CORRELATION OF RESOURCE PLAYS AND BIODIVERSITY PATTERNS: ACCUMULATION OF ORGANIC-RICH SHALE TRACKS TAXONOMIC TURNOVER

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ABSTRACT

Similar paleogeographic and paleotectonic settings characterize most self-sourced shale hydrocarbon plays. Their deposition occurred within similar orders of magnitude of eustatic events and during geologic periods characterized by "warm" (or transitional) climates and calcitic seas. In addition, the stratigraphic occurrence of shale plays parallels certain historical patterns of marine metazoan biodiversity. Such strong agreement among several correlation tools elucidates why these resources may be limited to discrete intervals of geological time.

Correlation of self-sourced shale with biodiversity trends indicates that the factors controlling the deposition of marine organic matter may not be independent of those that induced taxonomic turnover. Paleoecological changes promoted accumulation and preservation of Type II kerogen. Deposition of self-sourced shale appears to correspond to reductions in absolute biodiversity and declining percentages of bioturbating taxa, with concomitant increases in proportions of pelagic taxa relative to infaunal and epifaunal organisms. Whereas upwelling and anoxia may have contributed to the deposition of kerogen in source rocks throughout much of the sedimentary record, diminished consumption of biomass by benthic metazoans likely augmented the preservation of organic carbon during deposition of this shale type.

Rapid tectonic-plate reconfiguration induced coeval events, creating basins with sufficiently high rates of accommodation creation necessary to preserve additional organic material accumulating as the heterotrophic benthos suffered in response to rapidly changing environments. Combining sea-level curves, paleogeography, climate, and seawater chemistry provides a first-order approximation of the distribution of potential self-sourced shale in the geologic record. A model that predicts the stratigraphic distribution of self-sourced-shale deposition can aid in exploration of continuous hydrocarbon accumulations in self-sourced reservoirs globally.

INTRODUCTION

Although continuous oil and gas accumulations in the Marcellus, Barnett, and Eagle Ford shales and the Haynesville-Bossier formations satisfy some of the increasing demand for hydrocarbon fuel, the need for more prospects is growing. As a consequence, self-sourced shale plays are becoming more attractive to hydrocarbon producers (Slatt, 2011; Slatt et al., 2012b; Slatt and Rodriguez, 2012). Specific combinations of geological and paleoenvironmental processes were responsible for the depo-

sition and preservation of uncommonly thick and widespread accumulations of organic-rich marine sediment during parts of the Paleozoic and Mesozoic eras. Identification of these processes can be aided by comprehensive analysis and synthesis of relevant scholarly works.

Regionally continuous, self-sourced hydrocarbon accumulations appear to be limited to discrete time periods in geologic history (Fig. 1, columns A–C). With few exceptions, North American self-sourced shale resource plays are characterized by similar paleogeographic and paleotectonic settings, paleoclimatic conditions, and seawater geochemistry, and they temporally coincide with eustatic events of similar magnitude (Slatt and Rodriguez, 2012). North American self-sourced shale deposits appear to correspond to geologic periods characterized by high primary productivity but declining global biodiversity of marine metazoans (Bambach, 1993, 1999; Bambach et al., 2002; Bush and Bambach, 2011). Specifically, during this type of shale deposi-
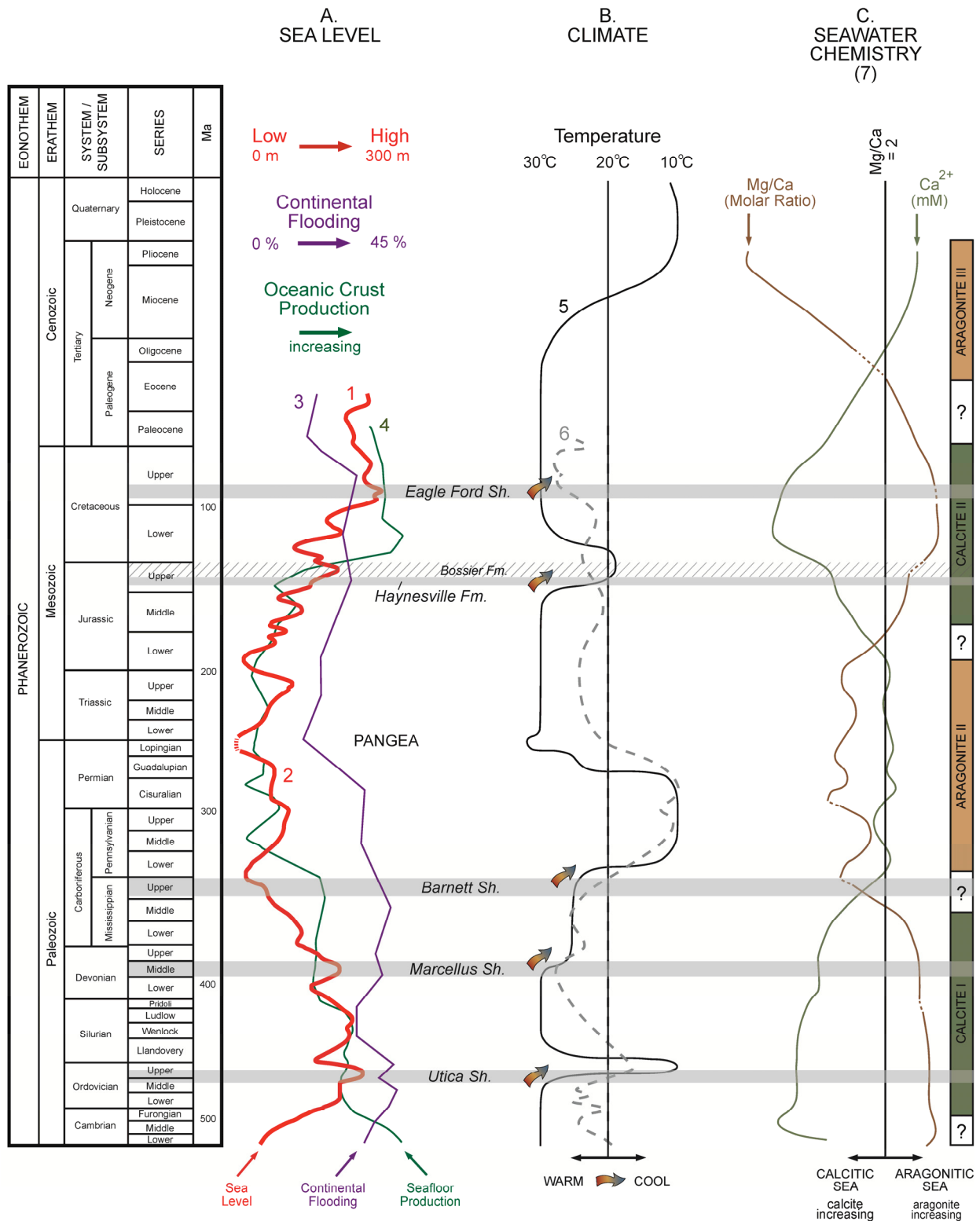
Figure 1. Temporal distribution of several North American self-sourced shale resource plays (gray horizontal bars). Most plays are associated with eustatic maxima (column A, red curve), warm or transitional ("warm" to "cool") paleoclimates (column B), and calcitic seas (column C). As depicted in column C, uncertainty exists regarding the dominance of calcitic versus aragonitic seas during certain periods of time (Stanley et al., 2010), including the middle Carboniferous (S. M. Stanley, 2012, written communication). Curves depicted are modified from: 1 – Haq et al. (1988); 2 – Haq and Schutter (2008); 3 – Hay et al. (2006); 4 – Demicco et al. (2005); 5 – Scotese et al. (1999); 6 – Frakes et al. (1992); and 7 – Stanley et al. (2010). Ages on geologic timescale are approximate. The seven curves were fitted to the timescale from their original vertical scales; therefore, stretching of the curves has affected their graphic resolution in this figure. For example, in column A the amplitude of eustatic change appears greater when a high-frequency event is superimposed on a low-frequency event of the same vector. In contrast, eustatic change appears muted when a high-frequency event is superimposed on a low-frequency event of opposite trend, such as is the case of the high-frequency flooding phase associated with the Barnett Shale.

tion the percentage of bioturbating taxa decreased, and the proportion of pelagic faunas increased with respect to infaunal and epifaunal taxa (Bush and Bambach, 2011). Although upwelling and anoxia may have promoted general source-rock deposition at other times, a different combination of processes augmented the deposition of potential self-sourced shale. Higher primary productivity generated greater volume of biomass in the water column, but rates of consumption of that organic carbon declined as benthic communities faltered during rapidly changing environmental conditions driven by tectonics and eustasy.

