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Godo, Ted, 2017, The Appomattox field: Norphlet Aeolian sand dune reservoirs in the deep-water Gulf of Mexico, *in* R. K. Merrill and C. A. Sternbach, eds., Giant fields of the decade 2000–2010: AAPG Memoir 113, p. 29–54.

The Appomattox Field: Norphlet Aeolian Sand Dune Reservoirs in the Deep-Water Gulf of Mexico

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ABSTRACT

Exploration for oil in the Norphlet reservoir in the deep-water Gulf of Mexico began in 2003 at prospect Shiloh (DC269). The well found oil but not an economic volume. The second prospect, Vicksburg (DC353), was drilled in 2007. This well found a larger in-place volume of oil, but with an immovable solid hydrocarbon component within pore spaces, there was great uncertainty as to the potential producible volumes. Two subsequent wells (Fredericksburg [DC486] and Antietam [DC268]) were dry and had a very small amount of oil, respectively. Finally, in late 2009, the fifth well (Appomattox [MC392]) was a significant discovery of high-quality oil in a thick aeolian Norphlet sandstone.

INTRODUCTION

The first oil discovery made in the Norphlet reservoir occurred in Mississippi in 1967. This discovery initiated exploration for the Norphlet reservoir that resulted to date with finding 32 small oil and gas discoveries (northeast Texas, 2; Mississippi, 15; Alabama, 14; and Florida, 2) (Figure 1). The fairway of Norphlet exploration extended southeast into the shallow Gulf of Mexico state waters of Mobile Bay. In 1979, a discovery in the bay was made whereupon further exploration continued there throughout the 1980s and 1990s. The first production in Mobile Bay occurred in 1989. Also during the 1980s, other exploration wells were drilled in federal waters of the Florida panhandle occurred with only small discoveries of oil and gas. None of these small discoveries in federal waters were ever produced.

Exploration of the Norphlet in the deep waters of the Gulf of Mexico deep-water Norphlet play segment began with lease acquisition in December 2001 (Figure 1). The first well drilled prospect Shiloh (DC269) and targeted three stacked Jurassic objectives (Cotton Valley [Tithonian] and Haynesville [Kimmeridgian] deltaic sandstones, and Norphlet [Callovian] aeolian sandstones) (Godo, 2006). At Shiloh, the only oil found was in the Norphlet sandstone, which was both sealed and charged by the overlying Smackover. The results at Shiloh prompted further exploration and drilling in the deep water for additional Norphlet prospects. Exploration drilling continued through 2009 with some oil found in the first Vicksburg well and a dry hole at Fredericksburg prospects, but no commercial success. The learnings from each well greatly helped to identify specific

DOI:10.1306/13572000M1133680

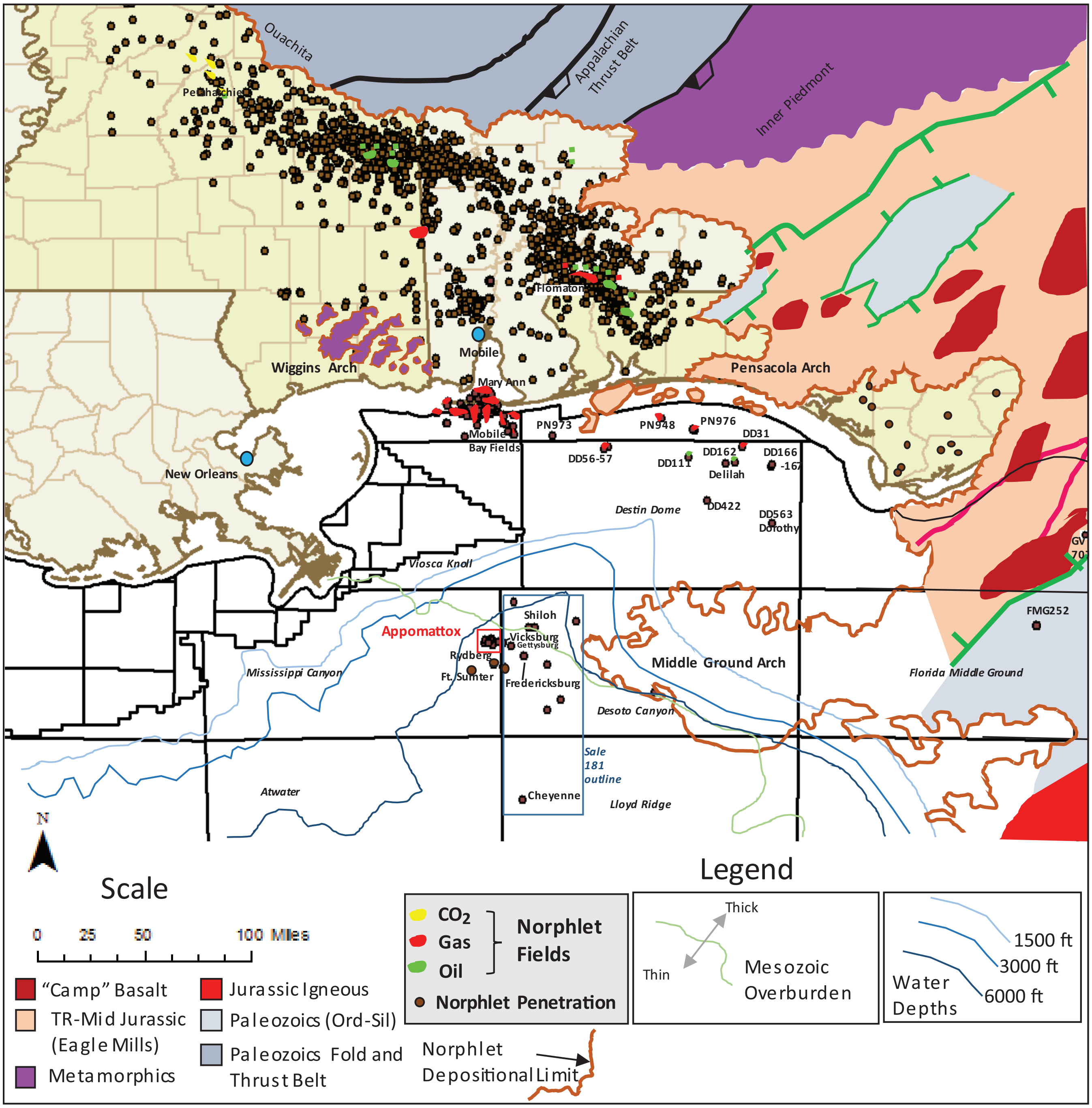

Figure 1. The Norphlet sandstone has been penetrated onshore in the Southern gulf coast states (brown circles). Offshore well locations are identified by the protraction abbreviation and the wells block number or their prospect name. Norphlet exploration since 2003 has been in water depths greater than 5000 ft (1524 m). The names of Shell's prospects were used from American Civil War battles.

critical risk factors to enhance the understanding of the key play elements. Finally, in late 2009, economic success was achieved with the discovery of the thick oil charged aeolian sands in the Appomattox field.

The Norphlet reservoirs discovered to date have shown that thick aeolian sand development (up to 900 ft [274 m] true vertical thickness) with high net-to-gross ratios are present in the current deep-water play environment. The oil has excellent qualities and low viscosity. At Appomattox, the Norphlet reservoir should average a peak production estimated to reach approximately 175,000 barrels of oil equivalent (BOE) per day and includes the development of approximately 650 million BOE resources from the Appomattox and adjacent Vicksburg fields. Additional new nearby discoveries by Shell at prospects Fort Sumter and Rydberg could easily bring the total resource volume to over 800 million BOE.

This chapter is intended to review the historical aspects of the Norphlet play as well as to summarize and integrate much of the excellent industry work that led to the discovery of the Appomattox field in 2009.

REGIONAL STRATIGRAPHY AND STRUCTURAL SETTING

Synrift Phase: Deposition of the Eagle Mills

The Gulf of Mexico began to form after the initial rift stage that separated North and South America. The earliest opening began along the Atlantic margin, with successive rifting beginning from the north and progressively younger age rifting to the south. The rift basins along the present-day Atlantic coast are filled with continent-derived fluvial and lacustrine red beds referred to as the Newark Supergroup (Olsen, 1997). Sediments in the Newark Supergroup consist of a dryland red bed sequence of alluvial and fluvial conglomerates, sandstone, and siltstone with occasional lacustrine mudrocks. All of these sediments are intruded by Jurassic diabase sills, dikes, and extrusive flow deposits. Basalt intrusions and flows occurred over a 10 million km^2 (4 million mi^2) area of central Pangaea, dated at approximately 200 Ma (also known as CAMP—Central Atlantic Magmatic Province) (Manspeizer et al., 1988; Olsen, 1997; Marzoli et al., 1999; Hames et al., 2000; McHone, 2000). In the onshore trend of rift basins, diabase igneous rocks in dikes have been radiometrically dated at 180 to 200 Ma (Scott et al., 1961; Baldwin and Adams, 1971; Ash, 1980; Chowns and Williams, 1983; Arthur, 1988).

In the southeastern United States, synrift deposition occurred from the Late Triassic into the lower Jurassic (Cornet and Olsen, 1985) (Figure 2). The South Georgia rift trend—the southern continuation

