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Reservoir Potential of Thin-bedded Sandstone in Continental Mudrock Successions - The Search for Hidden Treasures

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SUMMARY

The subsurface of the West European gas province contains up to several hundred meters thick continuous Upper Rotliegend and Lower Triassic mud rock sequences which have to date been labelled as non-reservoir 'waste zone'. The mud rock formed as fluvial floodplain deposits in a semi-arid climate. The sequences contain thin-bedded porous and permeable sandstone beds of crevasse-splay origin. A core study of Triassic deposits in the West Netherlands Basin shows that the sandstone beds are nested in up to 2-m-thick sand-prone heterolithic stacks with net-to-gross up to 0.5. Because of the heterolithic nature and small bed thickness the sand-prone intervals are not detected by the gamma-ray log. An outcrop analogue study of fluvial sediments in the Altiplano Basin of Bolivia shows that the crevasse-splay sediments amalgamate laterally to extensive sand sheets with surface areas of several square kilometres. Combination of the core and outcrop study suggests that the nested sandstone beds may constitute secondary plays with economically interesting gas reservoir volumes that may help postpone the end of field-life in mature production areas.

Introduction

Exploration efforts in mature hydrocarbon provinces are shifting towards secondary targets and previously by-passed stratigraphic intervals directly surrounding existing production infrastructure. Successful exploration of such secondary plays will help postpone the end of field life and the large expenditure for removing the (off-shore) production platform facilities.

In this study we will shed light on the reservoir potential of thick mud-rock sequences in the subsurface of the Northwest European gas province. The depositional sequences, often hundreds of meters thick and with very unpromising formation names such as Ten Boer Claystone Member (U. Rotliegend, Permian) and Solling Claystone (U. Triassic), were until now labelled as ‘waste zone’ and by-passed *en route* to the deeper-lying, proven thick reservoir intervals of the Slochteren Formation (U. Rotliegend, Permian) and Main Buntsandstein (L. Triassic), respectively.

The mud rock was deposited as floodplain sediment in a fluvial environment and contains thin-bedded porous and permeable sandstone intervals (Figure 1). The aims of this study are to: (1) analyse the depositional processes that led to the formation of the sandstone beds, and (2) present our ideas on size, shape, stacking patterns (or: geological reservoir architecture) and porosity-permeability distribution of the sandstones.

Data and methods

Thin-bedded sandstone in a mud-prone continental setting has been interpreted as crevasse-splay and terminal lobes deposits. Hampton and Horton (2007) and Donselaar et al. (2013) presented studies on the depositional processes and resulting deposits for contemporary thin-bedded fluvial sheet sandstones. Jones and Hajek (2007), Fisher et al. (2007) and Nichols & Fisher (2007) described and interpreted outcrop analogues displaying longer time intervals of avulsions and stacking of crevasse splays and terminal lobes. Donselaar et al. (2011) interpreted subsurface data of crevasse splays in the Upper Permian, low-N/G fluvial Ten Boer Member.

Lithofacies characteristics were studied in selected core intervals (total length 74 m) from two onshore wells, Pernis-West 1 (PRW-1) and Gaag 3 (GAG-3) in the West Netherlands Basin (Figure 2; Table 1). The studied stratigraphic intervals are the Rogenstein Member (L. Germanic Triassic), Solling Claystone Member and Lower Röt Fringe Claystone Member (Upper Germanic Triassic). A reservoir-analogue outcrop study on recent fluvial deposits in the semi-arid, endorheic Altiplano Basin (Bolivia) yielded data on the size, shape, sedimentary characteristics and depositional processes of thin-bedded fluvial crevasse-splay sands in a low net-to-gross (N/G) mud-prone environment (Donselaar et al, 2013).

Figure 1 Lithofacies characteristics, well PRW-1. Scale bar in cm.
 A: Heterolithic succession of thinly-bedded, very fine-grained sandstone (lighter color) and claystone (dark). Depth: 2994 m. B: Sharp, erosional basal surface and fining-upward grain size succession of thinly-bedded sandstone. 3190 m. C: Low-angle climbing ripple lamination. 3195 m. D: Sharp, erosional basal surface and clay rip-up clasts. 2998 m.

In addition, the development in space and time of thin-bedded crevasse-splay sand deposits in the Altiplano Basin was analysed with Landsat Multispectral Scanner (MSS) and TM (Thematic Mapper) imagery (Li et al., 2014).

Well	Depth (m)	Formation names
PRW-1	2984-2998	Lower Röt Fringe Claystone Mbr
	2998-3007	Solling Claystone Mbr
	3188-3221	Rogenstein Mbr
GAG-3	3638-3645	Lower Röt Fringe Claystone Mbr
	3645-3656	Solling Claystone Mbr

Table 1 Cored intervals used in this study. PRW-1: Pernis-West 1. GAG-3: Gaag 3.

Figure 2 Well location map, the Netherlands.

