Chapter 2

Sequence Stratigraphy of Fine-Grained "Shale" Deposits: Case Studies of Representative Shales in the USA and China

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Abstract

The fine-grained "shale" deposits host a vast amount of unconventional oil and gas resources. This chapter examines the variations in lithofacies, patterns of well logs, geochemistry, and mineralogy in order to construct a sequence stratigraphic framework of the representative marine Barnett, Woodford, Marcellus, Mowry, and Niobrara fine-grained "shales" (USA) and the marine Longmaxi shale and lacustrine Chang7 lacustrine shale (China). Practical methods are proposed in order to recognize the sequence boundaries, the flooding surfaces, the parasequences and parasequence sets, the system tracts, and variation patterns of facies and rock properties. The case studies for the sequence stratigraphy in the USA and China have revealed that the transgressive systems tract (TST) and the early highstand systems tract (EHST, if identifiable) of fine-grained "shales" have been deposited in anoxic settings. TST and EHST of the siliciclastic "shales" are characterized by high gamma ray, high TOC, and high quartz content, while TST and EHST of the carbonate-dominated fine-grained "shales" are characterized by low gamma ray, organic lean, and carbonate rich fine-grained deposits. The lithofacies, geochemistry, mineralogy, depositional evolution, and reservoir development have been predicted and correlated within a sequence stratigraphic framework for the suggested cases. The best reservoir with the best completion quality is developed in TST and HST in both siliciclastic-dominated and carbonate-dominated fine-grained "shales."

Keywords: sequence stratigraphy, shale, fine-grained, siliciclastic dominated, carbonate dominated

1. Introduction

The great success of shale gas exploration in North America has attracted increasing attention from petroleum geologists in the world. They are passionate about finding more commercial shale gas in other countries. Although the success of shale gas exploration in North America leads geologists to believe that shale gas exploration has a good prospect, how to find the sweet spot of shale gas in shale strata is still the main obstacle we need to face in the shale gas exploration and development. Sequence stratigraphy is a relatively new concept of stratigraphy and is a powerful tool to subdivide the stratigraphic intervals into geologically realistic and cyclic patterns and to predict the stratal patterns, the lithofacies variations, and the petroleum reservoirs within a chronostratigraphic unit. In the past 40 years, the sequence stratigraphic studies mainly focused on the coarse-grained siliciclastic and carbonate deposits and on the fine-grained turbiditic systems from lacustrine to deepwater settings, leading to a great success in the conventional petroleum exploration [1–5]. However, only limited studies on the high-frequency sequence and sedimentology have been conducted to study the sequence stratigraphy of shale strata deposited in deep water or restricted shallow water environment [6–8]. According to the traditional sequence stratigraphy, it is difficult to carry out a sequence stratigraphic analysis in relatively deep water areas where the shales are deposited [9]. This is due to the relatively homogenous and fine-grained nature of the shale interval [10] and to the conformity contact between upper and lower strata. Only newly acquired seismic data tied to geology can characterize the partial reservoir parameters, and it is very challenging to pick surfaces reflecting sea-level changes of fine-grained deposits on the seismic data if not tied by core and log data [11, 12]. Also, the GR log alone sometimes does not indicate high TOC of the maximum flooding surface within a sequence [13]. Nevertheless, some researchers have integrated the geochemistry, the geomechanics, the core and outcrop analysis, the seismic data, the well logs, the petrology, and the paleontology in order to perform a sequence stratigraphic analysis of the shales aimed at understanding the sequence boundaries, the major transgressive surface of erosion, the maximum flooding surface, the stacking patterns, the lithofacies variability, and the depositional models within the sequence [8–10, 14–25]. Some geologists have even tried to establish the criteria and models for sequence stratigraphy study in marine shale and predict the good reservoir potential shale gas vertically and laterally [8, 10, 12, 21, 22, 26]. So far, sequence stratigraphy of the shale is still poorly understood, and the traditional seismic stratigraphy approach to recognize the boundaries of sequences and system tracts does not work well for the fine-grained shale due to their relatively homogeneous fine-grained nature. Recent advances in property tests of the geochemistry, the mineralogy, the petrology, the petrophysics, and the geomechanics have provided the basis for the detailed characterization of the sequence stratigraphy of fine-grained shales. This chapter analyzes the spatial and temporal variations in the lithofacies, the well-logging responses, the geochemistry, the mineralogy, the hydrocarbon content and aims at developing the sequence stratigraphic frameworks for representative siliciclastic-dominated shales (marine Barnett, Woodford, Marcellus, and Mowry in the USA, Longmaxi and Chang7 shales in China) and carbonate-dominated shales (Niobrara, USA). The general variation trends of the shale properties have been analyzed within a sequence stratigraphic framework, so that they can be used to regionally correlate the shaly strata in a systematic manner and to identify, to predict, and to map the high-quality source rock and the productive fine-grained shale reservoirs.

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2. Data and methodology

The data for characterizing the sequence stratigraphy of fine-grained shales include the regional geologic data, the seismic data, the well logs, the lithofacies description in outcrops and cores, the organic geochemistry, the mineralogy, the thin sections, the SEMs, the QEMSCAN, and the geomechanics.

