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Valanginian Knowles Limestone, East Texas: Biostratigraphy and Potential Hydrocarbon Reservoir

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ABSTRACT

The Lower Cretaceous Knowles Limestone is the uppermost unit of the Cotton Valley Group in the northeastern Texas Gulf Coast. It is the oldest Cretaceous carbonate shelf deposit that is a prospective reservoir. This shallow shelf-to-ramp shoaling-up complex is an arcuate lenticular lithosome that trends from East Texas across northwestern Louisiana. It is up to 330 m (1080 ft) thick and thins both landward and basinward. Landward lagoonal inner ramp facies are mollusk wackestone and peloidal packstone. The thickest buildup facies are coral-chlorophyte-calcimicrobial boundstone and bioclast grainstone, and the basinward facies is pelagic oncolite wackestone. The base of the Knowles is apparently conformable with the Bossier/Hico dark gray shale. The top contact in East Texas is disconformable with the overlying Travis Peak/Hosston formations. Porosity resulted from successive diagenetic stages including early marine fringing cements, dissolution of aragonitic bioclasts, micrite encrustation, later mosaic cement, and local fine crystalline dolomitization.

The age of the Knowles Limestone is early Valanginian based on a calpionellid-calcareous dinoflagellate-calcareous nannofossil assemblage in the lower part and a coral-stromatoporoid assemblage in its upper part. The intra-Valanginian hiatus represented by the Knowles/Travis Peak unconformity correlates with the Valanginian "Weissert" oceanic anoxic event. Possibly organic-rich source rocks were deposited downdip during that oceanic low-oxygen event.

INTRODUCTION

The uppermost Jurassic–lowermost Cretaceous Cotton Valley Group in the U.S. Gulf Coast has been a significant but enigmatic hydrocarbon exploration target since it was first drilled in 1927 (Montgomery, 1996; Montgomery et al., 1997). The group is dominantly sandstone and shale with limestone lenses (Forgotson, 1954; Mann and Thomas, 1964; Petty, 2008; Salvador, 1991; Swain, 1944; Wescott and Hood, 1991; Woehnker, 2018). The Cotton Valley disconformably overlies the Haynesville Formation and the Gilmer Limestone, informally called the "Cotton Valley Limestone" (Walker et al., 1998), of the Upper Jurassic Louark Group (Bartberger et al., 2002; Dickinson, 1968; Swenson, 1993). The Cotton Valley disconformably underlies the Hosston/Travis Peak Formation of the Lower Cretaceous Trinity Group (Dyman and Condon, 2006; Mancini and Puckett, 2002; Mancini et al., 2012; Olson et al., 2015; Shearer, 1938). The Cotton Valley is composed of four formations from lower to upper: Bossier Shale, Cotton Valley Sandstone, Schuler Formation, and Knowles Limestone. Locally in northwestern Louisiana two younger limestone units, Calvin and Winn limestones, interbedded with shale and sandstone, are interpolated between the Knowles and the Hosston/Travis Peak (Bartberger et al., 2002; Coleman and Coleman, 1981; Loucks et al., 2013; Olson et al., 2015; Sullivan and Loucks, 1990).

The regional structure of the Texas-Louisiana Gulf Coast updip of the Comanchean Shelf margin is composed of three positive uplifts and surrounding basins (Dyman and Condon, 2006; Mancini et al., 2012). Down-to-the-basin faults form an arcuate zone around the updip margin. The top of the Cotton Valley Group dips basinward from 1200 m (4000 ft) below sea level to at least 4500 m (14,800 ft) (Fig. 1) (Dyman and Condon, 2006). The Knowles Limestone is downdip of the Mexia-Talco Fault System and overlies pillow structures of the deep Jurassic Louann Salt (Cregg and Ahr, 1984).

In northeastern Texas and northwestern Louisiana, three limestone units are in the upper Cotton Valley Group in stratigraphic order: the Valanginian Knowles Limestone, and the Lower Cretaceous Calvin and Winn limestones (Fig. 2). The Knowles represents a carbonate ramp with coral-chlorophyte-calcimicrobial buildups. Landward is a shallow lagoonal mollusk wackestone assemblage and basinward is a deeper water oncolite wackestone facies (Fig. 2) (Cregg and Ahr, 1984; Finneran et al., 1984). The Calvin and Winn limestones were deposited on a shelf slope and both are composed of facies representing backreef, reef and slope environments (Loucks et al., 2013).

The Tithonian-Valanginian age of the Cotton Valley Group is bracketed by Upper Jurassic fossils in the Bossier Shale and

