PS Rapid Recognition Approach for Stratigraphic Sequence in Shale and Enrichment Mechanism of Hydrothermal Activity on Organic Matter: A Case Study of the Lower Cambrian, Xiuwu Basin*

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Search and Discovery Article #51500 (2018)**
Posted July 16, 2018

*Adapted from poster presentation given at AAPG 2018 AAPG Annual Convention and Exhibition, Salt Lake City, Utah, May 20-23, 2018

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Abstract

In conventional oil and gas exploration, sequence stratigraphy has been widely used to identify the favorable section of the longitudinal direction. The sedimentary response of shale to sea-level change is weak for which are deposited in deep water. Therefore, the sequence identification method in the theory of classical sequence stratigraphy is not applicable to shale. Some methods of sequence identification in shale have been put forward in which core is needed. Based on some easily obtained data, like lithology and formation element logging curve, a new method of second- and third-order sequences in shale is proposed and then used in predicting the favorable section of Lower Cambrian shale, in the Xiuwu Basin.

First, identifying the lithology changes according to the logging data. The lithology and sedimentary environment changed suddenly in the boundary between Ediacaran to Cambrian and Lower Cambrian to Middle Cambrian which has been identified as second-order sequence boundaries. Second, obtaining the redox index (U/Th ratio), salinity index [Ca/(Ca+Fe) ratio] and provenance distance index (Ti/Al ratio) according to the calculation of formation elements logging data.

High U/Th ratio is supposed to be related to reducing environment (transgression) while low U/Th ratio related to oxidizing environment (regression). High Ca/(Ca+Fe) ratio indicates the increased salinity (regression) while low Ca/(Ca+Fe) ratio represents decreased salinity (transgression). Besides, high Ti/Al ratio indicates proximity to the provenance (regression) while low Ti/Al ratio indirectly suggests a distance from the provenance (transgression).

Wangyinpu Formation of Lower Cambrian present a high U/Th ratio, low Ca/(Ca+Fe) and Ti/Al ratio. On the contrary, Guanyintang Formation of Lower Cambrian over Wangyinpu presents a lower U/Th ratio, a higher Ca/(Ca+Fe) and Ti/Al ratio. Thus, the boundary of the Wangyinpu and Guanyintang Formation is the Maximum Flooding Surface (MFS). On the level of second-order sequence, Wangyinpu Formation is the Transgressive Systems Tract (TST), and Guanyintang is the Regressive Systems Tract (RST). On the level of third-order sequence, the Lower Cambrian was divided into 5 third-order sequences (SQ1-5) and each SQ was divided into a TST and a RST. The mineral content, effective porosity, TOC content and gas content of 5 third-order sequence shown that TST2 of SQ2 and TST3 of SQ3 are the most favorable section.

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INTRODUCTION

The classic sequence stratigraphy theory is based on the sediments of passive continental margin, unsuitable for the shale of the deepwater environments. Also the OM enrichment is closely related with the gas-bearing properties of shale and there are comprehensive work previously to be the basis. Thus based on the lithology, well logs, description of cores and outcrops and the introduction of the formation elements data, the study proposed a rapid recognition approach for stratigraphic sequences in shale, which applies the U/Th as the main indicator, the Ca/(Ca+Fe) and Ti/Al as the references. The mechanism of OM enrichment is studied from the two aspects of productivity and redox conditions by the elements of silicon and barium.

The study area is the shale interval of the Lower Cambrian Wangyinpu Fm. and the Guanyintang Fm. in the west of the Xiushui-Wuning syncline, Xiuwu Basin, the Yangtze plate.