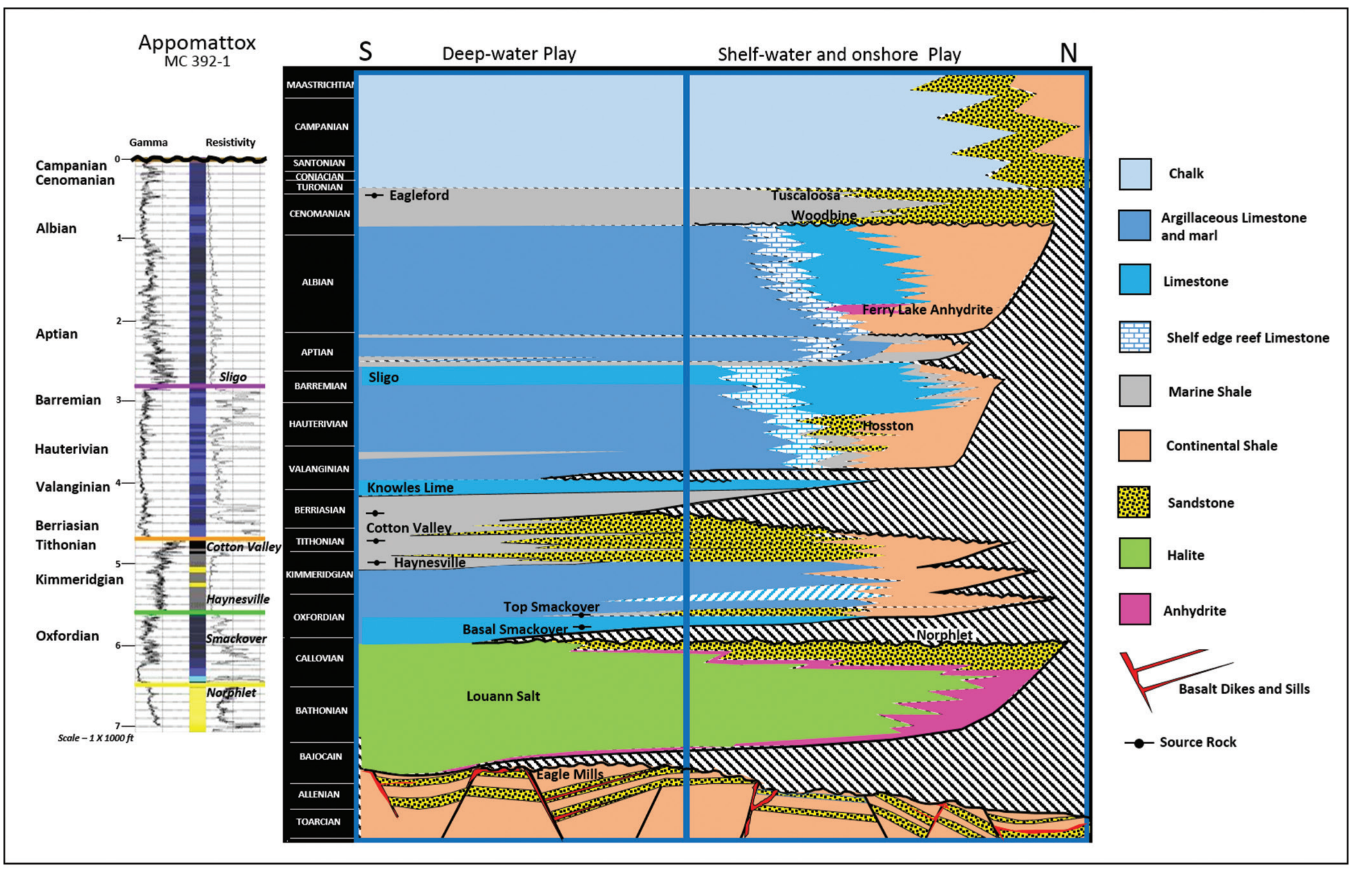

Figure 2. This stratigraphic column illustrates the lateral changes from shelf to basinal positions. This column only shows the Mesozoic stratigraphy of the eastern Gulf of Mexico highlighting general lithologies. Note the stratigraphic location of the Norphlet sandstone deposited directly on evaporites. The Norphlet clastic wedge represents the ephemeral fluvial wash and aeolian sands deposited around the rim edge of the forming Gulf of Mexico. The Appomattox well left of the column illustrates the typical gamma-ray and resistivity response of the stratigraphic column.

of the Atlantic rift margin—cuts across South Carolina and southern Georgia into northern Florida. The offshore extension of this trend into the northeast Gulf of Mexico covers portions of the Gainesville, Destin Dome, and Desoto Canyon protraction areas (Scott et al., 1961; Gohn et al., 1978; Mitchell-Tapping, 1982; Chowns and Williams, 1983; Moy and Traverse, 1986; Thomas, 1988; Raymond, 1989; Salvador, 1991; Burch and Weidie, 1994; Macrae and Watkins, 1995; Wood and Benson, 2000; Heffner, 2013; Parker, 2014). The Eagle Mills Formation was deposited within the rift grabens and then spilled across a wider initially sagging basin. The environment of deposition for Eagle Mills sediment was a dryland environment (Mitchell-Tapping, 1982; Harrelson and Ingram, 2000). These sediments consist of conglomerates from alluvial fans, varicolored mudstones, siltstones, and sandstones from ephemeral fluvial deposition and aeolian sandstones (Dawson and Callender, 1992).

The Eagle Mills Formation is known only from the subsurface and is named from the Amerada Eagle Mills No. 1 well located in Ouachita County, Arkansas (Weeks, 1938). The maximum thickness estimated for the Eagle Mills is approximately 7000 ft (2134 m), and it was deposited adjacent to the Ouachita Tectonic trend from Texas eastward into Arkansas and Mississippi (Gawloski, 1983). Mickus et al. (2009) define this rift trend area based on an analysis of its gravity and magnetic signature. In northeast Texas, Eagle Mills well penetrations are described as a succession of red siltstones, sandstones, and shales. These sediments have also been intruded by diabase dikes and sills, and often covered by lava flows. An erosional unconformity surface on these rocks is then transgressed by the Smackover (Green, 1989). Minor oil production from the Eagle Mills was discovered by Murphy Oil and occurs in two fields in east Texas (Green, 1989; Reed, 1991). In these fields, oil is sourced from the overlying Smackover source rock charging downward into the Eagle Mills. The fields lie up-dip from Louann Salt deposition. In the east Texas basin, deep well control below the Louann Salt, White et al. (1999) reported salt older than Louann salt he called the Rosewood formation and interpreted it to be a part of the Eagle Mills sequence. White proposed that deposition occurred continuously from the Late Triassic through the Upper Jurassic and limited to the deeper rift basins. The deep well that penetrated this older sequence is the Exxon-Fina Ray-1 well. This well drilled 4800 ft (1463 m) of subsalt sediments interpreted to range in age Lower to Middle Jurassic (White et al., 1999).

In southern Arkansas, estimates of Eagle Mills's thickness range up to 2 km (1.2 mi) of red beds (Scott et al., 1961; Vernon, 1971; Woods and Addington, 1973). The formation is not only confined to rift basin geometry but also fills and spills over the grabens with continued deposition marking the transition between rift and sag phases (Hutchinson and Klitgord, 1988; Green, 1989; Hurbert et al., 1992; Schlische, 1993; Withjack et al., 1998, 2012; White et al., 1999). In southwest Arkansas, fossil algae and leaf impressions from an Eagle Mills core indicate a Late Triassic age (Scott et al., 1961; Traverse, 1987; Wood and Benson, 1991). Based upon reported leaf impressions and other work, Rainwater (1968) proposed the possible existence of lacustrine facies deposited in rift valley lakes.

In the Gulf of Mexico, there are several undrilled, but seismically well-defined, rift-formed half grabens likely filled by continental red beds (Macrae and Watkins, 1995; Dobson and Buffler, 1997). The Sohio-1, in Gainesville 707, drilled a seismically defined half graben and found 4775 ft (1455 m) of siltstones and volcaniclastics, all intruded by basalt dikes, with no lacustrine or marine shale described (Applegate and Lloyd, 1985) (Figure 1). One particularly large undrilled graben underlies the Delilah wells, and a smaller half graben is present under prospects Shiloh (DC269) and Antietam (DC268) (Figure 1).

The Eagle Mills continental facies not only filled the half graben but was also deposited more widely across the areas between the grabens. The overfilling and spreading out of this continental facies was likely deposited as a sag phase was beginning but before seas that deposited the Louann Salt transgressed this unconformity. The Fredericksburg well located in Desoto Canyon Block 486 penetrated a small amount of the Eagle Mills formation (Figure 1). At the bottom of this well, below a thin Louann Salt weld, are red shales and silt intruded by basalt. The thin salt was evacuated by early subsidence as the dominantly fluvial facies of Norphlet inverted after landing on the basement. The basalt appears to be weathered at an unconformity on a small buried hill, rather than in a graben. The hill was left as a small structural high that remained prior to Louann Salt deposition. Seismic interpretation at the well supported erosional relief on the basement surface. Fractures were observed in the igneous rocks during drilling operations. Four rotary sidewall cores were taken in the igneous interval. The cores are described as coarse-grained basalt or possibly dolerite/diabase with large (>1 mm) phenocrysts of plagioclase that are suspended in a groundmass composed of plagioclase laths, pyroxene (augite), and magnetite. The basalt shows some likely hydrothermal alteration of chlorite with corrensite as a replacement of olivine. Pebble-sized, rounded fragments of basalt can be seen in contact with laminated mica-rich silty mudstone, suggesting the well drilled into a paleotopographic high. In addition, hematite content levels were relatively high at 6% for otherwise unweathered basalt. The age of this basalt is interpreted as having formed during either CAMP (200 Ma) or synrift/early breakup (190 to 165 Ma).

Regional Sag/Predrift Phase: Louann Salt–Norphlet Deposition

The Louann Salt was first penetrated in its stratigraphic position in the Lion Oil–A-9 Hays well located in Union County, Arkansas. The well was drilled in 1932 and penetrated nearly 1300 ft (396 m) of salt. From then until as late as 1960, workers suggested that the Louann Salt ranged from Permian to Jurassic in age (Andrews, 1960). A palynomorph assemblage of Middle or Late Jurassic age from the top of the Challenger Salt Dome in the Sigsbee Knolls area was reported by Kirkland and Gerhard (1971) and (Ladd et al., 1976). In addition, palynological data from several species were collected from diapiric salt domes in Texas and Louisiana. Jux (1961) assigned a Rhaetic-Liassic (Late Triassic to Early Jurassic) age to this salt. More recently, Stern et al. (2011) reported radiometric age dating from xenoliths of alkalic igneous sampled from salt domes in southern Louisiana. This age yielded a date of approximately 160 million years. Deeper older salt may be late Bathonian, and the uppermost part may extend into the early Oxfordian (Bishop, 1967; Salvador, 1991). Todd and Mitchum (1977) assigned the Louann Salt to a time interval from Aalenian to Bathonian (or Middle Jurassic). This is based on the Gulf of Mexico sediments lying between on trend with rift and early sag sediments in the Newark Supergroup (eastern coast of North America) and exposures in central Mexico (Salvador, 1991). General acceptance today for the youngest aged salt is mainly of Callovian age.

The Louann Salt was deposited as an aerially extensive and thick salt body during a sag phase of subsidence at the end of synrift sedimentation. Locally there were areas with time gap interruptions between the rift and sag phases (Figure 2). Examples of where Louann Salt was deposited in lower areas while erosion occurred on upthrown fault blocks can be found in the east Texas basin (Green, 1989; White et al., 1999). Other seismic examples, but not penetrated by wells, can be found in parts of the eastern Gulf of Mexico (EGOM) in Destin Dome, Desoto Canyon, and the deep basin of the Lloyd Ridge protraction area offshore.

The sag phase includes the initial subsidence phase that allows enough marine water to enter the basin to initiate salt deposition on top of the rift fill sequence. The first salt deposition begins to fill the remaining low topography of the rift, expanding regionally with more gulf subsidence. The sag phase plate reconstructions for Louann Salt deposition suggest that the most likely entry point for marine waters was from the Pacific. This inlet may have been through narrow opening(s) between land masses attached to Mexico at the same time and before the Yucatan began significant counterclockwise rotation (Marton and Buffler, 1994; Pindell, 1985, 1994; Pindell and Keenan, 2001, 2009; Bird et al., 2005). Separation between the Yucatan and the southern United States would provide wider potential access for water entering the Gulf of Mexico. Salvador (1991) suggested that water entry into the salt basin was probably intermittent during times of hurricanes or very high tides, whereas at other times, the Pacific waters would either close or become restricted to a few of the deeper channels that communicated with the Pacific. Padilla y Sanchez (2007, 2014) stated that the seawaters most likely began their advance toward the Proto–Gulf of Mexico from the Pacific through the central part of Mexico. This area today lies in the border area between the states of Zacatecas and San Luis Potosi.

An anhydrite facies of the Louann Salt is found along the updip margins of the salt basin where there occurred periodic flooding and drying. The thickest anhydrites are deposited on top of the periodically flooded paleo high blocks (e.g., Wiggin uplift) (Cagle and Kahn, 1983; Rhodes and Maxwell, 1993). Alternating wetting and drying at the salt basin margin produced gypsum, which converted to anhydrite with a thickness range of 10 to 40 ft (3 to 12 m). Oxley et al. (1967) first named the Pine Hill Anhydrite Member of the Louann Salt (Figure 2). Raymond (1989) designated the type well of the Pine Hill Anhydrite as the Brandon-Miller-1 well drilled near Pine Hill, Alabama. With the high density of the anhydrite, the Pine Hill can produce an excellent hard seismic event at the base of the Norphlet aeolian section. Thicker anhydrite, up to hundreds of feet, are found mainly in the depositionally updip areas, while in the more basinal position of Appomattox, the anhydrite is too thin or absent to map the base Norphlet. The Pine Hill anhydrite in the basinal positions of the onshore Mississippi salt basin is also not present (Mancini et al., 1999). Without the presence of anhydrite between the Louann halite and the Norphlet sands, water salinity within the Norphlet can spike extremely high with precipitation of halite cement (Hartman, 1968; Studlick et al., 1990; Schenk and Schmoker, 1993). In the literature, anhydrite that occurs at the base of the Louann Salt has also been given the lithostratigraphic name of the Werner anhydrite (Imlay, 1940; Hazzard et al., 1947; Oxley et al., 1967; Anderson, 1979; Tolson et al., 1983; Mink and Mancini, 1995; Raymond, 1989; Ericksen and Theiling, 1993). The Werner anhydrite has been reported in literature only from onshore well penetrations (Woods Addington, 1973; Salvador, 1991).