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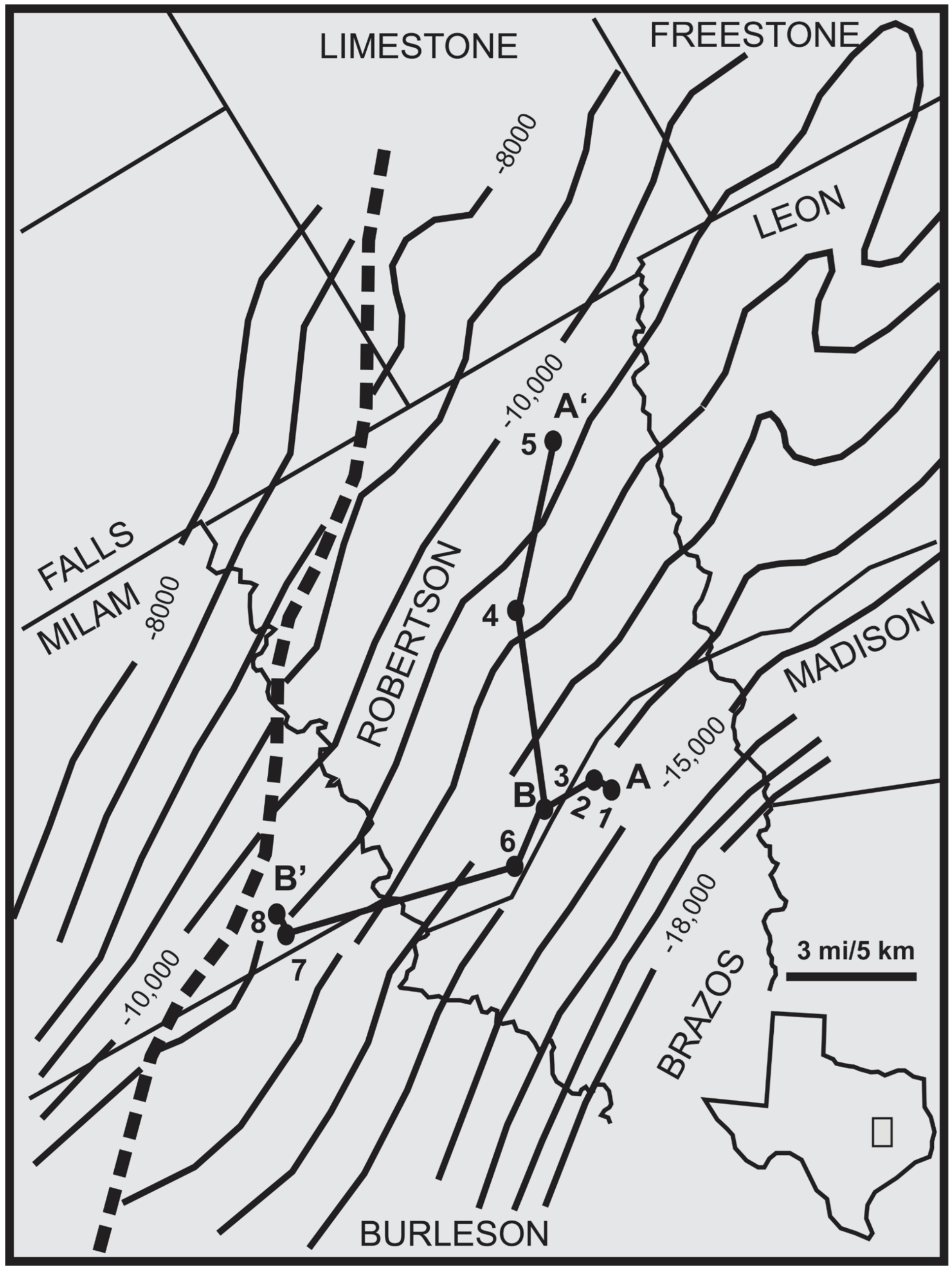

Figure 1. Structure map of Knowles Limestone in East Texas and key wells in cross sections A–A' and B–B' (Finneran et al., 1984). Contour interval 1000 ft (304.8 m).

Lower Cretaceous calpionellids, calcareous dinoflagellates and calcareous nannoplankton in the Knowles Limestone. Bossier ammonites correlate with lower Kimmeridgian to Tithonian stages (Imlay and Herman, 1984). A Tithonian-Berriasian calcareous nannofossil assemblage in the Bossier is consistent with this correlation (Cooper and Shafer, 1976). Three Lower Cretaceous ammonite genera are in uppermost part of the Schuler Formation in South Texas (Imlay and Herman, 1984, fig. 5). The calpionellid assemblage in the lower part of the Knowles is here revised to correlate with the lower part of the Valanginian Stage. In the eastern Gulf shelf Tithonian, Berriasian, and Valanginian zones are defined by nannofossils, dinoflagellates and ostracods (Petty, 2008).

METHODOLOGY

Slabbed cores of three wells in southern Robertson County and two wells in Milam County were examined and standard-sized petrographic thin sections prepared of selected samples for the former Amoco Production Company Research Laboratory (Table 1). Well logs of five other wells were used to correlate the Knowles in cross sections. Photographs of the cores and thin sections are preserved but the location of the thin sections is unknown. The thin sections were examined and photographed with a Leitz petrographic microscope at magnifications ranging from 30X to 500X. The three cores in Milam County were carefully and fully documented by Cregg and Ahr (1984) and Finneran et al. (1984).

GEOLOGIC DATA

Lithostratigraphy

Stratigraphic nomenclature of the Upper Jurassic and Lower Cretaceous units differs in Texas, Louisiana, and Mississippi (Dyman and Condon, 2006; Mancini et al., 2012; Petty, 2008; Steinhoff et al., 2011) (Fig. 2). In northeastern Texas, the Knowles Limestone is the uppermost interval of the Cotton Val-