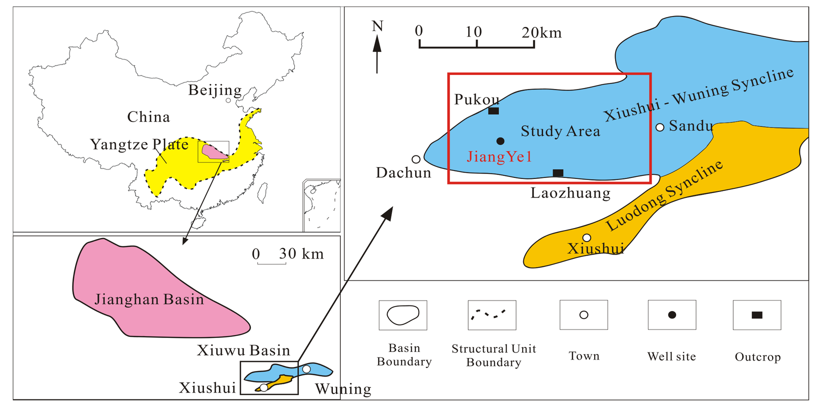

Fig.1. Xiuwu Basin is located in the southeast of the Jianghan Basin, the central Yangtze plate, comprised of Xiushui–Wuning and Luodong synclines.

There deposited upwards the underlain siliceous dolomite in the Late Sinia Piyuancun Fm., the shale in the Lower Cambrian Wangyinpu Fm. and Guanyintang Fm., the overlying grey micrite in the Mid Cambrian Yangliugang Fm., respectively.

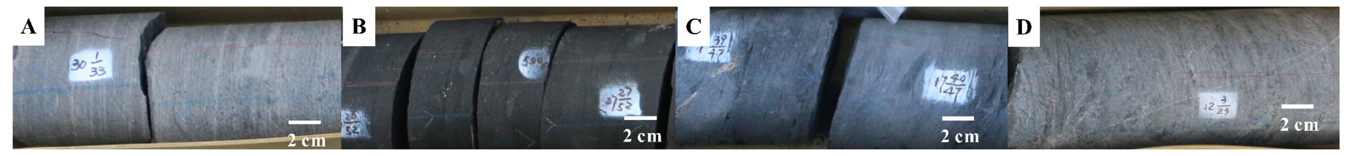

Fig. 2. Core photos of upper Sinian, lower and middle Cambrian of Jiangye-1 well. A: 2674m, the upper Sinian Piyuancun Fm., grey siliceous dolomite; B: 2637m, the lower Cambrian Wangyinpu Fm., dark siliceous shale; C: 2547m, the lower Cambrian Guanyintang Fm., dark grey siliceous shale; D: 2510m, middle Cambrian Yangliugang Fm., grey micrite.

METHODS

- Detailed description of outcrops and cores.
- The interpretation of well logs and ECS logs.
- Al-Fe-Mn ternary for genesis analysis of siliceous minerals.
- The calculation equation of the content of excess siliceous minerals and the excess barium.

RESULTS & DISCUSSION

Stratigraphic Sequence

The classic sequence stratigraphy theory is inadequacy to shale deposited in deepwater environments, unable to distinguish the LST and HST perfectly. In this paper the T-R cycle is been applied, where the sequence is subdivided into regressive system tract (RST), and transgressive system tract (TST). Also due to the weak sedimentary response to the change of sea-level in deepwater environments, the boundaries of sequences and system tracts are recognized according to the indicators (U/Th, Ca/(Ca+Fe) and Ti/Al) from the elemental capture spectroscopy (ECS), combined with the core description and regular well logs.

The Upper Simian Piyuancun Fm. is siliceous dolomite, indicating shallow carbonates sedimentary system; the Lower Cambrian Wangyinpu Fm. and Guanyintang Fm. are dark-grey siliceous shale, depositing in deep water environment; the Mid Cambrian Yangliugang fm. deposited grey micrite deposited indicating shallow carbonates sedimentary system. Thus obvious changes of ECS indicators and well logs are identified as the three boundaries. In the previous work, 2nd-order sequences last nearly 10–25 million years. The Early Cambrian lasts 30 million years making it ought to be a 2nd-order sequence.

At the depth of 2667-2615m, U/Th ratio gradually increased, Ca/(Ca+Fe) ratio and Ti/Al ration gradually decreased, and at the depth of 2615-2520m the situation is in conversion. The lithology of the black siliceous shale changes into the light colored dark grey siliceous shale. Therefore, the Wangyinpu Fm. is considered as the TST and the Guanyintang Fm. as the RST of the 2nd-order sequence.