Deposited on top of the Louann halite/Pine Hill anhydrite is a dryland clastic sediment wedge. This wedge can be found along the marginal edges of the gulf basin and has been named the Norphlet formation (Figure 1). The name Norphlet was given to these dryland sediments first drilled in a well located near a small community in Arkansas of the same name. The name Norphlet, interestingly enough, is a misspelling of the original intended name for this community. In 1891, a request was made by a Mr. Nauphlet, a local resident of the community, asking that the new post office be located there and use his name. However, due to either poor penmanship by Mr. Nauphlet or a government oversight, the name was spelled Norphlet, and the post office and town names were established. This deep well drilled near the town now named Norphlet was called the number 49 Werner Saw Mill. This new lithologic formation drilled at the bottom of the well found 170 ft (52 m) of clastics. Imlay (1940) proposed these sediments be named the Norphlet tongue of the Eagle Mills formation, using the nearby town's name. Five years later, in 1945, these 170 ft of gravelly red beds below the Smackover limestone and above the salt were formally named the Norphlet formation (Hazzard et al., 1947).

The Norphlet formation is composed of clastic sediments deposited in an arid climate by gravity, wind, and rain water. The water likely ran across ephemerally flowing sheet floods dispersing a flow across the salt flat. These thin and poorly developed sands found in southern Arkansas were likely deposited in the manner (Imlay, 1940; Hazzard et al., 1947). Not only in southern Arkansas but also in Texas, and Louisiana, the Norphlet is generally thin, averaging 50 ft (15 m) of total thickness (15 to 70 ft [5 to 21 m]). It is mostly composed of red shale, silts, and some thin sands (Dickinson, 1969). Further east, however, into Mississippi, Alabama, and Florida, the Norphlet thickens to over 1200 ft (366 m) locally with mostly aeolian sandstone (Studlick et al., 1990). Across this three-state area, the gross Norphlet thickness commonly ranges between 200 and 400 ft (61 and 122 m) (see Marzano et al., 1988, their figure 4).

There are distinct regional Norphlet sediment source terrains where rock fragment types have been used to define sediment provenance (Ryan et al., 1987). Norphlet sandstones found in Florida, Alabama, and Mississippi reflect an influence of metamorphic and feldspathic-rich plutonic rocks of the Appalachian Piedmont province (Thomas, 1985; Ryan et al., 1987). Sandstones in east Texas, northern Louisiana, and southern Arkansas were derived from the feldspar-poor sedimentary and metasedimentary rocks of the Ouachita System (Ryan et al., 1987). Thomas (1985, see his figure 2) provides a pre-Mesozoic map of likely exposed highland present during Norphlet deposition, which supports the rock fragments found in these Norphlet sandstones drilled onshore.

Norphlet sandstones drilled offshore in the Gulf of Mexico have igneous rock fragments. The highland source for the Norphlet is located in the present day Florida peninsula and in the adjacent Gulf of Mexico. The highland is made up of a Lower Paleozoic Ordovician through Devonian section intruded by and overlain with an igneous rocks section (Applin, 1951; Bass, 1969; Barnett, 1975; Smith, 1982; Klitgord and Popenoe, 1984). These Ordovician–Devonian age clastics in north to central peninsular Florida now subcrop beneath the Cretaceous and younger sediments (Pojeta et al., 1976). The basement terrain of southern Peninsular Florida is made up of Lower Cambrian to Precambrian granite and Lower Jurassic volcanics (Barnett, 1975; Smith, 1993). In offshore waters west of Florida, several wells have penetrated below the Upper Jurassic unconformity and found igneous rocks. For example, Shell penetrated some 550 ft (168 m) of weathered and solid granite in the PB7 number-one well. Texaco drilled a well in PB100 and drilled over 1000 ft (305 m) of diabase and rhyolite. Mobil also drilled a well and found over 700 ft (213 m) of Paleozoic metaquartzite intruded with diabase sills in EL915.

The Paleozoic rocks in Florida are an inherited remnant of the African continent (Klitgord and Popenoe, 1984; Christenson, 1990). Florida Paleozoic rocks have similar lithologic age counterparts on its conjugate margin located in the Bove basin of Guinea (Kilgord and Popenoe, 1984; Christenson, 1990; Villeneuve and Komara, 1991; McHone, 2000). Lovell and Weislogel (2010) have shown, from zircon ages taken from Norphlet sands drilled offshore and onshore but near the present coastline, that the offshore sands have their sediment source area as the Panhandle-African terrain seen in Florida Paleozoic rocks. Offshore in the Gulf of Mexico west of Florida are Ordovician clastics cored at the bottom of the Texaco 1 (Florida Middle Ground Bock 252) (Christenson, 1990). This well was drilled on a feature called the Middle Ground Arch. The Middle Ground Arch highland was exposed in part from at least Callovian until Late Kimmeridgian when the crest was finally buried by marine waters.

The aerial extent of the arch during Norphlet deposition as originally defined by Martin (1978) is very large and covered some 5000 mi^2 (12,950 km^2). This is nearly two thirds of the Desoto Canyon protraction area (Figure 1). This arch separated two salt embayments on the north and southern flanks. The Desoto salt basin lies off the north flank, and the West Florida basin is off the south flank (Martin, 1978; Dobson and Buffler, 1997; Pilcher et al., 2014). In addition to being a highland sediment source for the Norphlet, its geomorphic shape may have also acted as a wind barrier to focus wind out into the basin. The Norphlet depositional environment adjacent to this highland was dominated by alluvial fans, which built a sediment wedge thinning downdip. This sediment wedge along the north and west flanks of the arch is interpreted to range in thickness from 450 ft (137 m) to its facies pinchout. Norphlet alluvial fan facies are found in onshore wells drilled near the depositional highland front exposed during Norphlet deposition (Pepper, 1982). These fans consist of the coarser grain sandstone and conglomerate (see cross-sections by Tolsen et al., 1983; also Dinkins, 1968; Wilkerson, 1981; Pepper, 1982). Washing out beyond the toe of the alluvial fans are ephemeral deposits of sand, silt, and mud. Sediments washed outward of the fans were deposited by flooding basinward onto salt flats. The salt flats were likely either subaerially exposed or partially covered by the very shallow waters of the Louann Sea. This buildup of mud, silt, and sand out onto a flatland surface was an ideal location for winds to then redistribute these sediments across a dried fluvial outwash. Depending on wind direction and sediment supply, sands can be blown into sheet or dune sand morphologies, forming an aeolian sand sea (or erg) on top of the fluvial outwash deposits. Sediment supply and subsidence rates will determine whether sand sheets or dunes such as barchan, star, or longitudinal are formed. The common vertical stacking pattern of fluvial and aeolian facies are both present, then aeolian always overlays thinner fluvial sediments. Aeolian and fluvial facies that interfinger can happen nearer the foot of the alluvial or bajada fans.

Across the widespread dryland facies of the Norphlet that lay west and southwest of the Middle Ground Arch, small localized areas experienced very rapid subsidence rates. These areas were likely related to strike slip faulting occurring deeper and beneath the Louann salt. Being a more ductile body, the salt may have developed pull-apart basins where at the surface of the salt it became a gentle topographic low area. Rapid water runoff across the flat Norphlet plain would seek out these low areas and deposit the muds and silt. With more sediment concentrating deposition in these lows, subsidence rate increased only to continue collecting more water lain or water modified dryland sediments. These local areas received Norphlet sediments up to 1200 ft (365 m). Internally, the team referred to these active sinkhole like basins as pothole basins. The size of these pothole basins were small compared to the greater Norphlet desert area and ranged in area between 5 and 8 mi^2 (8 to 13 km^2). The subsidence rate within potholes was so high during the Norphlet that total evacuation of underlying salt resulted in the Norphlet sediments structurally inverting or turtling even as the Smackover transgression was occurring. Prospects Fredericksburg (DC486), Petersburg (DC525), and Swordfish (DC843) are examples of these drilled turtles.

Formation of dune and interdune architectures depend on the relationship of four variables (dune size, interdune size, dune migration rate, and dune aggradation rate) (Mountney, 2012). While increased sediment supply can produce a closely spaced dune complex, other variables such as wind velocity, and direction and rate of dune subsidence below the paleo water table, strongly control whether dry or wet dunes will be dominate. In Appomattox field, both wet (water table-influenced) and dry dune facies exist and are oil filled. Dry dune facies have the best reservoir properties mainly because the build topographically higher than wet dune. This added height will produce longer and steeper grainfall or avalanche bedforms deposited on the lee side of the dune. Steep angles of climb also enable larger proportions of the original bedforms to be preserved (Mountney and Howell, 2000). Several studies in literature show much better porosity and permeability in the grainfall facies (Schenk, 1981; Marzano et al., 1988; Dixon et al., 1989; Ajdukiewicz et al., 2010) as well as in all whole cores and calibrate image logs taken in Appomattox and surrounding discovery wells (Douglas, 2010; Godo, 2011). Better poro-perms in this bedform are primarily because it has the coarsest grain size and with later formation of diagenetic clay coats, pore throat size will be larger.

Conditions in the Norphlet dryland system were not conducive for preservation of paleontological data that could help age-date the formation. In the current deep-water play around Appomattox, wells have found only sparse material. The age dates that have been found give a wide age range from Upper Triassic (Carnian) to Middle to Upper Jurassic and consist of dinocysts, pollen, and spores such as found in the Fredericksburg well (DC486). Of course, some of these palynological dates likely represent dates from reworking of sediments exposed in the sediment source terrane. At Appomattox, for example, acritarchs of Devonian age were found in the Norphlet, which likely came from eroded Silurian or Devonian rocks in Florida.

Drift Phase: The Smackover Formation: Plate reconstructions in the Gulf of Mexico have been addressed by numerous publications. A favored timing and reconstruction described by Kneller and Johnson (2011) suggests seafloor spreading began at 163 Ma (Callovian). The first reliable and oldest age date from microfossils are found at the top of the Smackover Formation that represent the first carbonates on top of the Louann salt. The basal Smackover carbonate that represents the initial transgression of the sea is completely devoid of any life other than algae deposited in the highly saline waters. Above this basal Smackover carbonate is a period where salinity lessens as the underlying salt was completely buried and more seawater began to circulate. In the upper Smackover Formation, wave energy began to be high enough to develop some carbonate grainstones and it is in sediment deposited around this time that the Oxfordian age call from microfossils can be made.