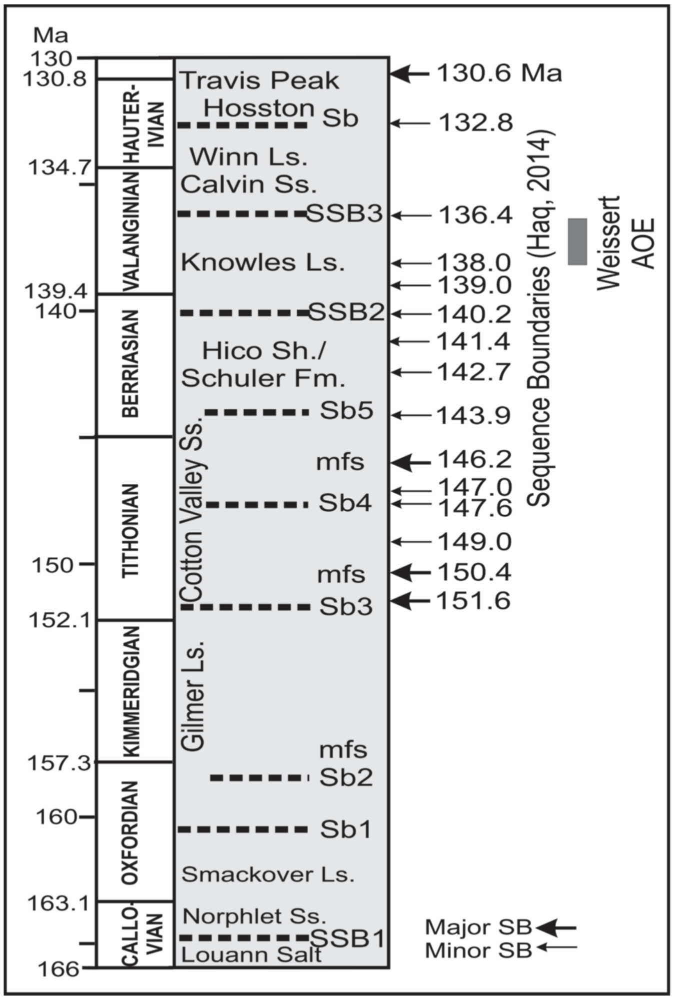

Figure 2. Stratigraphy of Upper Jurassic–Lower Cretaceous (in part) of the Cotton Valley Group (Coleman and Coleman, 1981; Dyman and Condon, 2006). Sequence stratigraphic model from Steinhoff et al. (2011) with ages of sequences posed by Haq (2014). Sequence boundaries indicated by dashed line; numerical ages estimated; and durations of hiatuses vary across the shelf.

ley Group and in northwestern Louisiana the Calvin and Winn limestones are locally present above the Knowles (Loucks et al., 2013; Mann and Thomas, 1964). In the Mississippi shelf-to-slope, three lower Valanginian prograding limestone platforms compose the Knowles Limestone (Petty, 2008).

The Knowles Limestone lenticular lithosome ranges in thickness from 36 m (120 ft) updip to 366 m (1200 ft) downdip (Table 1) and pinches out both updip and downdip (Finneran et al., 1984). In its type well at Knowles Field, Lincoln Parish, Louisiana, the Knowles is 95 m (310 ft) thick and is composed of gray argillic limestone and interbedded gray shale (Mann and Thomas, 1964). Here the base of the Knowles is a thick limestone bed with a distinct resistivity shift overlying the dark gray Hico Shale; apparently the base is conformable. Its top is the top of 10 m (33 ft) thick gray shale below the base of the lowermost sandstone beds of the Hosston/Travis Peak Formation. The disconformable contact between the uppermost Cotton Valley limestones and the Hosston is widespread in the Gulf region (McFarlan and Menes, 1991) and the hiatus represents in part the upper Valanginian Stage (Mancini et al., 2012). Gamma ray curves of numerous Knowles wells have been published (Coleman and Coleman, 1981; Cregg and Ahr, 1984; Dyman and Condon, 2006; Finneran et al., 1984; Mancini et al., 2012).

Biostratigraphy

The age of the Knowles Limestone was initially reported as Berriasian-Valanginian based primarily on calpionellids (Scott, 1984). Subsequent authors have correlated the Knowles with the Tithonian-Berriasian stage only (Dyman and Condon, 2006; Montgomery, 1996; Montgomery et al., 1997; Steinhoff et al., 2011). Since 1984, major advances have been made both in the precision of the calpionellid ranges and on paleobiologic understanding of the corals and other fossils. Twenty-four taxa were described in 1984, many of which have been revised taxonomically as new specimens have been discovered in other Tethyan sites (Appendix 1). The age ranges of some taxa have been revised based on new studies of their occurrences.

Most taxa of the Knowles Limestone characterize Late Jurassic and earliest Cretaceous carbonate environments. The calpionellids, however, provide a more precise age because they have been reported in many localities with ammonites and other age-diagnostic fossils (Scott, 2019; Wimbledon, 2017). Numerical ages of their ranges have been interpolated by plotting the ranges of specific sections to the current time scale (Ogg et al, 2016; Scott, 2019) (Appendix 1). The key taxon, *Calpionellites darderi* (Colom) (Fig. 3E), marks the base of the Valanginian (Reboulet et al., 2018) and its first appearance is dated at 139.50 Ma (Scott, 2019) or 139.40 Ma (Ogg et al., 2016). Other important calpionellids are *Calpionella alpina* Lorenz (Fig. 3A), *Calpionellopsis oblonga* (Cadisch) (Fig. 3B), *Calpionellopsis simplex* (Colom) (Fig. 3C), *Calpionellites major* (Colom) (Fig. 3D), and *Tintinnopsella carpathica* (Murgeanu and Filipescu) (Fig. 3F). The calcareous nannofossil, *Nannoconus kamptneri* Brönnimann (Fig. 3G), ranges from Valanginian to Aptian. The calcareous dinoflagellate *Colomisphaera conferta* Řehánek (Fig. 3H) is newly identified in the Knowles; its known first appearance is at the base of the Valanginian (Lakova et al., 1999). Three Berriasian-Valanginian (Turnŝek, 1997) colonial coral species are in the upper reef flat to back reef facies in the Inexco #1 Seale core, *Actinaraea* sp. aff. *tenuis* Morycowa, *Microsolena distefanoi* (Prever) and *Microsolena* sp. cf. *guttata* Koby (Scott, 1984). The base of the Valanginian Stage is calibrated at 139.4 Ma (Ogg et al., 2016); however, new data from the Argentinian Andes suggests that the base of Valanginian may be more than 2 Myr younger (Aguirre-Urreta et al., 2017).

