Black Mudrocks: Lessons and Questions from the Mississippian Barnett Shale in the Southern Midcontinent

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ABSTRACT

Although largely unstudied until recently, the Barnett Shale of the Ft. Worth Basin, Texas, has become one of the better known black mudrock successions in the world. Emerging results of new research on these rocks, based mostly on subsurface data, offer intriguing insights into fundamental aspects of mudrock formation. Among these insights is the recognition that mudrock facies are probably not widely continuous, that organic matter conversion to hydrocarbon may control distribution and abundance of nanoscale pores and thus permeability, that fracture distribution may be affected by mineralogical variations along a proximal-distal gradient, and that, based on trace element chemistry, the Barnett ocean may have been much more stratified than most other anoxic basins. Developing concepts of processes and products of mudrock formation being derived from Barnett research offer great potential for comparison to other mudrocks worldwide.

INTRODUCTION

Fine-grained siliciclastic rocks constitute as much as 75-80% of the sedimentary strata in the Earth's crust. These rocks, composed of varying amounts of silt- and clay-sized particles and including a wide range of textures, fabrics, and compositions, are variously referred to as shales, mudstones, claystones, siltstones, or mudrocks (*sensu* Blatt et al., 1972). Recently, economic successes in production of natural gas from such deposits have created a new wave of research on black "shales," or dark, organic-rich mudrocks. This explosion of interest in these mudrocks is delivering a wealth of new data and questions regarding every geological aspect of these rocks at scales ranging from regional to pore scale. Many data, especially 3-D geophysical data and cores, were previously unavailable; these new data offer exceptional opportunities for developing an understanding of this complex sedimentary system. Here we discuss emerging results of multidisciplinary studies of the Barnett Shale, a Mississippian-age succession in the Ft. Worth Basin, Texas (see cover), and one of the causes of this renaissance in mudrock research. The new data coming from studies of these rocks are equaled only by the questions that accompany them.

PREVIOUS STUDIES

Literature on mudrocks, like the rocks themselves, is voluminous. Most studies have until recently been focused on outcrops and ocean-bottom cores (DSDP, ODP). Compilations by Schieber et al. (1998 a, b) and Potter et al. (2005) provide an excellent overview of current knowledge. The April 2007 issue of the *AAPG Bulletin* is dedicated to recent studies of the Barnett Formation in the Ft. Worth Basin. Although preliminary, the volume provides insights into types of data being collected and questions being posed about Barnett mudrocks and related organic-rich mudrocks elsewhere.

KEY ISSUES IN MUDROCK CHARACTERIZATION

Our multidisciplinary team is investigating an array of geological issues in the Barnett. The work highlights many challenges to our understanding of the system that we think apply to mudrock systems. Some key issues are summarized here.

Facies and Depositional Setting

Despite their overt similarity, organic-rich mudrocks can accumulate in a wide range of depositional conditions (e.g., Potter et al., 2005). Basic attributes such as sediment-delivery mechanisms, oxygenation levels, and water depth are not well understood for many mudstone successions. Our Barnett studies reveal differences in texture, fabric, mineralogy, allochems, and chemistry that we think document changes in these attributes from more proximal to more distal settings. Distal Barnett mudrocks comprise several hundred meters of dominantly millimeter to submillimeter laminated, siliceous mudstones containing no evidence of infaunal or epifaunal biota and only rare indications of current reworking. These features suggest sedimentation by suspension settling and distal turbidity flow in a predominantly anaerobic, below storm-wave-base environment (Fig. 1). By contrast, more proximal facies contain evidence of infaunal activity, local traction sedimentation, and more abundant platform-derived faunal allochems. These attributes, as well as differences in pyrite morphology, suggest dysoxic or intermittently oxygenated conditions probably associated with shallower water. Although assignations of water depth are problematic, depths as great as 300 m have been suggested for distal Barnett and equivalent rocks (Gutschick and Sandburg, 1983; Loucks and Ruppel, 2007). More research is needed to explain the relationship between

