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RESEARCH PAPER

A new method for lithology identification of fine grained deposits and reservoir sweet spot analysis: A case study of Kong 2 Member in Cangdong sag, Bohai Bay Basin, China

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Abstract: Based on systematic coring of 500 m of Kong 2 Member of the Paleogene Kongdian Formation in Cangdong sag of Bohai Bay Basin, identification and XRD (X-Ray Diffraction) analysis of over 1000 thin sections, a simplified method to quantitatively calculate contents of fine grained minerals with conventional logging data such as acoustic travel time (AC) and density log (DEN) has been proposed, and a quick lithologic identification "green mode" has been worked out in this study. By fitting the relationship between normalization of logging curves and mineral content measured by XRD, the mineral contents of sections or wells not cored can be calculated to identify lithology. With this method, several dolomite sweet spot intervals and one sandstone sweet spot interval have been found in the Kong 2 Member of Cangdong sag, where high production oil and gas flows have been tapped from drilled wells. The study shows that the dolomite is in band distribution and enriched in local parts of the study area. This method is applicable to lithologic identification of fine grained deposits in front delta-lake basin center, especially lithologic identification of mud and dolomite dominated fine grained deposits with low sand content of semi-deep, deep lake facies.

Key words: fine grained deposits; lithologic identification; dolomite; tight oil; reservoir sweet spot; Paleogene Kongdian Formation; Cangdong sag; Bohai Bay Basin

Introduction

Along with prospecting and production of unconventional oil and gas all over the world, fine grained deposits have become a new frontier area after coarse deposits of river and delta facies[1–6]. Application of experimental analysis techniques such as scanning electron microscope, X-Ray Diffraction (XRD) analysis and pressure pulse decay test method, elemental capture spectroscopy logging (ECS), nuclear magnetic resonance logging (NMR), array acoustic logging has greatly improved the study accuracy of fine grained deposits, and given us a better understanding on the mineral composition, rock classification, sedimentary environment, reservoir characteristics, and sweet spot distribution[7–13]. Lithologic identification is the key in fine grained deposits study, and also the basis of sweet spot evaluation, prediction and prospecting well deployment. The current lithologic identification methods with conventional logs mainly include cross plotting, curve overlapping, discriminant analysis, mathematical statistics, fuzzy diagnosis, clustering analysis and artificial neural network[14–17], these methods, with their advantages and limitations, are more commonly applied in conventional sandstone-mudstone section in the coarse deposits area. In contrast, lithologic identification of lacustrine fine grained deposits more depends on ECS or special logging methods such as nuclear magnetic resonance logging or imaging logging to improve precision of the lithology interpretation [18–20], but high in cost, these logging series are not necessarily acquired items, and generally not used in old wells, which restrict promotion of their application. In this study, based on core description, sample homing, thin section identification, XRD analysis of 500 m cores systematically taken from Kong 2 Member of the Paleogene Kongdian Formation in Cangdong sag of Bohai Bay Basin, a new method of lithologic identification for fine grained deposits by using of the correlation between overlapping amplitude difference of logs and measured mineral composition based on conventional logging data has been proposed, and applied in lithologic identification of Kong 2 Member and finding (muddy) dolomite reservoir

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dessert on the plane, in the hope of providing reference for tight oil exploration in fine grained deposits areas.

1. Geological conditions

Cangdong sag, a secondary tectonic unit located between Cangxian uplift, Xuhei salient and Kongdian salient in Huanghua depression of Bohai Bay Basin, is a Cenozoic intracontinental faulted lake basin developed under regional extension [21–23] (Fig. 1). During the deposition period of Kong 2 Member, Cangdong sag was a closed inland lake in subtropical semi-arid and humid environment, where a set of 400–600 m thick dark mud shale with thin-medium fine sandstone, medium-fine sandstone and argillaceous dolomite in stable distribution deposited. Around the lake, multiple delta lobes developed, with sedimentary facies changing regularly from delta front sub-facies in the basin margin, a conventional sandstone area dominated by medium-fine sandstone, to front delta and semi-deep lake sub-facies in basin center, a major hydrocarbon source rock area and main tight rock facies in Kong 2 Member area dominated by mud shale and argillaceous dolomite; and a transitional zone between them dominated by the distal end of delta front and gravity flow deposits.