This chapter has employed a classic sequence stratigraphy model, consisting of the lowstand systems tract (LST), of the transgressive systems tract (TST), and of the highstand systems tract (HST) [2, 27]. The HST can be subdivided into early highstand systems tract (EHST) and late highstand systems tract (LHST) based on identifiable stacking patterns of parasequences and shale properties [24]. Slatt and Rodriguez [8] observed that many shales have cyclical patterns related to the eustatic sea-level fluctuations. They also stated that the general sequence stratigraphy of shales consists of a major transgressive surface of erosion or its correlative conformity and of an organic-rich TST bounded by a transgressive surface below and by a maximum flooding surface (MFS) or a condensed section (CS) above. The TST is then followed by upward decreasing gamma-ray trends within an interpreted HST (**Figure 1**, see appendix for the abbreviations used in this chapter). Typical time frames in which sea-level cycles (length of geologic time for a complete sea-level fluctuations) can be interpreted for shales (mainly based upon their fossil components) include second order, approximately 10–25 My; third order, approximately 1–3 My; fourth order, approximately 100,000–300,000 years [20].

For the methodology, this chapter adopts the following step-by-step workflow for the sequence stratigraphic analysis of fine-grained "shale" systems.

1. Study on regional geology;

2. Outcrop investigation on shale stratigraphy;

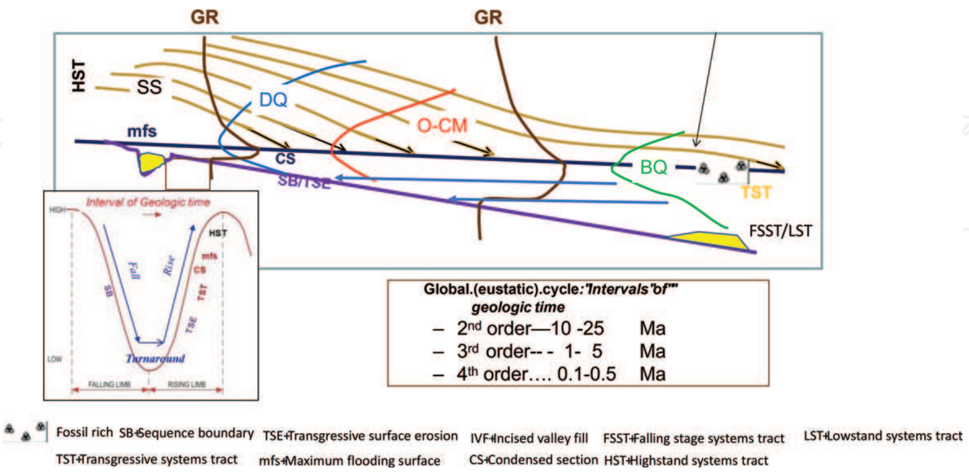

Figure 1. General sequence stratigraphic model of fine-grained shale. A conceptual gamma ray log is shown to indicate the log response of different fine-grained lithofacies (SS-shale rich in siltstone, DQ-shale rich in detrital quartz, O-CM-organic or clay rich mudstone, BQ-shale rich in biogenic quartz) in different stratigraphic interval within sequence stratigraphic framework. Modified from Slatt and Rodriguez (2012) and Slatt et al. (2014). See appendix for abbreviations of sequence stratigraphy from Van Wagoner et al. (1990).

3. Detailed lithological descriptions and preliminary interpretation of lithofacies from outcrop and cores;

4. Additional well logs and data collected from the cored wells were organized, including core-to-log depth corrections;

5. Lithofacies were identified based on core description, QEMSCAN analysis, thin section description, well log responses of spectral gamma ray, resistivity, FMI, density, and XRD data;

6. Seismo-stratigraphic, paleontological, geochemical, and mechanical data were used to identify the boundaries of different order sequences;

7. Vertical and lateral stacking patterns of the sequences were recognized;

8. High-frequency sequence stratigraphic framework was developed.

3. Lithofacies of shales

In the last few decades, the most of organic-rich shale-related plays, for example Barnett, Niobrara, Eagle Ford, Haynesville, and Bakken, have been labeled as "shale plays," and the terms "shale oil," "tight oil," and "resource play" are often used interchangeably in a public discourse [28–32]. The Barnett shale is a typical organic-rich siliceous shale (**Figure 2a**). The Eagle Ford shale is an organic-rich shale interbedded with thin fine-grained carbonate beds (**Figure 2b**). The lacustrine Green River shale consists of organic-rich shale with fine-grained ostracod rich carbonate (**Figure 2c**). The Niobrara shale play is dominated by a low permeability fine-grained chalk sourced by its adjacent marl source rock with continuous hydrocarbon accumulation [33]. The chalk and marl cannot be differentiated by naked eyes and appear like