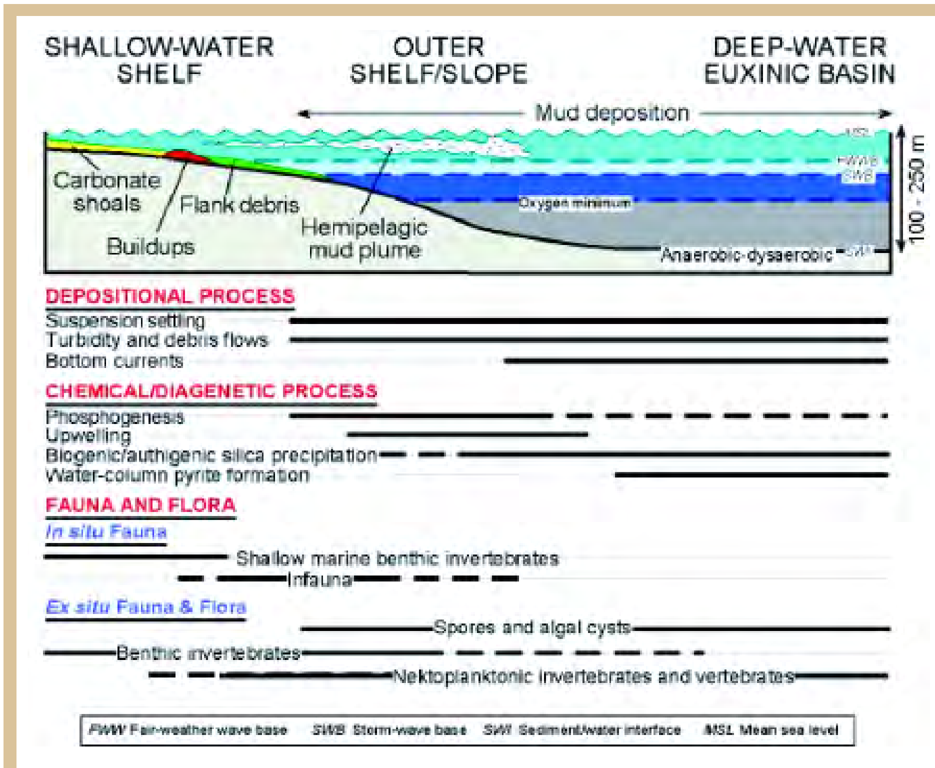

Figure 1. Model for deposition of Barnett Fm black mudrocks in the Ft. Worth Basin. Modified from Loucks and Ruppel, 2007.

water depth and sediment types, as well as to refine issues of basin geometry, sediment source area, and depositional processes.

Stratal Architecture

Understanding of the internal stratal architecture of mudrock deposits is crucial to interpreting depositional mechanisms and to correlation. Dark-colored, organic-rich mudrock successions commonly are considered by many to be composed of highly continuous units. Some workers have argued based on outcrop data that cycles can be defined and correlated over large areas using sedimentological criteria (e.g., MacQuaker et al., 1998; Brett et al., 2003). Others have interpreted subsurface data sets (e.g., wireline logs, seismic data) to indicate similar lateral continuity. (Bohacs, 1998; Algeo et al., 2004). Our work in the Ft. Worth Basin, however, suggests that sedimentological components within the Barnett are not widely correlative (W. Wright, personal communication, 2006; Loucks and Ruppel, 2007). Detailed description and comparison of 39 mostly continuous cores (900 m) reveal abundant vertical changes in texture and fabric, especially in more proximal areas of the basin, but few features that display systematic vertical stacking or other unique attributes permitting them to be laterally correlated. Our findings of limited continuity seem to be consistent with those of other workers who noted the abundance of local truncation, condensation, and differential compaction and diagenesis features at thin sections to hand samples scales (e.g., Schieber, 1998; Potter et al., 2005). Although some features could result from basinwide or even global events (e.g., eustasy, tectonics), their apparent lack of continuity suggests more local controls are common.

Recent studies of 3-D seismic data have provided documentation of larger-scale, karst-related stratal deformation of the Barnett succession. This research (McDonnell et al., 2007) has defined abundant subcircular areas of karst collapse in the underlying Lower Ordovician Ellenburger Group and showed that episodic reactivation of these features affected both the Barnett and overlying strata (Fig. 2). These findings imply that periods of reactivation and stratal collapse may have occurred before, during, and after Barnett mudrock deposition. No cores are available to examine this deformation directly; however, areas around these collapsed cave successions almost certainly contain widespread lithological and stratal discontinuities.

