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Research paper

Effect of sedimentary heterogeneities on hydrocarbon accumulations in the Permian Shanxi Formation, Ordos Basin, China: Insight from an integrated stratigraphic forward and petroleum system modelling

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A B S T R A C T

Sedimentary heterogeneities are ubiquitous in nature and occur over a range of scales from core, reservoir to basin scales. They may thus exert significant influences on hydrocarbon generation, migration and accumulation. The sedimentary heterogeneities of the Permian Shanxi Formation in the Ordos Basin, China were modelled using Sedsim, a stratigraphic forward modelling program. The simulation results were then used to construct a 3D petroleum system model using PetroMod. The effects of sedimentary heterogeneities on hydrocarbon accumulations were evaluated by comparing the integrated Sedsim-PetroMod model with the classic 3D basin model. The Sedsim simulation shows that considerable sedimentary heterogeneities are present within the Shanxi Formation, as a result of the interplay of the initial topography, tectonic subsidence, base level change and sediment inputs. A variety of lithologies were developed both laterally and vertically within the Shanxi Formation at kilometre and metre scales, respectively, with mudstones mainly developed in the depositional centre, while sandstones developed in the southern and northern margin areas. A typical source-ward retrogradation is well developed within the Lower Shanxi Formation.

A base-case classic 3D basin model was constructed to quantify the Permian petroleum system in the Ordos Basin. The geological and thermal models were calibrated using Vr and borehole temperature data. The source rocks of the Upper Paleozoic became mature ($R_o > 0.5\%$) and high mature ($R_o > 1.2\%$) in the late Triassic and late Jurassic, respectively, in the central and southern areas. During the Early Cretaceous, a tectonically induced geothermal event occurred in the southern Ordos Basin. This caused the source rocks to reach over maturity ($R_o > 2.0\%$) quite rapidly in the early Late Cretaceous in the central and southern areas. All the source rock transformation ratios (TR) at present are greater than 70% in the P_1 coal and P_1 mudstone layers with TR values approaching 100% in the central and southern areas. The transformation ratios of the P_1 limestone are close to 100% over the entire interval.

In the base-case model, a large amount of hydrocarbons appear to have been expelled and migrated into the Shanxi Formation, but only a minor amount was accumulated to form reservoirs. In the model, the Shanxi Formation sandstone layer was set to be homogeneous vertically and there was no regional seal rocks present at the top of the Shanxi Formation. Therefore hydrocarbons could not be trapped effectively with only minor accumulations in some local structural highs where hydrocarbons are trapped both at the top and in the up-dip direction by the adjacent mudstone facies. In contrast, the integrated Sedsim-PetroMod model takes into account of the internal lithological and sedimentary facies heterogeneities within the Shanxi Formation, forming complex contiguous sandstone-mudstone stacking patterns. Hydrocarbons were found to have accumulated in multiple intervals of lithological traps within the Shanxi Formation. The results indicate that lithological distinctions, controlled by sedimentary heterogeneities in three dimensions can provide effective sealing in both the top and up-dip directions for hydrocarbon accumulations, with gas being mainly accumulated near the depocentre where lithological traps usually formed due to frequent oscillations of the lake level.

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1. Introduction

Sedimentary heterogeneities refer to the spatial variabilities of a sedimentary body and in reservoir characterization they are represented by variations in porosity, permeability and capillarity (Alpay, 1972; Evans, 1987; Moraes and Surdam, 1993). Sedimentary heterogeneities are mainly controlled by sedimentary facies geometry, grain-size characteristics and diagenesis process (Haldorsen, 1986), and occur over a range of scales (Miall, 1990), ranging from micro scales to basin scales. Heterogeneities can cause variations in hydraulic conductivity, storage and porosity (Eaton, 2006), and thus strongly controls fluid flow and transport through rocks (Wardlaw and Cassan, 1979; Weber, 1982). Sedimentary heterogeneities can be well described not only using the conventional sedimentological approach, but also some quantitative alternatives, such as the fractional Levy fractional model and depositional modelling (Liu et al., 2002). A hydrodynamics-based stratigraphic forward modelling package, Sedsim, was shown to be useful tool to capture sedimentary heterogeneities from centimetre to kilometre scales by modifying spatial and temporal resolutions (Griffiths et al., 2001; Liu et al., 2002).