The purpose of this article is to present a preliminary conceptual model of the distribution of hydrocarbon accumulations in self-sourced shale that integrates different types of geologic and paleontological data from the literature that may have escaped the attention of industry and academic researchers. It is hoped that this initial version of the model will encourage more rigorous tests of the geological and linked paleoenvironmental–paleobiological relationships discussed in the following sections. Subsequent development of empirical models may then permit focused, global exploration of self-sourced shale reservoirs.

ORGANIC-RICH SHALE

Principal factors controlling the richness and petroleum potential of source rocks for conventional plays include, but are not limited to: (1) the type of organic matter; (2) the depositional setting and lithofacies composition; (3) basin geometry; and (4) the maturation of kerogen (Ulmishek and Klemme, 1990; Klemme and Ulmishek, 1991). Hannisdal and Peters (2011) tried to discriminate among drivers and responses in an attempt to distinguish "phantom" (Rosenzweig, 2002, p. 345) correlations from causations. Eustasy, in particular, has exerted strong control on both the deposition of organic-rich shale and the evolution of marine biota (Jenkyns, 1980; Hannisdal and Peters, 2011; Stigall, 2012).

Not all mature hydrocarbon source rocks are effective as self-sourced reservoirs. A conceptual model is needed that addresses the stratigraphic distribution of continuous hydrocarbon accumulations in self-sourced shale to encourage empirical studies and to support global exploration of these important resources. The sedimentary record documents the unique convergence of geological, paleoenvironmental, and paleobiological processes necessary for the development of uncommonly thick, rich accumulations of organic carbon (Ulmishek and Klemme, 1990; Klemme and Ulmishek, 1991; Hannisdal and Peters, 2011). In general, the following geologic processes and settings characterized deposition of self-sourced shale: (1) rapid tectonic-plate reconfiguration and concomitantly high sea level; (2) rapid subsidence and partial restriction of intra-cratonic, intrashelf foreland, or rifted passive-margin basins; (3) "greenhouse" or transitional (i.e., "warm" to "cool") climates; (4) calcitic seas; (5) extensive carbonate sedimentation in marginal or platform environments; and (6) low-latitude, high productivity of autotrophs (summarized in Eoff, 2012a, 2012b; see also Ulmishek and Klemme, 1990; Klemme and Ulmishek, 1991; Slatt and Rodriguez, 2012) (Fig. 1, columns A–C).

Unfortunately, correlation of self-sourced shale with biodiversity trends is limited by preservational and sampling biases (Peters and Berggren, 2005; Miller et al., 2005; Peters, 2007; Hannisdal and Peters, 2011). For example, sequence-stratigraphic architecture may alter the perception of evolutionary events (Holland, 1996, 2000). Deposition of organic matter in self-sourced shale occurred during cratonic flooding (Fig. 1, col-

umn A). Not only is the sedimentary record condensed during flooding, but facies and condensation biases may have affected the apparent tempo of taxonomic turnover (Holland, 2000). Although highly valuable, any conclusions regarding rates of evolutionary turnover during deposition of self-sourced shale, as discussed later, should be applied with some caution.

Sea Level, Seawater Chemistry, and Climate

Eustasy and Tectonics

Many shale source rocks in the geologic column were deposited during transgressions in flooded marginal-marine and cratonic basins (Jenkyns, 1980; Ulmishek and Klemme, 1990; Klemme and Ulmishek, 1991). Flooding of cratonic interiors resulted from a combination of rapid emplacement of oceanic crust, which elevated the seafloor, and limited glaciation, which increased the volume of water in ocean basins (Frakes et al., 1992; Frakes, 1999; Miller et al., 2005). The correlation of self-sourced shale with eustatic transgression (Slatt and Rodriguez, 2012) and early highstand is conspicuous when high-frequency transgression occurred during periods of low-frequency transgression and highstand (e.g., Utica and Marcellus shales, Fig. 1, column A). In contrast, the expression of high-frequency transgression or highstand during low-frequency falling stage or lowstand is comparatively muted (e.g., Barnett Shale, Fig. 1, column A). This relation is no less valuable, however, for predicting the temporal distribution of self-sourced shale.

North American self-sourced shale was deposited in cratonic sags, rapidly subsiding foreland basins, or semi-restricted basins on rifted passive margins, during periods of rapid reconfiguration of tectonic plates, specifically during the assembly and breakup of Pangea (Waples, 1983; Leckie et al., 2002; Miller et al., 2005; Hannisdal and Peters, 2011) (Fig. 1, column A). Rapid subsidence of incipient foreland basins resulted in sediment starvation, such that sedimentation was dominated by organic material (Ettensohn, 1994). Accumulation of organic matter was enhanced by partial restriction of rifted basins. Restriction resulted from the reactivation of basement features during later phases of extension, various salt-tectonic structures, or extensive growth of carbonate platforms or buildups.

Seawater Chemistry

The Phanerozoic is divisible into intervals in which seawater chemistry, the mineralogy of inorganic carbonates, and skeletal mineralogy (i.e., biological carbonates) are dominated by either calcite or aragonite crystal forms (Stanley and Hardie, 1998; Stanley et al., 2010). Periods when seawater was dominated by low-Mg calcite—calcitic seas—correspond to those of rapid tectonic plate movements (Sandburg, 1983; Stanley and Hardie, 1998; Stanley et al., 2010), in part because subduction removed magnesium cations from seawater (Riding, 1992). Such conditions characterized deposition of self-sourced shale in Paleozoic and Mesozoic strata (Fig. 1, column C). Seawater chemistry, by controlling the carbonate polymorph state, appears to have influenced biodiversity in ways that promoted deposition of shale that can be exploited for continuous hydrocarbon accumulations. As a corollary, the predominantly aragonitic chemistry during their deposition in aragonitic seas may be responsible for why other viable source rocks cannot be similarly developed as reservoirs.

Burial of organic-rich shale leads to progressive loss of porosity. Shale with abundant calcareous tests, however, is more

likely to preserve microporosity that hosts hydrocarbons and can be accessed using reservoir-stimulation techniques. Low-Mg calcite tests that accumulated in basins of calcitic seas would have been most resistant, both to early diagenetic alteration and later during burial (Iglesias-Rodriguez et al., 2008). For example, planktonic foraminifera (Middle Jurassic–Recent) and coccolithophores (Early Jurassic–Recent) are common low-Mg components of the Haynesville-Bossier formations (Hammes et al., 2011) and the Eagle Ford Shale (Harbor, 2011; Slatt and O'Brien, 2011; Slatt et al., 2012a). Their presence may contribute reservoir porosity more effective after stimulation than that of other, mechanically weaker source rocks. In contrast, overgrowth calcite on aragonitic tests lacks porosity and reduces effective porosity and permeability by isolating the aragonite or remaining void from other voids (Perdikouri et al., 2011).

Seawater chemistry not only influenced later diagenetic processes, but the performance of a potential self-sourced shale reservoir was also subject to a preservational control that operated during deposition. The "marine snow" that results from flocculation and pelletization of tests of calcareous plankton and their byproducts (Slatt and O'Brien, 2011) would have been subject to dissolution (Stow et al., 2004; Macquaker et al., 2010b), such that the preserved rock record is unlikely to document the original composition, diversity, and abundance of the biota. During "greenhouse" climates and high concentrations of atmospheric carbon dioxide (ρCO_2), the carbonate compensation depth (CCD) was shallower (Waples, 1983; Iglesias-Rodriguez, 2008). A shallow CCD may have caused lateral and proximal-offshore transitions among: (1) deposits that accumulated and were preserved unaltered; (2) areas within range of the lysocline that experienced partial dissolution of organic products; and (3) zones below the CCD that favored accumulation of siliceous detritus as calcareous material dissolved completely. Iglesias-Rodriguez et al. (2008) showed that the acidity of seawater during higher ρCO_2 (e.g., shallow CCD) does not limit calcification by modern coccolithophores as expected, and it may have likewise enhanced the productivity and size of other calcareous forms in the past by releasing bicarbonate ions as a carbon source.

If distribution of the preservation of calcareous tests is controlled by dissolution as hypothesized here, the variable effectiveness of reservoir stimulation techniques in shale plays may be explained in part by the distribution of preserved microporosity in calcareous skeletal debris. The assumed paucity or absence of calcareous fossils in organic-rich shale—which has been used to substantiate the importance of anoxia during deposition—may also be linked, instead, to seawater chemistry and dissolution.

