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 (Fig. 1A), a reservoir layer is assigned with vertical homogenous 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 hydrocarbons if overlain by another sandstone layer. However, in the scenario 2 (Fig. 1B), due to the high frequency oscillations of the sand/silt ratio, 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.

Geological Setting
- Ordos Basin is the second largest hydrocarbon-bearing shelf basin in China. It is located in central China with an area of approximately 250,000 km². The current basin configuration is characterised by a huge asymmetric syncline with gentle dip of 0.5°-1° 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 mudstones and limestones, were developed mainly in the C1, P1 and P2 formations. Reservoir rocks within the Upper Paleozoic petroleum system are best developed in the P1 and P2 formations. The P3 and P4 formations form the essential regional cap rocks of the Upper Paleozoic petroleum system.

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

SFM Results
- Sediment 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 meter scales.
- The Permian Shaanxi Formation can be divided into two members, namely the P1s and P2s 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 isopachous locations (Fig. 4).

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, pressures, temperatures and Rs, 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 P1s Formation (Fig. 6A), because it lacks heterogeneities in vertical and overlain directly by the P2s Formation. This 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 P1s Formation.

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