Prediction of deep reservoir quality using early diagenetic process models in the Jurassic Norphlet Formation, Gulf of Mexico

J. M. Ajdukiewicz, P. H. Nicholson, and W. L. Esch

ABSTRACT

We have developed process-based models for early grain coats and their impact on deep reservoir quality in the Jurassic eolian Norphlet Formation, Alabama, with implications for exploration and development in other conventional and tight-gas continental reservoirs. The Norphlet, a major gas reservoir to depths of 21,800 ft (6645 m) and temperatures of 419°F (215°C), displays contrasting intervals of high and low reservoir quality within compositionally similar cross-bedded eolian sands. Study results show that grain coats formed soon after deposition are responsible for differences in deep Norphlet porosity of up to 20% and permeability up to 200 md. Three types of grain coats were identified in Norphlet dune sands, each formed in a different part of a shallow groundwater system, and each with distinctive impact on deep reservoir quality. Diagenetic chlorite coats, formed where dunes subsided into shallow hypersaline groundwater, preserve good deep porosity (to 20%) and permeability (to 200 md). Continuous tangential illitic coats, formed in the vadose zone of stabilized dunes exposed to periodic fresh-water influx, preserve good deep porosity (to 20%) and permeability (to 200 md). Continuous tangential illitic coats, formed in the vadose zone of stabilized dunes exposed to periodic fresh-water influx, preserve good deep porosity (to 15%) associated with poor permeability (<1 md) due to linked formation of later high-temperature diagenetic illite. Discontinuous grain coats, formed in active dunes where grains were abraded by eolian transport, are associated at depth with tight zones of pervasive quartz cement, low porosity (<8%), and low permeability (<1 md). These concepts plus data

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from 60 wells were used to derive bay-wide predictive tight and porous-zone isopachs that can be used for well placement, geologic models, and field development.

**INTRODUCTION**

In deeply buried sandstones, favorable reservoir quality can be preserved by early-formed grain coats that inhibit later quartz cementation. Deep reservoir-quality models require accurate grain-coat prediction, but the processes controlling the distribution of these coats are not always well understood. We have integrated petrographic, core, log, facies, and seismic data to develop an understanding of grain-coat-forming processes in the Norphlet Formation and link them to mappable geologic features to predict deep reservoir quality. The study has broad implications for exploration and development in other deeply buried conventional and tight-gas continental reservoirs, especially but not exclusively eolian deposits such as the Nugget (United States), Rotliegende (Europe), and Unayzah (Middle East) formations. Current models for reservoir quality prediction calculate the effect of burial history on lithologies made up of depositional and early diagenetic characteristics. Models for the distribution of early diagenetic attributes such as grain coats can be developed and integrated with existing burial-history-based models to extend current exploration-scale reservoir quality prediction to more detailed field-scale models that can be used for development and production projects.

**Norphlet Geologic Setting**

The Upper Jurassic Norphlet Formation is a major deep-gas reservoir in eolian dune sands that were deposited during the late Oxfordian over parts of southern Mississippi, Alabama, Florida, and Mobile Bay (Mancini et al., 1985, 1990; Marzano et al., 1988; Dixon et al., 1989; Taylor et al., 2004). Despite present burial in the study wells to depths of 20,100–21,800 ft (6126–6645 m) and temperatures to 419°F (215°C), much of the lower Norphlet has as much as 20% preserved primary porosity and several hundred millidarcies of permeability. However, in the upper Norphlet in every Mobile Bay well, a zone of pervasive quartz cementation forms a tight zone of less than 8% log porosity and 1-md permeability. The thickness of this tight zone ranges from 10 to 190 ft (3 to 58 m) within structures and overprints eolian cross-bedded sandstones.
Figure 1. Location maps for Mobile Bay and subregional studies. Petrographic data and observations from 20 Mobile Bay and 11 onshore wells were included in the study.
that are similar in texture and composition to the sands making up the porous reservoir below. In onshore Alabama, much of the Norphlet consists of thick intervals of cross-bedded eolian facies that have good preserved porosity (average per well of 15%) but poor permeability (average per well of 1–2 md) due to associated pore-lining and pore-bridging diagenetic illite, a phase that occurs only rarely in Mobile Bay. A study of this variable, facies-independent diagenesis in the Norphlet was undertaken to assess reservoir quality paragenesis and distribution, interpret controlling processes, and develop a predictive reservoir quality model for application to Norphlet reservoir management (Figure 1).

In the study area, the Norphlet rests on a thick section of Jurassic evaporites, the Pine Hill Anhydrite Member and Louann Salt, and is overlain by the Smackover and lower Haynesville carbonates (Figure 2). Upper Jurassic paleogeographic reconstructions indicate that, during the Callovian, the Gulf of Mexico was a shallow restricted sea with a small opening to the Pacific on the southern margin but no opening to the Atlantic Ocean (e.g., Salvador, Salvador, 2004).

### Table 1: Stratigraphic Column

<table>
<thead>
<tr>
<th>Series</th>
<th>Stage (Ma)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td></td>
<td></td>
<td>Louann Salt</td>
</tr>
<tr>
<td></td>
<td>Callovian</td>
<td>Werner Formation</td>
</tr>
</tbody>
</table>

### Figure 2: Stratigraphic Column (based on Mancini et al., 1985, with dates from Mancini et al., 2004) and seismic images of Norphlet dunes in map (A) and cross section (B). The sand was deposited as linear dune complexes trending northwest–southeast on top of Louann Salt and is overlain by the Smackover and lower Haynesville carbonates. The dune complexes, which are up to 800 ft (244 m) thick today, sank into the underlying Louann Salt during deposition, resulting in a convex downward lower surface on each dune. The upper dune surface forms an upwardly convex surface that is interpreted to reflect present-day dune topography.
In this environment, the Louann Salt was laid down as a thick evaporite sequence. Subsequently, during the Oxfordian, Norphlet dunes were deposited along the coast on top of the salt, although the position of the strandline is unknown. At the Oxfordian–Kimmeridgian boundary, the opening of the Gulf of Mexico to the Atlantic resulted in the filling of the Gulf and flooding of the Norphlet dune field with marine water (Salvador, 1987), and deposition of the overlying Smackover and lower Haynesville carbonates (Mancini et al., 1984). The carbonates immediately above the Norphlet are a relatively deep-water, organic-rich facies, thought to be the source rock for the Norphlet hydrocarbons (Mancini et al., 1985, 2004). The absence of large-scale marine-reef sediments at the top of the Norphlet suggests that the flooding was of low energy (Mancini et al., 1985; Story, 1998).

Grain compositions indicate that Norphlet sediments were derived from erosion of the Appalachian Mountains to the north and deposited in an east-west–trending pull-apart graben system (Mancini et al., 1985, 1990; Salvador, 1987). In onshore Alabama, Mississippi, and Florida, the northernmost Norphlet consists of poorly sorted sandstones and conglomerates interpreted as alluvial fans and wadis that delivered sand-size sediments to the Louann coastal salt pan. The sand was reworked by prevailing winds into dunes that prograded southeastward over the salt (Mancini et al., 1985; Marzano et al., 1988).

Sand-thickness isopachs from three-dimensional seismic data show that the Mobile Bay Norphlet consists of northwest-southeast–oriented, subparallel, elongate sand bodies that are up to 800 ft (244 m) thick, 5000 ft (1524 m) across, and separated from each other by areas with sand thickness less than a seismic resolution of 300 ft (91 m) (Figure 2). The thick sand bodies have been interpreted from core, seismic mapping, and bedding dips to be longitudinal complex dunes made up of seif and star dunes (e.g., Story, 1998; M. Porter and M. Sweet, 2006, personal communication). The thinner Norphlet between the dunes is interpreted to be sandy interdunes, but these areas are rarely drilled and, hence, poorly characterized. Norphlet dunes may have been similar in morphology and scale to modern complex linear dunes in the western Namib Desert, southwest Africa (e.g., McKee, 1979). The Namibian dunes are elongate bodies made up of seif and star dunes and are up to 1060 ft (323 m) high.

In modern coastal dune fields, interdune sands are deflated to and stabilized by the water table (Fryberger et al., 1983). By analogy, Norphlet interdune surfaces may have been similarly pinned to a coastal water table related to sea level. Because the formation of evaporite cements is favored where the water table is close to the sediment-air interface, these cements should be more common in Norphlet interdunes than within the dune complexes, where the water table would have been buried beneath the thick active dune. Ground-penetrating radar studies in modern dunes have shown that the water table is nearly flat beneath active dunes in an arid setting due to the low capillary forces in the pore systems of clean dune sands (Bristow and Jols, 2003). However, in wetter periods, the water table rises beneath the dunes to form a concave downward surface subparallel to topography (Loope and Rowe, 2003). A similar water-table geometry may occur where dune sands become coated with high surface-area clays, resulting in smaller pore throats and higher capillary forces.

