Hydrocarbon generation potential of coal measure source rocks from lower Permian Shanxi Formation in the central-eastern Ordos Basin, China: control from sedimentary facies

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Abstract. Source rocks of Shanxi Formation widely distributed in the Ordos Basin were deposited in different sedimentary facies. Different sedimentary facies differ in sedimentary environment and could have great impact on the accumulation of organic matters. TOC content and S1+S2 values of shale and coal samples from different sedimentary sub-facies of Shan 1 and Shan 2 sections of Shanxi Formation were measured to investigate the influence of sedimentary facies on organic geochemistry characteristics. The results showed that the average TOC content of shale samples from the pro-delta sub-facies of Shan 1 section was higher than other sub-facies and the shale samples from the shore shallow lake sub-facies of Shan 2 section had higher TOC content when compared with other three sub-facies. Compared with Shan 1 section, the Shan 2 section was richer in organic matter. And the hydrocarbon generation potential of source rocks from Shan 2 section was better than that of Shan 1 section. More than 50% of shale samples from the Shan 2 section was of fair to good hydrocarbon generation potential. This study could provide a framework for the identification of potential areas for conventional and unconventional petroleum exploration.

1. Introduction

The Ordos Basin, located in northern-central China, is the second largest sedimentary basin in China. Several giant gas and oil fields have been discovered in this basin. In terms of the gas fields, except for the Jingbian gas field which was sourced from Ordovician deposits, other large gas fields, including Sulige, Wushenqi, Yulin, Daniudi and Mizhi, were fueled by the Upper Paleozoic source rocks [1-2]. The Upper Paleozoic source rocks were mainly distributed in Benxi, Taiyuan and Shanxi formations. The most promising source rocks of coal measures was the Shanxi shales, as the source rock was not only widely distributed in the basin, but also of the largest thickness in the middle and eastern part of Ordos Basin [3]. Many previous studies have reported the organic geochemical characteristics of shales and coals of Shanxi formation distributed in part of the Ordos Basin [4-7]. However, source rocks deposited in the fluvial-lacustrine environment is quite heterogeneous in organic matter type and content and sedimentary environment of source rocks is the main control [8]. Different sedimentary facies differ in sedimentary environment and could have great impact on the accumulation of organic matters [8-10]. Source rocks of Shanxi formation widely distributed in the basin
were deposited in different sedimentary facies [11], the influence of sedimentary facies on organic geochemistry characteristics is lack of study. The main objective of this work is to evaluate the hydrocarbon generation potential of source rocks from different sedimentary facies of Shanxi formation from Ordos Basin. The study was conducted to provide a framework for the identification of potential areas for conventional and unconventional petroleum exploration.

Figure 1. Geological tectonic plot of Ordos Basin and location of study area.

2. Geological background
The Ordos Basin comprises six major structural units, with the Yimeng uplift in the north, the Weibei uplift in the south, the Tianhuan depression and western edge thrust belt in the west, the linxi fold belt in the east and the central Yishan slope (figure 1). The study area is located in the central and eastern part of the Ordos Basin. During the Ordovician, Carboniferous and Permian time periods, the basin went through a transition from marine to continental facies, therefore, the lower part of Upper Paleozoic strata was deposited as transitional facies and the upper part of Upper Paleozoic strata was made up of terrestrial clastic rocks and coal measures. The shale and coal of Permian Shanxi formation was mainly developed in a fluvio-lacustrine environment, which was characterized by thin shale monolayers interbedded with sandstone and coal [12]. From north to south, sedimentary facies of braided river, delta plain, delta front, pro-delta and shore shallow lake were developed in turn [11]. The thickness of Shanxi shale layers ranges from 10m to 100m in the study area and the thickness range of coal measures is 1~10m [3]. The Shanxi formation could be separated into two sections, i.e. Shan 1 section and Shan 2 section. Shale was developed in both sections and coal measures was mainly distributed in Shan 2 section.

3. Method
Source rock core samples crushed to pass the 100 mesh sieve were selected for TOC and Rock-eval analysis. For the TOC analysis, about 10-100mg was placed in a crucible. Then 5% HCl was added into the crucible to remove carbonate. After the reaction under atmosphere temperature for about 12h, the plate with crucibles in it was placed in a water bath with a temperature of 80℃ for 1h. Then, the HCl were dumped and samples were washed with deionized water to neutral. After drying, the total organic carbon content was measured by a LecoC230 carbon analyzer. A Vinci Rock-eval 6 instrument was used to analyze the maturity and chemical composition of samples. For the analysis, about 10-100mg of power was needed.
4. Results and Discussion

4.1 The distribution characteristics of TOC for the shale of Shan 1 section

The TOC content of shale samples from the braided river, delta plain, delta front, pro-delta and shore shallow lake sedimentary facies of Shan 1 section was mostly smaller than 1%. Generally, the sample number decreased with the increase of TOC content. The TOC content of 27 samples from the braided river sub-facies ranges from 0.08 to 16.59%, with an average value of 1.76%. The 43 samples from the delta plain sub-facies has a TOC range of 0.08-6.11% and an average value of 1.70%. For the pro-delta sub-facies, the TOC range of 61 samples is 0.18-27.01%, averaging 3.24%. Lastly, the TOC content of 32 samples from the shore shallow lake sub-facies ranges from 0.16 to 7.79% and the average value is 1.47%. The statistical results showed that the TOC content of the pro-delta facies is the largest and the other three sub-facies had similar TOC content.