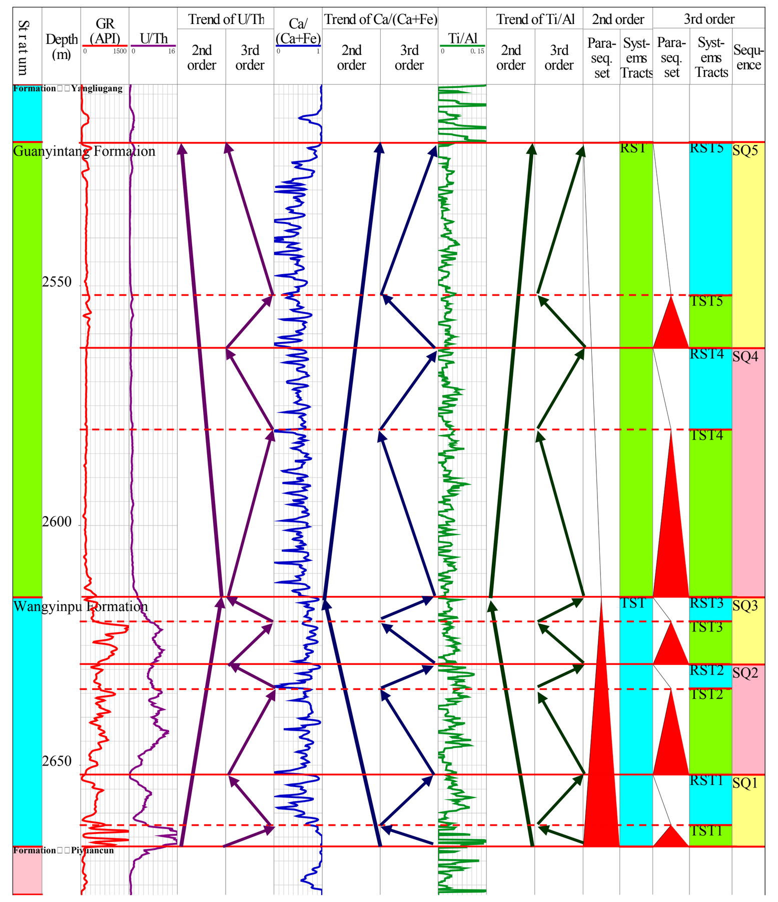

Fig. 3. Sequences division scheme of Jiangye-1 well. Second-order sequences and their system boundaries as well as third-order sequences and their system tract boundaries are determined based on ECS indicators (U/Th ratio, Ca/(Ca+Fe) ratio and Ti/Al ratio). The lower Cambrian is identified as a second-order sequence and five third-order sequences are further divided. See Fig. 1 for the well location. MFS = Maximum Flooding Surface; GR = Natural gamma ray; U = Uranium; Th = Thorium; Ca = Calcium; Fe = iron; Ti = Titanium; Al = Aluminum.

Inside the 2nd-order sequence, 3rd-order sequences can be further divided. Due to the difficultity to identify 3rd-order sequences by lithology alone, the combination of ECS indicators (U/Th, Ca/(Ca+Fe) and Ti/A) and well logs (GR, CNL, AC, DEN) is used. The intervals with the increased U/Th and decreased Ca/(Ca+Fe) and Ti/Al are recognized as TST; on the contrary, the intervals with decreased U/Th and increased Ca/(Ca+Fe) and Ti/Al are recognized as RST. Therefore the Lower Cambrian is further divided into 5 3rd-order sequences, of which 3 are belong to the Wangyinpu Fm. (SQ1, SQ2 and SQ3) and 2 are belong to the Guanyintang Fm. (SQ4 and SQ5), and each 3rd-order sequence is subdivided into a TST and a RST.

Origin Analysis of Siliceous Minerals

Generally, siliceous minerals originated from terrigeneous clastics, bio-deposition, and hydrothermal deposits. The excess siliceous mineral content (Si_{ex}) is the siliceous minerals that exceeds the content of normal siliceous minerals deposited in the deposition environment, which can be calculated by the following equation.

$$Si_{ex} = Si_s - [(Si/Al)_{bg} \times Al_s]$$

$(Si/Al)_{bg} = 3.11$, the average content in shale

From the result, the excess siliceous minerals are widely distributed in most intervals of the Wangyinpu Fm. and Guanyintang Fm..