The Smackover Formation was first penetrated near the town of Smackover Arkansas by the deepening of a well beneath the shallow Cretaceous reservoirs in the Smackover field. Bingham (1937) named this new 700-ft-thick limestone formation using its type locality as found in the Lion Oil Hayes No. 9-A well. The Smackover Formation in the Arkansas–Louisiana–east Texas area is divisible into three units, or members (Dickinson, 1968). Dickinson described the lower member as a dense and laminated limestone, the middle member as a sandy limestone, and the upper member as an oolitic limestone. Referring to the Mississippi salt basin, Oxley et al. (1967) described lower and upper Smackover facies. Oxley described and named the upper portion of the lower member as the "Brown Dense" limestone, which is described as dense to finely nonporous crystalline with a dark brown to dark gray color. Oxley further described the base of the brown dense limestone as grading into a dark gray to black, dense, argillaceous, thinly laminated, pyritic limestone.

More recently, Mancini et al. (1992) defined the Smackover in the greater Alabama area as consisting of three members defined as lower, middle, and upper (also in Moore, 1984; Benson, 1988). Benson (1988) described the lower member as a lime mudstone that contains stromatolites, intraclasts, and peloidal–oncoidal wackstone to packstone. The middle member was described as laminated mudstone with some peloidal and skeletal wackstone to packstones (Mancini and Benson, 1980; Benson, 1985). The upper member consists of subtidal to intertidal and supratidal fenestral mudstones and anhydrites (Mancini and Benson, 1980; Benson, 1988; Mann, 1988). Prather (1992, his figures 11 and 12), also working in the Alabama area, characterized the time-stratigraphic framework of the Smackover Formation. Prather recognized that the formation had an initial transgressive systems tract (TST) followed by a highstand systems tract (HST). A maximum flooding surface (MFS) marked the boundary at the top of the TST. At this maximum flooding surface are laminated mudstones that define a condensed zone. The maximum flooding surface contains the richest source rocks in the Smackover. The (upper) Smackover (HST) has a mud-supported facies of pellet wackstone that is overlain by a grain-supported facies of pellet packstone, oolite-pellet-intraclast lime grainstone and/or dolograinstone, and a mixed lithologic facies of dolomudstone, intraclastic grainstone, caliche-pisolite, and calcrete (Prather, 1992).

Offshore, in Desoto Canyon and Mississippi Canyon protraction areas, the Smackover has the same stratigraphic framework described by Prather (1992). Particularly evident is the seismically defined clinoform geometry in the central and southern portion of the Desoto Canyon area. Clinoforms demonstrate the progradational nature of the highstand systems tract. The clinoforms enter from the updip central portion of the Desoto embayment prograde southwestward subparallel with the northern margin of the Middle Ground Arch. The clinoforms are composed of shale, silts and some thin carbonates (e.g., at Dorothy DD563) (Figure 1). At more outboard well locations, such as at prospect Shiloh (DC268) and Antietam (DC269), the silty-shale clinoform sets are at a very low angle to the basal Smackover event, yet sands and silts are still present in this interval. The silts and sands in Shiloh are a mixture of upper fine-grained to coarse silt-sized detrital grains composed mostly of quartz, plagioclase, muscovite, and altered argillaceous rock fragments. The matrix is a mixture of detrital and authigenic clays derived from the alteration of lithic grains and carbonate grains with some cement present in small amounts. Carbonate grains are mostly ooids. Virtually all visible porosity has been eliminated in this sandstone due to quartz cementation, pore-filling clay, and extensive compaction. The basal Smackover (also called the brown dense member [Oxley et al., 1967]) lies directly on top of either the Norphlet or Louann Salt provided Norphlet was not deposited (e.g., wells DD166, DD167, and PN973) (Figure 1). The Smackover source rock in the Destin Dome area is less rich than in wells drilled further offshore. Possible source rock dilution due to clastic dilution by the sediments entering the basin shown by the progradational clinoforms may limit source rock richness in this area.

At Appomattox, the three members of the Smackover can be easily distinguished on well logs (Figure 3). The lower member represents the initial transgression (TST) and has three sub-members. The three submembers are made up of red shale, a high-density pyrite zone, and a basal carbonate with intervals of algal laminated source rocks (brown dense of Oxley et al., 1967). The middle member represents the distal

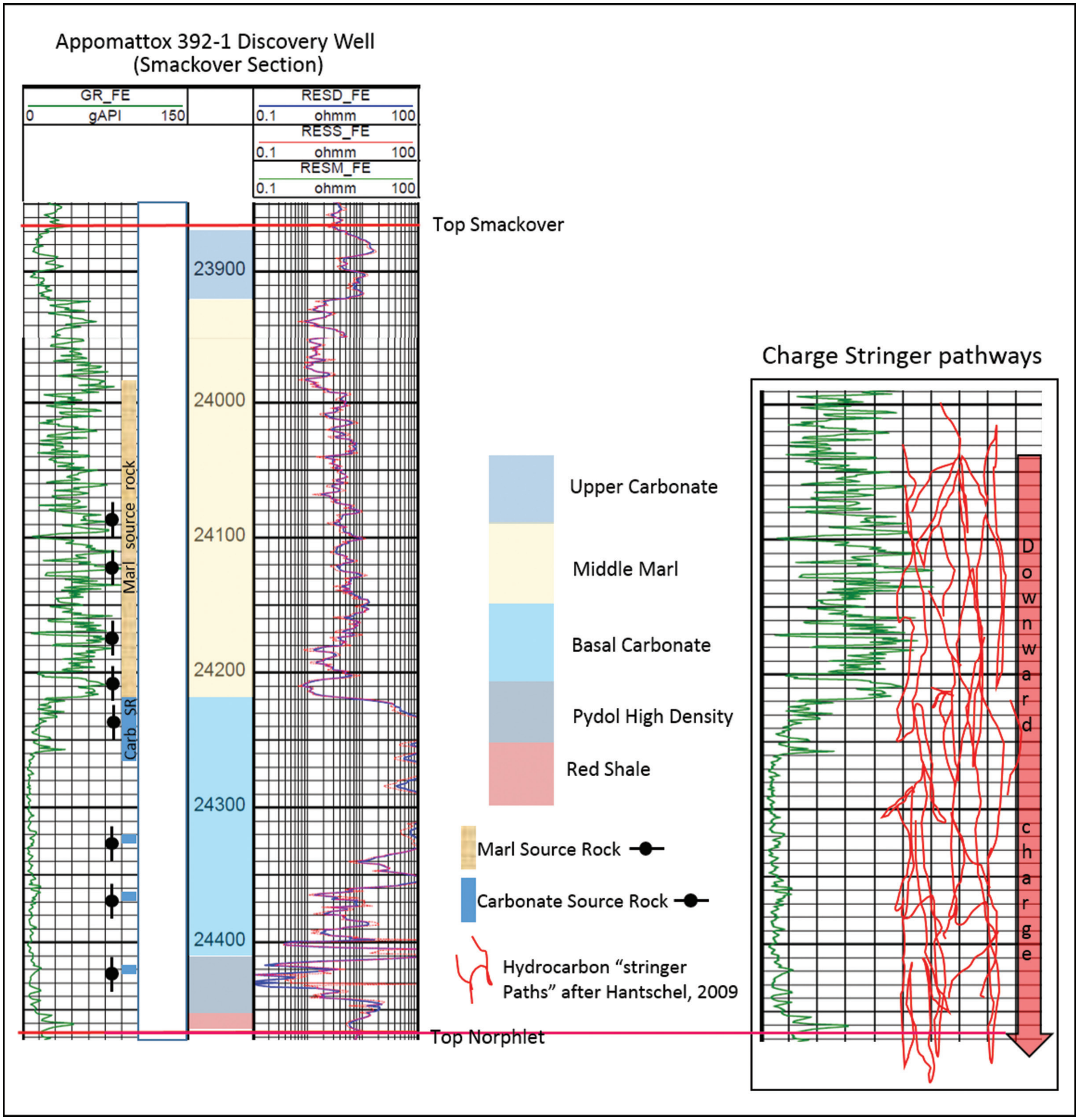

Figure 3. Smackover members. The five Smackover members are highlighted by colors in the depth column of the log. The members are: 1) thin red shale; 2) the high-density member locally referred to as the pydol section (pyrite-dolomite); 3) basal carbonate; 4) middle marl; and 5) upper carbonate. The Smackover has two source-rock types: 1) middle marl source rock and 2) MLZ carbonate source rock. The downward migration path shown conceptually by red lines are conceptualized and modeled after the stringer concept and illustration in Hantschel and Kauerauf (2009).

toesets of the clinoform package. The upper member is a limestone that represents facies deposited in a higher-wave energy environment (e.g., oolites, pellets, and some skeletal fractions) associated with the topset portion of the clinoform package. It is usually at this interval or slightly younger that the first paleontological faunae are present to interpret a top Oxfordian age.

Source rock intervals in the Smackover consistently show the two types of source rocks in two of the members. These two members are the basal carbonate limestone and the middle marl member. No whole cores have been taken in the Smackover in any of the deep-water wells. However, a significant amount of rotary core samples were taken systematically with overlapping section in each of the Smackover members from all Shell operated wells.

Basal Red Shale: The initial flooding at the base of the Smackover is represented by a variable thickness of red-colored shales and siltstones. The shale interval located on top of aeolian dunes is the thinnest and made up of a very distinctive red claystone shale. This red shale on top of the topographically high dunes can approach 10 ft (3 m) at a maximum. It is compositionally very different from the more typical red shales found in areas with no sand dunes. This red shale has compositional descriptions as extremely iron-rich and described as argillaceous ironstones, hematite claystones, and/or pyrite hematite ironstones. Hematite as measured with X-ray diffraction is upward of 50% hematite. At top of the dunes, only this thin iron rich claystone or shale is found before carbonate deposition occurs with the associated heavy mineral assemblage. In areas where there are no sand dunes to build the topographic relief, the depositional area was flat and received sediments by ephemerally flowing rainwater emptying into the encroaching seawater of the Smackover transgression. The silty shale and thin siltstones deposited in this interval thicken to four times (up to 40 ft [12 m]) due to the absence of the dune topographic relief. The red-brown silty shale deposited in this interval has less iron than the iron-rich claystone but more silt content and occasionally interbedded with thin siltstones. Only at the very top of this interval lies the thin iron claystone that underlies the first carbonate bed. The topographically low areas away from the dune fields filled first with red-brown silty shale and siltstone. Rising seawater during Smackover transgression expanded across the fringing Norphlet dryland red-clastic system. Gradually, the slow water rise entombed and preserved the Norphlet sand dunes that rose above the desert plain. The very shallow quiet waters that transgressed the Norphlet desert did not have conditions sufficient for the carbonate factory to go into production. The water column incorporated red clays of the transgressed desert redistributing and concentrating them into a layer. Carbonate precipitation lagged behind an initial drowning until the water became sufficiently deep (Ginsberg, 1971).

High-Density Zone: The matrix rock of the high-density zone is carbonate that was the first deposited overlying the very red iron rich claystone. The highdensity values cause the log signature to express a very characteristic spike in the density and on the resistivity and conductivity logs. This same zone is also known informally as the pydol zone by geologists working the Norphlet fields in Mobile Bay of the Alabama coast. The name pydol is a consolidation of the words pyrite and dolomite that together that dominate this zone in areas both in shallow and deep waters of the Gulf of Mexico. At Appomattox and the surrounding area, the high-density zone has been extensively sampled with rotary cores. The thickness of this zone averages around 35 ft (11 m), but in areas of thicker red shale, pyrite zone thickness can be up to 50 ft (15 m). Pyrite makes up to 50% of some rotary core samples based on point count and X-ray analysis data. The matrix rock is dolomitized micrite with remnant organic layers thought to be algal concentrations and anhydrite. Dolomitization renders any primary depositional forms as indistinguishable except for peloidal mud texture and these organic laminae. Also present in the lower pyrite zones are nodules of finely crystalline bassanite ($CaSO_4 \bullet \frac{1}{2}H_2O$). The nodules were deposited as gypsum as seawater evaporated within a sabkha setting. Bassanite is a transitional phase between gypsum and anhydrite. As the water column deepened, it became density stratified with a strong brine base overlain by more normal seawater. In the lower euxinic water column, organic material was effectively trapped at the redox boundary to promote localized sulfate reduction (Hurtgen et al. 1999). Under anoxic conditions, seawater sulfate is reduced to H_2S, which reacts with detrital iron minerals and ultimately forms pyrite (Goldhaber and Kaplan, 1974; Berner, 1984; Raiswell et al., 1988). Studies have shown that bacterial sulfate reduction with the formation of pyrite takes place within the uppermost centimeters of burial (Berner, 1970; Raiswell et al., 1988). Based on isotope work, it has been shown that pyrite in the Smackover is there due to bacterial sulfate reduction.