Pore-system Architecture

The need to better understand gas distribution and delivery mechanisms in hydrocarbon-bearing mudrocks has led to a new focus on size, distribution, and connectivity of mudrock pores. Results of recent studies at the Bureau of Economic Geology (e.g., Reed et al., 2007) show that most Barnett pores fall within the 5-200-nanometer (0.005-0.2-micron) range. This work, although preliminary, shows that pores can be reliably imaged only on flat, ion-milled surfaces. Previous work at lower magnifications and without these techniques must be viewed warily. Pores revealed by these studies are associated with organic matter (Fig. 3), implying that most pores may result from organic matter conversion to hydrocarbons. Barnett pores also seem to be poorly interconnected, suggesting that matrix flow through these rocks is limited. If organic matter conversion is the major cause of pore development, then its abundance and distribution may tie closely to mudrock permeability. The Barnett contains moderately high values of TOC (typically 4-10 %). Mudrocks with higher levels of TOC (e.g., Upper Devonian Woodford Fm of Texas and Oklahoma: up to 30% TOC) may be able to develop higher permeability and

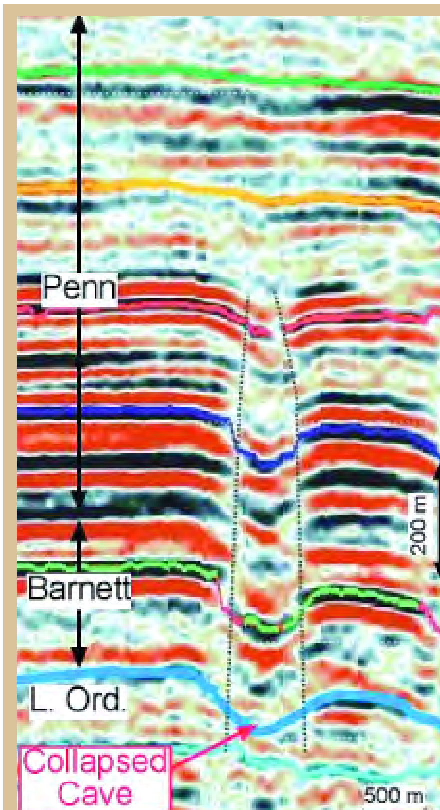

Figure 2. 3-D seismic section showing superstratal deformation in the Barnett and related strata over paleocaves. Image provided by A. McDonnell.

matrix flow. Further research is needed to (1) improve imaging techniques for nanoscale pore systems such as those that typify mudrocks; (2) define abundance, distribution, and origin of these pores; and (3) constrain the role that organic matter plays in pore formation.

Mineralogy, Chemistry, and Diagenesis

Basic X-ray diffraction studies reveal that besides clay minerals, quartz, feldspars, carbonates, phosphates, and pyrite are also common in mudrocks (Potter et al., 2005). Our studies suggest that these minerals vary in abundance across basins. In basin center areas (focus of Barnett gas production successes), mudrocks comprise subequal volumes of quartz and clay minerals (each averaging 35%) and subordinate amounts of carbonate and pyrite. Proximal, basin margin areas, by contrast, contain much higher volumes of clays (average 60%), abundant phosphate, and much less quartz (average 25%). Petrographic studies show that quartz composition also varies; detrital quartz is more common in proximal areas, whereas more distal rocks contain dominantly biogenic and authigenic quartz phases. These silica trends, which we have also seen in Upper Devonian (Woodford Fm) mudrocks in the Texas Permian Basin, document differential controls of upwelling and biogenic silica formation in distal areas vs detrital input from basin margin areas that probably characterize many mudrock successions.

Work is under way by Day-Stirrat et al. (in press; in review) to use limestone concretions (Fig. 4) common in many mudrock successions, including the Barnett, to better understand original fabric and textures. Formed during early shallow burial (e.g., Lash and Blood, 2004), these concretions can offer better insights into characteristics of uncompacted mud sediment, processes responsible for their deposition, and changes that occur during burial.

