figure 5B). Nevertheless, subtle changes in the elevation of up to 3 m (10 ft) on the top of the Norphlet Formation are observed in cross section BB′ (Figure 14) and cross section CC′ (Figure 15).

Table 4. Comparison of the Sedimentary Characteristics of the Thrombolite Buildups at Little Cedar Creek Field to the Characteristics of Microbial Buildups Associated with Basement Paleohighs

Parameter	Associated with Paleohigh	Little Cedar Creek Field
Thickness	As much as 58 m (190 ft)	As much as 11 m (36 ft)
Areal extent	As much as 6.2 km^2 (2.4 mi^2)	As much as 13 km^2 (5 mi^2)
Sequence stratigraphy	Late transgressive and regressive (early highstand) systems tracts	Late transgressive and regressive (early highstand) systems tracts
Underlying substratum	Paleozoic basement rocks	Localized cemented packstone to grainstone
Overlying facies	Grainstone, packstone, and wackestone	Lime mudstone, wackestone, and packstone
Lateral facies	Lime mudstone and wackestone	Lime mudstone and wackestone
Origin	Shallow water, outer inner ramp	Shallow water, nearshore inner ramp
Environmental conditions	Hard substrate; low background sedimentation; sea level rise; low energy; restricted circulation; fluctuating salinities, oxygen levels, and nutrient supply	Firm substrate; low background sedimentation; sea level rise; low energy; restricted circulation, fluctuating sediment and nutrient

