PS Effects of Sedimentary Heterogeneity on Hydrocarbon Accumulations in the Permian Ordos Basin, China: Insight From an Integrated Stratigraphic Forward and 3D Petroleum System Modelling*

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Abstract

The sedimentary heterogeneities of the Permian Shanxi Fm in the Ordos Basin, China were modelled using SEDSIM, a forward stratigraphic modelling program. The simulation results were then used to construct a 3D petroleum system model using PetroMod. The SEDSIM simulation result shows that considerable sedimentary heterogeneities are present in the Shanxi Fm, resulting from the interplay of initial topography, tectonic subsidence, base level change and sediment inputs. A variety of lithofacies were developed within the Shanxi Formation at meter scales, with mudstones mainly developed in the central area, while sandstone developed in the southern and northern areas. A base-case conventional 3D basin model was constructed to quantify the Permian petroleum system in the Ordos Basin. The geological and thermal models were calibrated using measured and field data. It shows that the source rocks of the Upper Paleozoic began to reach maturity (Ro > 0.5%) and high maturity (Ro > 1.2%) in the early Jurassic and early Cretaceous, respectively, in the central and southern areas. During the Early Cretaceous, a tectonically induced geothermal event occurred in the southern Ordos Basin. As a result, source rocks reached over maturity (Ro > 2.0%) quite rapidly in the early Late Cretaceous in the central and southern areas. Hydrocarbons began to charge into the Shanxi Formation in the Middle Jurassic and continued till the early Late Cretaceous. In the base-case model, a large amount of hydrocarbons had been expelled and migrated into the Shanxi Fm, but only a minor amount was accumulated to form reservoirs. In the model, the Shanxi Fm sandstone was set to be homogeneous and there was also lack of seal rocks at the top of the Shanxi Formation, thus hydrocarbons could not be trapped effectively with only minor accumulations in some local structural highs. In contrast, the coupled SEDSIM-PetroMod model took into account of the internal lithological heterogeneities within the Shanxi Formation, forming a complex contiguous sandstone-mudstone stacking patterns. Hydrocarbons were accumulated in multiple intervals of lithological traps within the Shanxi Fm. The calibration results indicate that the coupled SEDSIM-PetroMod model is much more reasonable compared with the base-case "layer-cake" model, showing that sedimentary heterogeneities can exert a significant influence on hydrocarbon accumulation especially for lithological reservoirs.

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Conceptual Model

We firstly proposed a conceptual model to discuss the effect of reservoir heterogeneities on hydrocarbon accumulations. In the scenario 1(Fig. 1A), a reservoir layer is assigned with vertical homogeneous lithofacies as often the case in the classic "layer-cake" basin modelling approach. When inputted such a scenario into a petroleum system model, the reservoir could accumulate hydrocarbons, forming only one big hydrocarbon pool, if it is overlain by a seal rock, and it will not accumulate hydrocarbon if overlain by another sandstone layer. However, in the scenario 2 (Fig. 1B), due to the high frequency oscillations of the sea/lake level, three segments can be divided in the reservoir layer, including 1) mainly sandstone, 2) mainly mudstone and 3) transitional zone. Hydrocarbons could be accumulated both at top of the reservoir, if a seal rock is present, and within the transitional zone, forming several small hydrocarbon pools. Even if a seal layer is absent above the target reservoir layer, several small hydrocarbon accumulations could still be formed in the lithofacies transitional zone. It shows that sedimentary heterogeneities can be critical for determining if hydrocarbons can be trapped, especially for cases where there is no major structural trap or regional seal present.