Basal Carbonate: Overlying the pyrite mineralized zone is a very clean, nearly clay-free (< 5% based on X-ray diffraction carbonate. Thicknesses vary from 125 to over 400 ft (38 to over 122 m). The basal carbonate is characterized on the gamma ray log by having the lowest count levels compared to all other lithologies. Depositional features are not diagnostic but rare mud pellets or ooids may be found in some intervals. Algal layers are present in mainly laminations but some are wavy and may represent some stromatolite or microbiolite growth structure. Other features found in this member are organic filled stylolites and patchy anhydrite concentrations with early dolomitization of lime mudstones. Micropores within the dolomitized units are usually oil filled. The limestone color is tan to light brown with intervals colored by zones of algal laminations. This more laminated zone is commonly referred to in industry as the MLZ, or microlaminated zone (Shew and Garner, 1990; Mancini et al., 1999). Algal microlaminations are randomly distributed in the lower member but are concentrated in the uppermost portion of the basal carbonate. The concentration of MLZs causes serrations on the otherwise consistently low gamma count. More argillaceous material is deposited with the algal material, which increases the gamma ray spikes.

Algal microlaminations were deposited in a quiet body of water during the initial transgression of the Smackover. Algal blooms could have occurred during the periodic rainfall providing fresh water runoff into the saline waters allowing the algae to proliferate on the top of the saline water. Hypopycnal flow of fresh water running across the top of the higher-density (hypersaline) water column would have been the mechanism to create this condition. Algae would instantly grow and thrive on this relatively still freshwater body. Gradually, through evaporation, the fresh water would become more saline, causing the algae to die and sink into the anaerobic body of standing water to accumulate and preserve in thin laminations. Clay particles also settle out of suspension through the process of flocculation (the clumping of clay particles together due to a positive–negative charge relationship created by the seawater). Settling together algae and clays created the laminations. These intervals are the source rocks that generate the early asphaltine products that make up the solid hydrocarbon residues found in the underlying Norphlet reservoir (Godo et al., 2011). The actual total organic content (TOC) of the microlaminations can be very rich. However, because the laminations or stylolites are thin, measuring the TOC of a thicker interval using a bulk rock analysis will have much lower apparent richness value. This is due to the dilution effect of the non-source matrix rock.

In summary, the Smackover transgression had no surf zone or beach environment for the Norphlet. The transgressive systems tract began with a gentle flooding of the Norphlet desert with minimal reworking of the sand dune topography. The water column was clay-rich water that deposited the characteristic red shale. As the water deepened, the column became stratified under anoxic conditions and highly saline waters near the water bottom. The source rock was deposited as algal blooms flourished and died.

Middle Member: The basal contact of this middle member with the underlying lower member is transitional from limestone to increasing interbeds upward of marl. This increased interbedded argillaceous amount is expressed through a serrations of the gamma ray curve that increases upward into the middle member (Figure 3). The middle member has more argillaceous material, but still has significant calcium carbonate content. A more accurate description and quantifiable lithology would be a marlstone. Here the clay content varies between 30 and 65% based upon X-ray diffraction results from rotary cores taken in all of the Smackover penetrations. Pettijohn (1957) defines a marlstone as containing 35 to 65% clay and 65 to 35% carbonate. Bedding in the marl is massive with no fissility. Within the middle marl member, the richest source rocks are present in the beds with the most argillaceous content as shown with the highest gamma ray log spikes. The richness has the highest levels of TOC, S2, and HI values. Onshore, the Smackover mudstones are also the main source rock facies in the North Louisiana salt basin, the Mississippi Interior salt basin, and the Manila and Conecuh subbasins (Oehler, 1984; Sassen et al., 1987; Sassen and Moore, 1988; Claypool and Mancini, 1989; Mancini et al., 2003).

Upper Member: The upper member of the Smackover Formation commonly has more high-energy facies, such as ooid grainstones, but they have very low porosity due to extensive cementation. The most outboard location of the seismically defined clinoform geometry is between Shiloh and the Mississippi Canyon protraction area. In this most outboard area around Appomattox, the upper Smackover is composed of more micritic limestone rather than the packstone to grainstone facies. The paleontologic pick for the top Oxfordian is generally found 200 to 300 ft (61 to 91 m) above this carbonate section, which is correlated as the top Smackover. No source rock material is present in this member.

THE NORPHLET PETROLEUM SYSTEM

The Norphlet petroleum system is fundamentally different from all other plays in the Gulf of Mexico. The Norphlet lies at the base of the sedimentary package above the salt. Therefore, in the Norphlet play, there is only one chance for charge by the overlying source rock, since all of the other source rocks of the Tithonian or younger age are not structurally positioned to provide charge. Only the source rocks in the overlying Smackover are in a position to provide oil charge for the Norphlet sandstone. Norphlet oil at Appomattox has been typed to the Smackover source rocks. As a result of stratigraphic juxtapositioning, the source rock and the reservoir rock experience the same heating necessary to generate and expel hydrocarbons. This means the reservoir has to withstand porosity and permeability degradation and destruction by both grain crushing and cementation. Cementation due to high temperatures is the primary cause of porosity and permeability loss in the Norphlet sandstones.

Porosity in the Norphlet is mostly primary intergranular porosity. Initial coarser grain sizes are more favorable to withstand later compaction and cementation resulting in the most permeable facies today. Waterlain sandstone facies in the Norphlet that were deposited by ephemeral fluvial outwash and have the lowest porosity and most importantly very low permeability. Permeability in the facies is low that there is no relative underpressuring of this interval to create a pressure relief point for the downward charge. As such only Norphlet aeolian facies receive and laterally move the hydrocarbon charge. Sand dunes have the coarsest grain size, particularly if found as avalanche facies deposited on the lee side of the dune face (Lupe and Ahlbrandt, 1979; Schenk, 1981; Fryberger et al., 1983; Lindquist, 1983; Marzano et al., 1988; Dixon et al., 1989; Net, 2003; Worden and Morad, 2003; Ajdukiewicz et al., 2010; Douglas, 2010). Cementation is inhibited from occurring in the sandstone by the thin chlorite that grew from the initial clay rims that coated the grains during and after deposition (Crone, 1975; Walker, 1979; Matlack et al., 1989; Turner et al., 1993; Shammari et al., 2011). This chlorite effectively insulates the detrital quartz grains from encountering silica-rich pore waters that precipitate out quartz cement by nucleation onto the detrital quartz grains. Transforming clay coats to chlorite is due in large part to the igneous detrital grain component derived from the sediment sources in the Florida highlands. Igneous sand grain components dissolved quickly after burial and supplied the clay elements needed to grow additional chlorite on the more stable quartz sand grains. In the Norphlet reservoir, it has been shown that the sand grains need to have at least 98% of the grain surface coated by chlorite to prevent extensive quartz cementation and thus preserve the permeability (Taylor et al., 2004). Significant quartz cementation that begins with temperatures over 200° Fahrenheit will cement and close smaller pore throats around the sand grains that are lacking clay coats. Potential Norphlet reservoirs must survive burial temperatures up to and over 350° Fahrenheit (Mobil Bay).

To charge the Norphlet sandstones with oil, downward charge occurs from the adjacent overlying source rocks in the Smackover Formation. Source rock intervals in the Smackover consistently show the two types of source rocks in two of the members. These two members are the basal carbonate limestone and the middle marl member (Figure 3). The middle marl member has the higher argillaceous content, with up to 85% in some beds, but does not exhibit bedding fissility. These intervals are the richest source rocks and display the highest gamma ray counts. Interbedded in this interval are some marls with lower argillaceous content. The generally high argillaceous percentages in the entire middle member would classify these rocks as argillaceous to calcareous mudstones (Pettijohn, 1957). The basal carbonate member has very little argillaceous content and is mostly all calcium carbonate (clean limestone) with some intervals of magnesium carbonate (dolomite). The source rock material in this unit is very different compared to the kerogen in the middle member. In the basal carbonate, the kerogen is found as thin algal microlaminations. When the laminations are concentrated enough to stack vertically, the gamma ray log will show a more serrated pattern. These serrations marked by algal laminations also contain a bit more argillaceous content that were deposited as the algal material sank to the seafloor. Laminations can be scattered throughout the basal carbonate but are always found near the top of this unit as it transitions into the overlying middle marl section. The Smackover source rock richness values are fairly consistent regardless of either lateral position or thickness changes. Greater thickness would equate to more of the same source rock rather than a change in the richness value.

Source rock maturation in the Smackover begins as all source rocks do, by initially filling all of the micro and macro porosity in the source rock. The organic richness of the source rock will control how much oil volume can first saturate the source rock pores before exiting. Kerogen in a source rock matrix is grouped as individual kerogen masses within the rock matrix. Both kerogen richness and its distribution (or fabric) within the rock matrix will affect how much heat will be required to initiate hydrocarbon expulsion. A lower heat will be required to expel hydrocarbons if the source rock has a higher kerogen richness and a fabric of interconnected kerogen masses (Pepper, 1991; Hantschel and Kauerauf, 2009). Conversely, for leaner source rocks with less connectivity, a higher heat is required for expulsion of hydrocarbons. Standard vitrinite reflectance charts, for example, may indicate hydrocarbon expulsion begins at a level of 0.65 to 0.75 VR. This is generally true for an average source rock richness with average kerogen connectivity. The Smackover source rocks require a higher threshold of heating than these standard values. If the kerogen is distributed in a more continuous network, the diffusion of hydrocarbons can occur much faster with the same amount of heat (Stainforth and Reinders, 1990; Thomas and Clause, 1990).

Overpressure has been widely accepted as the driving mechanism of petroleum expulsion (England and Fleet, 1991). The direction of expulsion is controlled by the relative impermeability of the overlying versus the underlying strata. If the underlying strata have significantly more permeability and a lower capillary entry pressure, the resulting pressure gradient will force a downward migration of petroleum into the permeable carrier beds (England et al., 1987; Sylta, 2004). Essentially, a permeable Norphlet reservoir acts as an underpressured sink for oil to enter. Microfracturing in the source rock, caused by overpressure due to source rock maturation, has also been cited as a method for adding pathways for primary hydrocarbon migration. Pepper and Corvi (1995a) suggested that microfracturing is formed through the amalgamation of desorbed molecules within a collapsing kerogen network and the weight of the overhead lithostatic load. The pathway to microfracturing is thought to first begin by the joining of oil molecules transformed from the kerogen masses within the matrix rock. The pathway of oil movement is by "stringers" that evolve from an expulsion point and move along a stringer pathway (Hantschel and Kauerauf, 2009) (Figure 3). In the Norphlet petroleum system, the permeable aeolian sand is the exit point for all of the stringer paths. Once created, pathways are filled by a continuous oil phase under pressure, and the pressure is relieved as oil enters the permeable Norphlet sand. From there, lateral permeability allows the fluid to move updip to an even less pressured area. The aeolian dune facies is the only permeable Norphlet sandstone. If present, this aeolian sand is both the first carrier bed out of the source rock and is also the objective reservoir to accumulate oil in the trap. The Smackover source rocks can be described as fair when comparing these source rocks with, for example, the much richer Tithonian source rock. The benefit in exploring for the Norphlet reservoir is its juxtaposition with the source rock to limit migration losses.