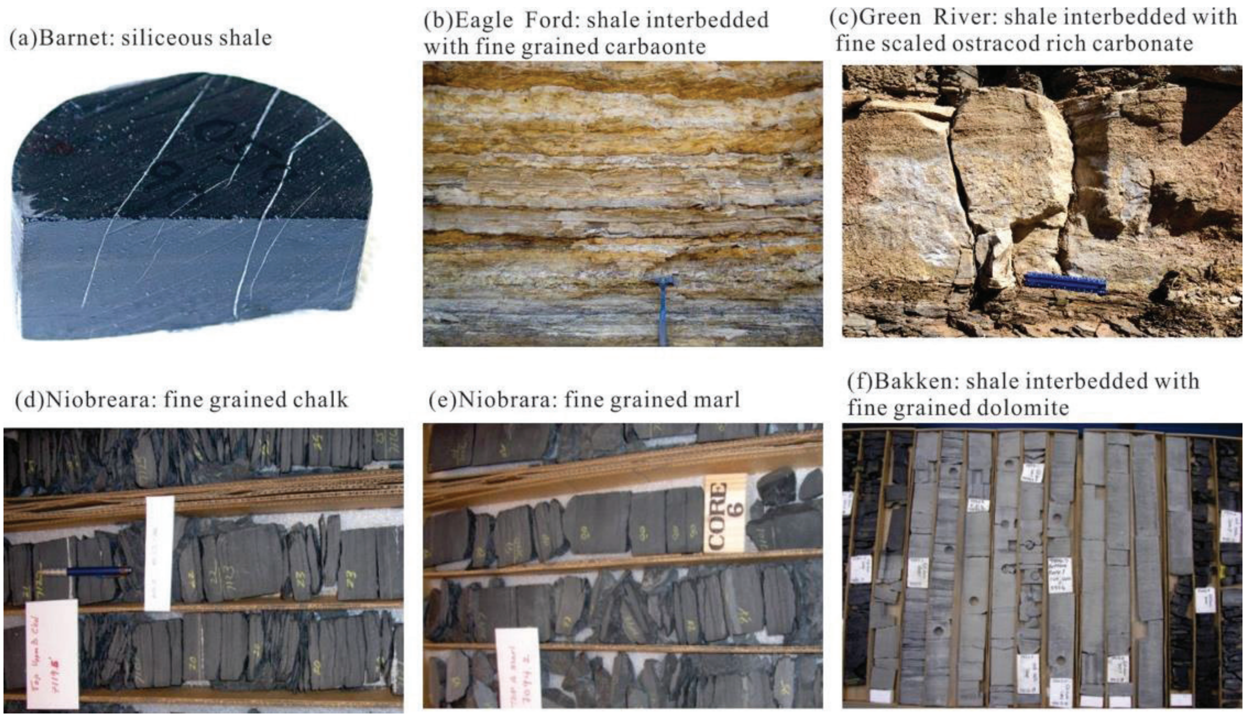

Figure 2. Lithofacies of typical fine-grained "shales" in U.S. The Green River Fm is of lacustrine environment and the rest are of marine environment.

organic-rich argillaceous shale due to fine-grained nature and both containing organic matter (**Figure 2d** and **e**). The Bakken/Exshaw play (the USA and Canada) mostly consists of permeable fine-grained tight dolomite within upper and lower organic-rich shales (**Figure 2f**). The reason for which all these different lithofacies are called shale is the fine-grained nature of these deposits. Shale is defined as a fine-grained sedimentary rock that is a mix of clay minerals and quartz, calcite, and so on. The typical grain size range of shale is less than 1/256 of a millimeter in diameter. The ratio of clay to other minerals is variable. Shale used to be mistakenly considered as clay. For the organic-rich source rock interval, it usually has a mixed succession of interlayered fine-grained shales, sandstone, and/or carbonates. They are often called shale play due to their fine-grained grain size and to their close relationships with organic-rich shale. The shales representing different geologic settings in this study from different basins around the world refer to the fine-grained stratigraphic interval consisting of siliciclastic-dominated and carbonate-dominated lithofacies ranging from primary organic-rich shale to minor fine-grained organic-lean carbonate or sandstone interbeds.

4. Sequence stratigraphy of siliciclastic-dominated shales

Siliciclastic shales are mainly composed of silicate minerals and transported and deposited as fine-grained particles. The basic sequence stratigraphy of representative siliciclastic Barnett, Woodford, Marcellus, and Mowry shales is herein presented based on the variations in lithofacies, geochemistry, well log responses, and cyclicity of relative sea-level change and its effects upon stacking patterns and stratigraphy.

1. Barnett shale

The Mississippian Barnett shale is divided into lower and upper Barnett shale intervals separated in the northern part of the basin by the Forestburg Limestone. The lower Barnett sits directly above an SB/TSE, which caps the underlying Viola/Ellenburger limestones. The lower Barnett is dominated by siliceous mudstones and the upper Barnett is dominated by calcareous mudstones [8]. These lithofacies form distinctive stacking patterns termed "gamma-ray parasequences" (GRP) [34] and termed "high frequency-sequences" by Abouelresh and Slatt [21]. We classify the Lower Barnett shale and Forsberg limestone as a third-order sequence consisting of organic-rich high gamma-ray TST above the Ellenburger limestone and HST of generally decreasing gamma-ray interval. The high gamma-ray lower section of Upper Barnett shale represents TST of another third-order sequence (**Figure 3a**).

2. Woodford shale

The Late Devonian-Early Mississippian Woodford shale comprises three members. They are represented by the Lower Woodford Black shale, unconformably (SB/TSE) overlying (SB/TSE) the Hunton Group carbonates, by the Middle Woodford organic-rich black pyritic shale, and by the more quartzose-phosphatic Upper Woodford. The Woodford shale was deposited during a second-order sea-level cycle consisting of several third-order sequences [22]. Each third-order sequence comprises a TST with upward increasing in gamma ray and a HST with upward decreasing in gamma ray (**Figure 3b**).