Climate

Periods of self-sourced-shale deposition in North America correlate with the terminal stages of prolonged intervals of global warmth (Fig. 1, column B). A number of feedback mechanisms associated with widespread volcanism during rapid tectonic-plate movements increased the concentrations of CO_2 in the atmosphere and oceans and promoted global warming; secondary effects included enhanced terrestrial and marine bioproductivity (Parrish and Curtis, 1982; Pedersen and Calvert, 1990; Ulmishek and Klemme, 1990; Jarvis et al., 2011). Carbonate-isotope ($\delta^{13}C$) excursions in the sedimentary record document perturbations to the global carbon cycle—namely, exchanges between, and the fates of, isotopically heavy inorganic carbon (C_{carb}) and isotopically light organic carbon (C_{org}). Rapid burial of C_{org} sequesters isotopically light carbon in marine sediment, causing positive $\delta^{13}C$ excursions, which are commonly associated with source rocks. Such burial during prolonged periods of enhanced primary productivity could have reduced ρCO_2 by nearly 25 percent at various times in earth history, which initiated cooling within or at the end of otherwise long-lived "greenhouse" conditions (Kump and Arthur, 1999; Leckie et al., 2002; Iglesias-Rodriguez et al., 2008; Jarvis et al., 2011). At the scale of this study, self-sourced-shale deposition is associated with global warmth and subsequent cooling (Fig. 1, column B).

Anoxia Versus Biotic Productivity

An estimated 90 percent of all organic matter in the ocean is destroyed through chemical processes or consumed (Arthur and Sageman, 1994; Stow et al., 2001). Production and preservation of organic matter in marine environments is attributed frequently to upwelling and anoxia (Jenkyns, 1980; Demaison and Moore, 1980; Parrish and Curtis, 1982; Algeo et al., 1995). Widespread anoxia is thought to have developed in the geologic past as oxygen in the water column was consumed during periods of high productivity of phytoplankton or because stratification of the water column limited oxygenation of deeper waters (Ozaki et al., 2011). However, had oceanic stratification triggered the development of anoxia, this same stratification may have limited upwelling (Wilde and Berry, 1984).

Laminated, organic-rich shale in the stratigraphic column cannot be used alone to infer periods of persistent anoxia (Waples, 1983; Pedersen and Calvert, 1990). Short incursions of anoxic waters also seem an unlikely explanation for preservation of organic carbon (Klemme and Ulmishek, 1991), especially in restricted basins that would not have responded as quickly to fluctuations in oceanic geochemistry (Waples, 1983). Organic-rich shale may represent relatively short periods of geologic time (Waples, 1983; Klemme and Ulmishek, 1991), depending on sedimentation rates and magnitude of condensation during flooding. Widespread anoxia, however, may have taken longer to develop, and the effects of anoxia would have been diachronous (Waples, 1983; Klemme and Ulmishek, 1991). If only upwelling and anoxia are invoked for accumulation and preservation of organic matter, the possible paleogeographic settings favorable for this ideal scenario are narrowed and new exploration opportunities scarce.

Organic matter preserved in self-sourced shale was likely the result of enhanced bioproductivity as well as the reduced consumption of organic matter (Parrish and Curtis, 1982; Pedersen and Calvert, 1990; see also Klemme and Ulmishek, 1991; Martin, 1996; Schieber, 2011). Lower latitudes, where penetration of sunlight is greatest, favor the generation of additional marine organic matter, but sustained planktonic production would have required replenishment of nutrients from depth or from lateral sources (Pedersen and Calvert, 1990). Greater terrestrial biomass and runoff during radiations in land-plant diversity elevated productivity in surface waters (Algeo et al., 1995; Martin, 1996; Bambach, 1993, 1999; Demicco et al., 2005). Although the consumption of organic matter by benthic metazoans is an efficient process (Waples, 1983; Klemme and Ulmishek, 1991), any limit on the diversity and abundance of benthos should have slowed consumption of this additional organic material, permitting it to accumulate in thick deposits. Unstable substrates of fluid-rich mud would have been a limiting factor for infaunal and epifaunal taxa (Klemme and Ulmishek, 1991; Peters, 2007; Dashtgard et al., 2008) during transgression and maximum flooding to earliest highstand conditions. Thixotropic muds, poor in silt-sized and

coarser fractions, precluded maintenance of burrows by benthos requiring structured dwelling or feeding burrows. The preservation of lower diversity burrows or "cryptobioturbate texture" (Pemberton et al., 2008, p. 274) created by "sediment swimmers" (Schieber, 2003, p. 5) would have been unlikely and interpretations, consequently, biased. In the Barnett Shale, Ottmann and Bohacs (2011) recently documented a low-diversity fauna adapted to muddy substrate. Fossils and associated ichnofacies in all self-sourced shale should be reevaluated to eliminate any historic prejudice by determining if biodiversity trends actually resulted from changes in oxygenation or substrate stability.

Exploration for new, self-sourced continuous hydrocarbon reservoirs should not be restricted to stratigraphic sections recording inferred upwelling or anoxia but directed toward rock successions documenting periods of macroevolutionary faunal turnover in paleogeographic settings that favored biotic productivity and preservation of organic carbon. It is important to remember that taxonomic turnover and accumulation rates of organic matter covary with sedimentation rates (Müller and Suess, 1979; Waples, 1983; Arthur and Sageman, 1994; Hannisdal and Peters, 2011). In addition, bedforms and bioturbation only become evident in sections having higher supply of silt-sized and coarser grains (independent of composition), but the absence of coarser material did not prohibit similar processes active during deposition of the mud fraction at other times (Schieber, 2003; Macquaker and Bohacs, 2007; Schieber et al., 2007; Macquaker et al., 2010a; Ghadeer and Macquaker, 2011).

PATTERNS OF MARINE BIODIVERSITY

The balance between biologic production and destruction controls preservation rates of organic matter (Klemme and Ulmishek, 1991). Most organic matter in aerobic environments is consumed by metazoans (Ulmishek and Klemme, 1990; Klemme and Ulmishek, 1991). In contrast, bacterial decomposition predominates in anoxic environments but does not completely oxidize the organic matter, leaving more stable components to accumulate (Klemme and Ulmishek, 1991). The correlation of organic-rich, self-sourced shale with intervals characterized by additional terrestrial and phytoplanktonic biomass (Bambach, 1993, 1999; Algeo et al., 1995), and with near-contemporaneous attenuation of marine metazoan diversity (Bush and Bambach, 2011) (Fig. 2, column A), suggests that these factors may be more important than development of anoxic waters.

Megatrends in Marine Metazoans

Standing taxonomic diversity is a function of the origination and extinction rates that drive taxonomic turnover (the appearance and disappearance of taxa over time). Ulmishek and Klemme (1990) noted that organic-rich marine rocks preserve less diverse faunas than adjacent organic-lean strata. The most successful North American self-sourced shale plays correlate broadly with several trends in biodiversity and paleoecology of marine metazoan genera as detailed by Bush and Bambach (2011), discussed below (Fig. 2, column A). Large-scale evolutionary turnover resulted from biotic or abiotic changes in the paleoenvironment (Bush and Bambach, 2011; Stigall, 2012), and several studies have noted an association between potential source rocks and mass extinctions (Riding, 1992: Schieber, 2011).

For the most part, the Utica, Marcellus, Barnett, Haynesville-Bossier, and Eagle Ford shale plays are broadly correlative

with geologic intervals characterized by: (1) declining absolute diversity of marine metazoan genera; (2) higher percentage of predators; (3) lower diversity of infaunal and epifaunal taxa, which increases the proportion of pelagic forms; and (4) waning percent occurrence of rapidly bioturbating taxa (Fig. 2, column A). Lower absolute metazoan diversity, when concurrent with reduced bioturbation but increased proportions of pelagic taxa, may have augmented the preservation of organic-rich accumulations. The accelerated "rain" of pelagic organic material outpaced the reduced consumption of biomass as infaunal and epifaunal taxa declined in response to changing environmental conditions and escalated predation. Under conditions in which bioturbation remained at background levels or increased, additional organic matter produced during enhanced bioproductivity would have had lower preservation potential.

Periods characterized by reductions in metazoan diversity (Fig. 2, column A) that do not appear to be associated with self-sourced shale are explained by the absence of other criteria necessary for the preservation of thick accumulations of organic matter (Fig. 1, columns A–C). During the Middle Cambrian through the Early Ordovician, the structure of metazoan paleocommunities and earliest Paleozoic ecosystems may not have been established for this model to apply (Bush and Bambach, 2011). The Middle Cambrian–Lower Ordovician Alum Shale in Europe affords an opportunity to test this model on a non-Laurentian/Laurasian landmass. The end-Permian and end-Triassic extinctions occurred in aragonitic seas and at times when fewer cratonic basins were flooded (Miller et al., 2005). Periods of lower absolute diversity in the Early and Middle Jurassic were characterized by low sea level (Fig. 1, column A), aragonitic seas (Fig. 1, column C), and increased infaunal diversity (Fig. 2, column A). If the latter can be used broadly as a proxy for the abundance or efficiency of advanced feeding mechanisms at this evolutionary scale, rates of consumption of organic matter accumulating in marginal-marine or cratonic settings would have increased.