The biostratigraphic data in the Inexco #1 Seale cores were composited with data in the Amoco #1 Seale to form a single section database (Table 2). This range data was then compared to age ranges in the Cretaceous Chronostratigraphic Database (CRETCSDB 16.1; Scott, 2019) (Precisionstratigraphy.com) and plotted on an X/Y graph (Fig. 4). CRETCSDB 16.1 is composed of biostratigraphic events, polarity chrons and radioisotope ages published in over thirty mainly Tethyan Realm outcrop sections. CRETCSDB 16.1 was constructed by X/Y plots of each section to the 2016 geologic time scale (Ogg et al., 2016). After each section was plotted, the stratigraphic range of each bioevent was calibrated to a numerical age and ranges were extended according to a correlation line (LOC) that was passed through the data by the operator. Graphic correlation is a transparent, testable method that integrates stratigraphic data. It is a quantitative but non-statistical technique that enables stratigraphic correlation experiments between two sections by comparing the ranges of event records in both sections (Carney and Pierce, 1995). The LOC is the most constrained hypothesis of synchroneity between the two sections and adjusts the ranges of the fewest bioevents. The LOC also accounts for hiatuses or faults at stratal discontinuities indicated by the lithostratigraphic record. The position of the LOC is defined by the regression line equation, which is calculated in caption of Figure 4.

CRETCSDB 16.1 includes sections with radioisotopically dated beds to constrain the accuracy of the numerical scale.

Table 1. Studied wells drilled into Knowles Limestone. 1000 ft = 304.8 m.

Well Name	County	Top (ft)	Base (ft)	Core Depths (ft)
Amoco #1 Seale	Robertson	14,792	15,700	14,873–15,120
Inexco #1 Seale	Robertson	14,956	15,909	14,962–15,017 15,587–15,599
Shell #1 Hamilton	Robertson	12,430	12,730	
Humble #1 Blair	Robertson	11,790	11,900	
Champlin #1 Harter	Brazos	15,600	16,590	15,640–15,650
C. Williams #1 Carraba	Brazos	16,100	17,300	
Shell #1 Ross	Milam	12,830	13,180	12,930–13,030
Shell #2 Adoue	Milam	13,980	12,420	14,050–12,230