The accumulation of Fe and Mn in the siliceous shale is related to the hydrothermal fluid and the enrichment of Al is mainly associated with terrigeneous materials (Adachi et al., 1986; Yamamoto et al., 1987). Fe–Mn–Al ternary scheme is an effective method to identify siliceous rocks of different origin (Wedepohl, 1971). The excess siliceous minerals concentrate in hydrothermal shale (region II in Fig. 14) in the Wangyinpu and Guanyintang formations (Fig. 14), demonstrating the hydrothermal origin of excess siliceous minerals in the Lower Cambrian in the Xiuwu Basin.

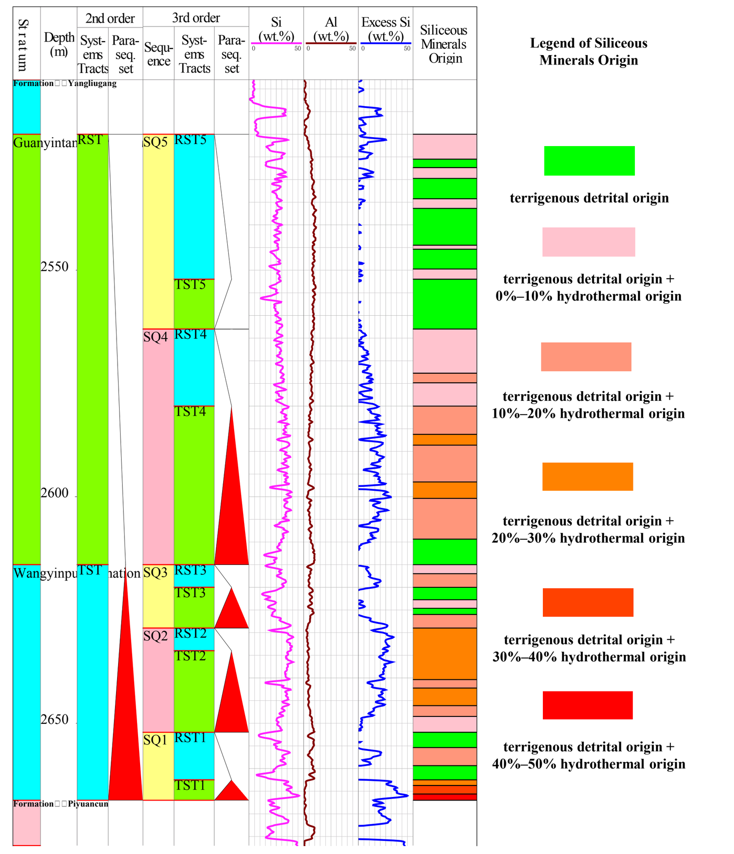

Fig.4. Vertical variation of the origin of the siliceous minerals in the Lower Cambrian of the Jiangye-1 well. SQ1: different siliceous origins vary greatly; SQ2 and SQ3: hydrothermal origin siliceous minerals exist in most intervals; SQ4: terrigeneous siliceous minerals begin existing, with several hydrothermal siliceous minerals; SQ5: terrigeneous siliceous minerals. See Fig. 1 for the well location.