The Silurian Period is a particularly noteworthy exception to the patterns previously discussed. Although eustasy, paleoclimate, and seawater chemistry were ideal for self-sourced-shale deposition during the early Silurian, characterization of the discussed trends in Silurian strata is hampered because about two-thirds of Silurian sections worldwide have been altered or destroyed (Ulmishek and Klemme, 1990; Klemme and Ulmishek, 1991; Peters and Berggren, 2005). There are fewer fossiliferous Silurian units preserved than those of most other periods of the Paleozoic (Peters, 2007), which limits comparison. During intervals of eustatic flooding in the middle Silurian (i.e., late Llandovery–Ludlow) (Fig. 1, column A), marine metazoan diversity appears to increase, rather than decrease (Fig. 2, column A).

Widespread extinctions at the end of the Ordovician, Permian, and Cretaceous are representative of mass depletions in diversity when extinction rates exceeded origination rates, and they occurred during falling sea level or eustatic lowstands (Bambach et al., 2004; Stigall, 2012). These mass extinctions were dissimilar to the losses in metazoan diversity associated with deposition of self-sourced shale. The latter resulted from "origination failure" that could not overcome static or only slightly elevated rates of extinction (Bambach et al., 2004, p. 535; Stigall, 2012) (Fig. 3, column B). The Marcellus, Barnett, Haynesville-Bossier, and Eagle Ford shale units record declines in generic diversity within the ±13.5 percent range of "background fluctuation[s] in diversity" (Bambach et al., 2004, p. 526), and all were deposited during rising or high sea level.
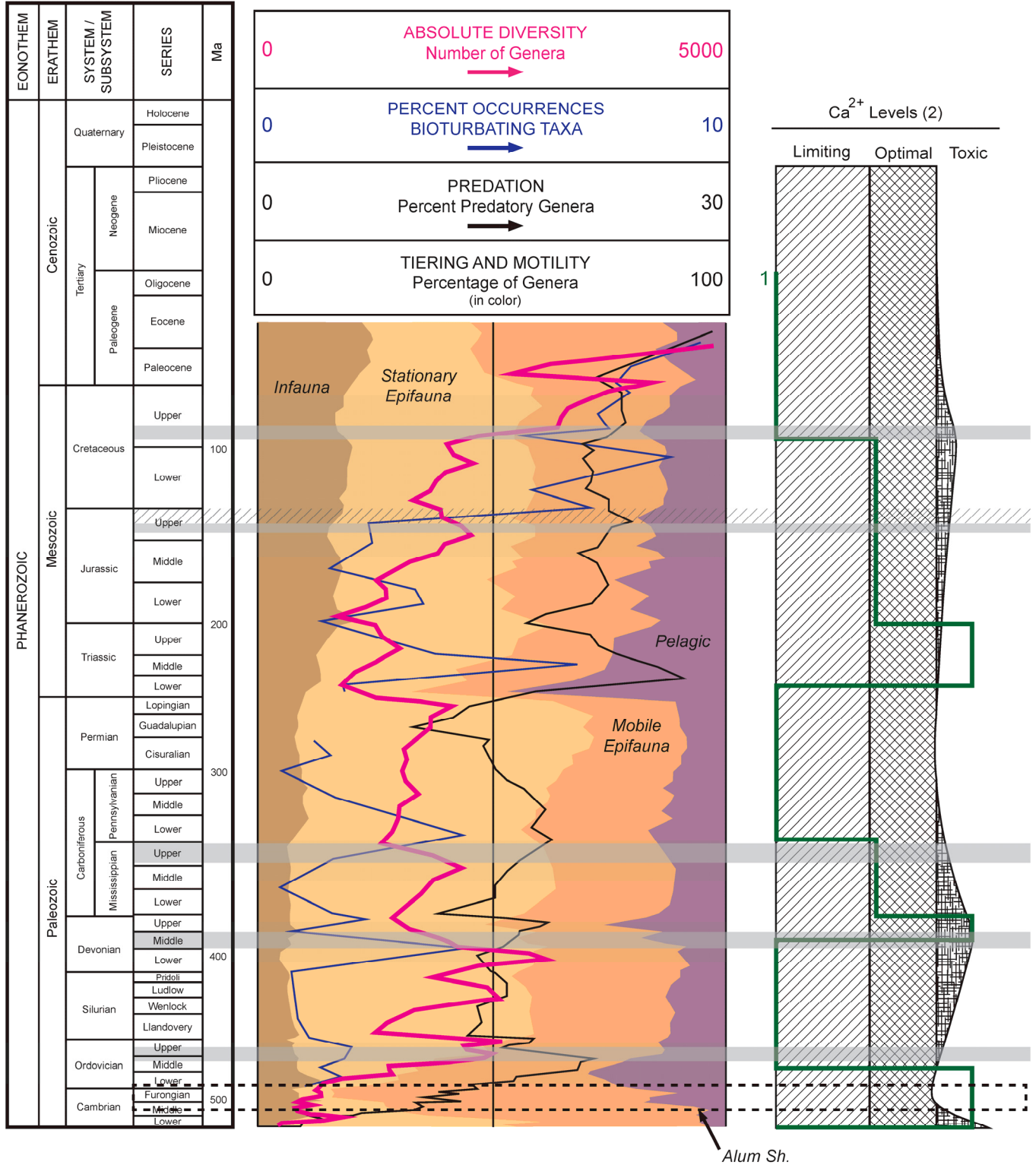
Figure 2. Column A. Marine metazoan diversity (Bush and Bambach, 2011). Most self-sourced shale plays (gray bars; see Figure 1 for corresponding stratigraphic nomenclature) correlate with geologic periods of (1) reduced absolute metazoan diversity (number of genera), (2) decreased percentage of rapidly bioturbating taxa, (3) increased predation, and (4) increased proportion of pelagic taxa with respect to infaunal and epifaunal taxa. The Middle Cambrian–Lower Ordovician Alum Shale (dashed) affords the opportunity to test this model both in the early Paleozoic and on a non-Laurentian/Laurasian landmass. Column B. Record of biocalcification episodes throughout the Phanerozoic. Curves depicted are modified from: 1 – Riding (1992); and 2 – Kaźmierczak et al. (1985).

Rapid transgression during any of these intervals would have impeded the geographical isolation that encourages speciation. For example, survival of ecological generalists and the extinction of specialist taxa were responsible for the Frasnian-Famennian diversity crises (Stigall, 2012), which correspond to Marcellus deposition.

Microfossil Diversity over Time

Abundant Type II (marine) kerogen in marine shale was derived primarily from enhanced productivity of phytoplankton (Demaison and Moore, 1980; Ulmishek and Klemme, 1990; Klemme and Ulmishek, 1991). Strata characterized by the near absence of fossil phytoplankton, such as many Permian sections, may document reductions in nutrient supply and primary productivity (Tappan and Loeblich, 1988). Stanley and Hardie (1998) and Stanley et al. (2010) showed that evolutionary trends in calcareous nannoplankton and algae were influenced strongly by changes in the Mg/Ca ratio of seawater. More importantly, several studies (Stanley, 2006; Pomar and Hallock, 2008; Iglesias-Rodriguez et al., 2008) found that when biocalcification releases inorganic carbon (CO_2) it then fertilizes primary producers, with a positive feedback in growth rates of microorganisms.

Hypercalcification is more common in warm seas (Stanley and Hardie, 1998), and secular changes in both the Mg/Ca ratio and absolute concentration of Ca^{2+} in seawater over the course of the Phanerozoic (Fig. 1, column C) stimulated important changes in biocalcification (Kaźmierczak et al., 1985; Riding, 1992; Stanley and Hardie, 1998; Brennan et al., 2004; Stanley, 2006; Stanley et al., 2010). Biocalcification may have resulted from near-toxic levels of Ca^{2+} or ρCO_2, especially in taxa that were not obligate calcifiers throughout their evolutionary history (Mackenzie and Pigott, 1981; Riding, 1992; Stanley, 2006; Pomar and Hallock, 2008). Most self-sourced shale was deposited during either Calcite I or Calcite II calcitic ocean periods of Stanley and Hardie (1998) (Sandberg, 1983; Stanley, 2006; Stanley et al., 2010) (Fig. 1, column C). Riding (1992) documented periods of heightened (i.e., his "mild") to intense biocalcification of cyanobacteria (Fig. 2, column B), each of which, like self-sourced shale, occurred during: (1) eustatic maxima; (2) first elevated then transitional global temperatures; and (3) maximum ρCO_2 followed by steep decline. The Devonian Marcellus Shale correlates with the Givetian-Famennian episode of "intense" calcification, and the Mississippian Barnett Shale correlates with the "mild" calcification episode of the Tournaisian-Serpukhovian boundary interval. Both the Haynesville-Bossier and Eagle Ford shale plays were deposited during a "mild" calcification episode (Hettangian to latest Early Cretaceous). Cyanobacteria discontinued biocalcification in response to declining Ca^{2+} concentrations during subsequent fall in sea level (compare Fig. 2, column B, to Fig. 1, column C; Fig. 1, column A). The preservation of organic matter and calcite remains of bacteria and other microfossils enhanced the organic richness and mineralogical stability of self-sourced shale reservoirs.