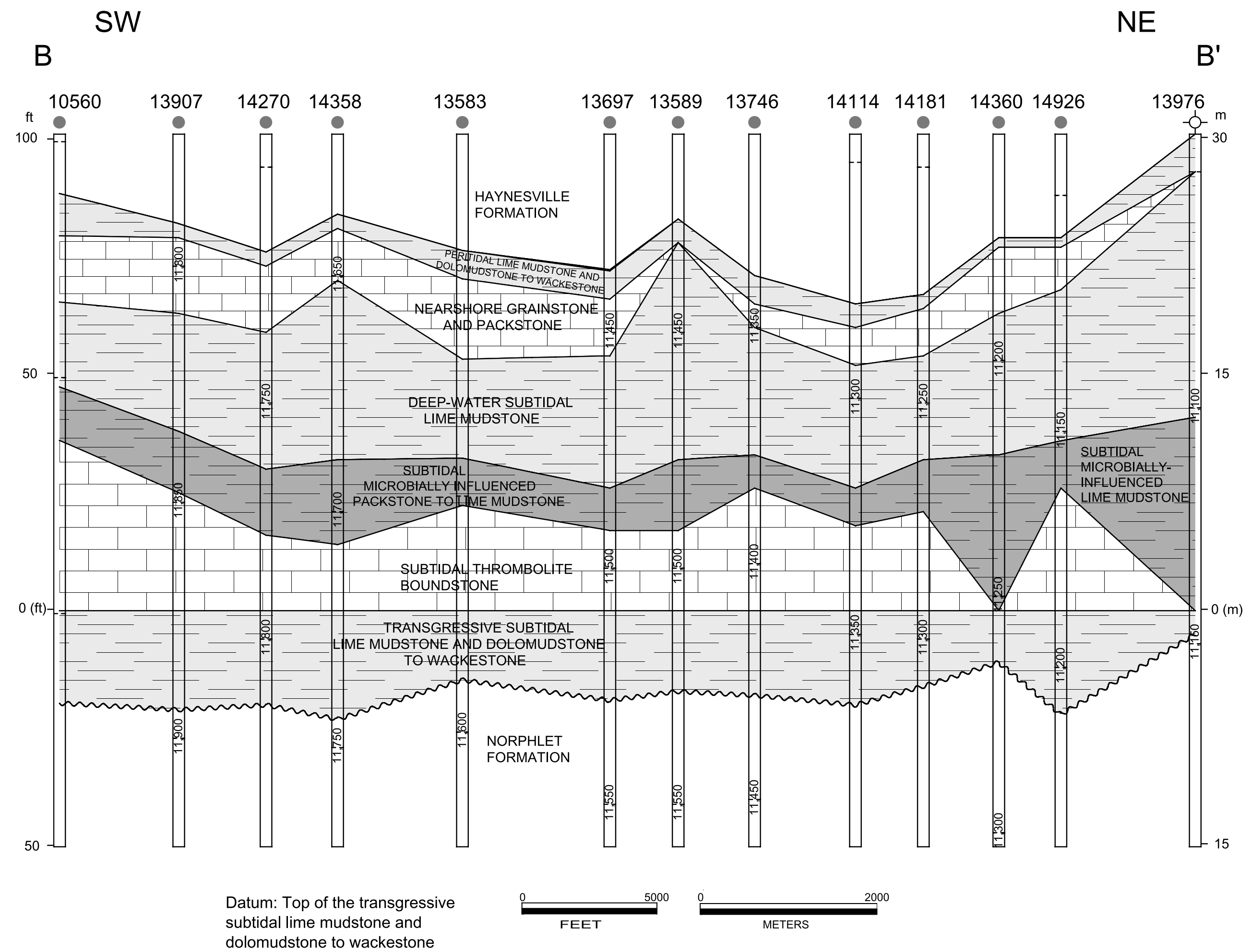


Figure 14. Stratigraphic cross section BB′ illustrating the vertical and lateral facies recognized in the Little Cedar Creek field area. Note that the upper grainstone and packstone reservoir and lower boundstone and packstone reservoir are interbedded with three lime mudstone and dolomudstone to wackestone units (upper peritidal, middle deeper water subtidal, and lower transgressive subtidal) throughout the field; and to the northeast and updip in well permit 13,976, the Smackover section essentially consists of lime mudstone and dolomudstone, supporting the interpretation that the petroleum trap for this field is stratigraphic. This section also shows the thinning of the Smackover transgressive subtidal facies over antecedent topography on the eroded surface of the Norphlet Formation and the presence of four thrombolite buildups in the field, three in the southwestern to south central part of the field and one in the southeastern part of the field. See Figure 2 for the line of cross section.

Additionally, the Smackover transgressive subtidal lime mudstone thins over these higher relief areas. These observations suggest that possible antecedent relief on the Smackover sea floor influenced the accumulation of transgressive lime muds, but antecedent topography on the Norphlet Formation apparently had little influence on development of the thrombolites.

Thrombolite development appears to be a result of a combination of environmental conditions, including bathymetry, hydrologic regime, siliciclastic and freshwater influx, current and wind patterns, water circulation, and the availability of localized hard substrates for nucleation. The occurrence of terrigenous kerogen (herbaceous and woody) and siliciclastic silt associated with the thrombolites indicates an influx of siliciclastic sediment, fresh water, and nutrients into these carbonate environments during microbial growth periods (Tables 2, 3). Wade et al. (1987) reported that Smackover carbonate facies near the paleoshoreline in the Manila subbasin are characterized by terrestrial kerogen. The thrombolites do not directly overlie Norphlet conglomeratic sandstone, but instead, overlie transgressive subtidal lime mudstone and dolomudstone to wackestone and localized packstone (Figure 8H), which