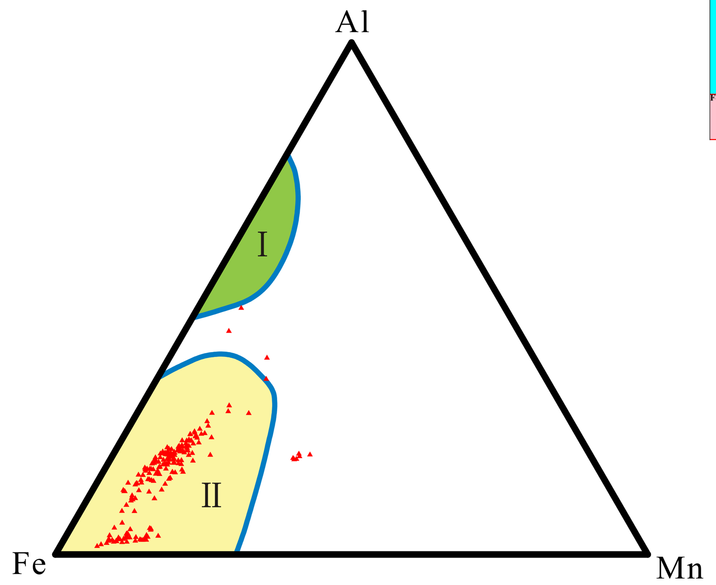

Fig.5. Origin analysis chart for the siliceous minerals of the Lower Cambrian in the Jiangye-1 well. See Fig. 1 for the well location. I: bio-origin, II: hydrothermal origin.

Specifically, siliceous origin of SQ1 varies greatly, part of intervals are terrigeneous origin and part of intervals are hydrothermal origin; most siliceous minerals of SQ2 and SQ3 are hydrothermal origin, whose content takes up 10%-30%; compared with SQ2 and SQ3, content of hydrothermal origin siliceous minerals drops in SQ4 and terrigeneous siliceous content increases; siliceous minerals of SQ5 originate from normal terrigeneous clastic deposition.

OM Enrichment Mechanism

Organic matter is an important factor for shale gas evaluation providing the main occurrence space for connected pores and controls total shale gas content. Residual TOC content depends on maturation and abundance of OM, the higher the maturation is, the smaller residual TOC content is; in the same interval, little difference exists in the maturation of OM, residual TOC content depends on OM abundance. Furthermore, according to the study above, it proves that the OM deposition in the study area is under the hydrothermal underground, which makes it important for the exploration of the effect of hydrothermal activity on the OM enrichment.

Hydrothermal activity provides siliceous minerals for shale. In addition, it affects productivity and water redox conditions, controlling the abundance of OM.

Redox Conditions

It is common to identify the sedimentary environment using elemental geochemistry indicator. The U/Th is one of the widely applied indicators. The U/Th of more than 1.25 indicates the anaerobic environments, of 0.75~1.25 for the oxygen deficiency and of less than 0.75 means the oxidation environments.

The water reducibility varied greatly when SQ1 deposited (U/Th ranges from 0.2 to 17.5); the reducibility was strong in SQ2 and SQ3 with relatively stable U/Th (9 on average). The U/Th of TST4 fell in 0.75–1.25 reflecting the oxygen-deficient environments and continued to decrease to 0.75 or less when RST4 was deposited, indicating the increase of the oxygen content of the environments. A transgression occurred in TST5; the U/Th increased to 0.75–1.25, revealing an oxygen-deficient environment. The U/Th became below 0.75 again in RST5 and the environments changed to the oxidization environments again due to the water regression.

The U/Th and TOC are positively correlated. The reducing environments in the period of SQ1–SQ3 were deposited changed into the oxidization environments in SQ4–SQ5. The TOC decreased sharply when the reducing environments (SQ1–SQ3) transformed into the oxidization environments (SQ4–SQ5), indicating that the redox conditions are of significance to the preservation of residual sedimentary OM.

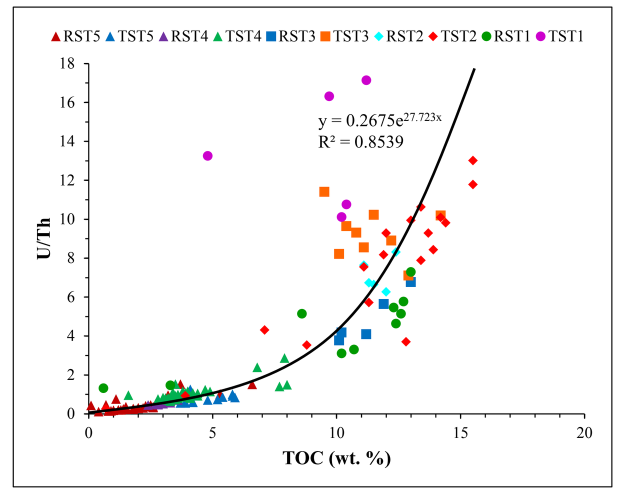

Fig 6. Correlation of the U/Th ratio and TOC content for each system tract in the Lower Cambrian of the Jiangye-1 well. See Fig. 1 for the well location.