Foraminifera

Throughout their long evolutionary history, most foraminifera secreted organic or calcareous tests (Stanley, 2006; Kaminiski et al., 2010). The generic diversity of agglutinated foraminifera increased in several stages within each interval of the middle Silurian to middle Carboniferous and the Early Triassic to middle Cretaceous (Kaminiski et al., 2010) (Fig. 3, column A). Maximum generic diversity of forams in the Paleozoic was achieved

in the Visean (Tappan and Loeblich, 1988), roughly correlative with deposition of the Barnett Shale. Like metazoan diversity, some trends in foraminiferal evolutionary history correspond to eustatic maxima and "greenhouse" conditions. Normalized origination rates increased dramatically during the Early Ordovician, early Silurian, late Carboniferous, Early Jurassic, and middle part of the Cretaceous, but most self-sourced shale corresponds to other, albeit lesser, peaks in or stasis of origination rates and initially higher, then rapidly decreasing, extinction rates (Tappan and Loeblich, 1988; Kaminiski et al., 2010) (Fig. 3, column A). Riding (1992) noted that, although global oceanic anoxic events were generally associated with decline in foraminiferal communities, not all coincided directly with turnover. The "anoxic benthic foraminifera paradox" of Cretaceous Oceanic Anoxic Events (OAEs) (Friedrich, 2010, p. 175), in which benthic forams are preserved in rock units otherwise indicative of anoxia, suggests that either anoxic to euxinic conditions could not have been permanent or the evidence for anoxia at these times requires more scrutiny (Macquaker et al., 2010b). Migratory behavior of modern foraminifera includes evasion of low-oxygen sediment (Gross, 2000). Thus, the abundance of foraminifera in self-sourced shale suggests at least partial oxygenation of bottom waters.

Agglutinated foraminifera are abundant in Devonian and Mississippian self-sourced shale (Milliken et al., 2007; Schieber, 2009, 2011). Schieber (2009) noted that the varying abundance of agglutinated foraminifera among Devonian black shale facies resulted from varying degrees of bioturbation, and that a mechanism other than anoxia is needed to explain the widespread deposition of organic-rich shale in which they are preserved. Benthic forms are common in the Jurassic Haynesville-Bossier formations (Hammes et al., 2011), and planktonic foraminifera are abundant in the Cretaceous Eagle Ford Shale (Dawson, 1997; Harbor, 2011). As mentioned earlier, short incursions of anoxic waters seem an unlikely explanation for the preservation of organic matter (Klemme and Ulmishek, 1991) in self-sourced shale, and documented abundances of foraminifera support this assertion.

Remarks

Ulmishek and Klemme (1990) and Klemme and Ulmishek (1991) recognized that the importance of anoxia was probably exaggerated in previous studies. In discussing the effects of paleobiological evolution on source-rock deposition, they explained the preservation of macrofossils in inferred oxygen-depleted sediment by postulating that periods of anoxia or dysoxia were interrupted by oxygenation. If, however, the intervals of supposed oxygenation were contemporaneous with steep declines in diversity of benthic metazoan consumers, there is no reason to presume anoxia was necessary for the preservation of organic matter in any part of the section. Prolific microorganisms provided organic carbon to accumulating sediment, but its destruction was retarded.

Evidence for shallowing of the CCD due to higher dissolved CO_2 and enhanced primary productivity (Waples, 1983) also confirms the importance of other depositional and preservational controls on the deposition of self-sourced shale (Iglesias-Rodriguez et al., 2008). For example, during the middle to late Mesozoic, the prolific siliceous microfauna preserved in organic-rich units would not be expected to have flourished during periods of highest nutrient supply to shallow-marine waters at the exclusion of calcareous microorganisms, such as coccolithophores. Rather, the latter were subject to different rates and (or) tim-
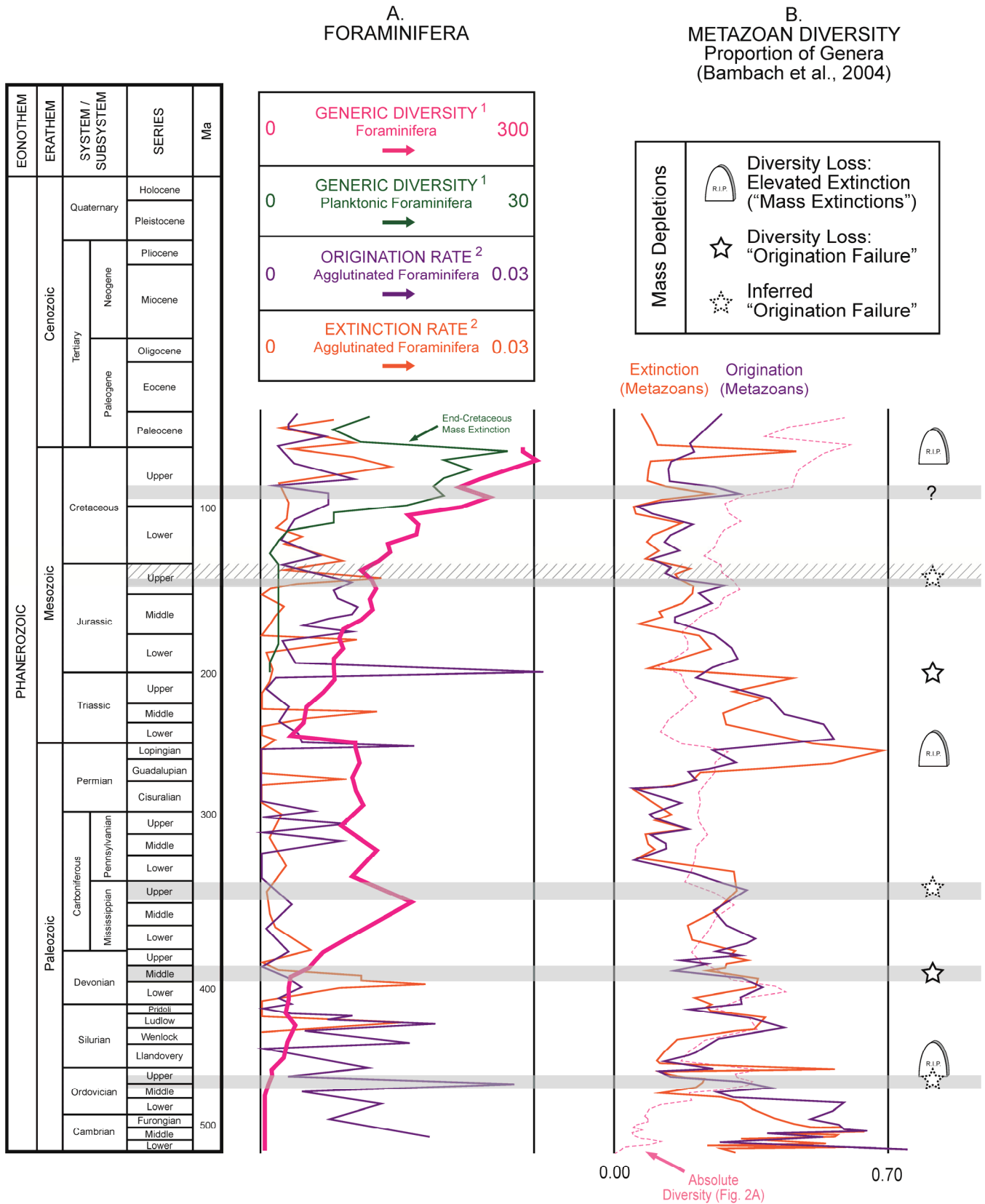
Figure 3. Column A. Diversity of foraminifera. Curves depicted are modified from: 1 – Generic diversity of foraminifera and planktonic foraminifera, Tappan and Loeblich (1988); and 2 – Per-capita origination and extinction rates of agglutinated foraminifera, Kaminiski et al. (2010). Column B. Metazoan diversity (proportion of genera) (modified from Bambach et al., 2004). "Mass extinctions" result when extinction rates are much greater than origination rates during an interval. Diversity loss from "origination failure" results during periods characterized by static or only slightly elevated extinction rates but reduced origination rates. Most North American self-sourced shale plays (gray bars; see Figure 1 for corresponding stratigraphic nomenclature) correspond to turnover of metazoan communities that resulted from origination failure.

ing of dissolution, but they were not victims to toxic waters. This reasoning emphasizes the proclivity of authors to invoke anoxia to explain the preservation of exceptionally thick accumulations of organic matter.