In seismic cross sections, Norphlet dune bodies are lenticular or pod shaped (Figure 2), with concave-downward top surfaces inferred to be remnant dune topography and concave-upward lower surfaces interpreted to result from the syndepositional sinking of the dunes into the thick underlying salt (e.g., Story, 1998; Taylor et al., 2004). Postdepositional sediment compaction, structuring, and salt tectonics have distorted the original dune configuration, but the overlying Smackover and lower Haynesville carbonates thin over Norphlet dune crests and thicken over interdunes, indicating that dune topography was present when the carbonates were deposited (Story, 1998). Present-day Norphlet dune topography has been estimated from seismic data to be several hundred feet high (Story, 1998), but these values are thought to be less than the original topography as a result of postdepositional sediment compaction, as discussed below under “Reconstruction Issues”.
Figure 3. Facies and diagenetic controls on Norphlet reservoir quality (RQ) in two wells. Reservoir quality zones include a quartz-cemented upper tight zone (UTZ, <8% porosity) which occurs at the top of all Norphlet wells and overprints all facies, including high dip-angle eolian avalanche, wind-ripple, and some massive beds that may have formed by bioturbation. In well 1, the transitional upper porous zone (UPZ, 8–10% porosity) is very short, but it is longer in well 2. The lower porous zone (with up to 20% intergranular porosity) makes up the main reservoir below the cemented zones. The facies interval labeled MR in Well 2 is a homogenous unit like those interpreted by some to be marine reworked. Depths are in feet.
Reservoir Characteristics

In the Mobile Bay wells studied, the Norphlet is buried to depths as great as 21,800 ft (6645 m), has bottom-hole temperatures of up to 419°F (215°C), and has formation pressures that are hydrostatic to moderately overpressured. Despite a limited range of facies, texture, and grain compositions that varies little overall from top to bottom of the dune complexes, the Norphlet in each Mobile Bay well is divided into three distinct reservoir quality zones based on log-porosity cutoffs (Figure 3). The upper tight zone, at the top of the Norphlet, with a log porosity of less than 8%, is pervasively quartz cemented with an 8% average quartz-cement abundance. Below the upper tight zone in some wells is a transitional interval of 8–10% porosity called the upper porous zone, which is partially quartz cemented (3% average quartz cement) and can range in thickness from zero to more than 100 ft (30 m) thick. The two cemented zones together are sometimes called the altered zone. Below these cemented zones lies the main reservoir, or lower porous zone, with log porosities from 10 to 20% and less than 1% average quartz-cement abundance. Analysis of well data indicates that the upper tight zone is thickest in Norphlet structural crests and thins on structural flanks (Ajdukiewicz et al., 1991). Seismic observations have been interpreted to show an approximately flat base of upper tight zone relative to the top Norphlet topography in the Fairway field in Mobile Bay (Taylor et al., 2004).

In some onshore Alabama fields, significant intervals of Norphlet eolian facies have good preserved porosities but orders of magnitude lower permeability than the same facies in Mobile Bay (Dixon et al., 1989; Ginger et al., 1995). This difference in permeability is caused by the extensive development of pore lining and pore-bridging diagenetic illite in the onshore areas, a phase that is rare in Mobile Bay. Present-day Norphlet hydrocarbons are dry gas, but traces of a paleo-oil reservoir occur at the top of the Norphlet in Mobile Bay wells as pyrobitumen stains on grain and grain-coat surfaces, and as solid hemispherical bodies under quartz cement in the tight zone (Figure 4). Clay grain coats in the Norphlet are of two main types: (1) tangential clay coats, made up of detrital clay particles lying flat against grain surfaces, and (2) diagenetic clay coats, made up of neoformed crystals oriented perpendicular to grain surfaces (Figure 5). Tangential coats are formed when clays in suspension in rainwater or floodwater are infiltrated or illuviated into the sand above the water table. When the rain or flood subsides and water dries in the pores, the clay particles dry flat onto grain surfaces and along fluid menisci (e.g., Crone, 1975). Repeated wetting, infiltration, and drying episodes can build up multilayered, continuous coats on grain surfaces called cutans or argillans in the soil literature (e.g., Matlack et al., 1989; Winspear and Pye, 1995; Retallack, 1997, 2001). Cutans form only in fresh water; in saline water, clays flocculate and form particles too big to be illuviated into pores (Gunal and Ransom, 2006). In the Norphlet, tangential grain coats have a high birefringence and appear to be mainly illitic in composition. Illuviated coats can be very continuous in the area in which they form, for example, in stabilized dunes subjected to seasonal rainfall or active, intermittently flooded dunes (Winspear and Pye, 1995). If coated dune sands are subsequently deflated and remobilized into active dunes, the coats are abraded by eolian transport (Walker, 1979; Ajdukiewicz et al., 2008; Esch et al., 2008). Such inherited abraded coats in active dunes are commonly discontinuous, present at some grain contacts, and often stained red, presumably by hematite. Stained remnant coats are responsible for the reddish color of many eolian sands (Walker, 1979). Coats are more completely abraded on coarse grains and less completely abraded on finer grains, possibly because the finer grains have more rugose surfaces (Walker, 1979). As a result, the fine-grained laminae of wind-ripple sands have more continuous inherited tangential grain coats than coarser sands, and the coats are more likely to be present at grain contacts. Illitic clays present at grain contacts have been shown to enhance intergranular pressure solution (Bjorkum, 1996; Harris, 2006).

Many previous workers have observed that the porous Norphlet reservoir is characterized by well-developed, highly continuous diagenetic chlorite.
Figure 4. Photomicrographs of upper tight zone clay coats, quartz cement, and pyrobitumen. (A) Quartz cement fills pores lined with pyrobitumen-stained clay coats. Coats are composed of both tangential illitic clays and perpendicular diagenetic chlorite (B). EDS = Energy Dispersive Spectrometer analyses. (C, D) Ashing to remove pyrobitumen shows discontinuous tangential illitic coats in thin section, with bright birefringence in crossed nicols. (E) Pyrobitumen and quartz cement are interlaminated in some wells, suggesting precipitation of both phases during the same period. (F) Small hemispherical pyrobitumen blebs are observed near the tops of some wells.
grain coats, with particles oriented perpendicular to grain surfaces (e.g., Dixon et al., 1989; Taylor et al., 2004). The perpendicular habit of the chlorite particles relative to grain surfaces indicates the diagenetic precipitation of the clay from pore fluids (Wilson and Pitmann, 1977). Mobile Bay chlorite is uncommonly Mg-rich compared to more Fe-rich marine chlorites (Kugler and McHugh, 1990). The coats may have formed initially as a nonchlorite precursor. The earliest chlorite precursor forming in hypersaline brines in an arid eolian setting is commonly saponite, an Mg-rich smectite, which may subsequently evolve with increasing temperature into an Mg-chlorite (Ryan and Hillier, 2002). Observations from modern middle-eastern sabkhas suggest that chlorite precursors begin to form very early at or just below the water table. In Persian Gulf sandy sabkhas, diagenetic clays with an Mg-Si-Al composition and delicate smectitic morphology were observed in sediments near the water table at less than 1-m (3-ft) burial depth (Ajdukiewicz et al., 2008).

Chlorite coats have been documented in numerous other reservoirs to preserve deep porosity by inhibiting the formation of later high-temperature quartz cement during deep burial (e.g., Heald and Larese, 1974, Pittman et al., 1992; Hillier et al., 1996). However, much of the Norphlet upper tight zone has patchy to well-developed clay coats under pore-filling quartz cement (Figure 4). Coat surface-coverage measurements indicate that the coats in the upper tight zone are less continuous (average

**Figure 5.** Schematic drawing of early grain coat formation and abrasion processes. Tangential coats form by infiltration or illuviation of detrital clays in the vadose zone. Detrital clays may have been originally illitic, or illite may have replaced detrital clays such as smectite, kaolinite, and illite-smectite at depth. Diagenetic clays begin to form at or below the water table in an eolian environment. Deflation and remobilization of coated grains lead to coat abrasion and discontinuities that allow later quartz cementation.
92%, +4% grain surfaces coated) than those in the lower tight zone (99%, +1%) (Taylor et al., 2004). Under the extreme thermal exposure experienced by the Norphlet, this small difference in coat coverage is interpreted to be sufficient to cause the differences in reservoir quality between the tight and porous zones, a conclusion supported by numerical modeling using Touchstone software developed by Geocosm LLC (Taylor et al., 2004; Lander et al., 2008).