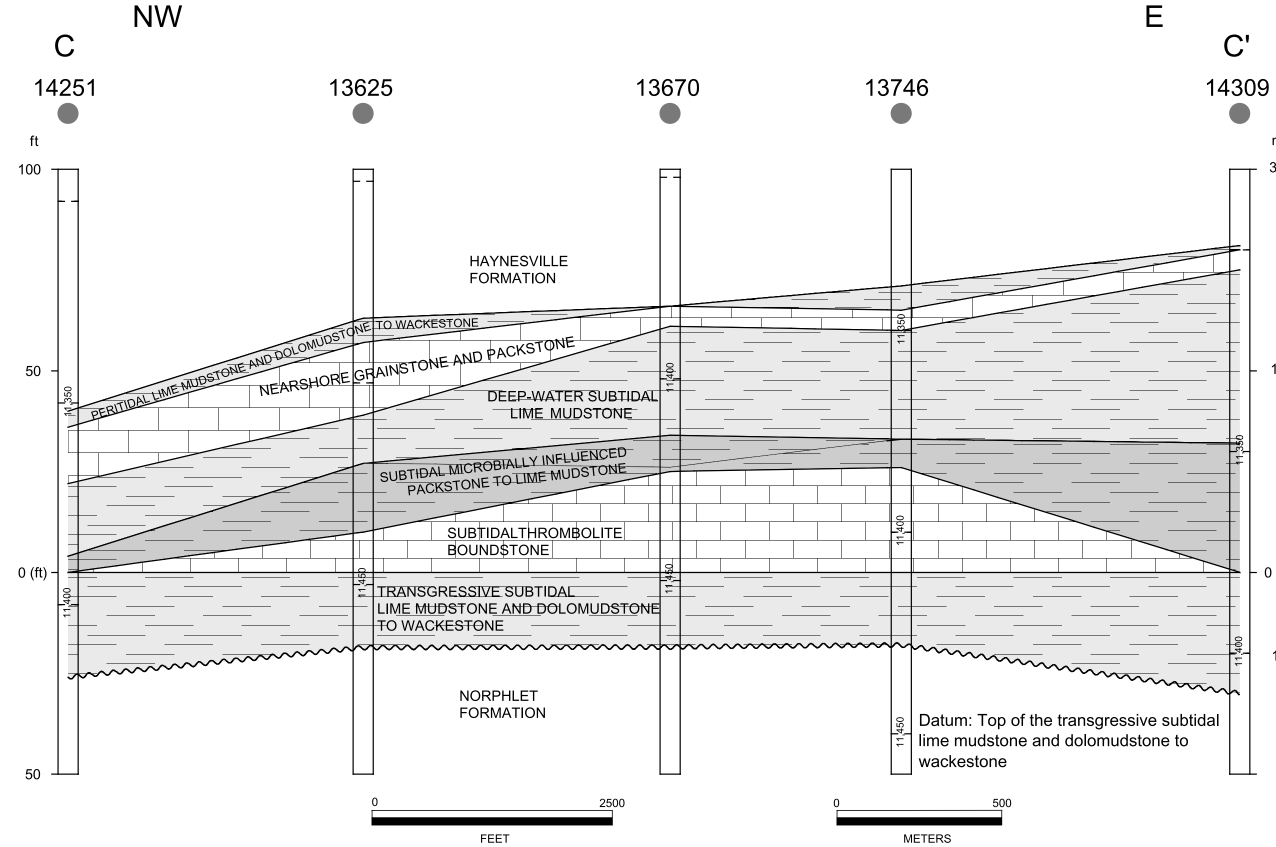


Figure 15. Stratigraphic cross section CC′ illustrating the facies relationship of a thrombolite buildup in the central part of Little Cedar Creek field. Note the lateral thickness changes in the facies, particularly the thinning of the high-energy grainstone and packstone to the east, where the thickness of the buildup thins and the transgressive subtidal lime mudstone and dolomudstone to wackestone facies thickness in the apparent Norphlet low-relief area. See Figure 2 for the line of cross section.

exhibit microbially influenced features. In addition, the buildups are overlain by microbially influenced packstone to lime mudstone (Figure 7). The microbially influenced facies is present throughout the field area (Figure 13A), but the thrombolite buildups are restricted to the southern part of the field. The microbially influenced facies varies in texture from packstone to lime mudstone. The packstone is a reservoir in parts of the field (Figures 8E, 9C), and the lime mudstone serves as part of the updip lateral seal in the northeastern area of the field. Thrombolites have the ability to nucleate on a localized favorable substrate such as a bivalve fragment or a cemented grainstone-packstone lens, and they have the capacity to bridge across soft substrates by producing biofilms. Because the buildups are not directly overlain by strandplain or shoal deposits, their demise was probably a result of an overall deterioration of environmental conditions, including a continued influx of freshwater and/or siliciclastic sediment.