Terrestrial Influences on Marine Diversification

Recycling of nutrients in marine ecosystems, derived initially from bacteria, algae, and other organic detritus, maintains the food chain. Land-derived nutrients replace those removed by sedimentation and can enhance coastal productivity, forming coastal or shelfal "halos" comparable in productivity to zones of marine upwelling of nutrients (Tappan and Loeblich, 1988; Ulmishek and Klemme, 1990; Bambach, 1993, 1999). Two intervals of critical change in the terrestrial realm affected marine biodiversity (Tappan and Loeblich, 1988; Ulmishek and Klemme, 1990; Bambach, 1993, 1999; Algeo et al., 1995) (see Eoff, 2012b, her Figure 3): (1) mid-Paleozoic expansion of plants into terrestrial settings and, in particular, the Devonian expansion of larger and more diverse vascular plants; and (2) evolution of angiosperms in the Cretaceous, which achieved greater abundance and diversity by the end of the period. Radiation of opportunistic floras during the Devonian and Cretaceous provided nutrients to oceans that were more easily utilized by autotrophs than slowly decaying organic material from gymnosperms that diversified during the latest Paleozoic (Martin, 1996).

Middle Paleozoic land-plant radiations resulted in increased weathering rates and delivery of terrestrial organic matter to shallow-marine environments (Algeo et al., 1995). Changes that occurred throughout the food chain suggest a positive correlation between enhanced land-derived nutrient supply that increased marine primary productivity and the more active feeding strategies on the additional biomass then available (Bambach, 1993, 1999). Both high-energy predators and non-predator taxa experienced turnover in response to the complexity of energy flow in this modified ecosystem (Martin, 1996; Bambach, 1999; Bambach et al., 2002). These changes are correlative with the organic-rich, self-sourced Middle Devonian Marcellus Shale and the lower Carboniferous (Upper Mississippian) Barnett Shale (Fig. 2, column A).

Diversity and abundance of angiosperm megafossils and palynomorphs began to increase by the late Early Cretaceous (Aptian-Albian), more than doubling by the Cenomanian (Bambach, 1999), approximately coeval with deposition of the Upper Cretaceous organic-rich Eagle Ford Shale. Diversification of highly productive angiosperms (Bambach, 1993, 1999) supplied additional nutrients to marine environments. The substantial increase in diversity of phytoplankton in the Cretaceous confirms this (Bambach, 1999; Bambach et al., 2002). An associated decrease in absolute diversity of metazoans is apparent in the middle part of the Cretaceous, but diversity rapidly recovered to fit the exponential trend of increasing diversity that characterized the Mesozoic and Cenozoic (Bush and Bambach, 2011) (Fig. 2, column A). In contrast, depletion of phytoplankton during the end-Cretaceous mass extinction (Fig. 3, column A) marks a rapid upset of the marine food chain (Arthur et al., 1987; Jablonski, 1991), and self-sourced shale should not be abundant at this time as a result.

Land-plant diversification also played a role in the preservation of organic matter. Apparent conflict between increased diversity of some microorganisms (Fig. 3, column A) and predatory metazoans (Fig. 2, column A) and the near-contemporaneous decline of absolute metazoan diversity (Fig. 2, column A) during deposition of self-sourced shale can be explained by the follow-

ing. Eutrophication resulting from elevated supply of terrestrial nutrients induced changes to marine food chains that favored suspension feeding and more, specialized predation (Tappan and Loeblich, 1988). This reduced rates of consumption of organic detritus in accumulating sediment. In contrast, background rates of marine productivity during attenuated terrestrial runoff encouraged diversification of slower-growing, benthonic, detritus-feeding taxa (Tappan and Loeblich, 1988). Other environmental factors being equal, relative consumption of organic matter increased. Of related importance, experiments on modern foraminifera showed that migratory activities of most benthic taxa decreased with additional food supply (Gross, 2000). Sessile forms would not have been as successful as their mobile counterparts at avoiding predation when a predominant feeding strategy in the ecosystem. Ultimately, plant radiations during the middle Paleozoic and middle Mesozoic increased the complexity of energy-flow in the respective biospheres (Bambach, 1993, 1999), creating changes in marine paleocommunities that both enhanced the production and benefited the preservation of organic carbon.

The correlation of self-sourced shale with biodiversity trends in terrestrial plants, microorganisms, and metazoans is too pronounced to ignore. Although Algeo et al. (1995) recognized that marine extinctions and deposition of black shale correlate with periods of greatest terrestrial plant diversification, they concluded that rapid burial of organic carbon, declining ρCO_2, and global cooling were secondary effects of higher weathering rates and presumed anoxia, without suggesting a mechanism by which the latter developed.

SUMMARY: PROPOSED MODEL

A model is proposed here to aid the prediction of the distribution of continuous hydrocarbon accumulations in self-sourced shale reservoirs globally. Future studies that help resolve the complex relationships—among tectonics, eustasy, seawater chemistry, climate, and evolutionary trends, in both marine and terrestrial biotas—that promoted the deposition *and* preservation of these valuable resources, will improve understanding of the apparent restriction of self-sourced shale to discrete intervals in geologic history.

The succession of processes that promoted the deposition of potential self-sourced shale is as follows:

(1) Rapid tectonic-plate reconfiguration and associated volcanism during supercontinent assembly and fragmentation caused flooding of cratonic interiors and the release of CO_2;

(2) Radiation and increased productivity of land plants resulted from higher ρCO_2;

(3) Enhanced productivity of marine phytoplankton and increased abundance of zooplankton, due to higher ρCO_2 and greater availability of terrestrial nutrients, initiated the deposition of organic-rich accumulations;

(4) Higher-energy feeding strategies in the modified ecosystem (e.g., Bambach et al., 2002) changed the balance between bioproductivity and the consumption by benthos to favor organic-matter preservation;

(5) Rapid burial of rich biomass sequestered carbon in marine sediment;

(6) Reduction of ρCO_2 induced temporary global cooling and slowed weathering rates, and this may have also deepened the CCD from its unusually shallow position; and

(7) Overturn of oceans in response to cooling induced additional evolutionary turnover, and any drop in sea level during ephemeral glaciations would have reduced the number of habitats available to taxa. General marine diversity, including metazoans and microorganisms, may have initially declined briefly as a re-

sult, but additional biomass continued to accumulate in condensed sections prior to siliciclastic dilution during subsequent progradational episodes.

Limited resolution of data over geologic timescales may obscure the fine details of this proposed series of steps, but correlation of eustatic trends with global climate and macroevolutionary trends in metazoan and plant communities can serve as a first approximation of the temporal distribution of self-sourced shale.

Although the importance of anoxia as a contributing factor is debated, shale deposition according to the model discussed herein suggests that it may not have been necessary for preservation of organic carbon. One should not, therefore, interpret the spatial and temporal distribution of self-sourced shale under the assumption that anoxia developed or persisted, but rather should evaluate contributing factors independently. Furthermore, the apparent restriction of these episodes to intervals of predominantly calcitic seas may explain why these shale units can be exploited for their continuous hydrocarbon accumulations but other source rocks cannot—microporosity in calcitic biomass would have been more resistant to diagenesis than aragonitic deposits, enhancing the ability to fracture-stimulate reservoirs.

CONCLUSIONS

Limits or biases are inherent in this model for self-sourced shale. First, as a model developed by integrating published work of others, use and interpretation of the data are restricted by differences in original scope, methodology, and parameters. One major concern is that the data were not published on the same geologic timescale and were "fitted" herein by geologic periods or dates to a single timescale. The model is also at risk for circular arguments because of the complexity of interactions that produced organic-rich shale. Nevertheless, incorporation of paleobiological studies with paleotectonic, paleogeographic, and geochemical studies is a worthy and ambitious goal because if the significance of correlations between biodiversity and geologic drivers can be confirmed at the largest scales, this model will provide a valuable predictive tool for hydrocarbon producers.