NORPHLET AREA EXPLORATION HISTORY

Pre-2001: Norphlet Onshore and on the Shelf

Although the Norphlet formation was first penetrated in 1935 and later given its formation name in 1947, another 20 years would pass before hydrocarbons were found in the formation (Figure 1). The Smackover was already a productive reservoir in 1967 when Shell made the Norphlet a primary objective at prospect Pelahatchie in Mississippi. The industry was quite surprised when a high-pressure oil discovery in the Norphlet formation was reported (Oxley et al., 1967; Karges, 1968; Hartman, 1968; Cockrell, 2005). With the results at Pelahatchie, the Norphlet became a new primary objective for exploration wells. Between 1967 and 1979, nearly every year saw between one and three Norphlet field discoveries made in Mississippi, Alabama, and Florida.

Alabama reported its first Norphlet discovery at Flomaton one year later. During development drilling at Flomaton, it was determined that the tight Smackover was actually not the top seal for the Norphlet. With offset drilling, Smackover porosity was found, and the team then realized that the actual top seal was stratigraphically higher in the Haynesville anhydrites. After final appraisal, the bulk of the hydrocarbons were determined to be in the Smackover reservoir facies. Today, the Smackover in this trend has the local field names of Flomaton, Jay, and Blackshear, all on this anticline. Jay field has cumulatively produced over 400 million barrels of oil from the Smackover reservoir (Ottman et al., 1973; Sigsby, 1976; Mancini et al., 1985a; Melas and Friedman, 1992), while Flomaton is the lone Norphlet field on the structure.

In total, 33 Norphlet fields have been discovered onshore in Texas (2), Mississippi (15), Alabama (14), and Florida (2) (Figure 1). Norphlet hydrocarbon traps are structural and involve salt anticlines, basement paleotopography, and normal (extensional) faults (Jackson and Harris, 1982; Mancini et al., 1985a). All of the discoveries were made before 1996. Seventeen of the fields were found between 1967 and 1980, with 10 fields found in the 1980s and 6 fields in the 1990s. The discoveries are dominantly oil, with five gas discoveries and six CO_2 accumulations (Studlick et al., 1990). The largest Norphlet oil field onshore is Flomaton field, where cumulative production was 10 million bbl of oil and 135 BCF as reported in 1984 with production in decline. All of the other Norphlet oil fields have ultimate recoveries that range from less than one million barrels with a few fields at 5 million barrels (Mancini et al., 1985a; Marzano et al., 1988; Champlin, 1996). The carbon dioxide (CO_2) production from the Norphlet in these fields represents the deepest commercial CO_2 gas fields in the world (Zhou et al., 2012). The CO_2 concentration and atomic makeup indicate a strong mantle signature rather than CO_2 derived from thermal decomposition of carbonate (Stevens et al., 2004; Zhou et al., 2012). The Jackson Dome intrusion, which is dated to about 70 million years ago, is the most likely source (Studlick et al., 1990).

Onshore, there are more Smackover fields than Norphlet fields. This is partly due to the fact that the Norphlet sandstone has a more limited areal extent than the porosity in the Smackover limestone. But the primary reason there are fewer Norphlet fields onshore is that the Smackover is a poor top seal and the closest seal is stratigraphically younger in the Kimmeridgian (Buckner anhydrites). Onshore, the structure in the Jurassic are generally lower relief compared to the offshore fields. In the lower relief fields, with the oldest topseal in the Kimmeridgian, the column heights required to force the hydrocarbons down in to the Norphlet larger than what the structures can accommodate. Where rarer Norphlet fields do occur onshore, it requires that local Smackover variations produce a Smackover top seal, and the hydrocarbon column can then fill the Norphlet. Smackover topseal formation is typically found in more basinal positions (closer to the present coastline and offshore) where the Smackover water depths were deep enough to become stratified forming tight limestone potential topseals. Basinal Smackover topseal development is found in the state waters of Mobile Bay and in the current deepwater play area of the Appomattox field.

Offshore, the Norphlet play began in 1969, when Mobil Oil Company leased offshore tracts in the state waters of lower Mobile Bay off the Alabama coast (Figure 1). Prospect Mary Ann was to be the first Norphlet exploration prospect. However, delays due to numerous legal and environmental issues had to be endured before Mobil was allowed to begin drilling (Wade et al., 1999; Frost, 2010). It was not until 1979 that Mary Ann finally completed drilling and was announced as a major gas discovery. The announcement was a needed boost for the Norphlet play. This boost was needed largely because during the 10-year wait to drill, the exploration drilling in the adjacent federal waters had no found any commercial success. The offshore drilling during this ten year time span began in 1973 lease sale. In this sale successful bidders acquired leases in the Destin Dome (DD) and Pensacola (PEN) protraction areas, which subsequently saw several wells drilled down to the Norphlet. Sun Oil leased DD block 166 and drilled the first well into the Louann Salt for a Smackover objective on a simple structure downthrown on the basin rimming fault (DD166). The well found shows in the Smackover, but the formation lay directly on salt without any deposited Norphlet section. Exxon had a different play in mind when it spent over $600 million for six contiguous blocks over Destin Dome in the 1973 federal waters lease sale. Their play was to test the upper Cretaceous Woodbine and Tuscaloosa sand pinchout traps on a flank of the Destin anticline. After drilling six wells on their blocks with no success, a seventh well was drilled deep to the Louann Salt. This well (DD162 #3) found over 300 ft (91 m) of aeolian sand (20 to 23% porosity) with 56 ft (17 m) of fluvial sediments below before reaching total depth in the Louann Salt. The top 100 ft (30 m) of the Norphlet whole core was oil stained, indicating a small residual oil column. The Exxon well is located less than 8 mi (13 km) south of the Sun well (DD166), where no Norphlet section was deposited. In 1977, Amoco drilled a structure on the basin rimming fault zone similar to the Sun well. Amoco drilled the well in block DD31 down to the Louann Salt. The well found 330 ft (101 m) of sandstone above 146 ft (45 m) of fluvial shale and silt on top of a thin Pine Hill anhydrite and Louann Salt. The top 30 ft (9 m) of Norphlet showed dead oil staining and intervals with gas shows over 120 ft (37 m) in variable porosity of 14 to 18%. The last true exploration well was drilled in Destin Dome in 1989.

To summarize the results of the Norphlet exploration in the Desoto salt basin: There are a total of 12 prospects that were drilled to the Louann Salt. Some of the wells found that no Norphlet was deposited (Pen973, DD167-Chevron1, DD422), or only thin Norphlet composed of alluvial gravel, sand, and silt was present (DD563). Thick seismic pod-shaped dunes of porous aeolian sands are found on the west side of the Destin Dome anticline. These seismic pods are identical in form to those found in the Mobile Bay area. This pod-shaped dune area represents a small sand erg with some wells finding thick dunes in proximity with other wells finding thin or no sand in and around the erg margin. The thickest penetration of a sand dune pod is in the Shell Delilah prospect. In this well, just over 1000 ft (305 m) of porous sand (19 to 20% porosity) was found with 80 ft (24 m) of oil. Another targeted seismic pod was at prospect Delilah-DD160-1, where Shell found another small oil column in the thick sand. At prospect Robin-DD111-1, volume calculations indicate it is a 5- to 6-million-barrel discovery. There also have been gas discoveries made in the Norphlet by Sohio (Pen 948), Texaco (Pen996), and Chevron (DD56-57). The Chevron (DD56-57) discovery is the largest, with likely reserves in the range of a few hundred BCF of gas. In 1988, the first offshore production from the Norphlet began at Mary Ann. Today, in Mobile Bay, there is a complex set of Norphlet fields around the initial Mary Ann discovery. This complex has over 60 Norphlet producing wells that are in 15 fields located on adjacent longitudinal seif dune ridges (Story, 1998; Bagnold, 2005). By 2006, there was cumulative production of over 4 tcf of gas from these fields. Estimated original proved gas from Norphlet reservoirs in the Alabama coastal waters and adjacent federal waters is 7.462 tcf (Kugler and Mink, 1999).

2001–2010: The Shift to Deep Water and the Discovery of Appomattox

In 1998, Shell assembled a multidisciplinary team to study the regional Mesozoic play in the deep-water EGOM. The intent was to understand the play for the upcoming lease sale 181, which was scheduled for 3 years later in December 2001 (Figure 1). Sale 181 was the first in the EGOM in 13 years; the last lease sale had been in 1988. The new sale area contained 256 deep-water blocks (or 1.47 million acres) with most blocks in water depths greater than 8000 ft (2438 m). The Shell strategy for the area was to capture blocks that had large Mesozoic structures with primarily Jurassic objectives in closure. Assuming discoveries in the largest hub volume prospects, smaller volume prospects would provide attractive tiebacks to the larger fields.

The specific primary objectives in the deep-water portion of the play were Jurassic-aged sandstones in the Cotton Valley (Tithonian), Haynesville (Kimmeridgian), and Norphlet (Callovian). Geologically, the Cretaceous rocks in the sale area were all deposited basinward of its shelf margin and the closest shelf well control is found in Main Pass blocks 253 and 254 (Petty, 1999; Mancini et al., 2001). In the deep-water play, Cretaceous objectives were potential turbidites spilling across the shelf margin into the sale 181 deep-water area. To support this, thick occurrences of coeval shelf sandstones are present in Valanginian- to Hauterivian-aged (Hosston) and Albian-(Paluxy)aged sediments. In the Upper Jurassic, this new sale area was reconstructed to be a shallow dipping ramp shelf margin with deltaic sands expanding in growth fault wedges. Below the deltaics and above the Louann Salt were the dryland objective reservoirs of the Norphlet charged by the overlying Smackover. Above the Smackover lie the Upper Jurassic Cotton Valley and Haynesville sandstones. In the Kung Fu well (VK117), the Cotton Valley, and upper Haynesville sandstones are interpreted as shallow-water deltaic sands. Interbedded shales with this section have source rock potential. The gross thickness of this clastic interval expands or thickens within growth faults located at the deltaic fronts. Extending further down depositional dip in the current deep-water play area, the sands thin, and the shale becomes a richer source rock (Figure 2).

Shell was very successful in lease sale 181, winning acreage on all of its top tier prospects. Three wells would be planned as the minimum number to test the play if only marginal success was found. The plan was to drill a well in the north half of the sale area and a second well in the southern portion. These wells were designed to test the full range of stratigraphic and structural opportunities and maximize exposure across the play area. The third well would depend on the relative success and would allow for concept learnings from the first two wells to select the location. Choosing which prospect would be the first to drill was a relatively easy decision.

Prospect Shiloh (DC269) was chosen as the first exploration well and was drilled in 2003. This prospect enabled a single well to stratigraphically test the entire Mesozoic section, where all three Jurassic primary objectives were stacked vertically, and the petroleum systems could be fully tested (Godo, 2006). Volumetric analysis at Shiloh revealed that the three objectives had unequal volumes inherent in the downthrown growth structure given that the area of closure became smaller with depth. The horizon with the largest volume potential was the Haynesville sand objectives with over 17,000 acres at the maximum closure. The Haynesville sands required the underlying Smackover source rock for vertical charge. At the Cotton Valley and Norphlet levels, the closures were much smaller. At the Norphlet level, two smaller closures were present beneath the larger simple closure in the Haynesville. This well would penetrate only the eastern closure (called Shiloh), leaving the western closure (named Antietam) as a potential follow-up well. The Smackover source rock was required to vertically charge downward into the Norphlet. Downward charge was a well-accepted concept due to the experience onshore with the same Norphlet charge mechanism.

