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Anoxia controlled by relative sea-level changes: An example from the Mississippian Barnett Shale Formation

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ABSTRACT

A continuous core drilled in the Barnett Shale Formation (Fort Worth Basin, Texas, United States), a remarkable example of Paleozoic organic-rich sediments deposited in a narrow inland seaway, was analysed by means of sedimentological, geochemical and biostratigraphic data. As the influence of sea-level fluctuations on benthic anoxia in ancient seas is still poorly understood, our work aims to shed light on the control exerted by relative sea-level variations on the paleoceanographic processes that drove fine-grained sediment deposition, organic matter dispersal and preservation during the sedimentation of the Barnett Shale Formation. Using spectral gamma-ray log a large second-order sequence modulated by a total of thirteen third-order sequences was inferred. Third-order relative sea-level cycles modulated the level of restriction of the basin through time, alternating pulses of bottom-water oxygenation and relatively more efficient watermass circulation with times of sluggish bottom-water and stagnation, which controlled the facies stacking pattern and organic matter preservation. In particular, relatively increased stagnation occurred during lowstand phases, while relatively reduced restriction was principally associated with transgressive and highstand systems tracts with more efficient bottom current circulation. On a larger scale, second-order eustatic cycles played a crucial role in determining the paleoceanographic and depositional processes responsible for anoxia. During the early phase of sea-level rise, the pre-existing topography was flooded establishing the conditions for a shallow strongly restricted anoxic basin. During the second-order regression the basin experienced increased isolation with bottom-water stagnation and deep-water renewal of ~6000 years. Anoxia terminated abruptly, corresponding to the eustatic sea-level rise associated with the beginning of a new second-order sequence. Therefore, the Barnett Shale Formation represents a significant example of the complex interplay between sea-level-controlled basin physiography and local paleoceanographic conditions.

1. Introduction

The Barnett Shale Formation, a world-class source rock of Mississippian age, is a remarkable example of how fine-grained sedimentary sequences are far from being homogeneous and monotonous. Facies heterogeneity (Hickey and Henk, 2007; Loucks and Ruppel, 2007; Singh et al., 2008; Breyer et al., 2012; Bunting and Breyer, 2012; Milliken et al., 2012), variable geochemical composition (Rowe et al., 2008, 2009) and petrophysical properties (Kale et al., 2010), complex depositional architecture (Baruch et al., 2012; Breyer et al., 2012; Monroe and Breyer, 2012) are evidence of the complexity and multitude of processes that shaped Barnett Shale Formation sediment deposition. The interaction of variable production of organic matter, changing redox state, and organic matter dilution controlled the fate of organic matter through time. Peculiar paleoceanographic conditions allowed the sedimentation of organic-rich black mudstones with average total organic carbon (TOC) content ranging between 4 and 5 wt.% with maxima up to 12 wt.% or even higher (Pollastro et al., 2007).

The Barnett Shale Formation deposited in a narrow inland seaway with an estimated water depth between 120 and 215 m (400 and 700 ft) (Loucks and Ruppel, 2007), in a physiographic setting that was likely sensitive to relative sea-level fluctuations. Many authors have discussed the control played by relative sea-level changes on the deposition of organic-rich sequences, with black shales frequently associated with transgressive surfaces (basal transgressive black shales) or with maximum flooding surfaces (maximum flooding black shales) (Wignall and Maynard, 1993; Wignall, 1994; Bohacs, 1998). While Barnett Shale Formation stratal architecture (Monroe and Breyer, 2012) and stratigraphic stacking patterns (Singh et al., 2008) have been widely studied, the influence of sea-level fluctuations on the deposition of the Barnett Shale organic-rich facies is still poorly understood. The objective of this study is to understand the control of relative sea-level variations on the sedimentation of the Barnett Shale Formation, with a particular attention to: 1) the physical processes that controlled sediment dispersal and deposition; 2) the variation in organic input through time; 3) the stratigraphic change in redox conditions; and 4) construction of a consistent paleoceanographic model that accounts for Barnett Shale Formation internal variability at different hierarchical orders.

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2. Geological setting and study area

The studied sequence is located in the Fort Worth Basin, an asymmetric, wedge-shaped foreland basin (Hill et al., 2007; Pollastro et al., 2007) formed during the late Paleozoic orogeny (Meckel et al., 1992; Breyer et al., 2012). The basin, which covers an area of approximately 40,000 km^2, is bounded by the Ouachita structural front to the east and southeast, the Llano Uplift to the south, the Muenster and Red River arches to the north and northeast, and the Bend Arch to the west (Walper, 1982) (Fig. 1).

The Barnett Shale Formation, a dominantly fined-grained succession of organic-rich mudstones, lies unconformably on the approximately 2000-m-thick Ordovician deposits of the Viola and Ellenburger Formations. Baruch et al. (2012), by analysing a 3-D seismic volume in the southwestern part of the Fort Worth Basin, showed that the unconformity is the result of a paleocave system collapse produced by subaerial exposure and carbonate dissolution. The Barnett Shale Formation is informally divided into lower and upper members when separated by the low gamma ray interval of the Forestburg Limestone (Henry, 1982), a carbonate-rich sequence that increases in thickness to the east and northeast, toward the Ouachita overthrust (Bowker, 2003; Montgomery et al., 2005; Pollastro, 2007; Singh et al., 2008). The Barnett Shale Formation interfingers with and is conformably overlain by the Lower Pennsylvanian Marble Falls Formation (Kier et al., 1980; Henry, 1982), a sequence of limestones laterally interfingering with marls that marks the reestablishment of normal oxygenated marine conditions (Fig. 1). The Marble Falls Formation is characterized by a lowermost shaly interval, frequently mistaken on subsurface well logs with the Barnett Shale Formation, and for this reason informally referred to as “false Barnett”, and an uppermost carbonate-rich interval called the Marble Falls Limestone (Pollastro et al., 2007).