Several hypotheses to explain the systematic differences in coat coverage and quartz cementation between the Mobile Bay tight zone and porous reservoir have been suggested. An early interpretation linked tight-zone formation to marine reworking of the upper Norphlet during the Smackover sea transgression (Marzano et al., 1988; Kugler and McHugh, 1990). Reworking was suggested to have removed early hematite grain coats needed to react with brine to form chlorite. However, subsequent authors documented that the tight zone overprints thick intervals of eolian cross-bedded sands in many wells (e.g., Ajdukiewicz et al., 1991, 2006; Emery and Robinson 1993; Taylor et al., 2004), indicating that the tight zone is not related to marine reworking. A depth-related change in Norphlet reservoir quality in the South State Line field, Mississippi, that coincides with a shift in diagenetic clay composition from dominantly illite in the upper, poor reservoir quality sands to dominantly chlorite in the deeper, better reservoir quality sands was ascribed to a change in grain provenance and composition across the boundary between the two zones (Thomson and Stancliffe, 1990). Subsequently, Emery and Robinson (1993) observed that, in the Mobile Bay 821-1 well, Norphlet grain coats changed with depth from tangential illitic coats in the upper tight zone to diagenetic chlorite coats in the porous reservoir. They suggested that the illitic clay coats formed after deposition in a paleovadose zone by clay infiltration above a paleowater table, but they did not explain how this clay infiltration occurred over an interval of several hundred feet in eolian sands or why the illitic coats did not inhibit quartz cement. Emery and Robinson hypothesized that the change in coat composition occurred at a paleowater table, but they were unable to test the hypothesis because their data were limited to a single well. Finally, the decrease in coat continuity in the tight zone was related to an inferred increased abundance in the upper tight zone of early (pre-chlorite-coat) anhydrite cement nodules in the tight zone (Taylor et al., 2004). These workers speculated that later dissolution of the nodules exposed clean grain surfaces on which quartz cement nucleated to form the pervasive upper tight zone (Taylor et al., 2004). These hypotheses, plus some new ones generated during this study, were tested using petrographic, well-log, facies, and seismic data from 60 Mobile Bay and 11 onshore wells.

**METHODS AND DATA**

Nineteen Mobile Bay and 11 onshore wells were selected for petrographic analyses to investigate the controls on Norphlet reservoir quality (Figure 1). Of the wells examined, most had continuous core, with the exception of one dune-margin well (75-2) that had only cuttings. Two hundred eighty thin sections from representative core plugs in 15 wells throughout the Norphlet section were cut and point counted with 300 counts per thin section. Potassium feldspars were stained yellow with sodium-cobaltinitrate. The resulting data were used to identify and quantify depositional and diagenetic reservoir quality trends and to select samples for additional analyses. Quantitative grain-size data were collected for 114 petrographic thin sections in 15 Mobile Bay wells. Grain-coat continuity was quantitatively measured in 23 samples from 3 wells by R. Lander of Geocosm. The mineralogy and habit of the upper tight-zone grain coats are difficult to characterize in thin section because they are stained by opaque pyrobitumen, and difficult to observe in the scanning electron microscopy (SEM) because the coats are overlain by pervasive quartz cement. To overcome these difficulties, a combination of procedures was used: low-temperature ashing to remove pyrobitumen from thin sections, by R. Larese, consultant; quantitative x-ray diffraction (XRD) analyses of clays in six wells using
RESULTS: CORE AND PETROGRAPHIC DATA

Present-day Norphlet reservoir quality is the cumulative expression of depositional attributes (grain composition, size, sorting, and inherited clay coats) acted upon by early diagenesis in the first few hundred meters of burial, and subsequently by later, deeper burial diagenesis.

Depositional Controls on Reservoir Quality

Cores from thick Norphlet complex linear dunes consist of continuous sequences of cross-bedded dune avalanche and wind-ripple facies, with very few damp or wet evaporite-cemented or crinkly laminated interdune intervals. The rarity of wet interdune facies results from the depositional style of longitudinal dune complexes, which build out along their long axes, with limited lateral migration (e.g., Glennie, 2006). Within the thick dune complexes, the water table was deeply buried, limiting the amount of evaporite cements formed. In most Norphlet dune core, evaporite cements occur as small (up to several millimeters in diameter) nodules of anhydrite, now replaced by quartz, and calcite. However, cuttings from a well drilled on dune margins (75-2) contain abundant pore filling evaporite cements, suggesting that wet facies may be more abundant in interdune areas. As discussed above, coastal dune analogues, in which the interdune is deflated to the water table and prone to evaporite cementation, support this interpretation (Fryberger et al., 1983). The only other occurrences of pervasive early evaporite cement in the Norphlet are observed at the top of a few wells, where thin zones of quartz and carbonate cemented sand occur. The lack of pyrobitumen stains on grains in these intervals indicates that the cement formed early, before oil emplacement. The quartz cement in these intervals may be a pervasive version of the nodular quartz cement inferred to replace early anhydrite, as discussed in detail below in the section Diagenetic Controls on Reservoir Quality.

In Norphlet dune cores, the sequence of eolian facies in a single well evolves vertically from thinner dune intervals and wind-ripple packages near the base of the Norphlet, upward through thick avalanche and wind-ripple beds into thinner eolian packages near the top of the Norphlet (e.g., Figure 3). This vertical facies evolution may reflect the change in depositional style at a single location as the linear dunes built out along their long axis, from smaller, more wind-ripple dominated facies in the nose of the dunes upward into the thicker avalanche packages of the main body of the prograding dunes. The thinner, more wind-ripple-dominated packages near the top of the Norphlet may record the smaller dune forms or plinths that covered the tops of complex dunes at end of the Norphlet deposition, when the Smackover sea level rose to flood the dunes.

The most common Norphlet eolian facies are avalanche and wind-ripple deposits. Grainfall was not recognized as a significant facies in the Norphlet, possibly because in large dunes, grainfall material does not reach the toe of the dune and is
generally reworked into avalanche and wind-ripple units, so is not well preserved (M. Sweet, 2001, personal communication). Rock texture (grain size and sorting) controls the initial intergranular volume (IGV), porosity, and permeability (Beard and Weyl, 1973). Texture is linked through the energy of the depositional environment to facies. In the Norphlet upper and lower porous zones, avalanche facies have higher reservoir quality than wind-ripple facies. In the upper tight zone, pervasive quartz cement obliterates most of the facies control on reservoir quality. Where diagenetic cement is abundant, as in the upper tight zone, differences in reservoir quality between avalanche and wind-ripple facies are nearly obliterated and reservoir quality is uniformly low (Figure 6A).

Detrital grain compositions for the Mobile Bay and onshore Norphlet wells are summarized in Figure 7. The Mobile Bay samples cover a narrow range of compositions. Most are arkoses and lithic arkoses by Folk’s classification scheme, with some subarkoses (Folk, 1980). Onshore wells have a wider range of sandstone grain compositions than those in Mobile Bay. Average grain size and sorting per well are shown in Table 1. Grain-size variability in Mobile Bay is limited, with most of the sands being fine grained, with a mean grain size of 0.16–0.25 mm (0.003–0.009 in.). Coarser grain sizes are encountered in some more northerly onshore wells closer to the sediment source: in the Shell Wefel well, mean grain sizes are 0.279 mm (medium grain size). Average Trask sorting values per well indicate that most samples are well to very well sorted.

Normalized grain compositions (quartz/feldspar/rock fragment ratio [QFR]) for Mobile Bay and onshore wells are shown in Figure 7. A breakdown by facies of grain size, sorting, QFR, and normalized rock

**Figure 6.** A. Porosity and permeability by facies and diagenesis in a single Mobile Bay well (Well 3 in other figures). Within each reservoir zone (colored ellipses), avalanche facies are represented by solid symbols and wind-ripple facies by open symbols. In the lower and upper porous zones, avalanche facies have better reservoir quality than wind-ripple facies. In the upper tight zone, pervasive quartz cement obliterates most of the facies control on reservoir quality. B. Comparison of reservoir quality in Well 3 with that in six onshore Norphlet wells dominated by either chlorite coats or tangential illitic coats. Average porosity-permeability values for three chlorite-coated onshore wells are similar to values for chlorite-coated samples in the Mobile Bay lower porous zone. Average values for three illitic onshore wells show slightly lower porosity but significantly lower permeabilities than chlorite-dominated wells. That both sets of onshore wells have good porosity suggests that quartz cement was effectively inhibited by either coat type. However, tangential clay coats form in fresh water, which also dissolves feldspar to form kaolinite, setting up later high-temperature diagenetic illite formation. As a result, tangential-illite-coated wells have significantly lower permeabilities from associated diagenetic illite than chlorite-coated wells, which contain little diagenetic illite. Well data in panel B (summarized in inset table) from Dixon et al., 1989.
fragment compositions (sedimentary/metamorphic/volcanic ratio) is shown for Mobile Bay well 3 in Table 2. In common with modern eolian sands, Norphlet sand grains in both the onshore and offshore areas are partially covered by discontinuous tangential illitic clay coats. Because coats are patchy, thickest in grain surface depressions, and occur at grain contacts, they are interpreted to be inherited abraded remnant coats present at deposition (e.g., Walker, 1979; Gaupp et al., 1993). Low-temperature ashing was used to remove pyrobitumen from several.