The results of Shiloh were both positive and negative. The Tithonian or Cotton Valley did not contain any significant sands. It did, however, show that the entire section was a marine source rock, which helped sustain later exploration efforts. The Cotton Valley had a small closure area, so there was still excitement as drilling began to penetrate the Hayesville large-volume potential objective. More significant disappointment came when the Haynesville was found to contain only calcareous mud sequences with no sandstones or porosity of any kind. Alternating carbonate percentages in the marls and shale of the Haynesville produced the necessary sonic and density differences needed to create Haynesville reflectivity. However, the pattern of seismic reflections did indicate a growth fault position. The Haynesville paleogeography around the Middle Ground Arch was similar to the present-day area between the Florida Keys and its mainland. This environment expanded into a fault system moving downdip in response to gravity loading on the Louann Salt adjacent to the Middle Ground Arch (also referred to as the southern platform [Dobson and Buffler, 1997] and the Desoto Arch [Christenson, 1990]). After penetrating the Haynesville and not finding any reservoirs, only the small closure area containing the Norphlet remained.

By this point, it was realized that no hub class volumes would be discovered at Shiloh no matter what the Norphlet might contain. As the Norphlet was about to be penetrated, some were already looking to the next well in the south (likely prospect Cheyenne) as the next hope. But drilling activity on Shiloh was not finished yet. Upon exiting the basal Smackover carbonate, the well took a 2 lb/gal inflow at the top of the Norphlet. The well circulated bottoms up, and the mudlog reported bright red shale cuttings and some sandstone. Drilling continued through sand with streaming oil cut florescence and a resistivity log that indicated a sharp oil water contact after only 170 ft (52 m). The well drilled only a total thickness of 250 ft (76 m) of Norphlet before encountering 20 ft (6 m) of Pine Hill above the Louann Salt. Recovering high-quality oil samples with low viscosity helped to justify a core to be taken in a bypass wellbore. This core would provide the information required for facies determination and more rock quality information. There was complete recovery of the bypass core, and the core displayed nothing but repeated cycles of high-angle aeolian cross-bedding. Petrographic analysis revealed chlorite coats around sand grains with oil-filled pores just like those found in the Destin Dome aeolian sands. With porosity values in the 15% range, the sharp oil–water contact was much too abrupt for rocks in this porosity range. There was no real transitional oil column with gradual decreasing saturations, nor was there pressure evidence of any water gradient. The presence of oil shows to the base of the formation also supported the interpretation that the present-day oil contact was in fact a residual contact. Shiloh was a small oil field with commerciality in question, but Shell had what was needed to develop an aeolian sand erg concept to further the Norphlet exploration play.

It was only 11 weeks after Shell had taken the core in Shiloh that a second deep-water sale, lease sale 189, was to be held. The area of the new lease sale was the same as the original lease sale 181 area. With the new information from Shiloh, the Norphlet play probability of success (PoS) in this area had been substantially upgraded. The Norphlet play was now potentially viable on its own and no longer required closures at other objective levels. New Norphlet prospects in sale 189 were named Vicksburg (DC353), Fredericksburg (DC486), and Gettysburg (DC398). It appeared that this new play was under the radar of Shell's competitors.

Three months after sale 189, yet another lease sale was held. This time the lease offering area was different, as it was in the central district of the Gulf of Mexico. This sale area was adjacent to the previous two lease sales. The new lease sale was numbered 190, and the prize was a Norphlet prospect called Appomattox. The Appomattox lease blocks had been newly released by the previous operator who had held the lease for 10 years without drilling. Also in this sale was the western closure culmination of the just leased Vicksburg prospect. As bids were being prepared, there was a feeling that competition would be limited, given it appeared that the industry had not yet caught on to the Norphlet play. Sale 190 was held, and Shell bid a relatively low amount and narrowly lost the key Appomattox block to a competitor that was targeting shallow Tertiary bright spots.

During late 2003 and early 2004, a second well was planned to test the southernmost portion of the Mesozoic play, and it targeted prospect Cheyenne. The well reached its total depth in August 2004 and was a test of the lower Tertiary through uppermost Jurassic stratigraphy. There was a very strong Miocene bright spot amplitude that the well would test, but it was not Shell's primary objective. The primary objective of Cheyenne was thought to be Cotton Valley sands encased in mature source rock on a four-way simple dip closure. Actual results were different below the base Aptian, as an unconformity minimized the thickness of the Cotton Valley section. No moveable hydrocarbons were found in the Mesozoic section. There was some oil recovered from the Smackover via a Modular Formation Dynamics Tester. The final result at Cheyenne was that it had made a shallow Miocene-aged gas discovery. At that point, Shell's partner Anadarko took over operations on the block and tied the gas discovery into the Independence semisubmersible production hub facility. With a second Mesozoic well now finished but no oil volumes being found, there was much less enthusiasm for committing to a third well. A smaller team remained focused on Norphlet exploration, following up on the results of Shiloh. The question was asked of the team, would Norphlet fields all be just small accumulations like those found at Shiloh, Destin Dome and in all of the onshore fields?

In 2004, with the Cheyenne well dry in the Mesozoic, there was no rush to select the third well to be drilled, if in fact even would there be approval for one. Appomattox was still the team's favorite prospect to drill but Shell did not own the lease. Shell continued negotiations with the lease owner to acquire the Appomattox block. Meanwhile, the team matured prospect Vicksburg in the portfolio. Three years passed before approval and in 2007, when Vicksburg was about to be drilled, Shell finally received word that the Appomattox leases had been acquired through commercial trade negotiations. However, drilling Vicksburg had already begun. With planning and permitting processes accelerated, Appomattox could not be drilled before perhaps two more years.

The Vicksburg well was drilled in 2007 and was timed to allow for the results to impact the evaluation of additional Norphlet prospects in the upcoming lease sale area. The Vicksburg (DC353) exploration well at location B, penetrated a thrust-faulted nose in the Norphlet sandstone, with the oil–water contact found in the hanging wall. The oil-in-place discovery at Vicksburg was in the mid-range of the predrill volume estimate (Godo et al., 2011). Shell integrated the Vicksburg results into the existing conceptual model and acquired several leases over a dozen new Norphlet prospects.

With the discovery at Vicksburg, there was a large momentum to drill soon, even before Appomattox could be drilled. At that time, only a few prospects in the Norphlet portfolio had approved paperwork that were ready to be drilled. Prospect Fredericksburg was one of these prospects. The four-way simple structure at Fredericksburg had an outward attractiveness; however, the prospect itself lacked some of the analogous characteristics of the previous Norphlet discoveries. Fredericksburg was drilled several months after Vicksburg, and the well was a confirmed dry hole with no oil shows.

The dry hole at Fredericksburg seemed to sound the death knell for the play. However, a clever strategy emerged to give the Norphlet one last chance to either find big oil or exit the play. That strategy had Shell drilling two Norphlet prospects back to back, regardless of the results of the first well. The two prospects chosen for this program were Appomattox (finally drill-ready) and Antietam. After all, it was said that both prospects were just a syncline away from discovered oil (Antietam to Shiloh and Appomattox to Vicksburg). Antietam found a very thin oil column over a larger residual oil column. But given the two-well commitment to the area, Appomattox would still be drilled.

In 2009, the exploration well at Appomattox (MC392-1) found porous aeolian sand filled with oil pay to the base of the well (Figures 4 and 5). Obviously, the team was very excited. That excitement was nothing, however, compared to the excitement level after a downdip sidetrack (AppoOHst) again found oil-filled sand with pay to the base of the reservoir. The implication of finding oil this deep on the structure had a palpitating effect. The depth of this oil section was deeper than what was thought to be the predrill spill point. This predrill spill point was defined as a syncline located on the northeast flank of Appomattox. Finding oil this deep in the sidetrack well combined with the observation that there was no apparent crestal faulting to give access to the predrill spill point led imaginations to soar regarding potential trap size. The key question was, “How big is this thing?” In order to find the oil–water contact (OWC) with the rig in this position, a third well was designed to go downdip and find the contact. The drillers designed an essentially horizontal well to stay within the Norphlet while drilling downdip on the structure in search of water. This second sidetrack ultimately penetrated the oil–water contact (OWC) in the most downdip sidetrack well (AppoOHbp) (see Figure 5) and proved up an oil column in excess of 2000 ft (610 m) in the south fault block. Appomattox appeared to be the hub class volume field the team had been in search of for nearly a decade.

Further Appomattox appraisal drilling was delayed by the Gulf of Mexico drilling moratorium that followed the Macondo incident in 2010. Despite the Gulf of Mexico drilling moratorium being lifted in October 2010, there were a series of new permitting issues to work through before appraisal of Appomattox could restart.

Appraisal operations resumed in July 2011, and the Appomattox Northeast Fault Block was successfully appraised by the MC348-1 well and an updip sidetrack in late 2011 and early 2012. The objective of this well was to penetrate a depth equivalent to the OWC contact found in the original hole in the Northeast Fault Block in order to test the mega case and potentially discriminate between a one- or two-hub development scenario. In addition, this well would test the connectivity of the structure and hold the MC348 lease.

The original Northeast appraisal well, designed to test the upside volume realization, was unsuccessful and found only thick, high-quality, wet Norphlet sand. However, the subsequent updip Northeast sidetrack confirmed the presence of a significant hydrocarbon accumulation in the Northeast Fault Block. Immediately after the Northeast Fault Block appraisal well was drilled, the western extension of the South Fault Block was successfully appraised, indicating hydraulic communication over geologic time in the southern half of the structure. In August 2012, this appraisal well was sidetracked to a target in the Northwest Fault Block with the aim of proving additional stock tank oil initially in place (STOIIP) and sizing the production system.

Appraisal continued through mid-2013 with the drilling of the nearby Vicksburg A pod in early 2013 followed by the eastern extension of the Appomattox field—Corinth, in early to mid-2013. Corinth was a dry hole; however, Vicksburg A added over 100 million BOE to the Appomattox resource.