The distribution of the shallow subtidal nearshore grainstone and packstone suggests that deposition was affected by subtle bathymetric and/or environmental controls. This high-energy nearshore facies is oriented in a southwest-to-northeast direction and thins or is absent along the southern margin of the field (Figure 12A). These deposits attain a maximum thickness in the central part of the field in three distinct carbonate bodies oriented parallel with the overall trend of this facies. Stratigraphic cross sections BB′ (Figure 14) and CC′ (Figure 15) show that where the high-energy grainstone and packstone is thickest, the underlying low-energy lime mudstone thins, suggesting a reciprocal sedimentary or facies relationship between these two units. The subtidal lime mudstone occurs throughout the field area (Figure 12B). Paleotopography does not appear to be a controlling factor in that no localized elevated features are evident on the structure map drawn on top of the underlying lime mudstone (Figure 6A). In addition, in cross sections BB′ and CC′ (Figures 14, 15), no consistent relationship between the thrombolite buildups and the overlying high-energy facies is observed. The development of the shallow subtidal nearshore facies is probably a result of a combination of conditions at the time of deposition, including bathymetry, hydrologic regime, current and wind patterns, and water circulation.

EXPLORATION STRATEGY

In 1967, oil was discovered at Toxey field, southwestern Alabama, in Smackover shoal and shoreface facies. The petroleum trap at this field is a Paleozoic basement paleotopographic feature related to the Choctaw Ridge complex (Figure 1). The first recognized Smackover microbial boundstone was encountered with the discovery of Uriah field in 1970. Smackover shoal and shoreface grainstone associated with a Paleozoic paleohigh related to the Conecuh Ridge complex were productive in this field. Vocation field, which is located on a Paleozoic high also related to the Conecuh Ridge complex, was discovered in 1971. Microbial boundstone and shoal and shoreface grainstone are hydrocarbon productive in this field. The Appleton field was discovered in 1983. This field produces from microbial boundstone and shoal and shoreface grainstone associated with a crystalline paleohigh.

The key to making these early Smackover field discoveries was the recognition of paleotopographic anomalies in seismic reflection data. As the play developed, a crucial element in determining drilling locations was the ability to predict whether reservoir facies developed on both the crest and flanks of a paleohigh or only on the flanks of the feature. This determination was particularly important because Paleozoic paleohighs were both emergent and submergent during Smackover carbonate accumulation (Mancini et al., 2004). Through the use of three-dimensional (3-D) seismic reflection technology, the assessment as to whether Smackover facies were present on the crest and/or flanks of a particular paleohigh was improved, and exploration risk was reduced.

With play maturity and field development, emphasis was placed on determining the distribution of favorable reservoir facies and depositional and diagenetic processes conducive to preserve and enhance reservoir quality. Mancini et al. (2004) and Llinás (2004) discussed the determination as to whether microbial boundstone and/or shoal and shoreface grainstone was associated with a given paleohigh. These authors developed stratigraphic and structural models for the development of potential microbial reservoirs on the crest and/or flanks of high-relief (emergent) and low-relief (submergent) paleohighs. They integrated outcrop studies with 3-D seismic data to identify potential microbial buildups associated with paleohighs (Figures 16, 17). These authors found that diagenesis (chiefly dolomitization) was a critical factor in preserving and enhancing reservoir quality, although the primary control on reservoir architecture and the distribution of the Smackover microbial boundstone and shoal and shoreface grainstone reservoirs was the fabric and texture of the depositional facies. They observed that productive microbial reservoir facies were characterized by a regular pattern of lower gamma-ray values coupled with higher neutron and density porosity values. This relationship between productive facies and wire-line log signature is also the case with the log response to the thrombolite reservoir facies in the Little Cedar Creek field area (Figure 7). They concluded that in the exploration for microbial buildups associated with paleohighs, it was important to focus on the identification and delineation of low-relief crystalline basement paleohighs associated with boundstone that was dolomitized. They reported that the use of 3-D seismic data provided the necessary technology to achieve exploration success. The knowledge of microbial growth characteristics and the results from 3-D geologic modeling of the development of a microbial buildup were found to be crucial in the design of a successful exploration strategy for these buildups.