**Figure 7.** Norphlet sand composition from petrographic data. Note that only the upper half of Folk’s grain composition plots is shown (Folk, 1980). Mobile Bay wells have a very limited range of compositions, whereas onshore wells have a greater range. Q = quartz; F = feldspar; R = rock.

**Table 1.** Mean Grain Size and Sorting per Well*

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<th>Well Name</th>
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<td>Exxon Wilkie</td>
<td>37</td>
<td>0.217</td>
<td>1.88</td>
<td>well</td>
</tr>
<tr>
<td>G.P. Klein</td>
<td>35</td>
<td>0.21</td>
<td>1.91</td>
<td>well</td>
</tr>
<tr>
<td>Getty Travis</td>
<td>8</td>
<td>0.187</td>
<td>1.73</td>
<td>well</td>
</tr>
<tr>
<td>Highland Steel</td>
<td>13</td>
<td>0.222</td>
<td>1.81</td>
<td>well</td>
</tr>
<tr>
<td>Philips IPC</td>
<td>12</td>
<td>0.187</td>
<td>1.58</td>
<td>very well</td>
</tr>
<tr>
<td>Shell Wefel</td>
<td>10</td>
<td>0.279</td>
<td>1.81</td>
<td>well</td>
</tr>
<tr>
<td>111-2</td>
<td>28</td>
<td>0.188</td>
<td>2.01</td>
<td>mod</td>
</tr>
<tr>
<td>114-2</td>
<td>15</td>
<td>0.182</td>
<td>1.92</td>
<td>well</td>
</tr>
<tr>
<td>76-2</td>
<td>21</td>
<td>0.182</td>
<td>1.99</td>
<td>well</td>
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<tr>
<td>77-2</td>
<td>17</td>
<td>0.189</td>
<td>1.92</td>
<td>well</td>
</tr>
<tr>
<td>821-1</td>
<td>35</td>
<td>0.19</td>
<td>1.96</td>
<td>well</td>
</tr>
<tr>
<td>95-3</td>
<td>31</td>
<td>0.189</td>
<td>1.76</td>
<td>well</td>
</tr>
</tbody>
</table>

*See well locations on Figure 1.
Mobile Bay tight-zone samples. Results show discontinuous tangential grain coats with a bright birefringence in crossed nicols that indicates illitic composition. The SEM analyses of thin sections confirm that tangential illite coat remnants underlie chlorite coats in the tight zone (Figure 4A and B). The high degree of intergranular pressure solution associated with finer grained lamellae of wind-ripple sands implies that illitic coats commonly occur at grain contacts in those sands.

Table 2. Mean Depositional Attributes by Facies for One Mobile Bay Well (Well 3)*

<table>
<thead>
<tr>
<th>Facies</th>
<th>n</th>
<th>Q</th>
<th>F</th>
<th>R</th>
<th>S</th>
<th>V</th>
<th>M</th>
<th>Grain Size (mm)</th>
<th>Average Sorting Diameter Ratio (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avalanche</td>
<td>16</td>
<td>67.79</td>
<td>21.86</td>
<td>10.35</td>
<td>46.08</td>
<td>8.01</td>
<td>45.91</td>
<td>0.17</td>
<td>1.71 (well)</td>
</tr>
<tr>
<td>Dipping Wind Ripple</td>
<td>6</td>
<td>69.54</td>
<td>22.09</td>
<td>8.37</td>
<td>44.27</td>
<td>5.32</td>
<td>50.41</td>
<td>0.21</td>
<td>2.25 (bimodal)</td>
</tr>
<tr>
<td>Horizontal Wind Ripple</td>
<td>7</td>
<td>70.37</td>
<td>20.33</td>
<td>9.30</td>
<td>39.44</td>
<td>6.58</td>
<td>53.99</td>
<td>0.18</td>
<td>2.26 (bimodal)</td>
</tr>
</tbody>
</table>

*QFR is normalized grain content, with Q = quartz; F = feldspar; R = rock fragment. SVM are normalized rock fragment types, with S = sedimentary; V = volcanic; M = metamorphic rock fragments.

Figure 8. Comparison of porosity and cement trends in a typical Mobile Bay well with hypersaline diagenesis, and an onshore well with early meteoric diagenesis. Diagenetic cement abundances by point count are plotted against depth. In the Mobile Bay well, depth trends in pyrobitumen and clay are observed in point-count data, but pyrobitumen forms an opaque stain on clay coats with variable morphology and habit, making hydrocarbon and clay volumes difficult to quantify by point count. To improve analytical accuracy, TOC measurements of pyrobitumen (Figure 15) and XRD analyses of clays (Figure 13) were also undertaken. UTZ = upper tight zone; UPZ = upper porous zone; LPZ = lower porous zone.

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Norphlet Reservoir Quality
enhancing pressure solution as suggested by Harris (2006).

**Diagenetic Controls on Reservoir Quality**

Many of the basic petrographic characteristics of the Norphlet have been thoroughly described in previous articles (e.g., Dixon et al., 1989; Taylor et al., 2004). New observations and interpretations relevant to the impact of early diagenesis on deep reservoir quality will be discussed in this article.

Paragenesis of the upper Norphlet varies significantly from Mobile Bay to onshore Alabama (Figures 8 and 9). Many diagenetic features such as mechanical and chemical compaction, chlorite grain coats, feldspar overgrowths, pyrobitumen, and quartz cement are common to both areas, but some features that are absent to rare in Mobile Bay are common in intervals of the updip, onshore-Alabama Norphlet. These latter features include continuous tangential illitic coats (as distinguished from patchy inherited coats), partially dissolved feldspars, traces of kaolinite, and abundant platy to fibrous pore-lining and pore-bridging diagenetic illite. In Mobile Bay, most porosity is primary and secondary porosity is ≤2%. Onshore, secondary porosity in dissolved feldspar grains is more significant (2–4%). Major cements and porosity types are plotted against

---

**Figure 9.** Paragenesis for Mobile Bay and onshore wells. Mobile Bay and some onshore wells are dominated by chlorite grain coats formed in early hypersaline pore fluids. In contrast, some onshore wells have intervals characterized by significant early meteoric diagenesis and later diagenetic illite. TSR = thermochemical sulfate reduction.
depth for a typical Mobile Bay and an illitized onshore well, the Getty Peter Klein in Figure 8, and are discussed in more detail below.

Compaction
Rigid-grained, moderately well- to well-sorted sands like those of the quartzo-feldspathic Norphlet undergo mechanical compaction with burial until the framework stabilizes at IGVs of 23–26%, similar to theoretical IGVs for spheres in closest packing (Paxton et al., 2002). In normally pressured, rigid-grained sands, this mechanical compaction is generally complete after 1–2 km (0.6–1.2 mi) of burial. However, many well-sorted Norphlet samples have significantly lower measured IGVs of 11 to 15%. Thin-section observations indicate that the cause of these low values is intergranular pressure solution, expressed as many sutured grain contacts (Figure 10A). Intergranular pressure solution is commonly more severe in wind-ripple sands, and many microstylolites seem to have initiated along finer grained laminae in this facies, apparently from the coalescence of individual pressure-solved grain contacts (Figure 10C). Macrostylolites are common,

Figure 10. Pressure solution in the Norphlet Formation. (A) Intervals of intense intergranular pressure solution occur in the upper tight zone. (B) In some sands, intergranular pressure solution develops into stylolites (S). (C) Incipient stylolitization: intergranular pressure solution developed into a microstylolite in the finer grained laminae of wind-ripple sand. The pressure solution in the area photographed does not appear to be associated with significant quartz cement on the scale of the thin section.
many with diagenetic muscovite flakes oriented parallel to vertical offsets in the seams (Figure 10B) (Thomas et al., 1993). The more continuous inherited tangential illitic coats on the smaller grains within fine-grained wind-ripple laminae may have catalyzed intergranular pressure solution and helped initiate stylolitization (Harris, 2006). Interestingly, intergranular pressure solution and stylolites are not always associated with quartz cementation at the thin-section scale (Figure 10C).

**Early Cementation and Dissolution**

The earliest Norphlet cements in both onshore and offshore areas are anhydrite and carbonate, which formed small nodules within the dunes (Figure 11). Most anhydrite nodules have now been replaced by quartz cement, with the original anhydrite present only as remnant inclusions common in nodular quartz cement. Within the center of the nodules, quartz cement overlies only thin, discontinuous inherited clay coats, with little or no pyrobitumen stain on the grains, indicating that the onset of anhydrite cementation predated diagenetic clay coat formation and oil emplacement. Toward the margins of some nodules, clay coats increase in thickness and continuity, suggesting that the anhydrite cement continued to form over the same period as the clay coat (Figure 11B and D). Nodules occur throughout the porous and tight Norphlet and are abundant enough to form internal tight zones in a few wells. Nodular tight zones occur in the middle of some wells, below the upper tight zone, and near the top of the Norphlet within the tight zone in others.