Much recent research is focusing on trace-element chemistry of Devono-Carboniferous black shales to interpret water-column chemistry and hydrography (e.g., Rimmer, 2004; Algeo et al., in press). Molybdenum seems to be an indicator of anoxia, basin geometry, and water circulation. Interestingly, current studies reveal much lower concentrations of Mo in the Barnett than in other mudrocks (Rowe et al., in press; in review). These findings indicate bottom-water restriction many times greater than modern anoxic, organic-rich, muddy basins and suggest that the Ft. Worth Basin may have differed significantly from comparable middle Paleozoic basins in the U.S.

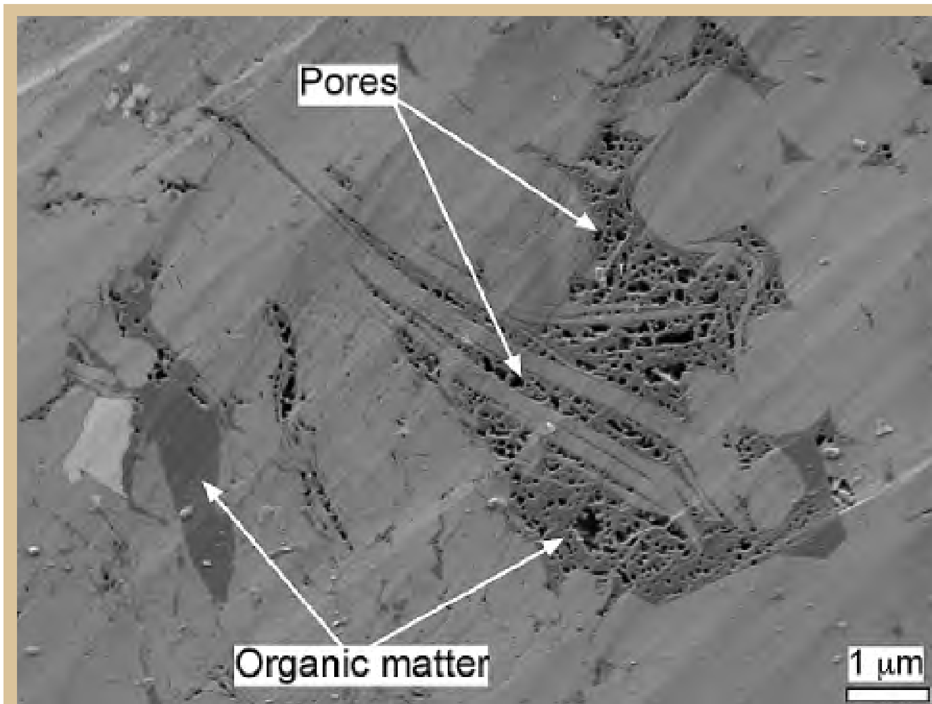

Figure 3. Field emission scanning electron photomicrograph of nanoscale pore architecture in the Barnett Formation. Image provided by R. Reed.

Fracture Development

Until recently, research into fracture development and roles that facies and tectonics play in their formation in mudrocks has been limited. Now, because of the importance of fracture formation and propagation in successful shale-gas production, new data are emerging. Gale et al. (2007) combined macro- and micro-scale fracture description of core samples with mechanical rock-property measurements to define orientation and size of natural fractures and thus infer fracture spacing, length, aperture, and connectivity. These studies reveal differences in apparent fracture abundance between mineralogically distinct proximal and distal Barnett mudrocks and also suggest that large open fractures may exist in clusters several hundred meters apart. Studies also show that clusters are oriented normal to present day in situ stress. A key question for further research is how mudrock variations affect fracture genesis.

Other emerging issues

Several other questions challenge mudrock researchers, including the relative roles that climate, eustasy, and tectonics play in controlling both architecture and lateral variations in mudrock properties. New findings of possible microbial control on mud accumulation and the mechanics of clay particle transports (e.g., Schieber, 2007; Schieber et al., 2007) show that our understanding of these enigmatic rocks is still in its infancy. New data from subsurface studies of potential shale-gas basins will provide new insights and questions for some time to come.

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Figure 4. Outcrop section of Barnett Shale containing limestone concretions. Inset shows similar concretion and surrounding mudrock in core.