The discovery and development of the Little Cedar Creek field have shown that the exploration strategy described by Mancini et al. (2004) and Llinás (2004) to find hydrocarbon-productive microbial buildups requires refinement. Little Cedar Creek field is projected to be ultimately one of the most productive Smackover fields in the eastern Gulf coastal plain based on the estimate of oil that is predicted to be recovered from this field (SOGBA Hearings, File Docket No. 9-29-04-4, 5, 6; 12-3-04-1; and 9-5-07-15, 2004 and 2007, personal communication). The petroleum geology of this field and its reservoirs are unique in comparison to other Smackover fields producing from microbial reservoirs. For example, the petroleum trap is stratigraphic, instead of a Paleozoic basement paleohigh or combination structural and stratigraphic trap as seen at Vocation and Appleton fields. At the Little Cedar Creek field, thrombolites nucleated and grew on a localized favorable substrate, instead of on elevated crystalline basement rocks (Table 4). The high-energy, nearshore reservoir facies is separated from the thrombolite reservoir facies by an intervening deeper water subtidal seal facies instead of directly overlying the thrombolite reservoir facies. Dissolution is the critical diagenetic element in producing grain-moldic pores in the grainstone and packstone reservoir and in producing vuggy pores in the

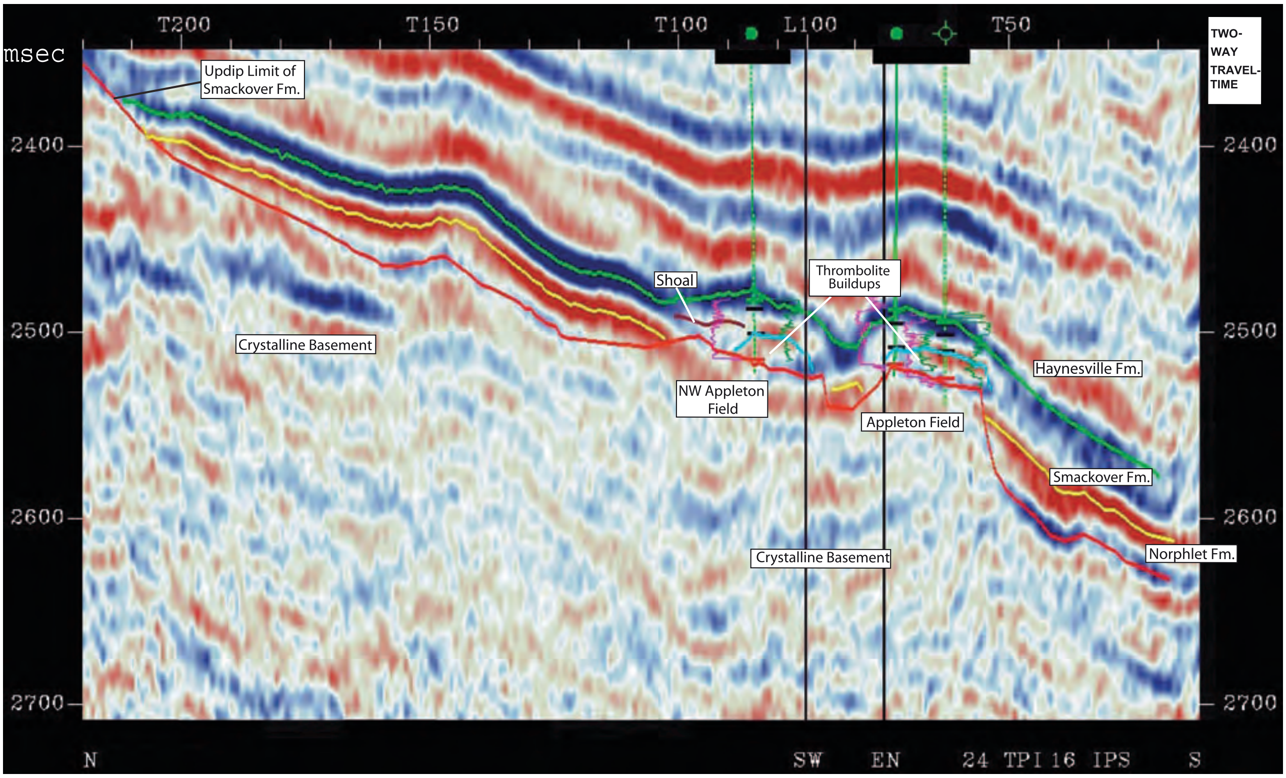


Figure 16. Seismic profile oriented in an approximate dip direction showing the Upper Jurassic Smackover thrombolite buildups on paleohighs in the Appleton and Northwest Appleton field area (modified from Mancini et al., 2004). Note that no buildups are observed near the updip limit of the Smackover Formation on this profile. The buildups at Appleton and Northwest Appleton fields are interpreted as bioherms. See Figure 17 for a comparison of these features to an outcrop analog.