Minor amounts of quartz cement may have formed early: small quartz prisms stained with pyrobitumen have been observed in the Norphlet (Taylor et al., 2004), and similar early quartz cement crystals have been observed in Pleistocene soils in the Middle East (Ajdukiewicz et al., 2008). The next phases to form are interpreted to have been clay grain coats. The updip Norphlet in onshore Alabama contains significant intervals of porous reservoir in which grains are coated with continuous tangential illitic clay coats (Figure 12). The high continuity of these updip tangential coats within eolian cross-bedded facies indicates that they formed in situ by clay illuviation into stabilized dunes (Winspear and Pye, 1995). In Mobile Bay, by contrast, observed tangential illitic coats are commonly discontinuous or have other features associated with remnant inherited coats; that is, they are thickest in grain-surface depressions and present at grain contacts (Figure 4).

Diagenetic chlorite coats with particles oriented perpendicular to grain surfaces overlie the remnant tangential illitic coats on Mobile Bay sand grains (Figure 4A–D). Quantitative XRD and petrographic analyses in six Mobile Bay wells indicate that, near the top of the tight zone chlorite is relatively scarce. The XRD illite data, thought to represent remnant tangential grain coats plus grain alteration products, show no systematic depth trend in Mobile Bay wells, although local excursions to higher values occur in low-angle wind-ripple facies and in pressure-solved and stylolitized intervals. Chlorite abundance, however, is low near the top of most wells and tends to increase downward toward the base of the upper tight zone in all six wells analyzed (Figure 13). Below the base of the upper tight zone, XRD chlorite abundance increases only slightly or remains relatively constant. The absolute values of the clays measured are small, but the consistency of the chlorite depth trend from well to well suggests that it is real (S. Hillier, 2009, personal communication). Thin-section observations support the XRD trend. Chlorite coats can be identified under the pyrobitumen stain in Mobile Bay by the perpendicular orientation of the clay particles, which makes the chlorite coats look thicker, with a more serrated edge, than the tangential illite coats (Figure 4). Chlorite coats are discontinuous in the upper tight zone near the top of the Norphlet tight zone and increase in continuity downward into the top of the porous reservoir, where they coat all quartz-grain surfaces adjacent to intergranular pores (Figure 14A).

Potassium feldspar overgrowths are present as minor components (<5%) throughout the Norphlet in all wells, but in Mobile Bay, they show little to no apparent difference in abundance between the tight and porous zones. Potassium feldspar grains and overgrowths have been albited but have undergone very little dissolution in the Mobile Bay
Nodular cement paragenesis

1. Early anhydrite cement forms soon after deposition
2. Early anhydrite cement prevents chlorite coats
3. TSR dissolves anhydrite ($\text{HC} + \text{CaSO}_4 \rightarrow \text{CaCO}_3 + \text{H}_2\text{S}$)
4. Quartz cement forms on uncoated surfaces
Late Cementation and Dissolution

In many wells, including all those studied in Mobile Bay, oil was emplaced in the upper Norphlet after grain coats formed. Pyrobitumen is absent within early cemented nodules, but outside the nodules, pyrobitumen stains grain and grain-coat surfaces and more rarely, near the top of the Norphlet, forms solid hemispherical bodies of pyrobitumen on grain and quartz-cement surfaces (Figure 4). Point-count analyses suggest that pyrobitumen content is highest toward the top of the Norphlet in Mobile Bay, as might be expected for the remnant traces of a paleo-oil leg (Figure 10), but these trends do not accurately reflect absolute pyrobitumen abundance because the paleo-oil occurs as a thin opaque stain on clay coats that themselves vary in thickness and habit. However, an upward increase in paleo-oil saturation was confirmed by Rock-Eval analysis of TOC in 14 wells. Two examples are shown in Figure 15. Maximum paleo-oil saturations were calculated from TOC values to be about 30%. The original oil became pyrobitumen through thermal cracking of the oil to gas and thermochemical sulfate reduction (TSR). TSR reactions beginning at temperatures of \( \sim 140^\circ\text{C} \) (\( \sim 284^\circ\text{F} \)) (Orr, 1977; Machel et al., 1995; Worden et al., 2000). The oil-cracking reaction produces CH\(_4\) and pyrobitumen. During TSR, anhydrite is consumed, and CaCO\(_3\), H\(_2\)S, and CO\(_2\) are produced. The reaction can be written as

\[
\text{CaSO}_4 + \text{CH}_4 \rightarrow \text{CaCO}_3 + \text{H}_2\text{S} + \text{H}_2\text{O} \quad (1)
\]

Because the original anhydrite cement partly predated and prevented clay-coat formation, TSR removal of the anhydrite exposed uncoated grain surfaces that were susceptible to quartz cementation at high temperatures (Dixon et al., 1989; Walderhaug, 1996, 2000; Taylor et al., 2004).

Quartz cement formation overlaps pyrobitumen and TSR formation (Figure 4). Quartz occurs...
Figure 12. Onshore well diagenesis observations. (A) Dissolved feldspars, onshore G. P. Klein well (potassium feldspars stained yellow). (B) For comparison, Mobile Bay Norphlet well, with pristine feldspars. (C) Pore-lining, perpendicular diagenetic illite clays stained with pyrobitumen and developed on continuous tangential illitic cutans in the G.P. Klein well. The XRD shows no chlorite at this depth in the G.P. Klein. (D) Same view as panel C in crossed nicols, showing continuous illitic cutans (bright birefringence) underlying oil-stained diagenetic illite coats. (E) Fibrous illite development after cutans, deeper in the G.P. Klein well. (F) Same view as panel E in crossed nicols.
in two distinct habits: one as a late replacement of early anhydrite cement nodules, in which the quartz cement nucleated at high temperature on relatively uncoated grain surfaces exposed by TSR (Figure 11), and the second as a pervasive pore-filling cement that forms most of the Norphlet upper tight zone in Mobile Bay wells (Figure 4). Quartz cement within nodules differs from pervasive quartz cement in that the nodular replacement cement contains remnant anhydrite inclusions, encloses grains with relatively thin inherited coats only partly stained with pyrobitumen (Figure 11), and is associated with late (postpyrobitumen) carbonate cement inferred to have formed as a result.

Figure 13. Quantitative x-ray diffraction (XRD) analyses in six Norphlet wells. Chlorite shows a common tendency to increase downward in abundance in all six wells analyzed, generally to approximately the base of the upper tight zone (UTZ). The XRD illite, probably comprising inherited coats and grain-alteration products, has no systematic depth trend. UPZ = upper porous zone.
Figure 14. Chlorite and illite grain-coat coverage with depth by thin section, x-ray diffraction (XRD), and coat-coverage measurements in Mobile Bay well 1. Thin coats are remnant tangential illite. Thick coats made up of particles oriented perpendicular to grain surfaces are interpreted to be chlorite. Chlorite coverage increases with depth in panels A, C, and E. The lack of anhydrite inclusions and optical continuity of overgrowths to adjacent grains in these tight-zone samples are shown in crossed nicol plates B, D, and F, from the same areas as plates A, C, and E. UTZ = upper tight zone. Depths are in feet.
of TSR. Nodular cement does not extend beyond nodule boundaries, a characteristic especially easy to see in nodules occurring within the porous reservoir (Figure 11). Pervasive quartz cement, in contrast, contains few to no anhydrite inclusions, commonly overlies chlorite grain coats that are strongly pyrobitumen stained in the paleo-oil leg, and is not systematically associated with carbonate cement. Pervasive quartz cement increases upward in abundance from the top of the lower porous reservoir to the top of the Norphlet (e.g., Figure 16). In most Mobile Bay tight-zone samples, anhydrite inclusions and carbonate cements are rare to absent, and underlying clay coats are heavily stained with pyrobitumen, indicating that most of the upper tight-zone quartz cement did not replace anhydrite (Figures 11 and 16). In crossed nicols, pervasive quartz-cement overgrowths in the upper tight zone can be seen to have nucleated on immediately adjacent grains, indicating that nucleation sites or coat breaks are present on many grains instead of restricted to scattered nodules (Figure 14).

In Mobile Bay, diagenetic illite is limited to localized occurrences, commonly in stylolites or within 1 cm (0.3 in.) of stylolites (Thomas et al., 1993). In addition, some rare intervals of massive pore-filling illite occur that may represent recrystallized concentrations of pore-filling illuviated clays (Ahlbrandt and Fryberger, 1980) or wind-deposited mud aggregates (Kilbarda et al., 2008). By contrast, in some onshore Alabama fields, pore-lining and pore-bridging diagenetic illite is widely distributed in intervals tens of feet thick (Dixon et al., 1989; Ginger et al., 1995), commonly in association with continuous tangential illitic coats, secondary porosity from feldspar grain dissolution, and occasional traces of kaolinite (<1%) as discussed above (Figure 8).

