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Sequence stratigraphy in the middle Ordovician shale successions, mid-east Korea: Stratigraphic variations and preservation potential of organic matter within a sequence stratigraphic framework

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ABSTRACT

The Jigunsan Formation is the middle Ordovician shale-dominated transgressive succession in the Taebaeksan Basin, located in the eastern margin of the North China platform. The total organic carbon (TOC) content and some geochemical properties of the succession exhibit a stratigraphically distinct distribution pattern. The pattern was closely associated with the redox conditions related to decomposition, bulk sedimentation rate (dilution), and productivity. To explain the distinct distribution pattern, this study attempted to construct a high-resolution sequence stratigraphic framework for the Jigunsan Formation. The shale-dominated Jigunsan Formation comprises a lower layer of dark gray shale, deposited during transgression, and an upper layer of greenish gray siltstone, deposited during highstand and falling stage systems tracts. The concept of a back-stepped carbonate platform is adopted to distinguish early and late transgressive systems tracts (early and late TST) in this study, whereas the highstand systems tracts and falling stage systems tracts can be divided by changes in stacking patterns from aggradation to progradation. The late TST would be initiated on a rapidly back-stepping surface of sediments and, just above the surface, exhibits a high peak in TOC content, followed by a gradually upward decrease. This trend of TOC distribution in the late TST continues to the maximum flooding surface (MFS). The perplexing TOC distribution pattern within the late TST most likely resulted from both a gradual reduction in productivity during the late TST and a gradual increase in dilution effect near the MFS interval. The reduced production of organic matter primarily incurred decreasing TOC content toward the MFS when the productivity was mainly governed by benthic biota because planktonic organisms were not widespread in the Ordovician. Results of this study will help improve the understanding of the source rock distribution in mixed carbonate–siliciclastic successions within a stratigraphic framework, particularly for unconventional shale reservoirs.

1. Introduction

Reservoir characterization of thick shale successions has attracted considerable interest since the full-scale development of shale gas. Recently, there have been numerous case studies on the characterization of shale reservoirs and especially, in shale gas fields, advanced techniques for evaluating shale reservoir properties have been developed and widely used because the production performance varies substantially, even for a single shale formation (Hackley, 2012; Hammes and Frébourg, 2012; Milliken et al., 2012; Romero and Philip, 2012). Sequence stratigraphy in fine-grained successions has been a principal technique in reservoir characterization in source rock reservoir fields. Thus, shale successions have been extensively studied from the viewpoint of sequence stratigraphy for better understanding of depositional environments, climate change, and basin evolution (Van Wagoner et al., 1987, 1990; Miall, 1997; Posamentier and Allen, 1999; Catuneanu, 2006; Zecchin and Catuneanu, 2015). Despite extensive studies, sequence stratigraphy based on analysis of geochemical properties has not been fully developed. For example, the stratigraphic distribution of the TOC content and geochemical properties in shale reservoirs, and its relationships among shale reservoir properties, have not been fully evaluated within a sequence stratigraphic framework (cf. Ver Straeten et al., 2011; Slatt and Rodriguez, 2012).

It has been known that TOC content and geochemical properties are influenced primarily by sedimentation rate (dilution), productivity, and redox condition of the bottom water (Wignall, 1991; Bohacs et al.,

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2005). The variation of TOC content provides a critical clue for locating the cryptic boundaries within shale-dominated successions (Loutit et al., 1988; Creaney and Passey, 1993; Tyson, 2001; Catuneanu, 2006; Nichols, 2009). Maximum flooding surfaces can be characterized by low sedimentation rates, with a constant supply of organic matter from planktonic sources, and commonly anoxic conditions favoring minimum decomposition of organic matter. Accordingly, MFS has been considered as a sweet spot for shale gas or oil production with a high TOC content (Wignall, 1991; Creaney and Passey, 1993; Catuneanu, 2006).

To establish a high-resolution sequence stratigraphic framework and investigate its relationship with TOC content and geochemical properties, we focused on the middle Ordovician shale-dominated Jigunsan Formation in the eastern margin of the North China Platform (Kwon et al., 2006; Woo and Chough, 2007; Ryu et al., 2009). Based on a detailed outcrop description and geochemical analyses, this study identified sequence stratigraphic key surfaces, including a subaerial exposure surface, maximum flooding surface, and inherent surfaces in transgressive systems tract, and obtained high-resolution analytical data on TOC content and geochemical properties. The results suggest that variations in TOC and location of “sweet spots” for shale-dominated source rock reservoirs would be different depending largely on which organisms (benthic or planktonic sources) played a role in productivity. A high-resolution geochemical analysis within the sequence stratigraphic framework provides a unique opportunity to predict the locations of the highest TOC intervals and location of “sweet spots” for shale reservoirs.

2. Geological setting

During the early Paleozoic, the Taebaeksan Basin was located in the eastern part of the North China Block (Choi et al., 2004; Choi and Chough, 2005). A marine carbonate–siliciclastic system developed in this basin, with a restricted occurrence of coarse siliciclastic sediments at the eastern margin of the basin throughout the Cambrian (Chough et al., 2000; Kwon et al., 2006). Across the western part of the basin, rapid accumulation of carbonate sediments resulted in the formation of a widespread shallow carbonate platform during the early Ordovician (Choi et al., 2004). This carbonate platform was characterized by low-relief topography, with shoals, lagoons, and tidal flats that persisted into the middle Ordovician. Marine sedimentation ceased throughout the basin in the late Ordovician. The basin was emergent during most of the middle Paleozoic, until marine transgression resumed in the Late Carboniferous (Choi et al., 2004).