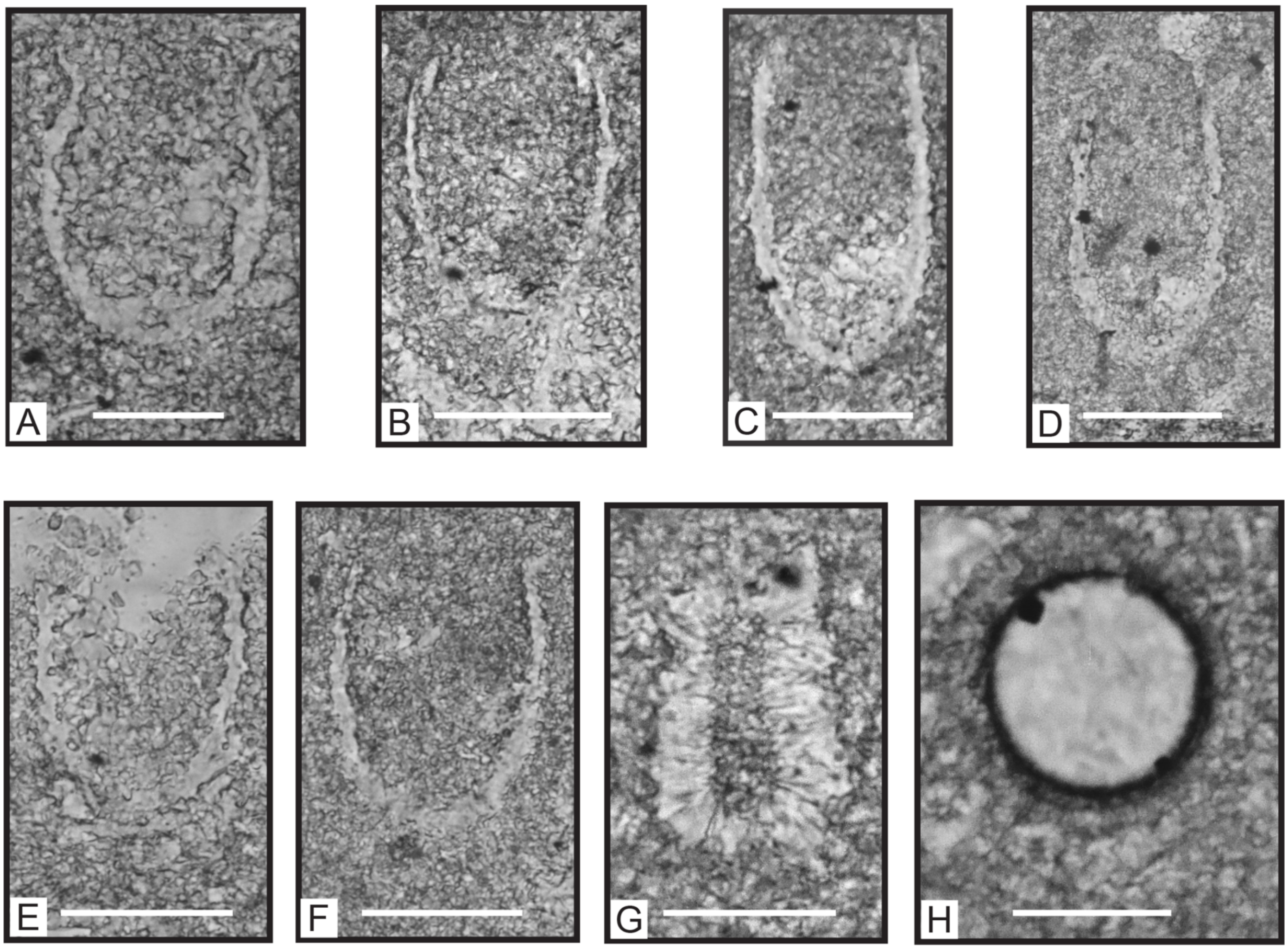

Figure 3. Photomicrographs of important microfossils in the Knowles Limestone; in parts A, G, and H, scale bar = 25 µm; in parts B–F, scale bar = 50 µm. (A) *Calpionella alpina* Lorenz, 145.70–139.38 Ma. (B) *Calpionellopsis oblonga* (Cadisch), 141.52–138.73 Ma. (C) *Calpionellopsis simplex* (Colom), 141.62–139.91 Ma. (D) *Calpionellites major* (Colom), 141.71–137.71 Ma. (E) *Calpionellites darderi* (Colom), 139.50–138.30 Ma. (F) *Tintinnopsella carpathica* (Murgeanu and Filipescu), 145.87–133.40 Ma. (G) *Nannoconus kamptneri* Brönnimann, 134.78–112.04 Ma. (H) *Colomisphaera conferta* Řehánek, 139.46–131.40 Ma. Ages from Scott (2019).

Ranges of first and last occurrences in each section were calibrated to mega-annums of Cretaceous stages defined by global boundary stratotype sections and points (GSSPs) or reference sections. This database serves as a look-up table for interpolating ages of other stratigraphic sections. The age ranges of some taxa and marker beds are preliminary and may be extended as new sections are added to the database.

The experimental plot of the composited Amoco-Inexco #1 Seale biostratigraphic data poses the hypothesis that the Knowles Limestone correlates with the early part of the Valanginian Stage

Table 2. Stratigraphic positions of key taxa of the Knowles Limestone. Sample depths in Inexco Seale core are composited with Amoco Seale core by subtracting 164 ft (50 m). 1000 ft = 304.8 m.

TAXA	Amoco Seale		Inexco Seale		Composited Depth		Shell #2 Adoue
	Base (ft)	Top (ft)	Base (ft)	Top (ft)	Base (ft)	Top (ft)	(ft)
Calpionella alpina			15,593		15,429	15,429	
Calpionella oblonga			15,593		15,429	15,429	
Calpionellopsis simplex			15,593		15,429	15,429	
Calpionellites darderi			15,593		15,429	15,429	
Lorenziella hungarica			15,593		15,429	15,429	
Remaniella cadischiana			15,558.5		15,394	15,394	
Tintinnopsella carpathica			15,593		15,429	15,429	
Cayeuxia piae	14,967				14,967	14,967	
Lithocodium aggregatum	14,905				14,905	14,905	
Micritosphaera ovalis	14,905				14,905		
Marinella lugeoni	14,914				14,914	14,914	
Nautiloculina oolithica	14,959	14,955	14,981		14,959	14,955	
Pseudocyclammina lituus	15,074				15,074	15,074	
Pfenderina sp.			14,955	14,391	14,791	14,227	
Trocholina cf. *elevata*	14,959				14,959	14,959	
Actinaraea aff. *tenuis*			15,006		14,842		
Microsolena distefanoi			14,974	14,972.5	14,810	14,808.5	
Microsolena cf. *guttata*			14974.5		14810.5		
Isastrea sp.					NA	NA	12,148
Stylosmilia sp.			14,964		14,800		
Shuqraia zuffardi	14,979.5		14,991		14,979.5	14,827	
Corynella mexicana	15,094	14,924.5			15,094	14,924.5	
Koskinobulina socialis	15,035	14,994			15,035	14,994	
Tubiphytes morronensis	15,094				15,094	15,094	

(Fig. 4). The base of the section is well constrained by the first appearance datum (FAD) of *Calpionellites darderi* (Colom) and the last appearance datum (LAD) of *Calpionella alpina* Lorenz (Fig. 4). The age of the upper part of the Knowles is bracketed by the LAD of the stromatoporoid *Shuqraia zuffardi* Wells and the FAD of the sponge *Corynella mexicana* Rigby and Scott. In addition, the overlapping ranges of three corals span Berriasian to Valanginian.

This correlation suggests that the Knowles in the two Seale wells ranges in age from 139.4 Ma to 138.2 Ma, about 1.2 Myr in duration. Thus, the unconformity at top of the Knowles Limestone may correlate with the sequence boundary dated at 138.0 Ma (Haq, 2014). The overlying hiatus would span the late Valanginian "Weissert" Anoxic Event (Weissert et al., 2008), which is composed of a 1.5‰ positive carbon isotope shift. The "Weissert" carbon stratigraphic unit is well documented in Italy and France (Weissert et al., 2008) and may be represented in downdip Gulf Coast strata. Several authors have calibrated its duration from 2.08 to 2.3 Myr (Charbonnier et al., 2013); here it is calibrated at 1.86 Myr (Fig. 4).

In the eastern Gulf, a succession of limestone units was deposited as shelf-edge ramps and are correlated by diverse microfossils (Petty, 2008). The Tithonian dinoflagellates are *Ctenodinium panneum* and *C. culmulum*, the nannofossil *Hexalithus noelae*, and the ostracod *Galliaecytherides postrotunda*. The Berriasian is identified by the coccoliths *Polycostella beckmanni* and *P. senaria*, and the ostracod *Hutsonia vulgaris elongata*, the dinoflagellate *Phoberocysta neocomica*, and the nannoconid *Nannoconus bermudezi*. A Valanginian dinoflagellate assemblage is in the upper limestone unit and overlying clastics.