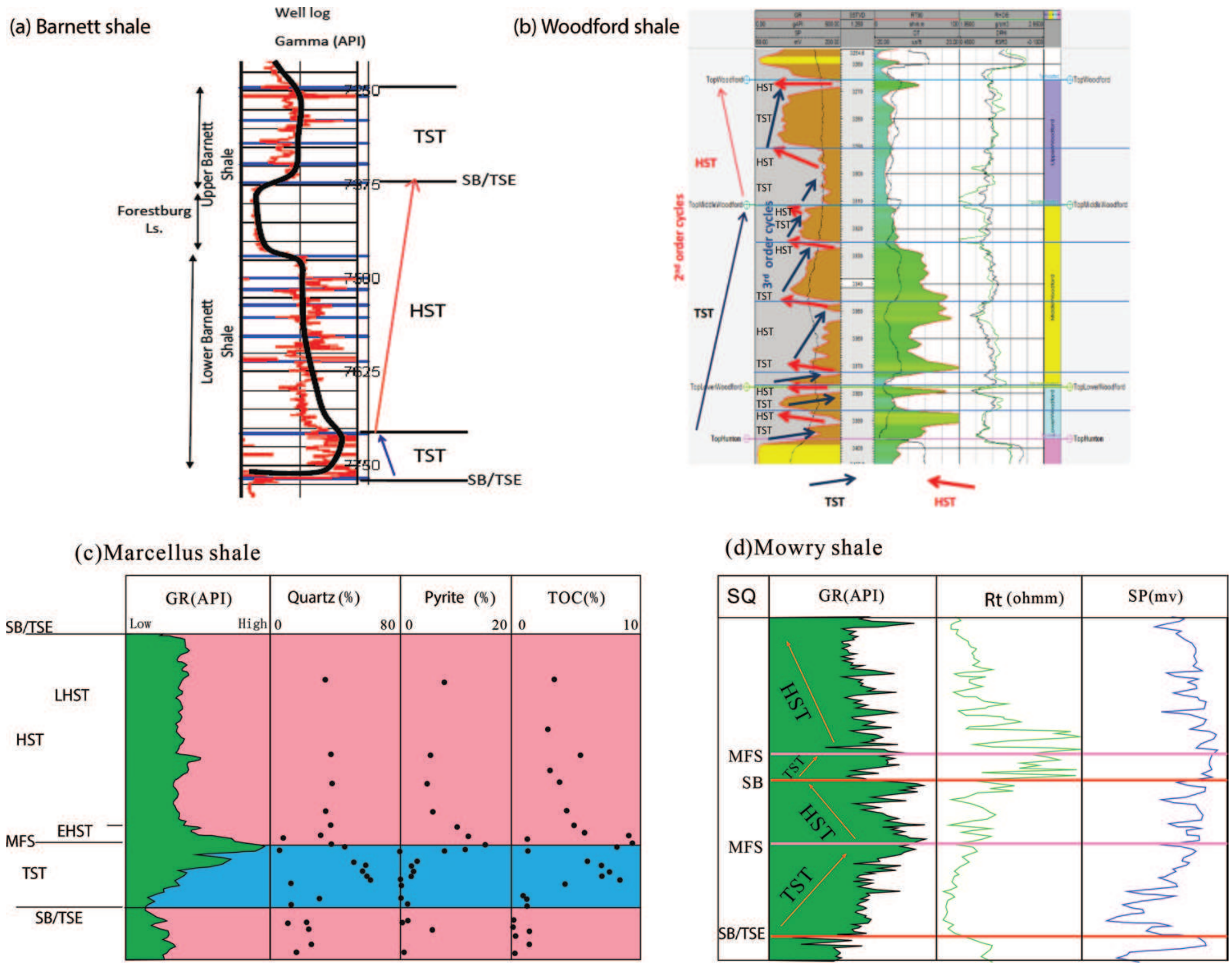

Figure 3. Sequence stratigraphy of typical Barnett, Woodord, Marcellus and Mowry siliciclastic marine shales in U.S. Original data of Barnett shale, Woodford shale, and Marcellus shale are from Slatt and Rodriguez (2012), Slatt and Rodriguez (2014), and Lash and Engelder (2011), respectively.

3. Marcellus shale

The organic-rich lower Union Springs Member of Devonian Marcellus Shale in the northeastern USA. was deposited as a third-order sequence in the Appalachian foreland basin [35]. This sequence consists of a lower, upward increasing API gamma-ray TST and an upper, upward decreasing API gamma-ray HST. The MFS constituting the highest gamma-ray shale separates the TST and HST, and the HST can further be divided into EHST (early stage) and LHST (late stage) (**Figure 3c**). Generally, the TST and EHST are rich in TOC and quartz content.

4. Mowry shale

The Cretaceous Mowry shale in Wyoming consists of third-order sequences with each consisting of TST and HST. TST sits sharply above the SB/TSE and is indicated by a shale interval of upward increasing in gamma ray and resistivity (R_t). The MFS has the highest gamma ray representing the highest sea level. HST generally consists of shale with upward decreasing in gamma ray and resistivity (R_t).