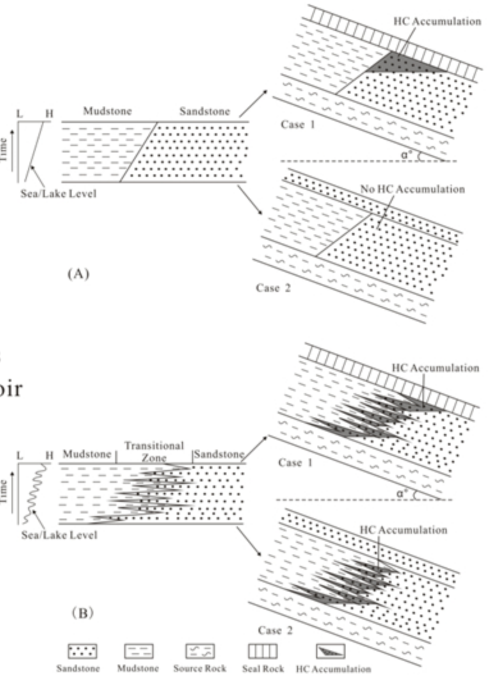

Fig. 1 Conceptual models showing effects of sedimentaryheterogeneities on hydrocarbon accumulations

Geological Setting

- Ordos Basin is the second largest hydrocarbon-bearing onshore basin in China. It is located in central China with an area of appropriately 250×10^3 km^2. The current basin configuration is charaterised by a huge asymmetric syncline with gentle dip of 0.5~1.0°toward the east and north.
- The Upper Paleozoic petroleum system consists mainly of Upper Carboniferous and Permian strata.
- Three types of source rocks, including coal seams, dark mudstone and limestone, were developed mainly in the C_2b, P_1t and P_1s formations. Reservoir rocks within the Upper Paleozoic petroleum system are best developed in the P_1s and P_2h_1 formations. The P_2h_2 and P_3q formations form the essential regional cap rocks of the Upper Paleozoic petroleum system.

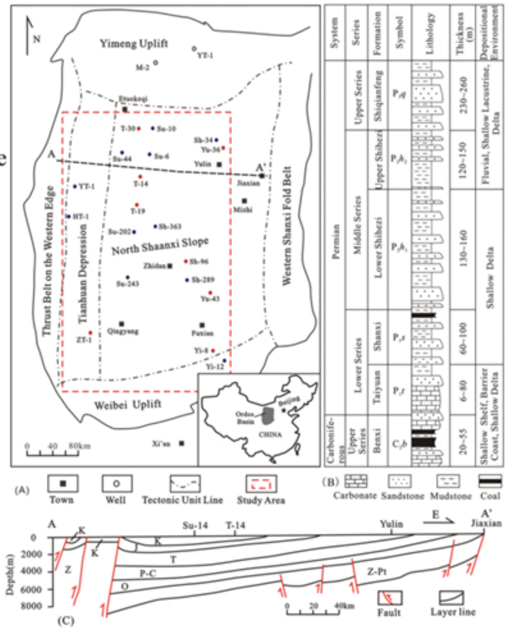

Fig. 2 Geology of the Ordos Basin. (A) Location of the study area; (B) Comprehensive stratigraphic column; (C) A near W-E cross-section.

Methodology

An integrated stratigraphic forward modelling (SFM) and basin modelling approach was used to study the hydrocarbon accumulation in the Permian Shanxi Formation. The SFM used is Sedsim, originally developed by Stanford University (Tetzlaff and Harbaugh, 1989).
The basin modelling program used is PetroMod 2015 from Schlumberger.

SFM Results

- Sedsim simulation outputs (Fig.3) show that sands are mainly developed in northern and southern parts of the study area, whereas clays are abundant in the central area. Sedimentary heterogeneities are present in both directions at metre scales.
- The Permian Shanxi Formation can be divided into two members, namely the P_1s_2 and P_1s_1 members. Isopach maps of these two members were used to validate the Sedsim simulation results, and the results show that modelled thicknesses of the two members have a good match with the real results, both in thickness and depocentre locations (Fig.4).