Bioproductivity

The Ba content is the main indicator reflecting the paleo-ocean bioproductivity and is widely used. High concentrations of SO_4^{2-}, reoxidized from H_2S react with Ba^{2+} on the surface of the decayed OM and then precipitate. The high content of $BaSO_4$ is therefore an indicator for high bioproductivity. There are two kind of trace element genesis determined, terrigenous origin and authigene. However, the terrigenous trace elements are useless for the characterization of the paleo-environment. Therefore, the terrigenous Ba $[Al_s(Ba/Al)_{PAAS}]$ has to be deduced from the total Ba content (Ba_s) to obtain the bio-origin Ba, which is defined as the excess Ba (Ba_{XS}). The excess Ba (BaXS) can be calculated with following equation.

$$BaXS = Bas - Als\ (Ba/Al)PAAS$$

Ba_s, the total Ba content of the shale sample; Al_s, the total Al content of shale sample; PAAS, the chosen Australian standard shale; $(Ba/Al)_{PAAS}$ = 0.0077, the average value of the ratio in PAAS.

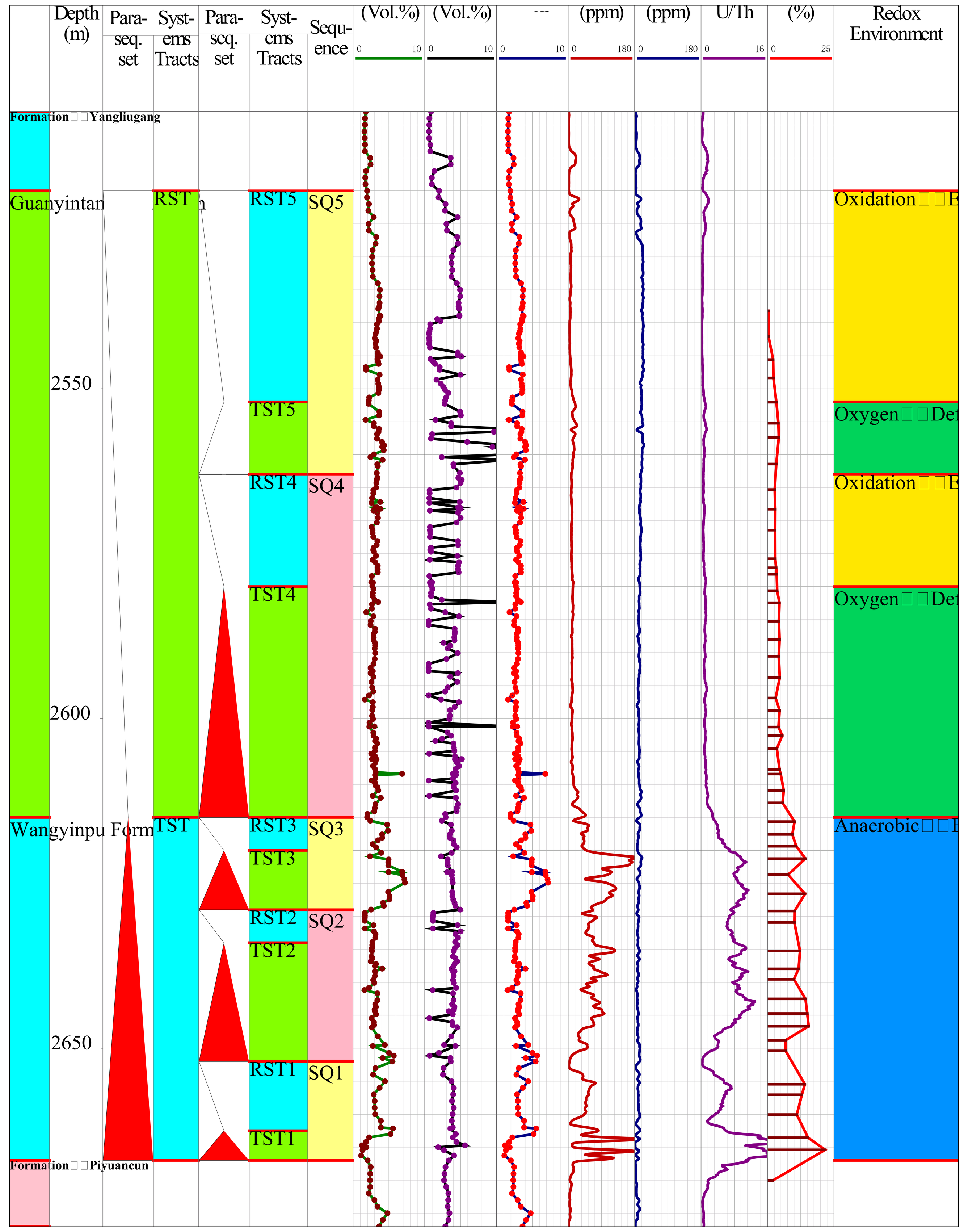

Fig 7. Redox conditions and bioproductivity (BaXS) of the Jiangye-1 well in the Lower Cambrian shale. SQ1, SQ2 and SQ3 are anaerobic environment, TST4 and TST5 are oxygen deficiency environments, RST4 and RST5 are oxidation environments. See Fig. 1 for the well location.

A negative correlation has been observed between the U/Th and Ba_{XS}, as a result of the reduction of SO_4^{2-} by the thiobacillus in the reducing environments leading to increased dissolution of $BaSO_4$. Therefore, the calculated bio-origin Ba (Ba_{XS}) decreases with the U/Th increasing. The reducibility was stronger when Wangyinpu Fm. deposited than that of Guanyintang Fm.. It can be indicated the Ba_{XS} of SQ1 and SQ2 is higher than that of SQ4 and SQ5, showing a higher bioproductivity of the Wangyinpu period than the Guanyintang. Besides, the Ba_{XS} of SQ3 is higher than those of SQ1 and SQ2. Therefore, the bioproductivity of SQ3 is the highest, SQ1 and SQ2 take the second place and SQ4 and SQ5 are the lowest among the five.