5. Longmaxi shale

The Lower Silurian Longmaxi shale with the best marine shale gas potential is a typical example. This shale is characterized by organic-rich marine shale with abundant graptolite [24]. The thicker organic-rich portion of this Silurian shale was mainly deposited in intra-shelf lows (bathymetric lows on the shelf) since the foredeep area was subject to clastic sediments dilution from the orogenic belt. The Lower Silurian Longmaxi shale was interpreted as a third-order sequence consisting of transgressive systems tract (TST) and highstand systems tract (HST). Based on the lithofacies and geochemical characteristics, the HST can be further subdivided into early highstand systems tract (EHST) and late highstand systems tract (LHST) (**Figure 4**). During the deposition of the lowstand systems tract (LST), wide shelf areas have experienced erosion, and the sediments have deposited in proximal intra-shelf lows. During the deposition of the transgressive systems tract (TST), the shoreline backstepped toward sediment source areas. The shale is generally deposited in the wide shelf, intra-shelf low, and slope area. The organic-rich shale interval with abundant in-situ graptolite, for example *Diplograptus* [24], high gamma-ray value, and high quartz content, is deposited in anoxic settings. During the deposition of the early highstand systems tract (EHST), the total organic content (TOC) in the shale may be high since the redox condition is still anoxic to dysoxic. The graptolite in EHST is characterized by transported microoffsite graptolite, for example *Monograptus* [24]. During

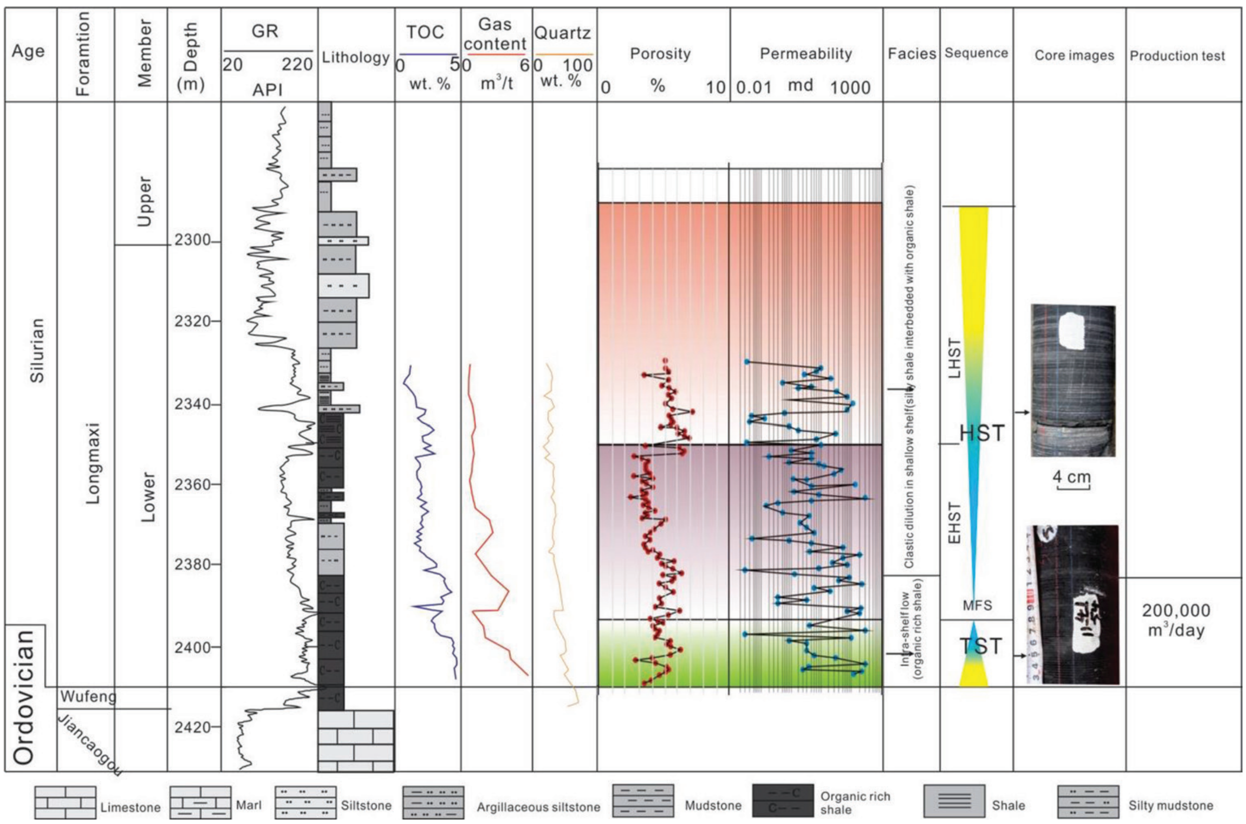

Figure 4. Sequence stratigraphy of Silurian siliciclastic dominated Longmaxi marine shale in Jiaoye1 well in SE Sichuan Basin, Southwest China.

the deposition of the late highstand systems tract (LHST), a further fall of sea level resulted in an increased input of siltstone and sandstone within the shales (see silty layer in core images of the LHST shale in **Figure 4**). During this time interval, sedimentary environment changes to oxygenated shallow marine setting and the coarsening-upward sequence made up of carbonatic shale and silty shales progrades basinward. The shale in LHST is organic-lean and clay-rich shale due to the dilution of clastic input. Generally, the Paleozoic marine shale in TST and EHST has high TOC, high quartz content, and high gas content and is the main target for shale gas play in China. The intervals with high TOC and quartz content in TST and EHST have higher porosity. The porosity in LHST is the highest due to the contribution of silty shale. The sandstone or carbonate in the LHST may trap gas migrated from the TST and EHST shale source rock, and they can form tight sand/carbonate gas play (**Figure 4**).