Tectonics was the initial driver behind several changes that promoted the accumulation of organic matter (Mackenzie and Pigott, 1981; Sandberg, 1983; Waples, 1983). Because the interactions of many geological and linked paleoenvironmental–paleobiological controls were complex, it is important to understand both first-order and subordinate mechanisms that most promoted the deposition of potential self-sourcing shale reservoirs. As data resolution increases, improved models will lead to better prediction of their distribution. Combined tectonic histories, paleogeographic reconstructions, and eustatic curves—in the context of paleoecological controls on the production and destruction of organic carbon—will be useful in global prediction of organic-rich shale suitable for continuous resource development.

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REFERENCES CITED

Algeo, T. J., R. A. Berner, J. B. Maynard, and S. E. Scheckler, 1995, Late Devonian oceanic anoxic events and biotic crises! "Rooted" in the evolution of vascular land plants?: Geological Society of America Today, v. 5, p. 45 and 64–66.

Arthur, M. A., J. C. Zachos, and D. S. Jones, 1987, Primary productivity and the Cretaceous/Tertiary boundary event in the oceans: Cretaceous Research, v. 8, p. 43–54.

Arthur, M. A., and B. B. Sageman, 1994, Marine black shales: Depositional mechanisms and environments of ancient deposits: Annual Review of Earth and Planetary Sciences, v. 22, p. 499–551.

Bambach, R. K., 1993, Seafood through time: Changes in biomass, energetics, and productivity in the marine ecosystem: Paleobiology, v. 19, p. 372–397.

Bambach, R. K., 1999, Energetics in the global marine fauna: A connection between terrestrial diversification and change in the marine biosphere: Geobios, v. 32, p. 131–144.

Bambach, R. K., A. H. Knoll, and J. J. Sepkoski, Jr., 2002, Anatomical and ecological constraints on Phanerozoic animal diversity in the marine realm: Proceedings of the National Academy of Sciences of the United States of America, v. 99, p. 6854–6859.

Bambach, R. K., A. H. Knoll, and S. C. Wang, 2004, Origination, extinction, and mass depletions of marine diversity: Paleobiology, v. 30, p. 522–542.

Bush, A. M., and R. K. Bambach, 2011, Paleoecologic megatrends in marine metazoan: Annual Review of Earth and Planetary Sciences, v. 39, p. 241–269.

Dashtgard, S. E., M. K. Gingras, and S. G. Pemberton, 2008, Grain-size controls on the occurrence of bioturbation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 257, p. 224–243.

Dawson, W. C., 1997, Limestone microfacies and sequence stratigraphy: Eagle Ford Group (Cenomanian-Turonian) north-central Texas outcrops: Gulf Coast Association of Geological Societies Transactions, v. 47, p. 99–105.

Demaison, G. J., and G. T. Moore, 1980, Anoxic environments and oil source bed genesis: American Association of Petroleum Geologists Bulletin, v. 64, p. 1179–1209.

Demicco, R. V., T. K. Lowenstein, L. A. Hardie, and R. J. Spencer, 2005, Model of seawater composition for the Phanerozoic: Geology, v. 33, p. 877–880.

Eoff, J. D., 2012a, Global prediction of continuous hydrocarbon accumulations in self-sourced reservoirs: American Association of Petroleum Geologists Search and Discovery Article 90142, Annual Convention and Exposition, Long Beach, California, <http://www.searchanddiscovery.com/abstracts/html/2012/90142ace/abstracts/eof.htm> Last Accessed September 12, 2012.

Eoff, J. D., 2012b, Global prediction of continuous hydrocarbon accumulations in self-sourced reservoirs: U.S. Geological Survey Open-File Report 2012–1091, 4 sheets.

Ettensohn, F. R., 1994, Marine, organic-rich, dark-shale deposition on North American parts of Pangea, Carboniferous to Jurassic: Effects of supercontinent organization, *in* A. F. Embry, B. Beauchamp, and D. J. Glass, eds., Pangea: Global environments and resources: Canadian Society of Petroleum Geologists Memoir 17, Calgary, Alberta, p. 743–762.

Frakes, L. A., J. E. Francis, and J. I. Syktus, 1992, Climate modes of the Phanerozoic: The history of Earth's climate over the past 600 million years: Cambridge University Press, U.K., 274 p.

Frakes, L. A., 1999, Estimating the global thermal state from Cretaceous sea surface and continental temperature data: Geological

Society of America Special Papers 332, Boulder, Colorado, p. 49–57.

Friedrich, O., 2010, Bethnic foraminifera and their role to decipher paleoenvironment during mid-Cretaceous oceanic anoxic event—The "anoxic benthic foraminifera" paradox: *Revue de Micropaleontology*, v. 53, p. 175–192.

Ghadeer, S. G., and J. H. S. Macquaker, 2011, Sediment transport processes in an ancient mud-dominated succession: A comparison of processes operating in marine offshore settings and anoxic basinal environments: Journal of the Geological Society of London, v. 168, p. 1121–1132.

Gross, O., 2000, Influence of temperature, oxygen and food availability on the migrational activity of bathyal benthic foraminifera: Evidence by microcosm experiments: *Hydrobiologia*, v. 426, p. 123–137.

Hammes, U., H. S. Hamlin, and T. E. Ewing, 2011, Geologic analysis of the upper Jurassic Haynesville shale in East Texas and west Louisiana: American Association of Petroleum Geologists Bulletin, v. 95, p. 1643–1666.

Hannisdal, B., and S. E. Peters, 2011, Phanerozoic earth system evolution and marine biodiversity: Science, v. 334, p. 1121–1124.

Haq, B. U., J. Hardenbol, and P. R. Vail, 1988, Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change: Society of Economic Paleontologists and Mineralogists Special Publication 42, Tulsa, Oklahoma, p. 71–108.

Haq, B. U., and S. R. Schutter, 2008, A chronology of Paleozoic sea-level changes: Science, v. 322, p. 64–68.

Harbor, R. L., 2011, Facies characterization and stratigraphic architecture of organic-rich mudrocks, Upper Cretaceous Eagle Ford Formation, South Texas: M.Sc. Thesis, University of Texas at Austin, 184 p.

Hay, W. W., A. Migdisov, A. N. Balukhovsky, C. N. Wold, S. Flögel, and E. Söding, 2006, Evaporites and the salinity of the ocean during the Phanerozoic: Implications for climate, ocean circulation and life: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 240, p. 3–46.

Holland, S. M., 1996, Recognizing artifactually generated coordinated stasis: Implication of numerical models and strategies for field tests: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 127, p. 147–156.

Holland, S. M., 2000, The quality of the fossil record: A sequence stratigraphic perspective, *in* D. H. Erwin and S. L. Wing, eds., Deep time: Paleobiology's perspective: Paleobiology, supplement to v. 24, p. 148–168.

Iglesias-Rodriguez, M. D., and 12 additional authors, 2008, Phytoplankton calcification in a high-CO_2 world: Science, v. 320, p. 336–340.

Jablonski, D., 1991, Extinctions: A paleontological perspective: Science, v. 253, p. 754–757.

Jarvis, I., J. S. Lignum, D. R. Gröcke, H. C. Jenkyns, and M. A. Pearce, 2011, Black shale deposition, atmospheric CO_2 drawdown, and cooling during the Cenomanian-Turonian oceanic anoxic event: Paleoceanography, v. 26, PA3201, p. 1–17.

Jenkyns, H. C., 1980, Cretaceous anoxic events: From continents to oceans: Journal of the Geological Society of London, v. 137, p. 171–188.

Kaminski, M. A., E. Setoyama, and C. G. Cetean, 2010, The Phanerozoic diversity of agglutinated foraminifera: Origination and extinction rates: *Acta Palaeontologica Polonica*, v. 55, p. 529–539.

Kaźmierczak, J., V. Ittekkot, and E. T. Degens, 1985, Biocalcification through time: Environmental challenge and cellular response: *Paläontologische Zeitschrift*, v. 59, p. 15–33.

Klemme, H. D., and G. F. Ulmishek, 1991, Effective petroleum source rocks of the world: Stratigraphic distribution and controlling depositional factors: American Association of Petroleum Geologists Bulletin, v. 75, p. 1809–1851.

Kump, L. R., and M. A. Arthur, 1999, Interpreting carbon-isotope excursions: Carbonates and organic matter: Chemical Geology, v. 161, p. 181–198.

Leckie, R. M., T. J. Bralower, and R. Cashman, 2002, Ocean anoxic events and plankton evolution: Biotic response to tectonic forcing during the mid-Cretaceous: Paleoceanography, v. 17, no. 3, p. 13–1 to 13–29.

Mackenzie, F. T., and J. D. Pigott, 1981, Tectonic controls of Phanerozoic sedimentary rock cycling: Journal of the Geological Society of London, v. 138, p. 183–196.

Macquaker, J. H. S., and K. M. Bohacs, 2007, On the accumulation of mud: Science, v. 318, p. 1734–1735.