**Coat Coverage Measurements**

Quantitative early grain-coat continuity measurements in three wells for this study support Taylor et al.’s (2004) conclusion that the clay coats in the
upper tight zone of Mobile Bay are less continuous than those in the porous reservoir. Coat coverage was measured as the percentage of grain surfaces on 50 grains per sample for this study. In general, coat coverage increases downward through the tight zone as chlorite-coat abundance increases (Figure 14). In shallower samples from the upper tight zone, a wide range of coverage values per grain were measured. With depth, this range decreases, and more grains become well covered until, at the top of the porous reservoir, grain coverage is uniformly high. Petrographic observations of tight-zone grain coats over the same interval show that, in the upper tight zone, discontinuous coats of both tangential illite and diagenetic chlorite occur. The thicker, crenulated chlorite coats are nonisopachous and commonly present in relatively short segments (Figure 14). Toward the base of the tight zone, the chlorite coats become very continuous until they achieve nearly perfect grain-surface coverage in the porous reservoir. The coat continuity measurements, XRD chlorite trends, and petrographic observations together support a trend of increasing chlorite-coat continuity downward through the tight zone.

**Grain Fracturing Measurements**

No systematic increases in grain or coat fracturing in the upper tight zone relative to the porous Norphlet were observed. A similar lack of correspondence between quartz cement and grain fractures was observed by Taylor et al. (2004). In thin section, the short segments of chlorite coats in the upper tight zone suggest that coats are incomplete instead of fractured (Figure 14A–F).
DISCUSSION OF CORE AND PETROGRAPHIC RESULTS

Processes Controlling Tight and Porous Reservoir Distribution in Mobile Bay

The observed decrease in chlorite-coat abundance and continuity above the porous reservoir is inferred to be responsible for the abundant late quartz cement forming the tight zone, but the processes controlling this coat-continuity trend remain to be explained. Taylor et al. (2004) speculated that a greater abundance of early anhydrite nodules and cement may have existed in the vadose dunes above a late-Norphlet water table, and that once TSR removed these nodules, the exposed uncoated grain surfaces allowed pervasive quartz cementation to occur.

This hypothesis is difficult to reconcile with the following observations.

1. Carbonate cement is absent or present in only trace amounts through much of the tight zone in many wells (Figure 16). As a product of TSR, significant carbonate cement should occur where anhydrite was once abundant, and carbonate cement is commonly observed in nodular quartz-cement zones.

2. Through most of the upper tight zone, grain and grain-coat surfaces are consistently pyrobitumen stained (e.g., Figure 4A), which should not be the case where abundant early anhydrite had been present.

3. Quartz overgrowths in the tight zone are in optical continuity with immediately adjacent grains, indicating that the overgrowths nucleated on local grains instead of scattered nodules (e.g., Figure 14).

4. Where anhydrite-replaced quartz-cement nodules occur in the porous reservoir, the quartz cement remains within nodule boundaries, that is, does not extend to make a pervasively cemented tight zone (Figure 10A).

The patchy chlorite-coat segments in the upper tight zone (Figure 14) suggest an alternative hypothesis for chlorite-coat discontinuities: they may be the result of transport abrasion. We suggest that the observed trends in coat coverage and reservoir quality within Norphlet dunes are the result of a changing balance between chlorite-coat formation and coat abrasion processes in different parts of the dunes. By analogy to the shallow diagenetic chlorite precursors observed forming near the water table in Saudi Arabian sabkhas, chlorite precursors could have formed on Norphlet sand grains at or below the water table in interdune areas, on dune margins, and within the lower parts of thick complex dunes at times of high water table. When the water table receded, coated grains were deflated from their point of formation, blown into active dunes, and abraded by eolian transport. In thin section, the grains in the upper tight zone are partly covered by both thin illite coats interpreted to be inherited from the onshore environment, and segments of thicker, spiky coats interpreted to be remnants of diagenetic chlorite inherited from sabkhas and dune margins (Figures 4A, 14A–D). The thicker chlorite-coat segments increase downward into the porous zone (Figure 14E, F), in parallel with the downward increase in chlorite abundance in the XRD plot (Figure 14G) and the measured coat coverage (Figure 14H). We propose that the chlorite coats are strongly abraded in the more active upper and flank parts of the dunes, and less abraded deeper within the body of the dune, where coats began to form in situ during periods of high water table. The mappable top of the porous reservoir is interpreted to represent a long-term paleo water table beneath which chlorite coats are completely undisturbed where they formed. The preservation of this chlorite-coat distribution to the present day suggests that the Smackover sea water that ultimately flooded the dunes was not conducive to chlorite formation: if it had been, complete in-situ chlorite coats would have developed through the whole of the upper Norphlet, and no tight zones would exist.

Processes Controlling Reservoir Quality in the Onshore Norphlet

The common occurrence in some areas of the onshore Norphlet of illuviated illitic cutans is indicative...
of episodic freshwater influx in the vadose zone (Gunal and Ransom, 2006). The association of these illuviated clays with dissolved feldspars, traces of kaolinite, and late pore-lining and pore-bridging diagenetic illite in the onshore Norphlet suggests that early meteoric diagenesis was responsible for much of the feldspar dissolution and kaolinite formation that set up the later high-temperature formation of diagenetic illite by reactions proposed for other areas (e.g., Bjørlykke and Aagaard, 1992; Bjørlykke et al., 1992, 1995) as

$$A_1\bar{2}Si_3O_8 + KA_1Si_3O_8 = KA_1\bar{2}Si_3O_{10}(OH)_2 + 2SiO_2 + H_2O \quad (2)$$

Kaolinite K-feldspar Illite

and

$$3A_1\bar{2}Si_3O_8(OH)_4 + 2KA_1Si_3O_8 + 2Na^+ = 2KA_1Si_3O_{10}(OH)_2 + 2NaAlSi_3O_8 + 2H^+ + 3H_2O \quad (3)$$

Kaolinite K-feldspar Illite Albite

Continuous illuviated cutans and diagenetic illite are abundant in many areas of the onshore Norphlet (Dixon et al., 1989; Ginger et al., 1995). The inferred early meteoric diagenesis in onshore wells contrasts with the hypersaline early diagenesis in Mobile Bay, where tangential illitic coats appear to be mainly inherited remnants, chlorite coats formed, feldspars remained undissolved, and diagenetic illite development is uncommon. An alternative reaction proposed for diagenetic illite formation, in which feldspars were dissolved at high temperatures by organic acids (e.g., Surdam et al., 1984, 1989; Burley et al., 1985) to set up the high temperature illite-forming reaction above, is not supported by the difference in diagenesis between the two areas. Both Mobile Bay and onshore Norphlet have the same source rock and being presumably exposed to the same organic acids during burial. The different diagenetic pathways followed in the two areas indicate that the extent of early meteoric diagenesis experienced by the Norphlet may be the main control on late diagenetic illite abundance and that late diagenetic illite formed at depth in a closed system as suggested for other reservoirs by Bjørlykke et al. (1995). If this is the case, late formation of Norphlet diagenetic illite would be maximized (other factors being equal) where meteoric diagenesis resulted in both reactants being present in approximately equal quantities, as suggested for other areas by Franks and Zwingmann (2010, this issue) and Lander and Bonnell (2010, this issue). Conversely, high-temperature illite formation would be less abundant where either very low amounts of feldspar dissolution limited the amount of kaolinite reactant, or very high amounts of feldspar dissolution limit the amount of the feldspar reactant. We infer that the former conditions apply in Mobile Bay and explain why diagenetic illite is rare in that area.

In the onshore Norphlet, abundant meteoric diagenesis suggests locally greater influxes of freshwater, either from greater amounts of seasonal rainfall, more overbank flooding from nearby wadis, or a fluctuating freshwater aquifer extending from updip recharge areas. In Mobile Bay, the abraded coats in the upper tight zone suggest more active dunes, and the relatively pristine feldspars indicate a more arid climate with little freshwater influence.

The effect of early meteoric diagenesis on updip Norphlet reservoir quality is significant. Where illuviated cutans are continuous, they inhibit later quartz cement and preserve porosity in deeply buried sands. In the Norphlet, porosities comparable to those preserved by chlorite occur where tangential illitic coats are overlain by diagenetic illite (Figure 6B). Assessing to what degree the diagenetic illite coats add to the effectiveness of the underlying tangential illite coats is difficult, but tangential coats form well before quartz cement, whereas diagenetic illite forms over the same high temperatures as quartz cement. This difference in relative timing suggests that the tangential coats are the main quartz inhibitors. We infer that where onshore Norphlet dunes were stabilized and subjected to illuviation, deep porosity is preserved. However, permeabilities associated with tangential coats are an order of magnitude lower than those associated with chlorite, because the early meteoric processes forming tangential coats also forms the kaolinite that leads to later diagenetic illite formation (Figure 6B).