Basin modelling technology has long been used to simulate hydrocarbon generation, migration and entrapment (Tissot and Welte, 1984). It has become an integral part of the petroleum exploration process (Verweij, 2009), and provides a strategy for optimizing exploration in frontier areas and evaluating new plays within well-explored basins (Schneider and Wolf, 2000). The technique has been successfully applied to search for new petroleum plays or evaluate exploitable oil and gas accumulations in numerous basins worldwide (Hakimi et al., 2010; Shalaby et al., 2011; Baur et al., 2011). The principles of basin modelling have been well documented by a number of authors including Welte and Yükler (1981), Welte and Yalcin (1987), Tissot et al. (1987), Welte et al. (1997), and Littke et al. (2008). A complete basin modelling system comprises the geological, thermal, hydrocarbon generation, migration and accumulation components or sub-model (Shi, 2004). Among all, the geological model is the fundamental component because others are constructed upon the geological model. While many researchers attempted to develop techniques to construct reasonable and realistic geological models, including subsidence rate method (Yükler et al., 1978), back stripping technique (Ungerer et al., 1984; Guidish et al., 1985; Shi et al., 1989), overpressure technique (Shi, 2002), and a combination of back stripping and overpressure methods (Shi, 2004, 2009), few studies have considered the effect of sedimentary heterogeneities of a petroleum system on hydrocarbon accumulations. Currently when constructing a 3D geological model, the following is a common practice: (1) a reservoir is usually considered as homogenous layer without considering either lateral or vertical heterogeneities (Kuhlmann et al., 2011); (2) lithologies is assigned by using an interpreted sedimentary facies map without considering any vertical heterogeneities (Duran et al., 2013), or (3) lithologies is assigned by directly conversing 3D seismic attributes into lithofacies (Huvaz et al., 2007), which is often inadequate or sometimes unfeasible due to the lack of basin-wide 3D seismic data and its restricted vertical resolution.

We used two conceptual models shown in Fig. 1 to illustrate the effect of reservoir heterogeneities on hydrocarbon accumulations. In the first scenario (Fig. 1A), a reservoir layer is assigned with vertical homogeneous lithofacies as often the case in the classic "layer-cake" basin modelling approach. This mimics the situation of the stacking of dual lithologies (sandstone and mudstone) during a gradual sea/lake level rise cycle. The reservoir layer shows lateral heterogeneities but no vertical heterogeneities (Fig. 1A). Assuming that no structural traps are developed in the model except for a regional tectonic tilting with an angel of α°. 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, as hydrocarbons could be sealed both by the overlying seal rock and the mudstone laterally (Fig. 1A, Case 1). However, no hydrocarbons can be accumulated if the reservoir layer were overlain by another sandstone layer, due to the lack of effective sealing conditions (Fig. 1A, Case 2).

If taking into consideration of both lateral and vertical heterogeneities as shown in the second scenario (Fig. 1B), the entire reservoir unit can be considered to consist of three segments, (1) a mainly sandstone proximal part near the source, (2) a predominant mudstone distal part and (3) a transitional zone with alternating between the sandstone and mudstone, developed due to the (high frequency) oscillations of the sea/lake level (Fig. 1B). 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, sealed by alternating mudstone layers (Fig. 1B, Case 1). 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 (Fig. 1B, Case 2). A comparison of the two conceptual models suggests 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. Therefore, the classic "layer-cake" homogenous model may be inadequate in modelling spatially extensive lithostratigraphic or unconventional sandy reservoir plays that do not have major regional seals or structural traps.

The Upper Paleozoic of the Ordos Basin contains numerous tight sand gas resources and approximately 10.37×10^{12} m^3 (366 TCF) of geological resources have been found in 2010 (Fu et al., 2010; Yang et al., 2012a; Zhao et al., 2014). Five giant gas fields have so far been discovered, namely the Sulige, Yulin, Wushenqi, Daniudi and Shenmu gas fields, with proven reserves of over 100×10^9 m^3 (3.5 TCF) in each field (Yang et al., 2012a; Zhao et al., 2014). The Permian Shanxi and the Lower Shihezi formations are the main gas bearing units (Hu et al., 2010; Zhao et al., 2012; Yang et al., 2012b) with gas mainly sourced from the underlying coal seams within the Upper Paleozoic petroleum system (Dai et al., 2005; Hu et al., 2008). Structural traps are absent in the area and hydrocarbons are mainly accumulated in large-scale lithological traps, controlled by lithologies and deposition facies (Yang et al., 2005a; Zhao et al., 2012). Regarding petroleum system modelling of the Upper Paleozoic section of the basin, numerous one-dimensional models were constructed, mainly to study thermal (Liu et al., 2007; Ren et al., 2008), pressure (Wang and Chen, 2007) and hydrocarbon generation (Dai et al., 2009) evolution in some parts of the basin. Some two dimensional basin models were also established mainly with specific focus on the oil and gas migrations in 2D cross sections at different geologic times (Wang et al., 2006) and to quantify hydrocarbon generation (planar) intensities (Dai et al., 2009). There is no full three-dimensional basin modelling work done for the study area. Liu (2005) and Yu (2012) constructed three dimensional models mainly to investigate the thermal and maturity evolution and did not consider the reservoir heterogeneity within the Upper Paleozoic petroleum system.

In this study, a full three dimensional basin model, with sedimentary heterogeneities in the reservoir units being considered, was constructed by integrating the Sedsim simulation results and the PetroMod petroleum system modelling. The major objectives of this study are to: (1) quantitatively simulate the stacking pattern of the Permian Shanxi Formation and to characterise the sedimentary heterogeneities using Sedsim; (2) construct a three-dimensional basin model for the Upper Paleozoic petroleum system and to investigate the source rocks maturity evolution and hydrocarbon