Macquaker, J. H. S., S. J. Bentley, and K. M. Bohacs, 2010a, Wave-enhanced sediment-gravity flows and mud dispersal across continental shelves: Reappraising sediment transport processes operating in ancient mudstone successions: Geology, v. 38, p. 947–950.

Macquaker, J. H. S., M. A. Keller, and S. J. Davies, 2010b, Algal blooms and "marine snow": Mechanisms that enhance preservation of organic carbon in ancient fine-grained sediments: Journal of Sedimentary Research, v. 80, p. 934–942.

Martin, R. E., 1996, Secular increase in nutrient levels through the Phanerozoic: Implications for productivity, biomass, and diversity of the marine biosphere: *Palaios*, v. 11, p. 209–219.

Miller, K. G., M. A. Kominz, J. V. Browning, J. D. Wright, G. S. Mountain, M. E. Katz, P. J. Sugarman, B. S. Cramer, N. Christie-Blick, and S. F. Pekar, 2005, The Phanerozoic record of sea-level change: Science, v. 310, p. 1293–1298.

Milliken, K., S.-J. Choh, P. Papazis, and J. Schieber, 2007, "Cherty" stringers in the Barnett shale are agglutinated foraminifera: Sedimentary Geology, v. 198, p. 221–232.

Müller, P. J., and E. Suess, 1979, Productivity, sedimentation rate, and sedimentary organic matter in the oceans—I. Organic carbon preservation: Deep-Sea Research, v. 26A, p. 1347–1362.

Nance, R. D., and J. B. Murphy, 1994, Orogenic style and the configuration of supercontinents, *in* A. F. Embry, B. Beauchamp, and D. J. Glass, eds., Pangea: Global environments and resources: Canadian Society of Petroleum Geologists Memoir 17, Calgary, Alberta, p. 49–65.

Ottmann, J. T., and K. M. Bohacs, 2011, The Barnett shale—A sequence stratigraphic view of depositional controls, reservoir quality, and resource density: American Association of Petroleum Geologists Search and Discovery Article 90122, Hedberg Conference, Austin, Texas, <http://www.searchanddiscovery.com/abstracts/pdf/2011/hedberg-texas/abstracts/ndx_ottmann.pdf> Last Accessed September 12, 2012.

Ozaki, K., S. Tajima, and E. Tajika, 2011, Conditions required for oceanic anoxia/euxinia: Constraints from a one-dimensional ocean biogeochemical cycle model: Earth and Planetary Science Letters, v. 304, p. 270–279.

Parrish, J. T., and R. L. Curtis, 1982, Atmospheric circulation, upwelling, and organic-rich rocks in the Mesozoic and Cenozoic eras: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 40, p. 30–66.

Pedersen, T. F., and S. E. Calvert, 1990, Anoxia vs. productivity: What controls the formation of organic-carbon-rich sediments and sedimentary rocks?: American Association of Petroleum Geologists Bulletin, v. 74, p. 454–466.

Pemberton, S. G., J. A. MacEachern, M. K. Gingras, and T. D. A. Saunders, 2008, Biogenic chaos: Cryptobioturbation and the work of sedimentologically friendly organisms: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 270, p. 273–279.

Perdikouri, C., A. Kasioptas, T. Geisler, B. C. Schmidt, and A. Putnis, 2011, Experimental study of the aragonite to calcite transition in aqueous solution: *Geochimica et Cosmochimica Acta*, v. 75, p. 6211–6224.

Peters, S. E., 2007, The problem with the Paleozoic: Paleobiology, v. 33, p. 165–181.

Peters, S. E., and W. A. Berggren, 2005, Geologic constraints on the macroevolutionary history of marine animals: Proceedings of the National Academy of Sciences of the United States of America, v. 102, p. 12326–12331.

Pomar, L., and P. Hallock, 2008, Carbonate factories: A conundrum in sedimentary geology: Earth-Science Reviews, v. 87, p. 134–169.

Riding, R., 1992, Temporal variation in calcification in marine cyanobacteria: Journal of the Geological Society of London, v. 149, p. 979–989.

Rosenzweig, M. L., 2002 (first published 1995), Species diversity in space and time: Cambridge University Press, U.K., 436 p.

Sandberg, P. A., 1983, An oscillating trend in Phanerozoic non-skeletal carbonate mineralogy: Nature, v. 305, p. 19–22.

Schieber, J., 2003, Simple gifts and buried treasures—Implications of finding bioturbation and erosion surfaces in black shales: The Sedimentary Record, v. 1, no. 2, p. 4–8.

Schieber, J., 2009, Discovery of agglutinated benthic foraminifera in Devonian black shales and their relevance for the redox state of ancient seas: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 271, p. 292–300.

Schieber, J., 2011, Marcasite in black shales—A mineral proxy for oxygenated bottom waters and intermittent oxidation of carbonaceous muds: Journal of Sedimentary Research, v. 81, p. 447–458.

Schieber, J., J. Southard, and K. Thaisen, 2007, Accretion of mudstone beds from migrating floccule ripples: Science, v. 318, p. 1760–1762.

Scotese, C. R., A. J. Boucot, and W. S. McKerrow, 1999, Gondwanan palaeogeography and palaeoclimatology: Journal of African Earth Sciences, v. 28, p. 99–114.

Slatt, R. M., 2011, Important geological properties of unconventional resource shales: Central European Journal of Geosciences, v. 3, p. 435–448.

Slatt, R. M., and N. R. O'Brien, 2011, Pore types in the Barnett and Woodford gas shales: Contribution to understanding gas storage and migration pathways in fine-grained rocks: American Association of Petroleum Geologists Bulletin, v. 95, p. 2017–2030.

Slatt, R. M., N. R. O'Brien, M. Romero, A. Andrea, and H. Rodriguez, 2012a, Eagle Ford condensed section and its oil and gas storage and flow potential: American Association of Petroleum Geologists Search and Discovery Article 90142, Annual Convention and Exhibition, Long Beach, California, <http://www.searchanddiscovery.com/abstracts/html/2012/90142ace/abstracts/slatt.htm> Last Accessed September 12, 2012.

Slatt, R. M., P. R. Philp, Y. Abousleiman, P. Singh, R. Perez, R. Portas, K. J. Marfurt, and S. Madrid-Arroyo, 2012b, Pore-to-regional-scale integrated characterization workflow for unconventional gas shales, *in* J. Breyer, ed., Shale reservoirs—Giant resources for the 21st century: American Association of Petroleum Geologists Memoir 97, Tulsa, Oklahoma, p. 1–24.

Slatt, R. M., and N. D. Rodriguez, 2012, Comparative sequence stratigraphy and organic geochemistry of gas shales: Commonality or coincidence?: Journal of Natural Gas Engineering and Science, doi:10.1016/j.jngse.2012.01.008.

Stanley, S. M., 2006, Influence of seawater chemistry of biomineralization throughout Phanerozoic time: Paleontological and experimental evidence: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 232, p. 214–236.

Stanley, S. M., and L. A. Hardie, 1998, Secular oscillations in the carbonate mineralogy of reef-building and sediment-producing organisms driven by tectonically forced shifts in seawater chemistry: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 144, p. 3–19.

Stanley, S. M., J. B. Ries, and L. A. Hardie, 2010, Increased production of calcite and slower growth for the major sediment-producing alga *Halimeda* as the Mg/Ca ratio of seawater is lowered to a "calcite" sea level: Journal of Sedimentary Research, v. 80, p. 6–16.

Stigall, A. L., 2012, Speciation collapse and invasive species dynamic during the late Devonian "mass extinction": Geological Society of America Today, v. 22, p. 4–9.

Stow, D. A. V., A.-Y. Huc, and P. Bertrand, 2001, Depositional processes of black shales in deep water: Marine and Petroleum Geology, v. 18, p. 491–498.

Stow, D. A. V., H. G. Reading, and J. D. Collinson, 2004 (first published 1978), *in* H. G. Reading, ed., Sedimentary environments: Processes, facies, and stratigraphy: Blackwell Science, Oxford, U.K., 688 p.

Tappan, H., and A. R. Loeblich, Jr., 1988, Foraminiferal evolution, diversification, and extinction: Journal of Paleontology, v. 62, p. 695–714.

Ulmishek, G. F., and H. D. Klemme, 1990, Depositional controls, distribution, and effectiveness of world's petroleum source rocks: U.S. Geological Survey Bulletin 1931, 59 p.

Waples, D. W., 1983, Reappraisal of anoxia and organic richness, with emphasis on the Cretaceous of North Atlantic: American Association of Petroleum Geologists Bulletin, v. 67, p. 963–978.

Wilde, P., and W. B. N. Berry, 1984, Destabilization of the oceanic density structure and its significance to marine "extinction" events: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 48, p. 143–162.