Depositional Model

The Knowles Limestone is a shallow shelf to ramp complex forming an arcuate lenticular lithosome from East Texas across northwestern Louisiana (Coleman and Coleman, 1981; Cregg and Ahr, 1984; Finneran et al., 1984). It is up to 330 m (1080 ft) thick and thins both landward and basinward. Landward lagoonal inner ramp facies are sandy mollusk wackestone with benthic foraminifera, gastropods and bivalves in a lime mud matrix. Peloidal packstone and pelletal oolite grainstone have a diverse fossil assemblage of benthic foraminifera, calcareous algae, bivalves, gastropods, and echinoderm parts. The micritic limestone is interbedded with dark gray shale. Sandy argillic dolomitic mudstone-wackestone updip of buildup facies represent tidal deposits (Cregg and Ahr, 1984).

The buildup is composed of shoaling up facies representative of flank and core environments. The flank facies are oncoid-intraclast skeletal wackestone-packstone and coral-stromatoporoid floatstone (Cregg and Ahr, 1984). The core is composed of a facies succession that suggests shoaling up from bioclastic

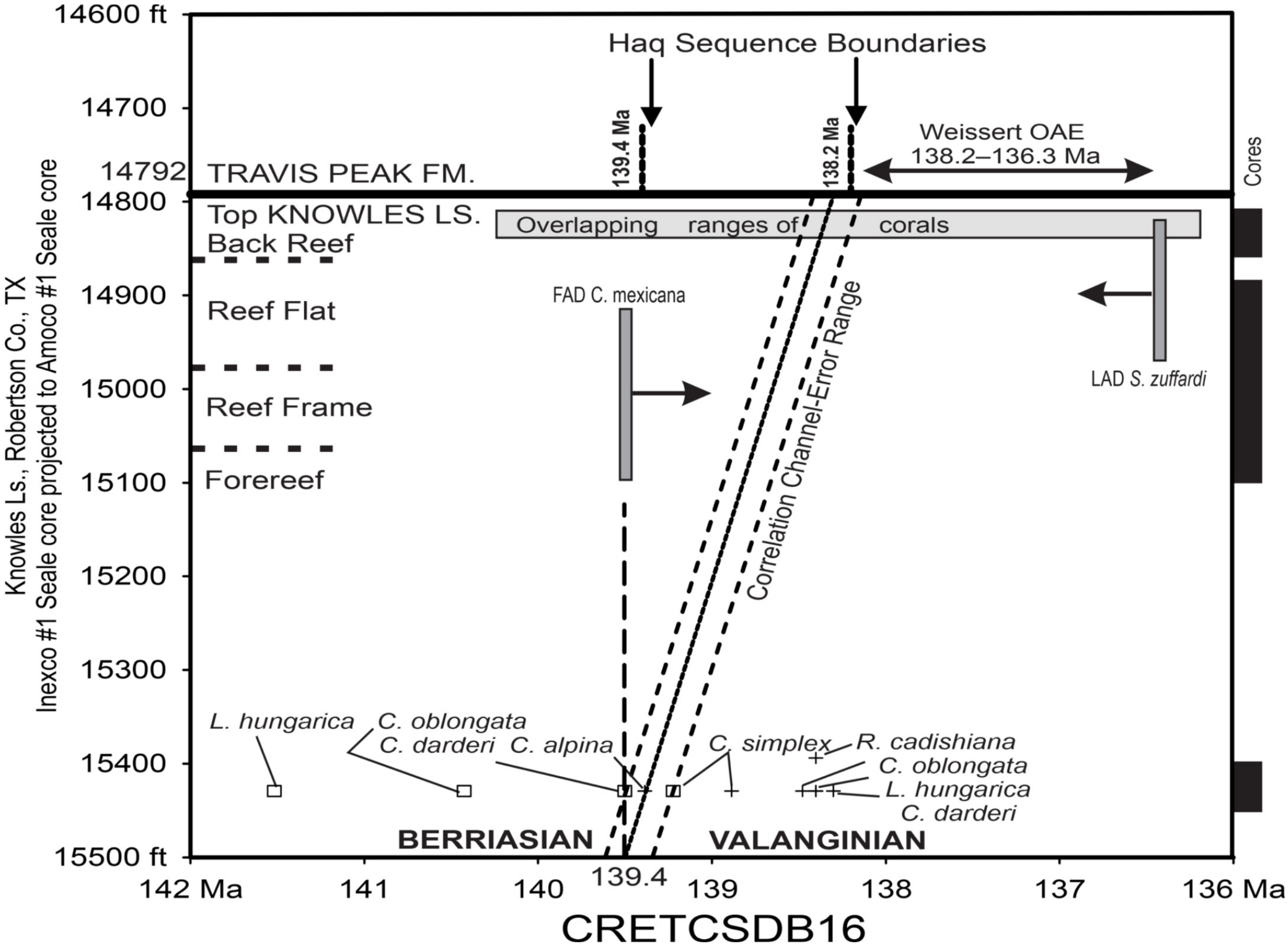

Figure 4. Chronostratigraphic plot of fossil ranges in Amoco #1 Seale and Inexco #1 Seale cores composited to depths in the Amoco well on Y axis. Top Knowles in the Amoco well at 14,792 ft (4508.6 m) is 164 ft (50 m) shallower than in Inexco well at 14,956 ft (4558.6 m). First appearance datums (FAD) of taxa are marked by square symbols and last appearance datums (LAD) by plus sign. Age ranges of taxa plotted in mega-annums on X axis are interpolated from the compositing of ranges in more than thirty sections in CRETCSDB16.1. Vertical dimensions of gray boxes show stratigraphic ranges of species in feet in the composited Amoco well; width of coral box indicates the overlapping age range of three coral species and the stromatoporoid and sponge species based on published data. The box for *Shuqraia zuffardi* marks its LAD in the Valanginan Stage. The box for *Corynella mexicana* marks its FAD in the Valanginian Stage. Dashed inclined lines propose two correlation hypotheses: (1) based on the FADs of *Calpionellites darderi* in CRETCSDB16.1; and (2) on the limit of the "Weissert" event. Vertical dashed line marks the age of the base Valanginian Stage (Ogg et al., 2016). Bold arrows across top of plot show positions of inferred global sequence boundaries in Haq (2014). The age range of the "Weissert" event is marked by short vertical dashed lines. 100 ft = 30.5 m.

wackestone to coral-stromatoporid-chlorophyte-calcimicrobial boundstone overlain by bioclastic grainstone and packstone. Coral morphotypes change upsection from vase-shaped to laminar corals encrusted by cyanobacterial micrite, to massive domal to hemispherical corals suggesting shoaling up. The thickest part of the buildup is capped by bioclastic packstone composed of fragments of the underlying fossils. Well-sorted bioclast grainstone and rippled-laminated sandstone are interbedded suggesting currents or waves (Finneran et al., 1984).