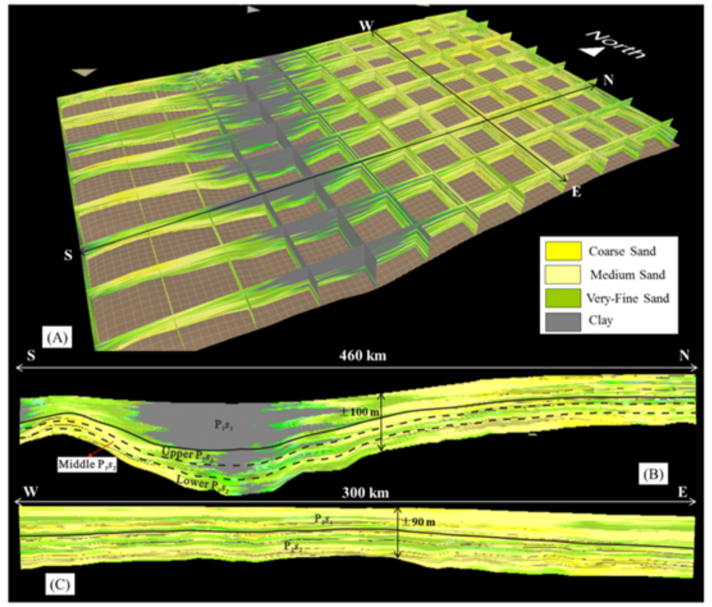

Fig. 3 Sedsim simulation outputs of the Shanxi Formation.

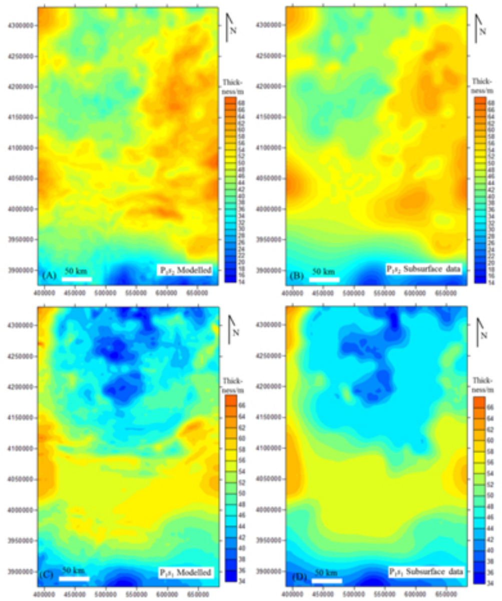

Fig. 4 Validation of the Sedsim simulation outputs by comparing thicknesses of the P_1s_2 and P_1s_1 formations between the modelled and the real results, derived from the RIPED, Lang Fang Branch (2010).

Base-case 3D Petroleum System Modelling

- One 3D model was constructed using a classic "layer-cake" stratigraphic model with limited layers (base-case) (Fig. 5). Both the geological and thermal models were calibrated using measured data, e.g. well depths, porosities, temperatures and Ro, etc., showing reasonably for further hydrocarbon generation, expulsion and accumulation modelling.
- Although reservoir rocks were well developed in most part of the study area, few gas pools were formed within the P_1s Formation (Fig. 6A), because it lacks heterogeneities in vertical and overlain directly by the P_2h_1 Formation, which is also a major reservoir unit (Fig. 6B). Gas mainly accumulated in local structural highs or lithology transition regions and overlain by seal rocks directly in the P_1s Formation.

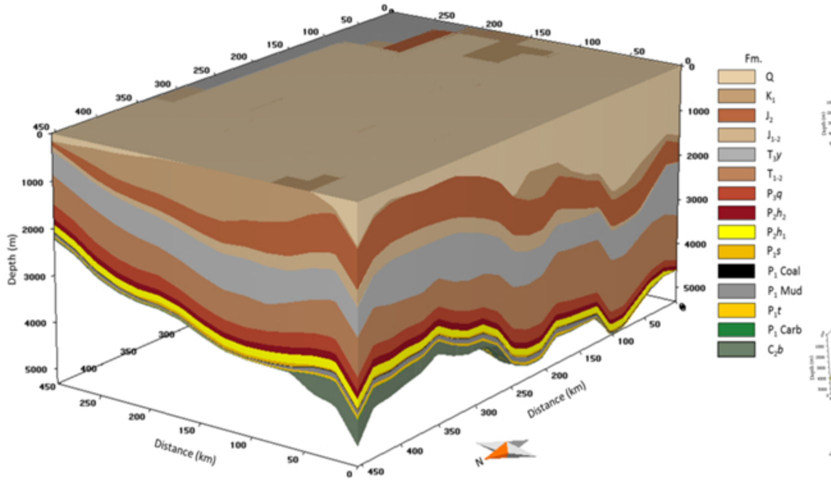

Fig. 5 A 3D geological model of the study area in the Ordos Basin.