Above all, the reducibility of the Wangyinpu Fm. is far stronger than that of Guanyintang Fm. during the Early Cambrian. The reducibility varies greatly when SQ1 deposited, while it is generally high in SQ2 and SQ3 and is relatively low in SQ4 and SQ5. The bioproductivity of SQ3 is the highest among SQ1–SQ3 (Wangyinpu). There is little difference found in bioproductivity of SQ1 and SQ2, which are higher than those of SQ4 and SQ5 (Guanyintang), leading to the different abundance of sedimentary OM in different intervals.

Model of OM Enrichment

Sedimentary model of the Xiuwu basin during the early Cambrian has been concluded based on the above. In the Early Cambrian, the Xiuwu basin was located near the junction of the Yangtze and Cathaysian plates in the periphery of the craton basin in the Mid Yangtze area, separated by the ancient South China Ocean. The large-scale transgression took place in the period of Wangyinpu Fm. During that time, the expansion of the oceanic crust caused the strong tectonic extension, the injection of the plates, and the development of faults. The materials upwelled from deep down in the crust and entered faultsalong with the seawater forming a hydrotherm rich in mineral substances (Si, N, P, Fe, and Zn). On one hand, the hydrotherm driven by upwelling entered into the deep shelf. In addition, the nutrientshydrotherm carried promoted the growth of plankton in the surface ocean and enhanced the bioproductivity. on the other hand, the hydrotherm lead to the formation of the reducing environments in the bottom of the ocean, which was beneficial to the preservation of residual sedimentary OM. The residual sedimentary OM, terrigenous clay minerals, siliceous clastics, several calcareous minerals, and bio-organic matter were deposited in the ocean bottom and formed the Lower Cambrian Wangyinpu Fm. shale with large amounts of hydrothermal siliceous minerals and high TOC content.