The Taebaek Group is divided into ten formations—the Jangsan/Myeonsan, Myobong, Daegi, Sesong, Hwajeol, Dongjeom, Dumugol, Makgol, Jigunsan, and Duwibong Formations in ascending order (Choi et al., 2004; Kwon and Chough, 2005, Fig. 1). The Jigunsan Formation was deposited during the Darriwilian stage under siliciclastic depositional systems and is composed of thick shale and siltstone successions (Table 1). The formation overlies the carbonate-dominant Makgol Formation and is overlain by the carbonate-dominant Duwibong Formation, which formed with a general rise in the relative sea level. The Jigunsan Formation has been interpreted as a transgressive systems tract of a second- or third-order sequence. A lot of sedimentological and paleontological research has been carried out (Choi et al., 2004; Choi and Chough, 2005; Kwon et al., 2006; Woo and Chough, 2007). Recently, some sequence stratigraphic research has also been conducted in this Formation, especially focusing on the lower part of the Jigunsan Formation (Kwon et al., 2006; Woo and Chough, 2007; Ryu et al., 2009). Due to the ambiguity and difficulty of the sequence stratigraphy at the fine-grained succession (Ver Straeten et al., 2011), however, principal sequence stratigraphic surfaces, such as transgressive surfaces and maximum flooding surfaces, have not yet been clearly defined and have remained controversial (cf. Woo and Chough, 2007; Ryu et al., 2009).

3. Facies analysis

Based on a detailed description of the outcrop in the Seokgaejae and Gumunso sections, thirteen facies, including carbonate and siliciclastic lithofacies, were identified throughout the Jigunsan Formation, uppermost part of Makgol Formation (Figs. 2 and 3). These facies are grouped into six facies associations representing different depositional environments. Fig. 4 illustrates a columnar section of the Seokgaejae and Gumunso sections with representative facies associations.

3.1. Facies association 1 (FA 1)

FA 1 consists of thickly laminated lime mudstone (LMt), finely laminated lime mudstone (LMl), lime paleosol (P), bioturbated wackestone (Wb), and gray oolitic grainstone (Go) (Fig. 4). These facies form meter-scale cyclic successions with some subaerially exposed paleosols. This association occurs in the uppermost part of the Makgol Formation, and it is interpreted as a subtidal to supratidal platform environment, without slope-related facies (i.e., limestone breccia; coarser-grained carbonate lithoclast). The horizontal and slightly inclined bioturbation can also be interpreted as a shallow subtidal environment (Paik, 1987; Overstreet et al., 2003) and the cryptalgal lamination of LMl can be interpreted as upper intertidal to supratidal (Hardie, 1977; Shinn et al., 1983; Woo and Chough, 2007).

3.2. Facies association 2 (FA 2)

FA 2 is composed of nodule-bearing black shale (Snb) and gray lime mudstone (LMg) (Fig. 4). This association occurs in the lowermost part of the Jigunsan Formation. The LMg beds are interbedded in the Snb. Most of the nodules within the Snb exhibit pyrite grains as concentric rims on the nodules (or concretion). The lower part of the Snb contains many fossil fragments and is partly calcareous. LMg contains abundant fossils and partially-formed hardgrounds. Richly fossiliferous horizon (*Dolerobasilicus* fauna) is located lower part of FA 2 associated with LMg beds (Choi et al., 2001). This association represents the low-energy basin floor. The almost completely unfossiliferous interval appears in the middle and upper part of FA 2.

Trilobite: Lee and Choi (1992) based on a re-evaluation of the Jigunsan trilobite fauna concluded that only four species are recognizable within the formation. They are *Dolerobasilicus yokusensis*, *Basiliella kawasakii*, *Basiliella typicalis*, and *Ptychopyge dongjeomensis*. Choi et al. (2001) proposed the *Dolerobasilicus* Zone for the fossiliferous interval, which is in the lower part of FA 2.

Cephalopods: The cephalopods from the Jigunsan Formation comprise three subclasses and are dominated by orthoceroids and actinoceroids, with some endoceroids (Yun, 2011). Only two species, *Sactorthoceras makkolense and Holmiceras coreanicum*, were found in the lower part of FA 2.

3.3. Facies association 3 (FA 3)

FA 3 consists of alternating laminated calcisiltite (CZl) and homogeneous mudstone (Mh) (Fig. 4). This association occurs in the middle Jigunsan Formation. The CZl beds have very sharp and slightly erosional lower boundaries and gradational upper boundaries, commonly disturbed by various burrows (Woo and Chough, 2007). Most of CZl displays grading with partial bouma sequences (mostly Tc-Te) with burrows at the upper part. CZl also includes oversized nodules formed by early cementation. Thickness of CZl is highly variable, but individual beds are less than 15 cm. Mh can be interpreted as settlement of suspended sediments from the water column. The environment for FA 3 is suggestive of a basin floor or mud dominated carbonate toe-of-slope (Woo and Chough, 2007; Playton et al., 2010; Beauchamp et al., 2013; Minzoni et al., 2013).