Basinward outer ramp facies are interbedded pelagic oncolite wackestone, stromatolite-thrombolite boundstone and calcareous terrigenous mudstone. Thrombolites are carbonate mudstone characterized by a mesoscopic clotted fabric. In contrast stromatolites are thinly irregularly laminated carbonate mudstone apparently formed by microbial communities that facilitated precipitation and trapped carbonate mud. This facies is well developed in pre-Sligo Hauterivian–lowermost Aptian slope deposits in Louisiana and Texas dated by the calcareous nannofossils *Nannoconus steinmannii* Kamptner and *Nannoconus wassallii* Brönnimann (Mancini et al., 2005; Tyrrell and Scott, 1989). Brachiopods, corals, serpulid clumps, and sponges are rare. Pelagic calpionellids and calcispheres are common.

Diagenesis

Successive diagenetic stages in the Knowles Limestone include early marine fringing cements, dissolution and calcite replacement of aragonitic bioclasts, micrite encrustation, later mosaic cement, and local fine crystalline dolomite. In northwestern Louisiana, the overlying Calvin Limestone is separated from the Knowles by siliciclastic strata and was deposited in a similar lagoon, buildup and slope environmental setting. Microporosity is dominant in the Calvin and may have formed in a meteoric groundwater system (Sullivan and Loucks, 1990). Potential reservoir facies are coral-stromatoporoid microbially encrusted boundstone and bioclastic grainstone.

As an alternate diagenetic model, the Upper Jurassic Gilmer Limestone has up to 25% secondary porosity mainly from vugs and microcrystalline pores; framework, intraparticle and shelter porosity are less common (Montgomery et al., 1997). The older Smackover Formation is a different deep-shelf carbonate reservoir composed of ooid and peloidal grainstone. Porosity is intraframe vugs and later solution-enhanced vugs and molds (Al Haddad and Mancini, 2013; Wescott, 1983). Porosity is as high as 15–20% and permeability is up to 4 md. The buildup core facies is composed of ooid-peloidal grainstone associated with coral-stromatoporid-chlorophyte-calcimicrobial boundstone that is analogous to the Lower Cretaceous shelf to slope buildups.

Sequence Stratigraphy

Sequence stratigraphic interpretations of the Gulf uppermost Jurassic–lowermost Cretaceous strata result in different schemes. Steinhoff et al. (2011) considered the Knowles to be the transgressive systems tract of Supersequence B and top of Knowles is the maximum flooding contact (Fig. 2). The interpretation by Olson et al. (2015) interpreted the Cotton Valley Group to be composed of two supersequences: Cotton Valley–Knowles (CVK) and Cotton Valley–Bossier (CVB). The uppermost CVK includes the Knowles, Winn, and Calvin limestones and the overlying disconformable sequence boundary, Va2_sb, is dated at 137.68 Ma (Olson et al., 2015). Sequence stratigraphic units of the Smackover and Cotton Valley groups were in part affected by antecedent structure and paleotopography (Steinhoff et al., 2011) (Fig. 3). In addition, relative sea level fluctuated driving the transgressive-regressive facies stacking pattern of the Oxfordian-Hauterivian deposits (Föllmi et al., 2006; Haq, 2014; Petty, 2008). The Knowles Limestone represents a single flooding-transgressive to shoaling-regressive cycle and is capped by a regional unconformity (Dyman and Condon, 2006; Finneran et al., 1984; Steinhoff et al., 2011). The top of the Knowles Limestone is here correlated with the mid-Valanginian sequence boundary dated at 138.2 Ma (Haq, 2014). The overlying Calvin Sandstone/Limestone and the Winn Limestone represent younger regressive-transgressive events that await biostratigraphic age calibration.

EXPLORATION PLAY CONCEPTS

Because detailed petrophysical studies of the Knowles Limestone are rare, data of associated limestone units provide clues. The Upper Jurassic Gilmer Limestone ("Cotton Valley Lime," Louark Group) produces gas from pinnacle-shaped buildups up to 200 m (650 ft) thick and up to 3.24 km^2 (800 ac) in aerial extent in East Texas (Montgomery, 1996; Montgomery et al., 1997). Porosity of up to 20% is reported in the upper part of the pinnacles in shallow-water facies and directly below the contact with the Bossier Shale. The origin of the porosity may be early-stage intergranular and/or leached moldic where subaerially exposed; fractures may enhance permeability (Montgomery et al., 1997; Walker et al., 1998).

The Knowles Limestone in northwestern Louisiana produces oil, gas and condensate from reservoir zones 3–18 m (10–60 ft) thick. Well logs indicate variable interbedded porosities and permeabilities (Cregg and Ahr, 1984; Finneran et al., 1984; Mann and Thomas, 1964). Porosities range from 9 to 18% and permeabilities are up to 300 md (Mancini et al., 2012). The top of the Knowles is a regional unconformity (McFarlan and Menes, 1991), which is a potential site for vuggy porosity.