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REFERENCES

ALGEO, T. J., SCHWARK, L., and HOWER, J. C., 2004, High resolution geochemistry and sequence stratigraphy of the Hushpuckney shale (Swope Formation), eastern Kansas): implication for climato-environmental dynamics of the Late Pennsylvanian midcontinent seaway: Chemical Geology, v. 206, p. 259-288.

ALGEO, T.J., LYONS, T. W., BLAKEY, R., and OVER, J. D., 2007, Hydrographic conditions of the Devono-Carboniferous North American Seaway inferred from sedimentary Mo-TOC relationships: Palaeogeography, Palaeoclimatology, Palaeoecology v. 256, p. 204-230.

ALGEO, T.J., HECKEL, P.H., MAYNARD, J.B., BLAKEY, R., and ROWE, H., in press, Modern and ancient epicratonic seas and the superestuarine circulation model of marine anoxia. In: Holmden, C., Pratt, B.R. (Eds.), Dynamics of Epeiric Seas: Sedimentological, Paleontological and Geochemical Perspectives. Geological Association of Canada Special Publication.

BLATT, H., MIDDLETON, G., and MURRAY, R., 1972, Origin of sedimentary rocks: Prentice Hall, 634 p.

BOHACS, K. M., 1998, Contrasting expressions of depositional sequences in mudrocks from marine to non marine environs, in Schieber, J., Zimmerle, W., and Sethi, P. S., eds., Shales and Mudstones I. Basin Studies, Sedimentology, and Paleontology: E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany, p. 33-38.

BRETT, C. E., ALGEO, T. J., and MCLAUGHLIN, P. I., 2003, Use of event beds and sedimentary cycles in high-resolution stratigraphic correlation of lithologically repetitive successions: The Upper Ordovician Kope Formation of northern Kentucky and southern Ohio, in Harris, P. J., ed., Approaches in High-Resolution Stratigraphic Paleontology: Kluwer, Amsterdam, p. 315-350.

DAY-STIRRAT, R. J., APLIN, A.C., SRODON, J., and VAN DER PLUIJM, B.A., in press, Diagenetic reorientation of phyllosilicate minerals in Palaeogene mudstones of the Podhale Basin, southern Poland: Clays and Clay Minerals.

DAY-STIRRAT, R. J., LOUCKS, R. G., MILLIKEN, K. L., HILLER, S., and VAN DER PLUIJM, B. E., in review, Phyllosilicate orientation as evidence for early timing of calcite cemented concretions in the Barnett Shale (Late Mississippian), Fort Worth Basin, Texas (U.S.A): Sedimentary Geology.

GALE, J. F. W., REED, R. M., and HOLDER, JON, 2007, Natural fractures in the Barnett Shale and their importance for hydraulic fracture treatments: AAPG Bulletin, v. 91, no. 4, p. 603-622.

GUTSCHICK, R., and SANDBERG, C., 1983, Mississippian Continental Margins on the Conterminous United States, in Stanley, D. J. and Moore, G. T., The Shelf Break: Critical Interface on Continental Margins: SEPM Special Publication 33, p.79-96

LASH, G.G., and BLOOD, D.R., 2004, Geochemical and textural evidence for early diagenetic growth of stratigraphically confined carbonate concretions, Upper Devonian Rhinestreet black shale, western New York: *Chemical Geology*, v. 206, p. 407-424.

LOUCKS, R. G., and RUPPEL, S. C., 2007, Mississippian Barnett Shale: lithofacies and depositional setting of a deep-water shale-gas succession in the Fort Worth Basin, Texas: American Association of Petroleum Geologists Bulletin, v. 91, no. 4, p. 579-601.

MACQUAKER, J. H. S., GAWTHORPE, R. L., TAYLOR, K. G., and OATES, M. J., 1998, Heterogeneity, stacking patterns, and sequence stratigraphic interpretation in distal mudstone successions: examples from the Kimeridge clay formation, U.K., in Schieber, J., Zimmerle, W., and Sethi, P. S., eds., Shales and Mudstones I. Basin Studies, Sedimentology, and Paleontology: E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany, p. 163-186.

MCDONNELL, A., LOUCKS, R. G., and DOOLEY, T., 2007, Quantifying the origin and geometry of circular sag structures in northern Fort Worth Basin, Texas: paleocave collapse, pull-apart fault systems, or hydrothermal alteration? AAPG Bulletin, v. 91, no. 9, p. 1295-1318.