Recent dissolution of early carbonate or anhydrite cement has also been proposed as a mechanism for porosity preservation in the Hatter's
Figure 17. Cross sections of upper tight-zone thickness relative to the top Norphlet in cross sections through dunes. Map of porous Norphlet thickness (contour interval = 100 ft [30 m]) shows well locations relative to dune thicks. Each cross section is datumed on the top of the lower Haynesville, i.e., the lower Haynesville picks above the Norphlet are aligned horizontally as if they were a flat surface. The top of the Norphlet dips into the basin on cross sections 2, 3, and 4 due to regional dip and rollover into the growth fault at the top of map. Depth scales within each cross section are constant. The upper tight zone, shaded on the cross sections, is thick where the top of the Norphlet is high and thins where the top is low in cross sections 1, 2, and 4. Cross section 1 intersects a thin sand flanked by two large dunes.
Pond area (Ginger et al., 1995), but this hypothesis requires development to explain why quartz cement has not subsequently filled pores from which the inferred early cement has vanished. Such quartz cement replacement is abundantly observed in nodular Norphlet cements.

Illuviation may limit the thickness of the upper tight zone occurring in the onshore Norphlet. However, in the upper Norphlet of Hatters Pond field, very tight quartz-cemented intervals of sand with little clay content occur (Ginger et al., 1995, p. 270). We interpret these tight intervals to represent dunes that were not subjected to early post-depositional coat formation either by illuviation or diagenesis, and therefore have only discontinuous inherited coat remnants. These dunes make poor deep reservoirs because the lack of continuous grain coats allowed later pervasive quartz cementation.

In sands subjected to significant illuviation, bulk-rock XRD is not a reliable measure of diagenetic illite abundance, given that XRD cannot reliably distinguish among neoformed illite crystallites and illite in the illuviated clays that may either be detrital or a replacement of other detrital clays (e.g., smectite).

RESULTS: PREDICTIVE MOBILE BAY TIGHT-ZONE MODELS FROM WELL AND SEISMIC DATA

The geometry of the quartz-cemented upper tight zone has been interpreted from seismic data as flat-based relative to the top of the Norphlet in Fairway field (Taylor et al., 2004), but the details of tight-zone configuration are generally challenging to observe directly from seismic data because of the poor impedance contrast between the quartz-cemented tight zone and the overlying Smackover, and between the commonly gradational base of the upper cemented zone and the porous reservoir. To evaluate the tight-zone geometry in more detail, well-log, core, facies, and petrographic data were integrated and used to analyze cemented zone configurations and develop predictive reservoir-quality models for Mobile Bay.
Cross Sections

A series of cross sections were made through Norphlet wells on individual dunes south of the Northwest Gulf fault (Figure 17). To minimize the effects of postdepositional compaction and salt tectonics on original Norphlet topography, these cross sections were datumed on the first reliable log pick above the Norphlet, the top of the lower Haynesville or Buckner anhydrite, about 5 m.y. younger than the top of the Norphlet (Mancini et al., 2004). The resulting geometries reflect Norphlet topography at the lower Haynesville time, assuming that the top of the lower Haynesville was a flat surface at deposition. The cross sections show a relatively consistent relationship between Norphlet tight-zone thickness and height of the reconstructed dune; that is, in any well, the higher the top of the Norphlet, the thicker the tight zone. In general, the dunes dip along their length into the basin, following regional dip. In cross section 1, which intersects a small dune between two large dunes, the base of the tight zone is deeper under the top of the small dune than it is under the large flanking dunes, a configuration that is incompatible with a flat tight-zone base. In the dip direction, along the crest of the dunes, the base of the tight zone is relatively flat with respect to the top of the dune (cross section 3) but increases in thickness toward the growth fault immediately to the north in cross sections 2 and 4, possibly in response to the structural rollover into the fault. Complications in the interpretation of paleotopography and tight-zone configuration resulting from postdepositional sediment compaction and salt tectonics are discussed in a following section.

Interval Thickness Measurements from Well Logs

To expand the analysis of cemented and porous zone geometries, the following surfaces were identified in well logs from 60 Mobile Bay wells: top lower porous zone, top upper porous zone, top upper tight zone, top Norphlet, and top lower Haynesville. The carbonate interval thickness from the top Norphlet to the top lower Haynesville was used as an inverse proxy for dune topography. Results of these analyses show a strong inverse correlation between well picks for upper tight-zone thickness and the overlying carbonate interval thickness (Figure 18), that is, a positive correlation between the upper tight-zone thickness and paleodune height at the well location. The correlation coefficient $R$ for the best-fit trend to the data for all 60 wells is 0.587 ($R^2 = 0.344$), which is significant at the 0.1% level for 60 data points; that is, highly significant (Figure 18C). The scatter in the well-data correlation for the 60-well data set is about ±50 ft (15 m) for the upper tight-zone thickness at any given value of carbonate thickness. However, these 60 wells cover a large area (Figure 18A), over which postdepositional salt tectonics are likely to have caused variable Norphlet deformation. To reduce the scatter from this deformation, the Mobile Bay Norphlet was divided into separate fault blocks and an individual transform derived for each block (e.g., Figure 18D). Correlation coefficients for each block vary but are in general significantly higher than for the 60-well data set. Within each block, most predicted upper tight-zone thicknesses are within 10 to 20 ft (3 to 6 m) of the best-fit trend line. The equations associated with the best-fit lines were used to transform seismic isopachs of the carbonate interval into maps of tight-zone thickness over Mobile Bay, and the map was flexed to the well data (Figure 19). Error analysis for the predictive map was undertaken by extracting predicted tight-zone thicknesses at each well site before the predictive map was flexed to the well data. The unflexed map predicts an upper tight-zone thickness with an error of ±40 ft (12 m) for 90% of all Mobile Bay wells and ±25 ft (8 m) for 64% of the wells (Figure 19, inset).

Total Cemented Zone Thickness

The base of the total cemented zone (upper tight plus upper porous zones) is also the top of the lower porous reservoir. The thickness of the total cemented zone was plotted against the overlying carbonate thickness. Results for a single fault block and comparison to the upper tight-zone trend for
the same block are shown in Figure 20B. The slopes of the trends formed by the two zones relative to paleotopography differ but would intersect at a carbonate thickness of 2000 ft (610 m), interpreted to be the level of the interdune surface in this block.

The equations for the relationship between carbonate thickness (or inverse Norphlet topography) and thickness of the upper tight zone and total cemented zone are shown in Figure 20B. These equations were used to calculate the configuration of the tight-zone surfaces in a schematic dune (Figure 20C). A range of typical carbonate thicknesses were used to construct a schematic Norphlet dune top in cross section, and the cemented zone thicknesses were calculated for each point using the equations in Figure 20B. The bases of the upper tight and total-cemented zones form surfaces below the dune crest that dip down the flanks of the dunes, thinning systematically as the top dune drops toward the interdune (Figure 20C). The configuration shown is appropriate for the block from which the well data were taken, but the approach could be used to model the distribution of tight and upper porous zones in any part of Mobile Bay by (1) transforming the seismic carbonate interval thickness to Norphlet topography, and (2) using the equations derived from well data (e.g., Figure 20B) within the area of interest to calculate the configuration of cemented zones.

**DISCUSSION: TIGHT-ZONE CONFIGURATION**

Some inferences can be drawn about the configuration of the tight zone relative to dune topography.
A. Diagram showing the water table, vadose zone, phreatic zone, interdune (sand with evaporites), abraded coats, and diagenetic chlorite coats. Louann Salt is noted as not to scale.

B. Graph showing the elevation on dune (ft) vs. carbonate thickness (ft) with equations:
- $y = -0.3969x + 813.56$
- $y = -0.1736x + 347.57$

C. Hypothetical Norphlet dune in cross section. Cemented zone configurations calculated from carbonate thickness using equations in B.
at lower Haynesville time from the well-log data analysis. First, the data trends make it clear that the base of the upper tight zone is not a flat surface relative to the top of the Norphlet except in cross sections where the top of the Norphlet is at a uniform height, i.e., along the crests of the dunes in the dip direction. In the strike direction, across the dune thicks, the upper tight and upper porous zones thin with decreasing elevation to the edge of the interdunes and the base of the tight zone has an arcuate geometry (Figure 20).

The upper tight zone, defined by a log porosity cutoff (<8% porosity), may reflect the distribution of the most active parts of the dune, where grains were subjected to the greatest abrasion and where the many coat breaks resulted in a particularly pervasive quartz cementation. The base of the total cemented zone (upper tight plus upper porous zones), which is also the top of the porous reservoir, may be related to a long-term water table. A schematic drawing of the processes interpreted to create this configuration is shown in Figure 20A.

Reconstruction Issues

Reconstruction of the tight-zone geometry and original dune topography is complicated by burial compaction of the dune sands and overlying carbonate sediments and by post-depositional salt tectonics.