4.2 The distribution characteristics of TOC for the shale of Shan 2 section

Similar with the TOC frequency distribution of Shan 1 section, number of samples of TOC smaller than 1% was the largest for the four sub-facies of Shan 2 section. TOC of samples was mainly smaller than 3%. For samples with TOC content larger than 1%, the number of samples decreases when the TOC content increases. The TOC content of 28 samples from the braided sub-facies ranges from 0.43 to 12.08% and the average value is 2.86%. The 77 samples from the delta plain sub-facies has a TOC range of 0.08-23.93% and average value of 3.01%. The TOC content of samples from the pro-delta sub-facies has a TOC range of 0.08-26.18%, averaging 2.27%. For the shore shallow lake sub-facies, the TOC content ranges from 0.25 to 26.18% and the average value is 4.48%. The average TOC content of shore shallow lake sub-facies was the largest among the four sub-facies. And the average TOC content of three other sub-facies was similar. The TOC content of shale samples from the Shan 2 section was larger than that from the Shan 1 section.

The TOC content could be calculated from the logging data. Based on the logging data and measured TOC content, the TOC contour of Shan 2 section in the study area was presented. Generally, the TOC contour of Shan 2 section distributed in the north-south direction. In the northeastern part of the Basin, the TOC content ranges between 3.0 and 5.5%, and the TOC content range is 3.0-4.0% for shale in the southeastern part. The TOC content increases from the east to the central and from the west to the central part (figure 2). Apparently, the TOC content of shale in the eastern part is higher than that from the western part.

Figure 2. TOC contour of shale samples from Shan 2 section
4.3 The distribution characteristics of TOC for the coal of Shan 2 section
Coal measures were distributed in the braided river, delta plain, delta front, prodelta and shore shallow lake sub-facies of Shanxi formation. And coal samples from the four sub-facies had similar TOC content range and average TOC content. As shown in table 1, the TOC content of the coal from the four sub-facies generally distributed in the range of 30-85%. Except for the shore shallow lake sub-facies, the TOC content is mainly higher than 60% and the average value is in the 60-67% range.

| Sedimentary sub-facies  | TOC range (%) | Average TOC (%) |
|------------------------|---------------|-----------------|
| Braided river          | 33.8–84.8     | 66.5 (9 samples)|
| Delta plain            | 31.3–87.4     | 60.9 (20 samples)|
| Pro-delta              | 30.3–86.0     | 63.4 (18 samples)|
| shore shallow lake     | 32.1–83.9     | 58.4 (15 samples)|

4.4 Evaluation of hydrocarbon generation potential
The Tmax value (mostly higher than 480°C) of shale samples from Shanxi formation indicated that of most of the samples from Shan 1 and Shan 2 sections used in this study were in the middle to over mature stage (Ro=1.2~2.5%). Based on the relationship between S1+S2, chloroform bitumen “A” and Ro of coal samples from Qinshui Basin, South North China Basin and North China Basin, it was found that the S1+S2 and chloroform bitumen “A” decreased exponentially with increasing Ro [13]. The criteria used to evaluate the hydrocarbon generation potential of samples of low thermal maturity is not appropriate for the evaluation of samples of middle-high thermal maturity [14]. Therefore, the criteria reported by [13] was used to estimate the hydrocarbon generation potential of Shanxi source rocks. As shown in figure 3, the hydrocarbon generation potential of shale samples from Shan 2 section was better than that of samples from Shan 1 section. More than 50% of shale samples from the Shan 2 section was of fair to good hydrocarbon generation potential. And about 50% of the coal samples from the Shan 2 section was of fair to good hydrocarbon generation potential.

Figure 3. Evaluation of hydrocarbon generation potential for source rocks from Shan 1 and Shan 2 sections.

5. Conclusions
The impact of differences in sedimentary sub-facies of on the organic matter content and hydrocarbon
generation potential of source rocks from Shanxi Formation was investigated based on the TOC content and Rock-eval data. TOC content of shale samples from the pro-delta sub-facies of Shan 1 section and shale from the shore shallow lake sub-facies of Shan 2 section was higher than other sub-facies. Coal samples from different sub-facies show little difference in TOC content distribution and average content. Hydrocarbon generation potential of source rocks from Shan 2 section was better than that from Shan 1 section. More than 50% of the source rocks from Shan 2 section was of fair to good hydrocarbon generation potential.

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