boundstone reservoir at the Little Cedar Creek field; in contrast, dolomitization and leaching are the crucial diagenetic elements in producing dolomite intercrystalline, grain-moldic, and vuggy pores in reservoirs at Vocation and Appleton fields. Two seals to the vertical migration of hydrocarbons are present at the Little Cedar Creek field, instead of a single vertical seal at other Smackover fields. The seals consist of an upper top seal of Haynesville (Buckner) argillaceous beds and Smackover lime mudstone and dolomudstone to wackestone that overlie the grainstone and packstone reservoir and a lower top seal of lime mudstone that overlies the boundstone and packstone reservoir. The Buckner anhydrite member of the Haynesville Formation that overlies the Smackover Formation is the top seal throughout most of the eastern Gulf coastal plain.

Geoscientists have searched for an updip Smackover stratigraphic trap for decades in the eastern Gulf coastal plain, and the information acquired from the discovery and development of Little Cedar Creek field indicates that at least one example of this type of petroleum trap has been discovered at this field. The challenge now is the design of an effective exploration strategy to find additional Smackover stratigraphic traps in this area. The current exploration strategy of relying on seismic data to find paleohighs and associated productive microbial facies requires refinement because of resolution limitations of seismic data caused by the thinness and depth of the reservoir intervals at the Little Cedar Creek field. In addition, the petroleum trap at this field is not a combination trap associated with a localized basement paleohigh. The key elements to be considered in the design of a refined exploration strategy to identify new wildcat well-drilling sites include thorough knowledge of the regional geology of the area targeted for exploration, refined subsurface interpretation of the stratigraphy and structure of the prospective area, and detailed subsurface mapping, in conjunction with reservoir characterization, based on an integration of wire-line log and core data. An improved fieldwide development plan requires the consideration of the following: logging, coring, and testing of the drilled wildcat wells; detailed geologic, petrophysical, geochemical, and engineering studies of the acquired wire-line