APPOMATTOX FIELD DEVELOPMENT

Following the Appomattox and Vicksburg field discoveries and in parallel with appraisal, significant engineering studies have been completed that have led to the final selection of a development concept for

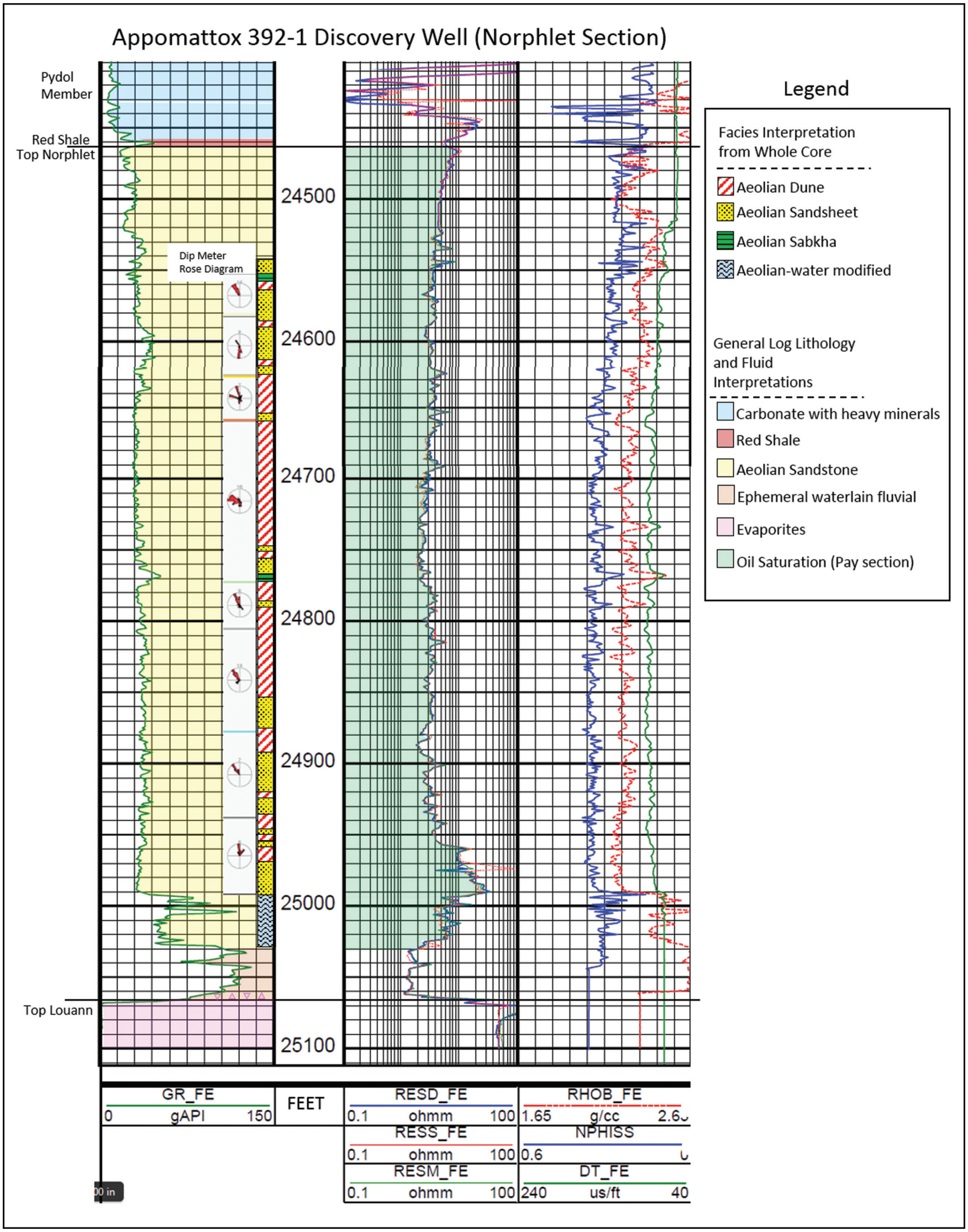

Figure 4. The log shown is the discovery well for the Appomattox field. Nearly 600 ft (183 m) of gross Norphlet section with most of it aeolian sandstone (colored yellow by the gamma ray curve). The green colored area under the resistivity curve illustrates the section of very high oil saturation. A continuous whole cored section describes in more detail the specific facies types: 1) Aeolian dune deposits have a dominance of avalanche strata relative to wind-ripple strata, together with the unimodal and consistent dip azimuth, they support a barchan/barchanoid dune morphology. Avalanche strata are typically interbedded with flat-lying wind-ripple strata, suggesting that successive dune deposits are separated by interdune facies. 2) Aeolian sandsheet deposits typically made up of decimeter to meter scale sets of flat-lying wind-ripple to low angle laminated sandstones. 3) Sabkha deposits are dominated by flat-lying, irregularly bedded sandstones with reworked anhydrite clasts, with preserved wind-ripples having a low mud content. 4) Sheet/streamflood deposits are characterized in core by sharp-based, occasionally erosive with rip up mud clasts. They are normally graded beds of massive and/or flat-lying laminated sandstones. These likely represent rapid deposition under an upperflow regime conditions likely in an unconfined, ephemeral sheetflood depositional setting.

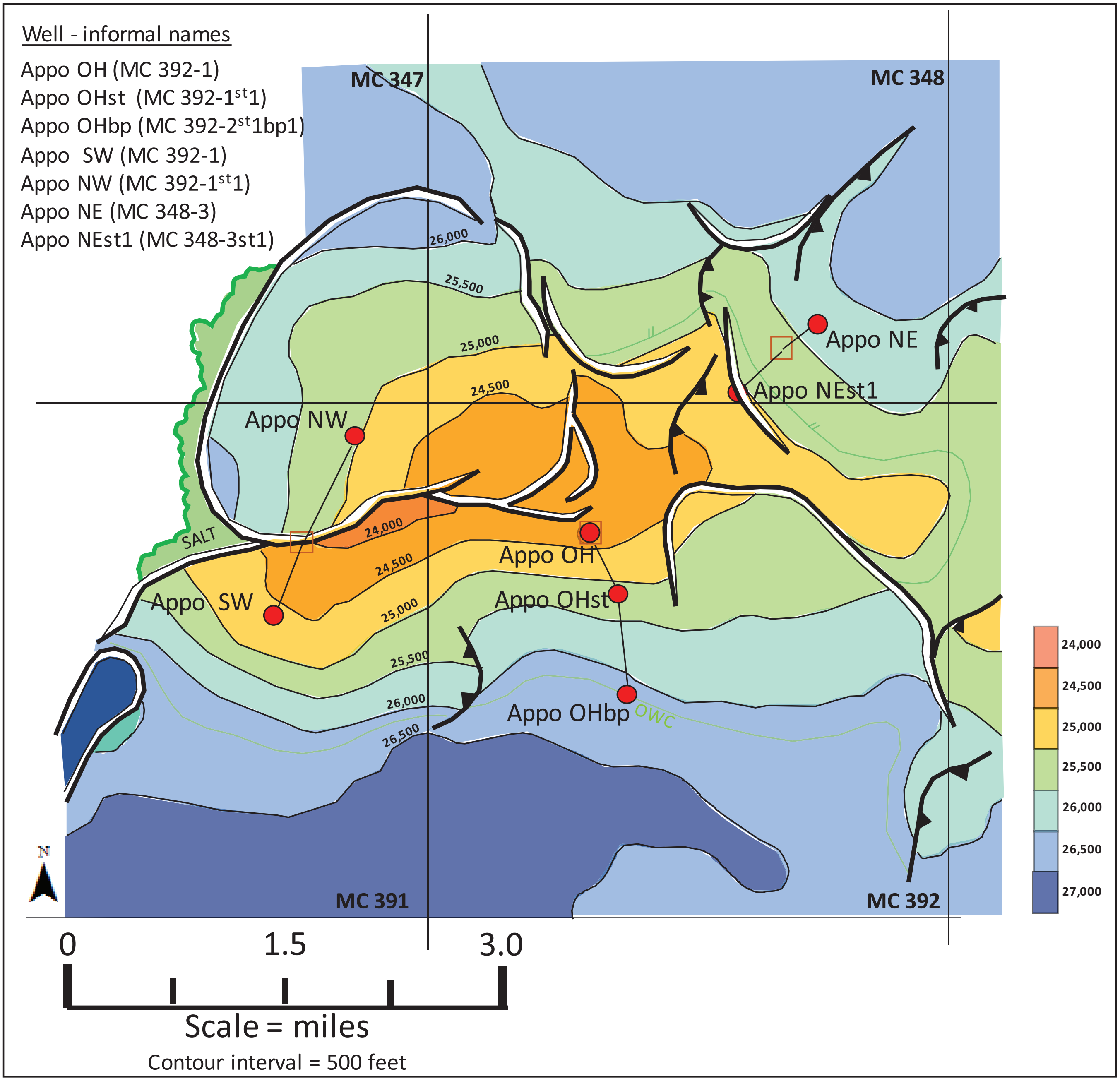

Figure 5. The four-way dip closure of the Appomattox oil field located in Mississippi Canyon (MC) blocks 391, 392, 347, and 348. The discovery well for this field is the MC292-1 well and was followed up with 2 downdip sidetrack wells drilled to the Louann salt. Three subsequent appraisal wells then tested the structural flanks of the discovery. The first appraisal well location was in the Northeast flank of the structure (MC348). The final two appraisal penetrations were in the southwest and northwest flanks of the structure (MV391). The square boxes represent the surface locations of the rigs for the discovery and appraisal programs.

the fields. Sanctioned in 2015, the Appomattox development host will consist of a semisubmersible, four-column production host platform, a subsea system featuring six drill centers, 15 producing wells, and five water injection wells (Figure 6). The upsized export pipeline will serve the Appomattox host for oil export and will have preinstalled subsea connection points, which will allow for future interconnections.

The Appomattox development will initially produce from the Appomattox and Vicksburg fields, with average peak production estimated to reach approximately 175,000 BOE per day. This will be the

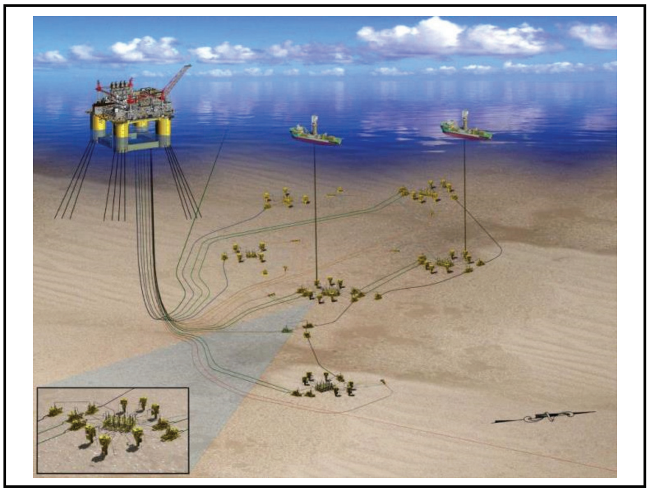

Figure 6. The Appomattox development concept.

largest output of any of the Shell projects in the Gulf of Mexico. The platform and the Appomattox and Vicksburg fields will be owned by Shell (79%) and Nexen Petroleum Offshore U.S.A. Inc. (21%), a wholly owned subsidiary of CNOOC Limited.

The sanctioned project includes capital for the development of 650 million BOE resources at Appomattox and Vicksburg, with start-up estimated around the end of this decade. Additional discovered opportunities in the area that could be tied back into the Appomattox hub would bring the total estimated discovered resources in the area to more than 800 million BOE. Shell continues exploration prospecting and drilling in the Norphlet area of the Gulf of Mexico.

ACKNOWLEDGMENTS

The author is honored to present this information on the giant Appomattox discovery as one of the oil fields selected for this AAPG Memoir.

The author wishes to thank and acknowledge both Shell and Nexen for permission to share this information. Thanks are also given for allowing the expansion of this paper to include a historical perspective of the play as well as provide a current perspective on the deep-water play segment, something that the authors feel is an important part of preserving this play-opening history in the Gulf of Mexico.

The support and tenacity shown by management through times of repeated exploratory challenges has been remarkable. Despite somewhat limited economic success over years of exploration in the play, it has demonstrated to be both a commercial success and an outstanding learning experience for the geoscientists involved. Thankfully, this knowledge has paid off with success at Appomattox, Vicksburg, Rydberg, and Fort Sumter in the current deep-water play. Of course, all these learnings could not have happened without the rich history of former geoscientists working this play. Acknowledgment and gratitude are given to all of those individuals who span nearly 50 years of Norphlet work. Though there is not enough space to give proper credit to all of them, to all of them we extend our humble gratitude.

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