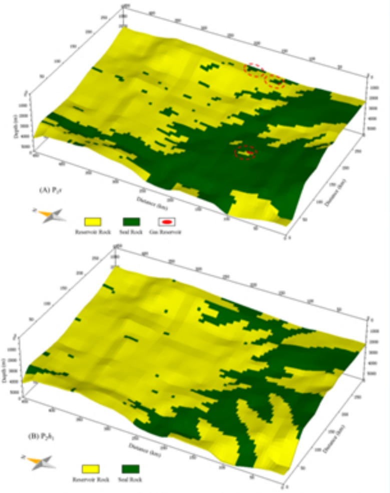

Fig. 6 Hydrocarbon accumulation results in the P_1s Formation from the base-case 3D model.

Integrated Sedsim-PetroMod Model Results

- 20 sub-layers were firstly subdivided based on the Sedsim results of the P_1s layer, then defined ages and lithologies of each sub-layer, and finally replaced the previous single P_1s layer with the 20 sub-layers in the PetroMod model with other input parameters remaining unchanged. An integrated Sedsim-PetroMod model was established.
- Numerous small gas pools are formed in the P_1s Formation due to heterogeneities existing in both lateral and vertical directions (Fig. 7).
- The integrated Sedsim-PetroMod 3D model yields far more greater HC volumes in the P_1s Formation than that from the base-case model (Fig. 8).

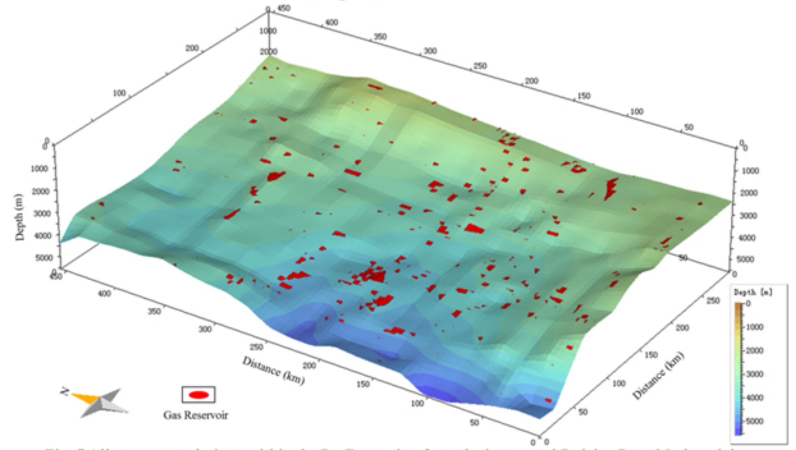

Fig. 7 All gas accumulations within the P_1s Formation from the integrated Sedsim-PetroMod model.

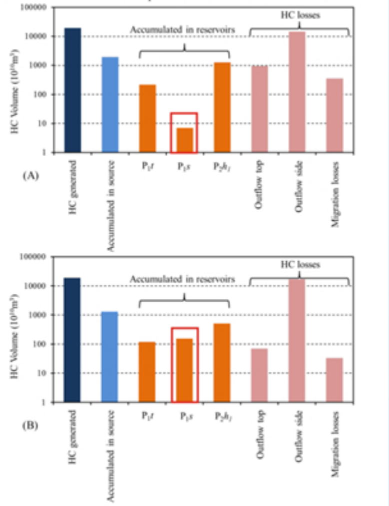

Fig. 8 Quantitatively comparison of the HC volume between the base-case model (A) and the integrated Sedsim-PetroMod model (B).

Conclusions

Sedimentary heterogeneities have significant effects on the hydrocarbon accumulations. Lithology distinctions, controlled by sedimentary heterogeneities, in both lateral and vertical directions can provide effective barriers in both top and up-dip directions for hydrocarbon accumulations, with gas being mainly accumulated near the depocentre where lithological traps usually formed due to a frequent oscillations of lake/sea levels.