The Calvin Limestone in northwestern Louisiana is composed of coral-stromatoporoid microbial boundstone overlain by bioclastic grainstone (Sullivan and Loucks, 1990). Microporosity formed by recrystallization by meteoric waters. Downslope organic-rich deposits may be encountered like the Gemsmättli-Pygurus organic-rich, glauconitic, phosphatic sands overlying a shallow-water carbonate shelf limestone in Switzerland (Föllmi et al., 2006). The Knowles overlies the Bossier Shale, a proven source rock (Mancini et al., 2012).

Basinward of the Sligo-Edwards shelf margin, Lower Cretaceous slope bioclastic and carbonate mud deposits are a potential play (Fritz et al., 2000; Mancini et al., 2012; Tyrrell and Scott, 1989). These wedge- to mound-shaped strata range in age from Berriasian to Albian (Tyrrell and Scott, 1989). Micritic carbonate thrombolite-stromatolite buildups tend to be tight and would be reservoirs where unusual diagenetic processes created microporosity or fractures (Mancini et al., 2005). Slump faulting and pre-existing structures are potential trapping mechanisms. Associated basinal muddy carbonates, some of which were deposited during the Valanginian, Aptian, and Albian anoxic events, may be source rocks (Fritz et al., 2000).

CONCLUSIONS

The Knowles Limestone is the uppermost unit of the uppermost Jurassic–lowermost Cretaceous Cotton Valley Group in the northeastern Texas Gulf Coast. The Knowles shoaling-up carbonate shelf to ramp lithosome lens thins updip and downdip and is up to 366 m (1200 ft) thick. Landward the lagoonal inner ramp facies are mollusk wackestone and peloidal packstone. The thickest buildup facies are coral-chlorophyte-calcimicrobial boundstone and bioclast grainstone, and the basinward facies is oncolite wackestone. The base of the Knowles is apparently conformable with dark gray shale of the Bossier/Hico shale. The top contact is disconformable with the overlying Hosston/Travis Peak Formation. In northwestern Louisiana, the Calvin and Winn limestones overly the Knowles and are separated by siliciclastic strata.

The lower Valanginian age of the Knowles Limestone is based on a calpionellid-nannofossil-dinoflagellate assemblage in the lower part and a coral-stromatoporoid assemblage in its upper part. Multiple porosity types are developed and locally vuggy porosity may be developed below the uppermost unconformity. Potential traps may be combination stratigraphic and structural.

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APPENDIX

Biostratigraphic and Taxonomic Notes: Numerical Ages and Stratigraphic Ranges

Numerical ages interpolated from compositing multiple measured sections (Scott, 2019):

Calpionella alpina, 145.70–139.39 Ma
Calpionellopsis oblonga, 143.94–138.68 Ma
Calpionellopsis simplex, 142.45–139.91 Ma
Calpionellites darderi, 139.70–138.40 Ma
Lorenziella hungarica, 141.52–138.40 Ma
Remaniella cadischiana, 144.77–138.40 Ma
Tintinnopsella carpathica, 145.87–138.40 Ma

Known stratigraphic ranges:

Actinaraea tenuis Morycowa is known in Berriasian to Aptian stages (Turnŝek, 1997) or Valanginian-Santonian (Fossilworks.org, PaleoDB taxon number 119705; accessed 01/31/2019).

Corynella mexicana Rigby and Scott is a sponge in Caribbean Albian reefal paleocommunities; this occurrence extends its range to the Valanginian Stage. It has been re-assigned to the genus *Endostoma* (Finks et al., 2004).

Crescentiella [Tubiphytes] morronensis (Crescenti) in Senobari-Dayran et al. (2008) is a long-ranging, common tubular micritc fossil in Upper Jurassic and Lower Cretaceous Tethyan carbonates (Senobari-Daryan et al., 2008). They interpret *C. morronensis* to be symbiotic accumulations of micritic cyanobacteria encrusting foraminifera.

Koskinobulina socialis Cherchi and Schroeder is an encrusting bulbous microorganism of uncertain affinity, possibly an alga or foraminifer; it is common in Tethyan Upper Jurassic–Lower Cretaceous carbonates (Uţa and Bucur, 2003).

Lithocodium aggregatum Elliott is either a symbiotic group of foraminifers and photoautotrophic micritic encrusters (Schmid and Leinfelder, 1996) or is an heterotrichale ulvophycean alga that has two life stages (Schlagwintweit et al., 2010). This complex ranges from Triassic to Cretaceous and is common in Upper Jurassic–middle Cretaceous carbonates.

Marinella lugeoni Pfender is a red alga that is no older than Late Jurassic and is as young as Albian (Granier and Dias-Britto, 2016). According to the review by Granier and Dias-Britto (2016) the reported age of the type locality is actually Kimmeridgian not Lias.

Microsolena distefanoi (Prever) has global reported range is Berriasian-Cenomanian (Turnsek, 1997).

Microsolena guttata Koby is known to range from Valanginian to Barremian-Aptian (Turnsek, 1997) or Berriasian-Aptian (Fossilworks.org, PaleoDB taxon number 148115; accessed 01/31/2019).

Pseudocyclammina lituus Yokoyama, Tithonian-Valanginian (González-Fernández et al., 2014) or Tithonian-Hauterivian (BouDahger-Fadel, 2018).

Shuqraia zuffardi (Wells) is the senior synonym of *S. arabica* Hudson according to Woods (1981); it is an Upper Jurassic milleporid sponge common in Arabian shelf carbonates that here ranges into the Valanginian Stage.

No changes in these taxon reports: *Nautiloculina oolithica* Möhler, *Trocholina* cf. *T. elevata* Paalzow, *Micritosphaerea ovalis* Scott, and *Cayeuxia piae* Frollo.