Post-depositional compaction of the sand dunes reduced original dune topography. The average IGV of the dune sands at present burial depths is about 22%, or approximately half the inferred depositional IGV of 45% (Paxton et al., 2002). The original sand thickness can be calculated using a formula by Lander and Walderhaug (1999).

\[ v = v_0 \left( \frac{1 - \phi_0 - m_0}{1 - IGV'} \right) \]  

where \( v \) is the volume of the rock at depth, \( v_0 \) is the volume at deposition, \( \phi_0 \) is the porosity at deposition, \( m_0 \) is the matrix at deposition, and \( IGV' \) is the IGV at depth.

Assuming that all volume change is associated with intergranular porosity loss due to grain rearrangement by compaction and that the original sand
was clean, with no matrix, and using an initial porosity and IGV at deposition of 0.45, with a final IGV at depth of 0.22, the final compacted sand volume or thickness is calculated as

\[ v = \frac{1(1 - 0.45)}{1 - 0.22} = 0.705 \]  

or about 0.7 of the original value (Figure 21A). An original maximum dune sand thickness of 1150 ft (350 m) before compaction would yield the observed present-day maximum sand thickness of 810 ft (247 m). Dune topography would have been significantly less than that value because the dunes were partially submerged in the underlying salt.

Compaction of the overlying carbonates would vary with lithology. Datuming on the lower Haynesville, as was done for this analysis, would reduce the apparent present-day Norphlet dune topography. Assuming for this analysis equal compaction everywhere in the carbonates, a greater proportional loss of carbonate thickness would occur in the initially thicker carbonate interval between the dunes (Figure 21B). The effect would be to drape the carbonates over Norphlet dune crests in cross section. Present-day seismic cross sections
show a draping of the lower Haynesville over the dune crests that may be related to compaction (Figure 2B). Flattening this surface artificially by datuming on the lower Haynesville surface reduces some of the present-day real Norphlet topography (Figure 21C). If the true present-day configuration of the Haynesville were used to calculate tight-zone geometries, the current Norphlet dune topography and cemented zone surfaces would be steeper than the configuration that results from using a flat lower Haynesville top (Figure 21C).

Post Norphlet salt tectonics have also distorted present-day dune topography in several ways. (1) The rollover of the dunes into the crosscutting growth faults has created structurally related topographic highs just south of the growth fault (Story, 1998). The thickening of the tight zone under these highs suggests that the movement on the growth fault and the associated rollover may have initiated during Norphlet deposition. (2) After the overlying carbonate was deposited, the thicker sediment over the interdune areas may have caused greater salt withdrawal between the dunes, with the effect of steepening Norphlet dune topography and internal surfaces.

The original Norphlet dune height was likely to have been greater than the present-day topography of several hundred feet observed in seismic data. The measured difference of 600 ft (183 m) between the minimum (∼1300 ft [396 m]) and maximum (∼1900 ft [579 m]) carbonate thickness from well data may more closely approximate the original dune topography. This value is well within analogue Namibian dune heights of up to 1060 ft (323 m).

In any case, the observed relationships between the Norphlet tight-zone thicknesses and the overlying carbonate isopach are empirical, so the transforms and models based on this relationship can be used predictively despite reconstructive uncertainties.

CONCLUSIONS

• Deep Norphlet reservoir quality distribution is linked to the type and surface coverage of early grain coats. Active dunes make poor deep reservoirs unless they have been subjected to post-depositional coat formation by illuviation or diagenesis. In depositionally invariate Norphlet dune sands, the continuity and type of early grain coats result in present day deep reservoir quality differences of up to 20% porosity and several orders of magnitude permeability.

• Three early grain-coat types were identified in Norphlet eolian sands, each formed in a different part of a paleogroundwater system and each with a distinctive impact on deep-reservoir quality. The coats, their inferred environment of formation, and their effect on deep-reservoir quality are summarized in Figure 22 and below.

1. Diagenetic chlorite coats. Diagenetic chlorite coat precursors (most likely saponite, an Mg-smectite) formed on grain surfaces where the lower parts of the dunes sank below the paleowater table into a hypersaline groundwater. The precursor clays ultimately recrystallized to high-temperature chlorite with burial. At depth, the highly continuous chlorite coats effectively inhibit quartz cement, preserving deep porosities of up to 20% and permeabilities of several hundred millidarcies. Chlorite-coat continuity is highest and best porosity is preserved below a mappable surface inferred to be a long-term, late-Norphlet water table.

2. Continuous tangential soil cutans. In parts of the updip Norphlet affected by periodic early freshwater influx, tangential clay coats formed where detrital clays suspended in rain or sheet-flood waters were infiltrated or illuviated into vadose-zone sands, and dried onto grain surfaces when the water influx stopped. Repeated wetting, illuviation, and drying formed continuous grain coats or cutans. In stabilized dunes, these high-coverage coats remained undisturbed, so that during later burial, the coats inhibited quartz cement and preserved good deep porosity. However, the freshwater influx also dissolved feldspars to form kaolinite, setting up a later high-temperature reaction between kaolinite and remnant potassium feldspar to make diagenetic illite. As a result, porous sands with continuous illuviated coats...
are commonly associated with diagenetic illite and low permeabilities.

3. Abraded coats. Discontinuous abraded coats of both tangential illite and diagenetic chlorite occur where coated grains were remobilized from their area of formation, incorporated into active Norphlet dunes, and abraded by eolian transport. In the onshore, active dunes may be represented by very tight, clay-poor intervals. In Mobile Bay, above the long-term water table, coat discontinuities were abundant enough to allow later quartz cement to pervasively fill the pore system, creating the low porosity and permeability of the upper tight zone. The downward increase in chlorite-coat abundance and coverage in Mobile Bay wells may result from a shift in the balance between coat formation and abrasion in different parts of the dune. The greatest amount of coat abrasion would have occurred in the most active upper and flank parts of the dunes, where the present-day tight zone is best developed. Coat formation outstripped abrasion in the lower parts of the dune, where the pore system was periodically flooded by a fluctuating hypersaline groundwater and the coat coverage of grain surfaces making up pore walls was much higher than in the upper dune.

- The different diagenetic pathways followed in Mobile Bay and the onshore Norphlet suggest that the high-temperature reaction in the Norphlet to form illite occurs in a closed system, and that diagenetic illite abundance is related to the extent of early meteoric diagenesis. Other factors such as thermal exposure being equal, the greatest amount of illite formed where early diagenesis resulted in nearly equal amounts of kaolinite and feldspar. Too little or too much feldspar dissolution would limit either the kaolinite or feldspar reactant and decrease the amount of illite formed.
of later illite formed. The lack of early freshwater dissolution of feldspar is interpreted to be responsible for the scarcity of diagenetic illite in Mobile Bay.

- Well data show a strong empirical relationship between the thicknesses of the quartz-cemented Norphlet upper tight and upper porous zones and the overlying carbonate interval, used as an inverse proxy variable for Norphlet dune topography. This inverse relationship is compatible with the interpretation of the top of the porous reservoir in Mobile Bay as a paleogroundwater table. Because the carbonate interval thickness can be mapped from seismic data, we were able to use the equations of the best-fit lines for correlations between carbonate and tight-zone interval thicknesses to transform seismic maps of carbonate thickness to isopachs of the upper tight zone. The relationships and models are valid despite distortions of original dune topography by postdepositional sediment compaction and salt tectonics. Error analysis shows that the model predicts a tight-zone thickness with +20 ft (6 m) accuracy for 65% of the wells and +40 ft (12 m) for 90% of the wells. The upper porous zone configuration can also be mapped. Detailed models for the upper tight and upper porous zones in each dune were built using local well data, as shown in Figure 20.

- Analysis of tight-zone geometry from well data interval thickness shows that the upper tight zone is not of uniform thickness or flat based within structures relative to Norphlet topography. Instead, the thickness of the cemented zones decreases systematically from dune crests downward along dune flanks to the interdunes forming an accurate basal surface (Figure 21). Both the upper tight zone and upper porous zone are thickest in dune centers.

- In more onshore areas, where additional porosity is preserved by continuous illuviated cutans in intervals affected by early meteoric diagenesis, the relationship between dune topography and tight-zone thickness cannot be applied. Onshore tight zones are interpreted to represent active dunes that were never subjected to in-situ coat formation by illuviation or diagenesis, and their distribution is less well constrained in the onshore.

- The Norphlet study demonstrates that early grain-coat-forming processes can be reconstructed within a paleogeographic and paleohydrologic framework and linked to seismically mappable features to model the distribution of early diagenetic overprints on depositional lithologies. The resulting maps of depositional and early diagenetic lithofacies can be integrated with existing models for reservoir quality prediction that calculate the effects of burial history on porosity and permeability. The final products of this integration predict deep reservoir-quality distribution at a more detailed field scale that are useful for building geologic models, planning field development, and identifying sweet spots for production in both conventional and tight-gas reservoirs.

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