Lithofacies of Deepwater Fine-Grained Depositional Systems and their Significance for Shale Gas and Oil Exploration in Lacustrine Basin: An Insight from Qingshankou Formation, Qijia-Gulong Depression, Songliao Basin, Northeast China*

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Abstract

Prompted by marine shale oil and gas exploration in North American, play optimization and resource potential evaluation for continental shale oil/gas has been carried out successively in the Sichuan Basin, Erdos Basin and Songliao Basin of China. However, study of shale oil/gas was mainly focused on reservoir space types and optimization of organic geochemical indicators and little research has been carried out on lithofacies of deepwater fine-grained depositional system of lacustrine basins. Deepwater gravity current (downslope process) and deepwater bottom current (along slope process), and interaction between the two were developed in a lacustrine basin, leading to the development of lithofacies with different lithology and structure affected by provenance, topography and hydrodynamic forces in different locations of deepwater areas. The distribution rules of lithofacies is not only controlled by lithology, but also the key parameters of play optimization for shale gas/oil exploration (such as occurrence of organic matter, pore types, and hydrocarbon enrichment rules in shale). Therefore, it was necessary to carry out study on lithofacies of deepwater fine-grained depositional system in lacustrine basin to figure out the identification criteria for different types of lithofacies, providing reliable parameters for "sweet point" optimization in shale oil/gas.

Lithofacies Types of Deepwater Fine-Grained Depositional System

Based on the differences in lithology, sedimentary structures, and sedimentation mechanism, six lithofacies have been identified in the deep water area of the study area, which are oil shale, lacustrine mudstone, bottom current reworked sand (BCRS), shelly beach, turbidite, and mass transport deposits (MTD).The identification criteria (including core description, well logs and seismic response) and distribution characteristics are shown in Figure 1.

Lithofacies Types and Their Significance for Shale Oil/Gas Exploration

Relation between Lithofacies and the Occurrence Modes of Organic Matter

The occurrence modes of organic matter determine the amount of total hydrocarbon generation, the difficulty degree of micro-fracture development, and structural types of matrix pores in shale. Based on whole core maceral analysis of 36 samples in deep water area of the Qingshankou Formation in the study area, the occurrence modes of organic matter was divided into three types, which are (1) enriched along the layer, (2) dispersed, and (3) enriched along layer-reworked.

Organic matter enriched along the layer was mainly developed in the oil shale and lacustrine mud with very little clastics. Organic matter is parallel to or almost parallel to the bedding. In the fluorescent microscope, sporophyte appears evenly distributed as a short line with yellow-brown fluorescent (Figure 2A). Dispersed organic matter was developed in mudstone of relatively coarse-grain size with some siltstone-sized clastics (Figure 2B), which was usually developed near the shelly beach and BCRS. Organic matter was dispersed in clay matrix by continuous bottom current. Organic matter that was enriched along layer-reworked was developed in the fine-grained mudstone near the turbidite and MTD. Primary occurrence modes of organic matter is found parallel or almost parallel in the fluorescent microscope, which indicates a quiet deep water environment when primary deposited. However, affected by hydrodynamic disturbed in the later stage, rotational deformation was developed in the short line organic matter (distributed along layer) with yellow fluorescence (Figure 2C).

Relation between Lithofacies and Reservoir Space Types

The type of reservoir space was one of the key parameters for "core area" evaluation in shale oil/gas. Based on thin section analysis and field emission scanning electron microscope (FE-SEM) analysis of 58 samples (from different lithofacies) in the deepwater area of the Qingshankou Formation in the study area, it has been confirmed that different types of lithofacies have different reservoir spaces.

Oil shale and lacustrine mud were dominated by pores in organic matter (Figure 2D, pore size is 0.2-1.5 um), intergranular pores in clay minerals (Figure 2E, about 60-150 nm), intergranular pores among authigenic pyrite grains (Figure 2F, about 0.8-4.5 um with good connectivity) and micro-fractures (the width of fracture was 0.2-3.0 um, well developed with good connectivity). The visceral of shell in shelly beach was usually filled with recrystallized calcite with locally intercrystalline dissolved pores, where the pore size was 10-180 um with poor connectivity (Figure 2G). Grain size of BCRS, turbidite and MTD was relatively coarse, where primary pores and secondary dissolved pores were developed. Most primary pores were triangular or polygonal (Figure 2H, red arrow), pore diameter was 0.05-0.2 mm and the connectivity of pores was relatively good. Intergranular dissolved pores were dissolution of feldspar, debris, cements or matrix margins around the primary pores to enlarge the pores (Figure 2H, yellow arrow) with irregular shape and good connectivity. Intragranular dissolved pores can connect with primary pores, forming effective reservoir space (Figure 2I, red arrow).