5. Sequence stratigraphy of carbonate-dominated shales

The sequence of carbonate-dominated shale has been studied using the Niobrara shale in Wyoming and Colorado (USA), for example. For the carbonate-dominated sequence, its sea-level response is different from that one of siliciclastic-dominated shales. For the siliciclastic shales, the sea-level rise has responses of increase in organic matter content and gamma ray (GR) of uranium. For the carbonate-dominated sequence, the sea-level rise means less input in siliciclastic clay and deposition of limestone in clean and quiet water. For the Niobrara equivalent formation in the Cretaceous Seaway, the sequence boundary is indicated by the maximum input of siliciclastic clay indicated by the highest GR in proximal Utah and clay-rich marl in Colorado (**Figure 5**). The TST is indicated by upward decrease in GR and deposit

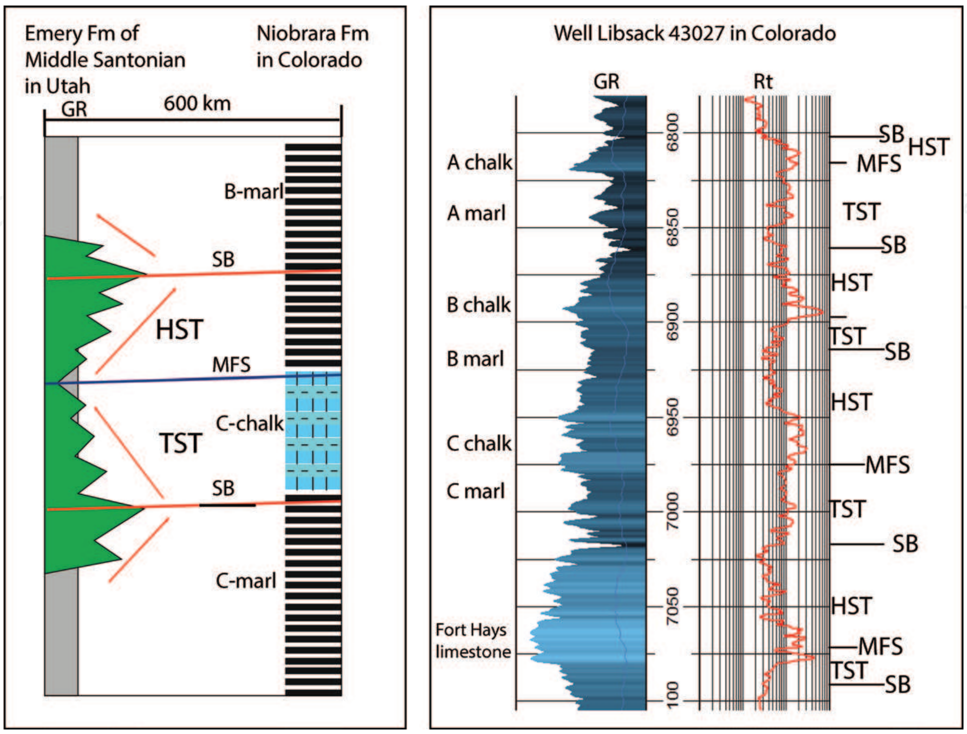

Figure 5. Sequence stratigraphy of carbonated dominated Niobrara shale in U.S.

of chalk. The HST is indicated by increase in GR and deposit of marl. The MFS is indicated by the lowest GR, the highest Rt, and clean chalk. The case study of Well Libsack 43,027 in Colorado in **Figure 5** clearly shows the sequence stratigraphic framework of Niobrara shale formation consisting of chalk and marl.

6. Sequence stratigraphy of fine-grained shale interval in lacustrine basin exampled by Ordos Basin in China

The late Cretaceous evolution of lakes and the corresponding depositional systems in the Ordos Basin of Northern China have been controlled by the changes in the lake level, the sediment supply, and the tectonic setting. The lakes expanded and shrank similarly to littoral to shallow marine environments [36]. Therefore, the sequence stratigraphy and system tracts developed in littoral to shallow marine environment can be applied in the lacustrine Ordos Basin [37] due to similarities of geologic processes in marine and lacustrine settings. To this aim, we have adopted methodology and terminologies of classical sequence stratigraphy also in lacustrine settings, such as the lowstand systems tract (LST), the transgressive systems tract (TST), the highstand systems tract (HST) [1, 2, 8].