Kong 2 Member is a complete third-order sequence ($SQEk_2$) deposited in the largest lacustrine flooding period of Kongdian Formation, and can be divided into 4 fourth-order sequences from bottom to top ($SQEk_2^4$, $SQEk_2^3$, $SQEk_2^2$, $SQEk_2^1$). $SQEk_2^4$ is low-stand systems tract, dominated by grey fine sandstone and grey mudstone of the delta front facies. $SQEk_2^3$-$SQEk_2^2$ is the lake transgressive systems tract, its top is the maximum flooding surface, which is confirmed to be about 30 cm thick black-dark grey mud shale with high TOC content from core observation. During this period, a set of fine grained deposits of semi-deep lake facies dominated by mud shale and argillaceous dolomite deposited, with siltstone-fine sandstone of gravity flow at the top. $SQEk_2^1$ is a high-stand systems tract, its lower part mainly consists of dolomite interbedded with mud shale, with base level falling, and its upper part is a set of mudstone of shallow lake facies with thin sand of the delta front at the top. According to the change of lithological combination, TOC, and mineral composition, 10 fifth-order sequences, SQ①-SQ⑩, were identified in $SQEk_2$ (Fig. 2).

2. Experiments

Firstly, 500 m cores from Well GX-A were sectioned, that is they were cut open at one third of them, a third of them were reserved for core description, the remaining for sampling analysis. Secondly, log curves were corrected on the basis of core description, over 1200 sections, samples for XRD analysis and physical properties test were selected according to the lithologic change and log curve characteristics, sections and samples of the desired size for XRD analysis were prepared after drilling standard core plugs with a diameter of 2.5 cm to ensure the maximum extent of correspondence between the thin section, XRD analysis and physical properties analysis, with the rest used for physical properties analysis. Identification, XRD and physical property analysis of thin sections were done by State Key Lab of China University of Petroleum (East China).

The XRD analysis was performed on X'pert Pro MPD with CuKα ray, under laboratory conditions of 40 kV, 40 mA, 2θ (mineral diffraction angle) measuring range of 5°-60°, and 2θ sampling step width of 0.016°. The porosity and permeability were measured by QKY-Ⅱ gas porosimeter, STY-Ⅱ gas permeability tester, with precision of 0.5% and 0.01×10^{-3} μm^2, under measuring pressures of 0.7 MPa and 1.0 MPa respectively. The analysis and testing data is shown in Fig. 2.

3. Lithologic characteristics

Fine grained sedimentary rock, with grains less than 0.062 5 mm in diameter accounting for more than 50%, is mainly composed of terrigenous clastic particles including clay (less than 0.004 0 mm in diameter) and silt (0.004 0–0.062 5 mm in diameter) or endogenetic carbonate, biological siliceous, phosphate and other particles, lithologically mud shale, siltstone, carbonate and their transitional rocks but not including carbonates formed in onshore high-energy environment (bioclastic limestone, oolitic limestone and its diagenetic epigenic dolomites, etc.), and is mainly developed in the prodelta - semi deep - deep lake. Since grains in the fine grained sedimentary rock are very fine, it is difficult to identify its contents of minerals by conventional thin section method accurately, while XRD is a quantitative analysis method determining the mineral composition and calculating the contents of minerals in samples based on the proportional relation between characteristic diffraction pattern, contents of different minerals and their diffraction peak intensity, which is able to identify a wide variety of minerals. XRD analysis shows that fine grained deposits are dominated by 5 kinds of essential minerals, quartz, feldspar, calcite, dolomite, clay mineral, and accessory minerals such as pyrite, siderite, zeolite and gypsum. According to XRD analysis results, fine grained deposits of Kong 2 Member in Cangdong sag have an average clay minerals content of 16%, average quartz and feldspar content of 33%, average calcite and dolomite content of 35%, average analcite content of 14%, and average pyrite + siderite content of 2%. The deposits in different areas and sedimentary environments differ somewhat in mineral composition, but have no obvious dominant mineral, and clay minerals content of less than 30% in general, and are mainly transition rocks lithologically.

Previous understandings on the fine grained deposits of semi deep - deep lake facies in Kong 2 Member are based on logging data, few cores and sidewall coring data. $SQEk_2$ was regarded as a set of dark grey mudstone and grayish brown oil shale before, after a new round of centimeter-level core