Relation between Lithofacies and Shale Oil/Gas Accumulation Types

Oil shale and lacustrine mud were related to matrix-dominated hydrocarbon accumulation, where shale oil/gas was accumulated in matrix micro-pores or micro-fractures in shale. Shelly beach, BCRS and turbidite were referred to interlayer-dominated hydrocarbon accumulation. Thin carbonate rock, siltstone or silt-fine sandstone of shelly beach, BCRS and turbidite had relatively good porosity and permeability. Brittleness of shelly beach, BCRS and turbidite was strong, which was easier for fracturing and were favorable targets for shale oil/gas exploration. MTD was confirmed as pore-dominated hydrocarbon accumulation. MTD sandstone was usually developed in shale as lenticular bodies. Affected by overpressure and dissolution in organic acid of shale section, primary pores were well preserved and secondary dissolved pores were well developed. MTD sandstone can be charged by hydrocarbon from the adjacent horizons through short-distance migration.

Conclusions

Six lithofacies were identified in the deepwater fine-grain depositional system of the Qingshankou Formation: (1) oil shale, (2) lacustrine mudstone, (3) bottom current reworked sand (BCRS), (4) shelly beach, (5) turbidite, and (6) mass transport deposits (MTD). High correlation has been found between lithofacies and occurrence modes of organic matter, reservoir space types, and hydrocarbon accumulation types. Oil shale and lacustrine mudstone mainly facilitate matrix-dominated hydrocarbon accumulation, whose reservoir space types are dominated by organic matter pores, intergranular pores between clay minerals, intergranular pores between authigenic pyrite, and microfractures. Shelly beach, BCRS and turbidite was related to interlayer-dominated hydrocarbon accumulation, which are the favorable targets for shale oil/gas exploration. MTD was confirmed as pore-dominated type with well-developed primary pores and secondary dissolved pores.