For the shale play located in the Chang7 source rock of the Ordos Basin, we have used the first lacustrine shale gas well, LP177, for the shale play located in the Chang7 source rock of the Ordos Basin in order to reconstruct the lacustrine sequence stratigraphy. The Chang7 interval in well LP177 is characterized by organic-rich black shales overlain by gray organic-lean shales with sandstone interbeds (**Figure 6**). The SB is characterized by a change in depositional environments from semideep lake to shallow lake and by a corresponding change in lithofacies from thin siltstone within shale to thicker siltstones within shales. The LST is characterized by siltstone within shale. The transgressive surface bounding the LST and the TST has been identified through the sharp difference in color from gray shale to black shale and through the variations of the TOC content. The MFS is characterized by the highest gamma ray, the highest acoustic transit time (AC), high resistivity, and the highest TOC. HST is identified by coarsening-upward interval. The lower part of HST is characterized by organic-rich shale representing early highstand systems tract (EHST). The upper part of HST is characterized by silty interval representing later highstand systems tract (LHST). Within this sequence stratigraphic framework, the organic-rich shale having TOC of 2–6% was deposited during TST and EHST (**Figure 6**). Tests on five samples from the organic-rich Chang7 shale have indicated a porosity of 3–3.5% and a permeability of 60–100 nD. The 1.5–8 mg/g S1 in the shale reservoir interval indicates the accumulation of free oil in the shale or the presence of shale oil. The siltstone and sandstone intervals in LST and LHST are interpreted as turbidite deposits due to their position in semi to deep lake settings and their association with thick shale. GR curves and lithologies show sharp contact with the underlying and overlying shales confirming the nature of the turbidite deposits. Tests on the lower sandbody indicate a porosity of 11% and permeability of 0.1 mD (millidarcy), and it is classified as a tight oil play. The upper sandbody was tested to have a porosity of 14% and permeability of 1.3 D (darcy) and is classified as a conventional turbidite sandstone reservoir in large part due to the darcy-range permeability (**Figure 6**). The maturity of 0.77–0.95% of this organic-rich shale puts the Chang7 shale in the oil to wet gas window. The reported gas production of 2350 m^3/day (82,990 ft^3/

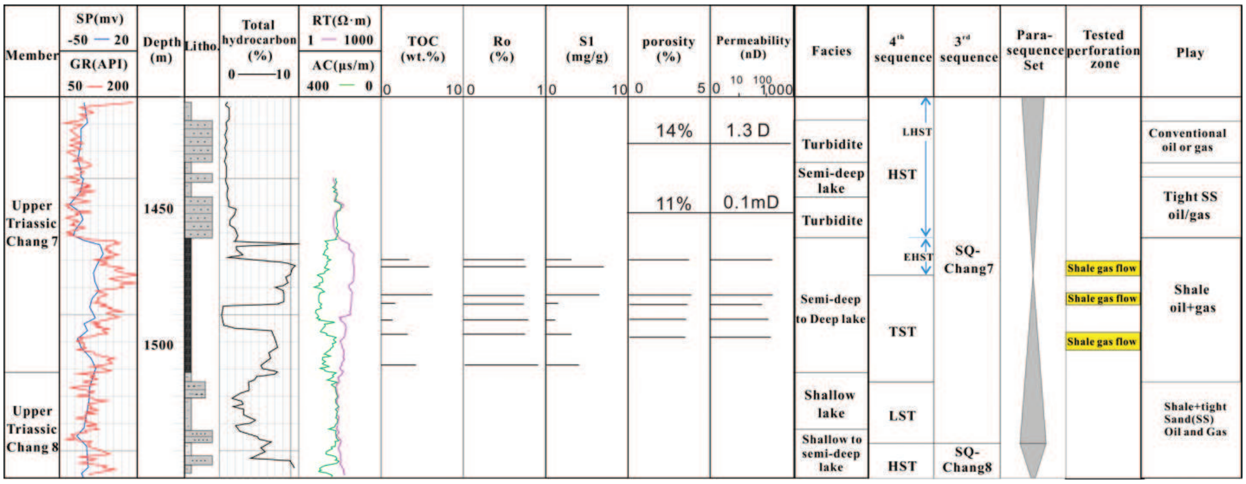

Figure 6. Sequence stratigraphy and its application of Triassic lacustrine Yanchang Formation, LP177 well in Ordos Basin, China.

day) from this organic-rich shale interval is probably wet shale gas indicated by the maturity. These results indicate that the LST and LHST within the sequence stratigraphic framework of lacustrine sediments tend to develop conventional and unconventional tight (sandstone) reservoirs, while TST and EHST are prone to develop shale gas and oil reservoirs.

7. Application

As shown above, an understanding of sequence stratigraphy can be a very powerful tool for building a sequence stratigraphic framework for the lithofacies prediction. It can also help to interpret the depositional history and to predict fine-grained unconventional resource plays for a single well to a basin (**Figure 3–6**). **Figure 4** shows the successful production of 200,000 m^3/day shale gas is from the predicted high-quality shale reservoir in TST and EHST interval with high TOC, high quartz content, and high gas content. At a regional scale, sequence stratigraphy can be used for the correlation of the stratigraphy, the lithology, the mineralogy, the geochemistry, and even rock fabrics. **Figure 7** shows that TST has the highest TOC content, total gas content and quartz content from Jiaoye1 well to Pengye1 well. At the same time, the TOC content has the similar changing patterns to gas content within Sequence A (lower member of the Longmaxi Fm): both show decreasing trends from TST to LHST. Also, gas content decreases with decreasing quartz content from TST to LHST, which indicates the shale in TST is high-quality fracturing susceptible shale gas reservoir with the highest TOC, gas content, and brittle minerals content (**Figure 7**). The positive relationship between TOC, quartz content, and shale gas content in the Silurian Longmaxi shale is similar to that one of the Bartnett shale in the USA, which is attributed to the formation of biogenic quartz in an anoxic environment that is favorable for organic matter preservation [24]. Laterally, shale gas content and quartz content in TST decreases from Jiaoye1 well to Pengye1 well even though they have similar TOC. These