When the Guanyintang Fm. deposited, weakened hydrothermal activity resulted in the decrease of the hydrotherm and reduction of nutrients provided to the ocean water surface, declining in the bioproductivity. Besides, the reducibility in lower part of the sea level-weakened than that in the bottom of the sea, so that the residual sedimentary OM is more likely to be exposed to the oxidization environments and be destroyed. Furthermore, due to the fact that regression occurred in Guanyintang Fm., the contents of clay minerals and siliceous clastics increased and the Guanyintang Fm. shale characterized by the low hydrothermal Si and TOC contents was formed.

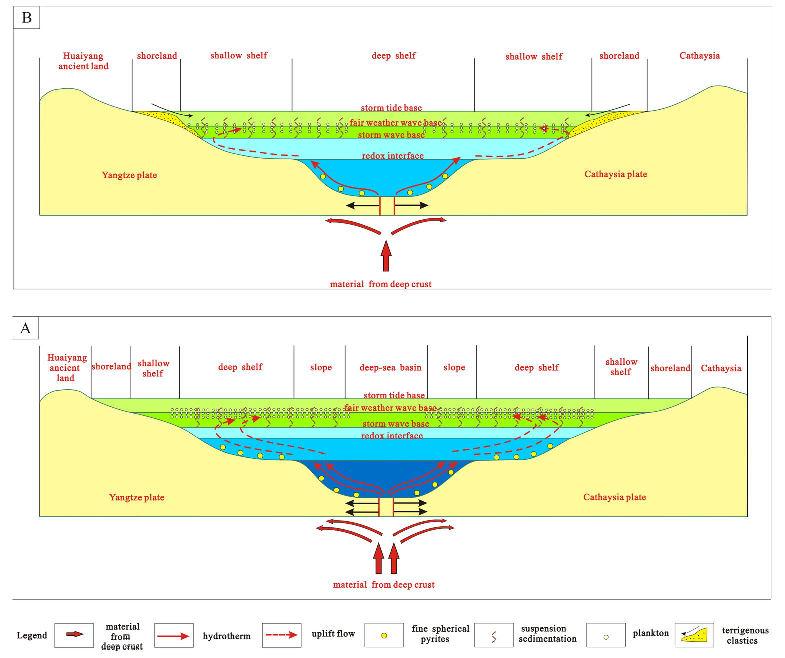

Fig 8. OM enrichment model scheme for the shale of the Lower Cambrian Wangyinpu and Guanyintang Formations in the Xiuwu basin. A: OM enrichment model scheme the Early Cambrian Wangyinpu Formation; B: OM enrichment model scheme of the Early Cambrian Guanyintang Formation. See Fig. 1 for the well location.

CONCLUSION

- A rapid recognition approach for stratigraphic sequence is proposed, based on the description of outcrops and cores, lithology, well logs and ECS logs. The main indicator is the U/Th, with the Ca/(Ca+Fe) and Ti/Al as references. The Wangyinpu and Guangyintang Fm. is indentified as a whole 2nd-order sequence, with 5 3rd-order sequences contained.
- Besides the terrigenous siliceous minerals, large amounts of hydrothermal origin siliceous minerals exist in lower Cambrian Wangyinpu Fm. and Guanyintang Fm.. Specifically, the siliceous origin of SQ1 varies greatly with terrigeneous and hydrothermal origin at the same time. Most siliceous minerals of SQ2 and SQ3 are hydrothermal origin, whose content takes up 10%-30%. The siliceous minerals content of hydrothermal origin decreases in SQ4 and the that of terrigeneous origin increases. The siliceous minerals of SQ5 originate from normal terrigeneous clastics.
- The reducibility varies greatly in SQ1, generally strong in SQ2 and SQ3 and is weaker in SQ4 and SQ5. The bioproductivity in SQ3 is the highest and similar in SQ1 and SQ2, while it is lowest in SQ4 and SQ5.
- Hydrothermal activities are helpful for the increase of reducibility of seawater and enhancing bioproductivity, the sedimentary OM abundance is thus controlled and the enrichment of shale gas is further affected. The intervals deposited when frequent hydrothermal activities occurred are exactly the favorable targets of shale gas in lower Cambrian.

Acknowledge

This study was supported by the National Science and Technology Major Project (No. 2017ZX05035-002), the Science Foundation of the Ministry of Land and Resources of China (No. 12120114046701) and the National Natural Science Foundation of China (No. 41472112).