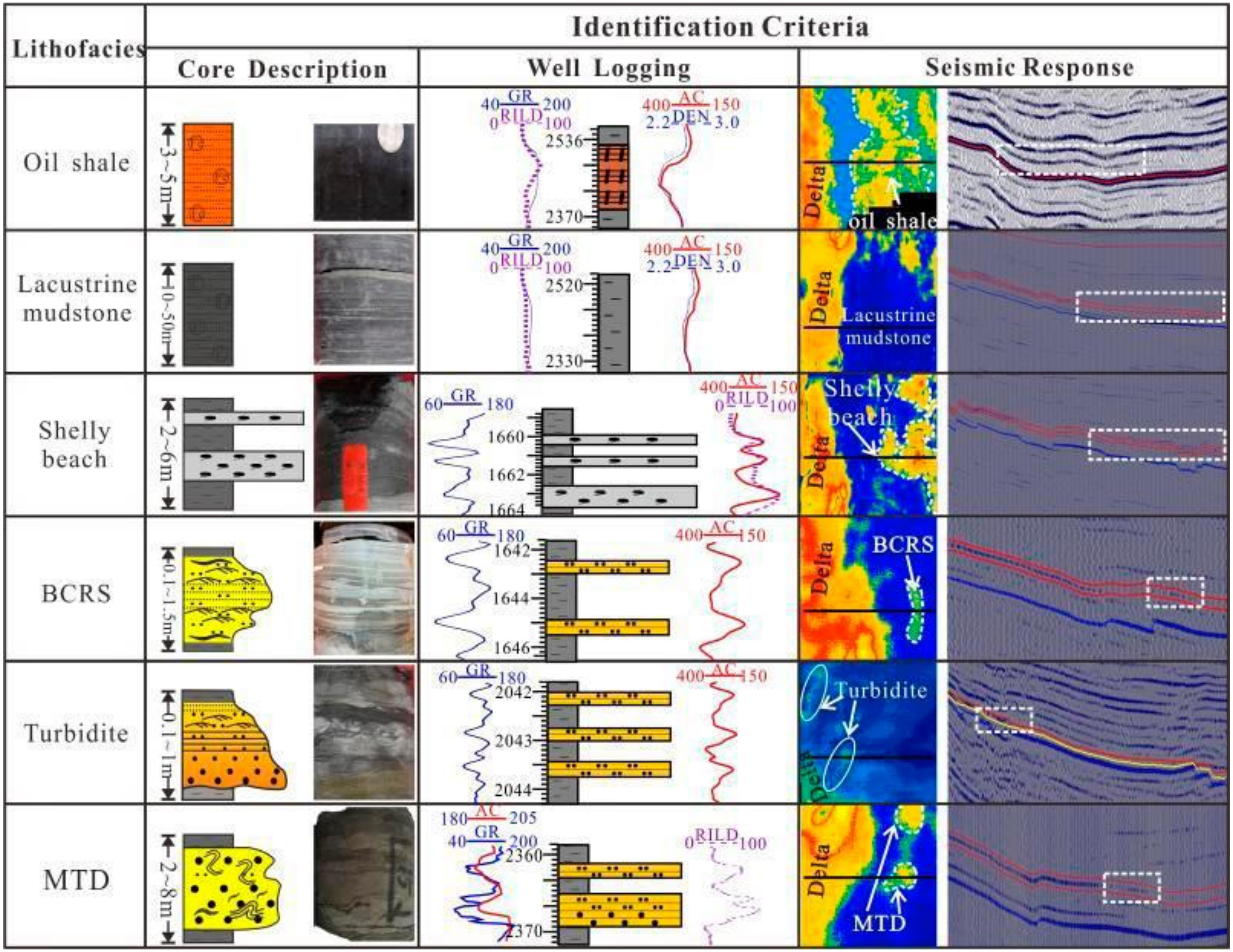

Figure 1. Lithofacies types of deepwater fine-grained depositional systems and their identification criteria.

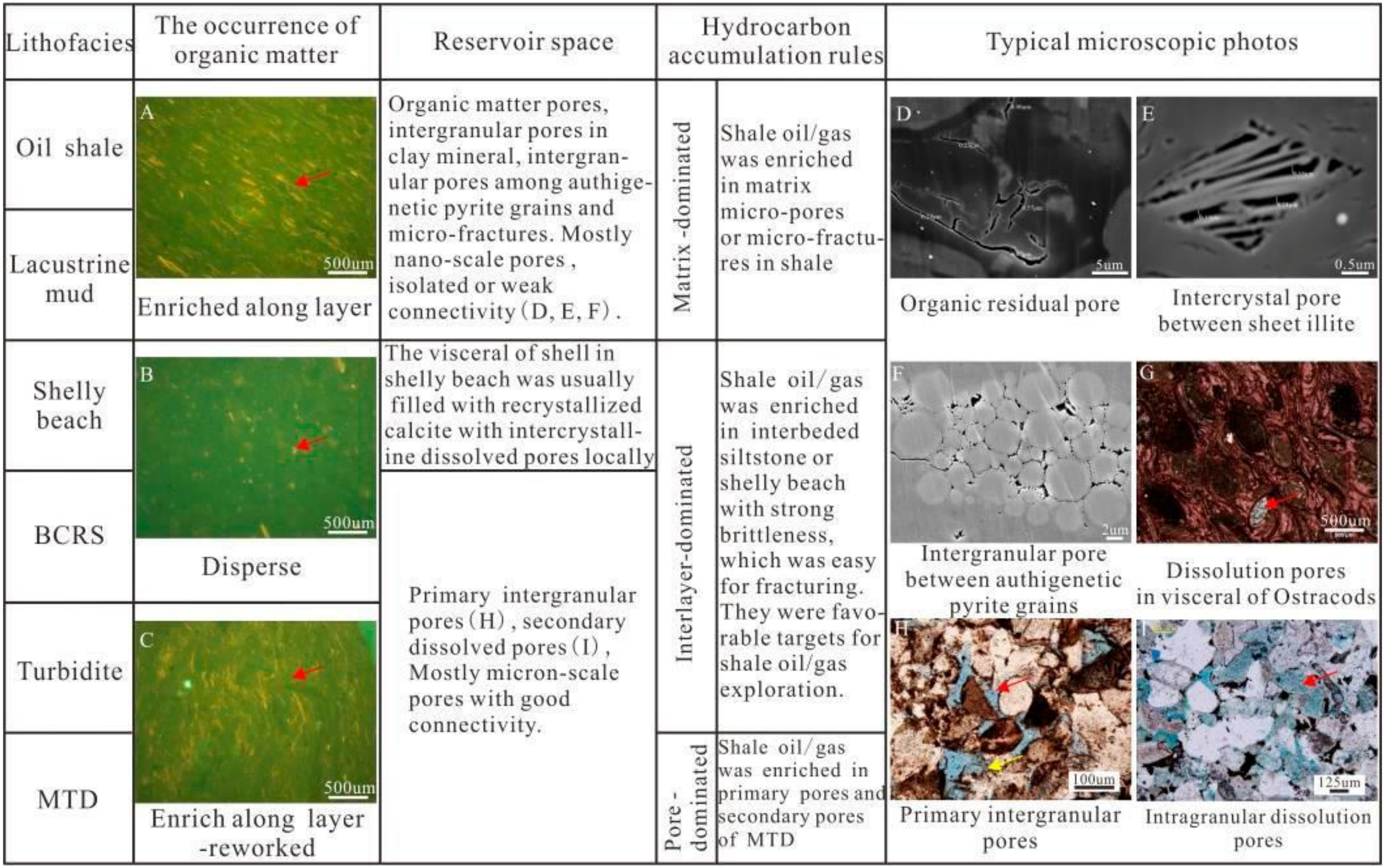

Figure 2. Relationship between lithofacies and occurrence modes of organic matter, reservoir space types, and hydrocarbon accumulation types.