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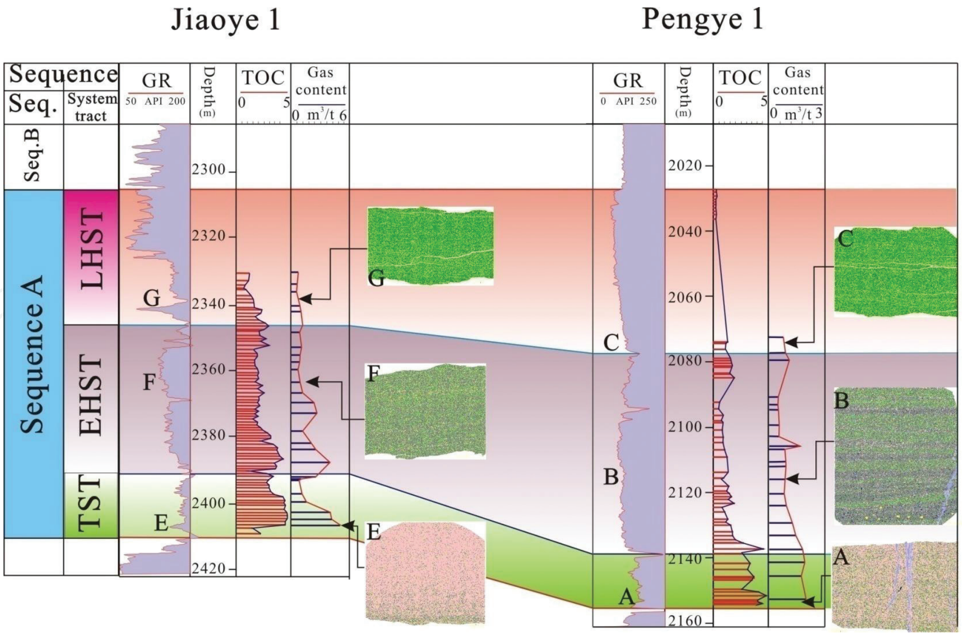

Figure 7. Correlation of stratigraphy, geochemistry, mineralogy, gas content, and rock fabrics within sequence stratigraphic framework across Jiaoye1 well and Pengye1 well. The light pink color represents quartz and the dark green color indicates clay minerals. The color indicates quartz content decreases upward and clay content increases upward at each well location.

verify the TST shale at the Jiaoye1 well has the better reservoir quality in time and space. The commercial development of the Jiaoshiba Shale Gas Field where Jiaoye1 is located proves the prediction of high-quality shale gas reservoir by using sequence stratigraphic approach.

8. Conclusions

The theory, approach, and terminology of clastic sequence stratigraphy developed for relatively coarse-grained deposits can be applied to fine-grained “shale” since their depositions are both controlled by sea- or lake-level changes. The sequence stratigraphic studies of marine and lacustrine shales in the USA and China have indicated that the sequence boundary of shales coincides with an unconformity formed during a relative sea-level or lake-level fall. The different and eventual occurrence of LST, TST, and HST has delineated the occurrence of both complete and/or incomplete depositional sequences, depending on their location. Many sequences of marine shales in the USA and China are incomplete, since they have developed only TST and HST. On the other hand, the lacustrine shale represented by the Chang7 shale in the Ordos Basin has developed complete depositional sequences, including LST, TST, and HST. HST can be further divided into EHST and LHST.

The investigation of siliciclastic-dominated fine-grained “shale” and carbonate-dominated fine-grained “shale” has revealed that lithofacies and well log responses to sea- and lake-level changes are strongly different. Previous proposals stated that high gamma ray and organic-rich shale are indicative of TST or the highest gamma ray and TOC are criteria for identifying MFS of siliciclastic-dominated fine-grained shales exampled by Barnett, Woodford, Marcellus, Mowry, and Longmaxi shales do not work for carbonate-dominated fine-grained shale. The sequence stratigraphy of the Niobrara carbonate-dominated fine-grained shale in this chapter shows that the rise in the sea level resulted in deposit of fine-grained low gamma-ray organic-lean chalky carbonate in clean water and the fall in the sea level resulted in clay-rich, high gamma ray, and organic-rich marl due to the increase in clay input during the sea-level drop.

Both siliciclastic-dominated "shale" and carbonate-dominated "shale" are usually located in anoxic depositional settings, for example, intra-shelf low and slope. The brittle minerals in rich siliciclastic marine and lacustrine shales with high TOC and high hydrocarbon (oil and gas) content occur in the transgressive systems tract (TST) up to the early highstand systems tract (EHST). The brittle condensed section of MFS has the best reservoir quality and completion quality.

Similarly to clastic sequence stratigraphic models developed for sandstones and carbonates, the sequence stratigraphy of fine-grained shale provides a powerful tool for predicting and mapping stratigraphy, variations of lithology, geochemistry, mineralogy, and shale gas content in time and space, and ultimately the most productive facies of unconventional gas shales.

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A. Appendix

Abbreviations for sequence stratigraphy used throughout this chapter include: SB, sequence boundary; TSE, transgressive surface of erosion; RSE, regressive surface of erosion; LST, lowstand (falling stage) systems tract; TST, transgressive systems tract; HST, highstand systems tract (consisting of EHST—early highstand systems tract and LHST—late highstand systems tract); CS, condensed section; MFS, maximum flooding surface; MRS, maximum regressive surface; TOC, total organic content (wt.%).

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