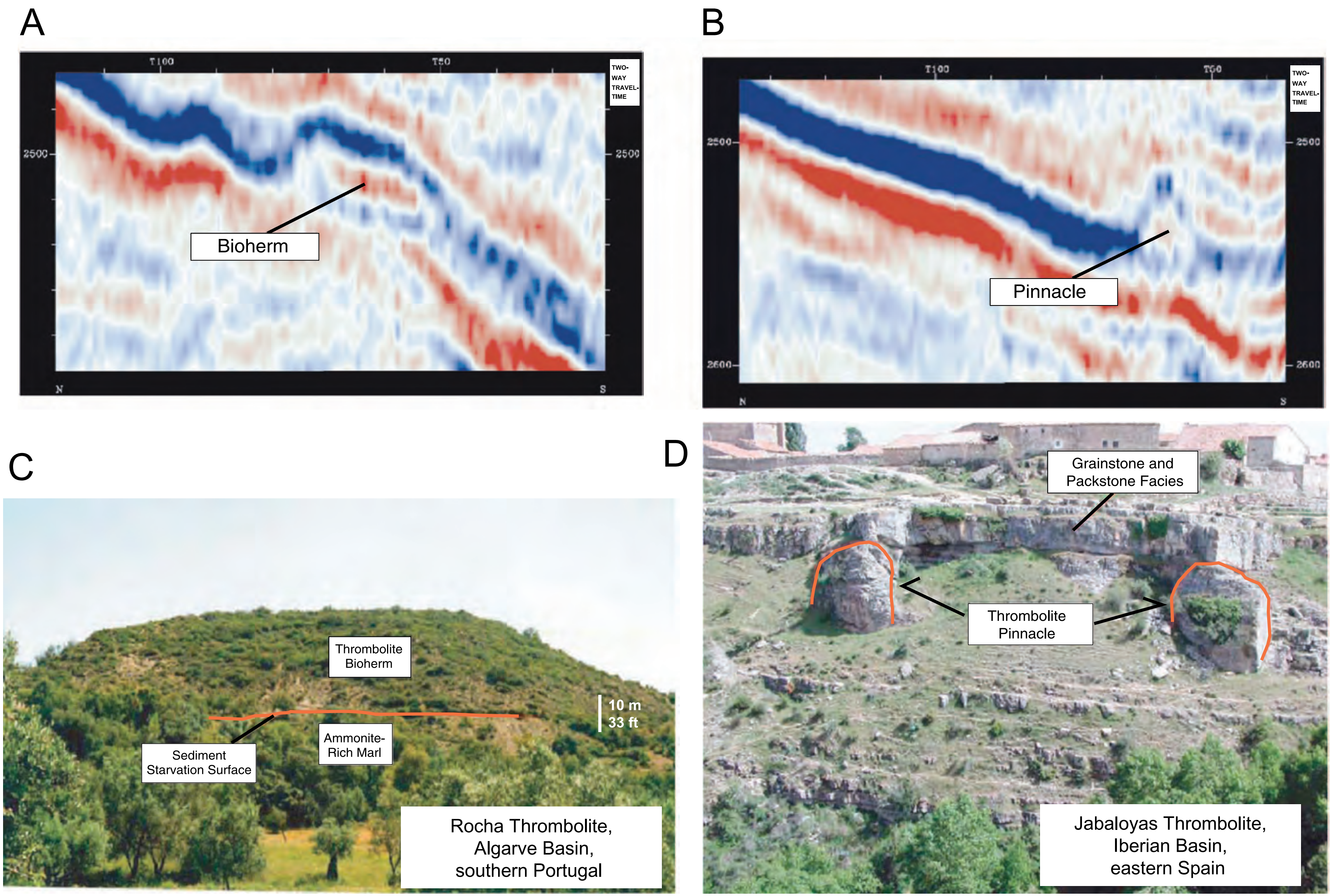


Figure 17. (A) Example of a thrombolite bioherm interpreted in Figure 16 and (B) example of a microbial buildup west of Appleton field interpreted as a pinnacle feature not seen on the seismic profile illustrated in Figure 16. Photographs (modified from Mancini et al., 2004) of these respective thrombolite buildups as viewed in outcrop from western Europe (Portugal and Spain) are included for reference. Bioherms attain a thickness of 30 m (98 ft) and cover an area of 2.3 km^2 (0.9 mi^2) in Portugal, and pinnacles attain a thickness of 16 m (52 ft) in Spain.

log, core, and well-test data; and reservoir characterization, performance analysis, and modeling studies to evaluate reservoir heterogeneity and connectivity. The reservoir characterization and modeling of the petroleum trap and reservoirs at the Little Cedar Creek field presented in this study have demonstrated the importance of these elements in the formulation of an exploration strategy and in the design of a field-scale development plan.

CONCLUSIONS

The development of the Little Cedar Creek field has shown that hydrocarbon-productive microbial and high-energy, nearshore carbonate facies were deposited in shallow subtidal water depths in an inner ramp setting near the Upper Jurassic (Oxfordian) Smackover paleoshoreline in the eastern Gulf coastal plain of the United States. These buildups, which are composed of thrombolites, did not grow directly on localized Paleozoic crystalline basement paleohighs.

The petroleum trap at the Little Cedar Creek field is a stratigraphic trap near the updip limit of Smackover deposition. The upper grainstone and packstone reservoir and lower boundstone and packstone reservoir are interbedded with three lime mudstone and dolomudstone to wackestone units that encase these reservoirs vertically and laterally. Updip and to the northeast of the field, the Smackover section consists of lime mudstone and dolomudstone, thus providing the updip seal for this stratigraphic trap.

To be successful in the search for the Upper Jurassic hydrocarbon accumulations in microbial and high-energy, nearshore facies associated with stratigraphic traps in the Gulf coastal plain, it is important to have a thorough knowledge of the regional geology of the area targeted for exploration, to perform refined subsurface interpretation of the stratigraphy and structure of the prospective area, and to conduct detailed subsurface mapping and reservoir characterization studies based on an integration of wire-line log and core data.

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