The Barnett Shale Formation and its nearshore equivalent, the Chappel Limestone (Henry, 1982; Ruppel, 1984), were deposited over a 25-million year (Myr) period (Loucks and Ruppel, 2007) during the initial flooding of Laurussia after a prolonged period of exposure and karsting in the middle Paleozoic (Breyer et al., 2012). As many other black shale-rich sequences, Barnett Shale Formation has been interpreted both as a shallow-water and a deep-water deposit (Monroe and Breyer, 2012). The lateral transition to the Chappel Limestone and the fauna observed in the shale, led many authors (Mapel et al., 1979; Kier et al., 1980; Henry, 1982) to interpret the Barnett Shale Formation as a shallow-water deposit. Paleogeographic reconstructions suggest the presence of a narrow restricted seaway (McBee, 1999; Blakey, 2005; Loucks and Ruppel, 2007), bounded by a shallow-water carbonate shelf to the west and an island arc to the east, with water depths ranging between 120 and 215 m (400 and 700 ft) (Gutschick and Sandberg, 1983; Loucks and Ruppel, 2007) (Fig. 1). The particular basin configuration hindered an efficient circulation with the open ocean, inducing euxinic bottom waters that enhanced the preservation of organic matter (Loucks and Ruppel, 2007).

3. Methods

A 151.49-m-long continuous core drilled from a well located in the Bend Arch-Fort Worth Basin (Texas, USA) was described and analysed for this study. This work integrates facies, mineralogical data, total organic carbon and Rock-Eval, palynofacies, and major and trace element geochemical data (Appendix A).

3.1. Sedimentological logging

At first the meter-scale variability of the analysed core was performed by means of spectral core gamma-ray log directly measured on core by Schlumberger Reservoir Laboratories. The core sedimentological description was performed at a mm-scale: any recognizable litho-textural unit characterized by observable lithological changes and facies associations were defined on the basis of texture, composition and structures. Detailed bed-by-bed lithological description was complemented by microfacies analysis on thin-section and scanning electron microscopy (SEM). We adopted the nomenclature and description guidelines for fine-grained sedimentary rocks described in Lazar et al., 2015.

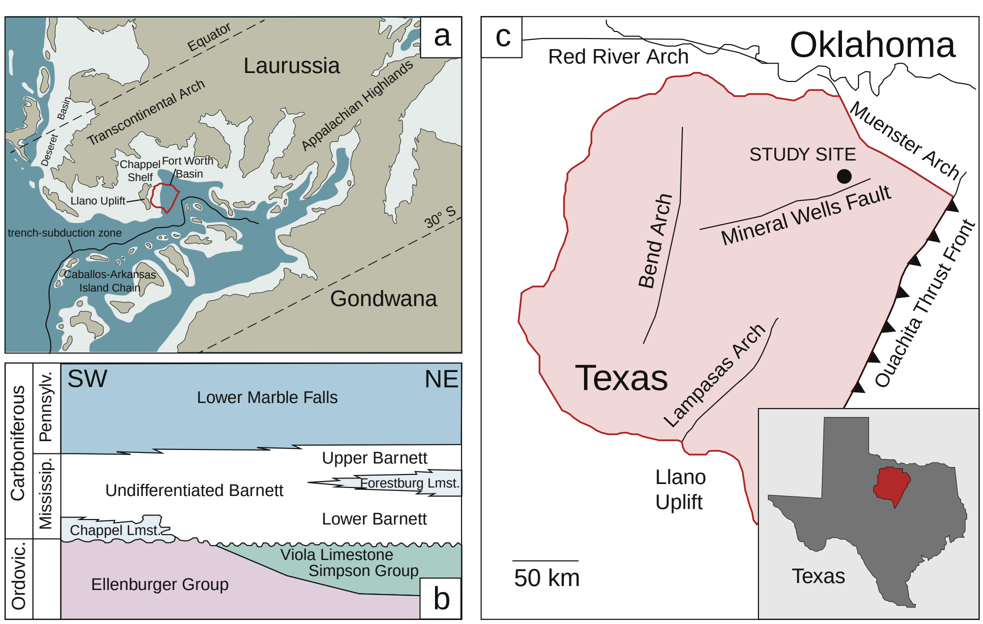

Fig. 1. Top left: paleogeographic reconstruction of the mid-continent region during the late Mississippian (325 My) (modified after Loucks and Ruppel, 2007, plate reconstruction by Blakey, 2005). The approximate paleo-location of the Fort Worth Basin is outlined in red. Bottom left: schematic stratigraphy of the Barnett Shale Formation in the Fort Worth Basin (modified after Breyer et al., 2012). Right: Present-day geographic map of the Fort Worth Basin (modified after Pollastro et al., 2007). The principal geological features are reported.