POTTER, P. E., MAYNARD, J. B., and DEPETRIS, P. J., 2005, Mud & Mudstones: Introduction and Overview: Springer, Berlin-Heidelberg-New York, 297 p.

REED, R. M., LOUCKS, R. G., JARVIE, D. M., and RUPPEL, S. C., 2007, Nanopores in the Mississippian Barnett Shale: distribution, morphology, and possible genesis (abs.): Geological Society of America Abstracts with Programs, v. 39, no. 6, p. 358.

RIMMER, S.M., 2004, Geochemical paleoredox indicators in Devonian-Mississippian black shales, central Basin, Texas: bulk geochemical constraints on the severity of hydrographic restriction and the biogeochemical cycling and fate of iron: Chemical Geology v. 206, p. 373-391.

ROWE, H. D., LOUCKS, R. G., RUPPEL, S. C. and RIMMER, S.M., in review, Mississippian Barnett Formation, Fort Worth Basin, Texas: bulk geochemical constraints on the severity of hydrographic restriction and the biogeochemical cycling and fate of iron: Chemical Geology.

ROWE, H. D., LOUCKS, R. G., RUPPEL, S. C. and RIMMER, S.M., in press, Mississippian Barnett Formation: Bulk mineralogical constraints on the severity of hydrographic restriction and the biogeochemical cycling and fate of iron: AAPG Annual Convention.

SCHIEBER, J., 1998, Sedimentary features indicating erosion, condensation, and hiatuses in the Chattanooga shale of Central Tennessee: relevance for sedimentary and stratigraphic evolution, in Schieber, J., Zimmerle, W., and Sethi, P. S., eds., Shales and Mudstones I. Basin Studies, Sedimentology, and Appalachian Basin (U.S.A.), Chemical Geology, v. 206, p. 373-391.

SCHIEBER, J., 2007, Microbial mats on muddy substrates-examples of possible sedimentary features and underlying processes, in Schieber, J., Bose, P., Eriksson, P. G., Banerjee, S., Sarkar, S., Altermann, A., and Catuneau, O., eds., Atlas of Microbial Mat Features Preserved within the Siliciclastic Rock Record, 2, Chapter 5, 18 p.

SCHIEBER, J., SOUTHARD, J., and THAISEN, K., 2007, Accretion of mudstone beds from migrating floccule ripples: Science, v. 318, no. 5857, p. 1760-1763.

SCHIEBER, J., ZIMMERLE, W., and SETHI, P. S., editors, 1998a, Shales and Mudstones I. Basin Studies, Sedimentology, and Paleontology: E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany, 384 p.

SCHIEBER, J., ZIMMERLE, W., and SETHI, P. S., eds., 1998b, Shales and Mudstones II. Petrography, Petrophysics, Geochemistry and Economic Geology: E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany, 296 p.

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SEPM Presentation Winners

The awards listed were earned from presentations at the SEPM Annual Meeting in San Antonio, Texas, April 2008. The awardees will be recognized at the SEPM Annual Meeting in 2009.

Oral Presentation (Co-Awardees)

Sherry L. Becker
Lowstands on the Rise?

Linda Hinnov and James Ogg
Applications of the Sedimentary Record of Astronomically-Driven Paleoclimate Oscillations and Trends

Poster Presentation (Co-Awardees)

Beatriz Garcia-Fresca, Jerry Lucia and Charlie Kerans
Numerical Model of Reflux Circulation during the Deposition of the Permian San Andres Formation, Guadalupe Mountains and Algerita Escarpment

Martin P. Crundwell and Malcolm J. Arnot
Sub-Millennial Anatomy of Late Miocene Deep-Water Mass-Transport Deposits: Case Studies of the Use of Foraminifera to Decipher the Stratigraphic Significance of the Mount Messenger Depositional System, Taranaki Basin, New Zealand

Honorable Mention Posters

Christopher R. Mattheus and Antonio B. Rodriguez
Controls from Late Quaternary Valley Incision: a Look from Coastal-Plain Systems from the mid-Atlantic and Northern Gulf of Mexico Margins

Jamie L. Shamrock and David K. Watkins
Evolution of the Cretaceous Nannofossil Genus Eiffellithus and Its Biostratigraphic Significance