Results

The bulk of the studied stratigraphic intervals consist of grey mudstone that formed as fluvial floodplain sediment. Individual sandstone beds in core are 5-60 cm thick and characterized by a sharp, erosional basal surface lined with clay rip-up clasts; and a fining-up grain-size succession from very fine-grained sandstone to claystone (Figure 1). Parallel lamination, low-angle climbing-ripple lamination (Figure 1C), wave ripples, flaser and linsen bedding and convoluted bedding are the most conspicuous sedimentary structures. Pyrite and calcrete nodules are found in this facies, and haloturbation is common in the Lower Röt Fringe Claystone Member. The lithofacies characteristics are typical for sediment transport in a unconfined, high-energy, high-density suspension flow. The crevasse-splays form during peak water discharge in seasonal, short-duration rain periods which cause massive overbank flooding and floodplain inundation (Donselaar et al., 2013). The elongate clay rip-up clasts are eroded from mud-crack polygons at the floodplain surface. Energy loss by friction and crevasse-splay flow divergence over the unconfined, flat floodplain surface leads to flow deceleration and deposition of the suspension load as climbing ripples in a fining-upward grain size succession. The haloturbation signifies semi-arid climate conditions which prevailed in the Early Triassic (Ziegler, 1990).

Petrophysical properties of the sandstone beds from core plugs range from 5 to 15 % porosity and 0.1 to 10 mD permeability. N/G of the studied intervals is up to 0.5. However, because of the small bed thickness and the heterolithic nature of the deposits, the gamma-ray log remains well above the sandstone line for the underlying Hardeggen reservoir, even where the thin sandstone beds are clustered in up to 2-m-thick sand-prone heterolithic intervals (Figure 3).

Vertical aggradation of crevasse-splay deposits implies sediment storage capacity on the floodplain. Kjemperud et al. (2008) proposed a scenario (for braided channel belts) where the river builds up levees and alluvial ridges under conditions of gradual base-level rise.

Figure 3 Gamma-ray log (blue line), PRW-1. Red dotted line: clean sandstone from Hardeggen reservoir. Brown boxes: sand-prone heterolithic intervals.

The channel belt thereby rises above the adjacent floodplain ('super-elevation') and thus creates floodplain accommodation space where crevasse-splay deposits stack vertically with sand-on-sand contacts. Dalman et al. (2015) presented a high-resolution sequence-stratigraphic model in which floodplain aggradation takes place by means of compensational stacking in order to approach base level on the floodplain.

An estimate of the reservoir volume attached to wells is provided by the outcrop and remote sensing study. In the semi-arid setting of the endorheic Altiplano Basin the rivers show a gradual downstream decrease of bankfull width and depth and, hence, of cross-sectional area. Donselaar et al. (2013) interpreted this decrease by the combined effects of the extremely low gradient on the floodplain, transmission losses due to high evapo-transpiration rates in the semi-arid climate, and river water infiltration in the channel floor. This implies that during peak river discharge periods the volume of water transport by far exceeds the river capacity (cross-sectional area), and massive flood-outs will occur that produce extensive, laterally-amalgamated crevasse-splay sand sheets all along the river trajectory (Figure 4). A time series analysis of Landsat imagery reveals that successive crevasse splays fill up the topographic lows between existing crevasse splays (Li et al., 2014). The compensational stacking effectively fills the area adjacent to the river with a continuous sheet of crevasse splay sand.

Figure 4 Laterally amalgamated crevasse splays extend over the floodplain on either side of the river. Río Colorado, Altiplano Basin, Bolivia. From: Donselaar et al. (2013).

We have analysed the theoretical gas reservoir potential of a laterally-amalgamated crevasse-splay sheet sand complex in the Altiplano Basin study. The surface area of the complex is 7,483,936 m² and the average thickness 20 cm, hence the Rock Bulk Volume (RBV) is 1,496,787 m³. At reservoir conditions comparable with the studied wells in the West Netherlands Basin, i.e., a burial depth of 3000 m, porosity of 10%, water saturation (S_w) of 0.2, and a gas formation volumetric factor (B_{gi}) at 3000 m depth of 299.523, the gas initially in place (GIIP) can be calculated using the equation:

$$GIIP = RBV \cdot \phi \cdot N/G \cdot (1 - S_w) \cdot B_{gi} \quad \text{Equation 1}$$

and amounts to 12,225,634 m³ for a single level of crevasse splay sandstone. In case of vertical stacking with sand-on-sand connectivity in up to 2-m-thick heterolithic sequences with a N/G of 0.5 the GIIP can reach economically interesting volumes in the order of 60·10³ m³ of gas.

Conclusions

Thick fluvial mud rock sequences of Permian and Triassic age in the subsurface of the Northwest European gas province have to date been labelled as non-reservoir 'waste zone'. We have demonstrated that the mud-prone sequences contain thin-bedded crevasse-splay sandstone beds with reservoir potential. Nesting of the beds forms up to 2-m-thick sand-prone heterolithic stacks with a N/G of up to 0.5, porosity of 5 to 15 %, and permeability of 0.1 to 10 mD. Vertical aggradation of the

crevasse-splay deposits occurred in an environment of relative base level rise and inherent floodplain storage capacity. An outcrop analogue study of fluvial sediments in the Altiplano Basin of Bolivia showed that the crevasse-splay sediments can laterally amalgamate to continuous sand sheets with surface area of several square kilometres. The thin-bedded sandstone sheets can be stratigraphically pin-pointed if the sequence stratigraphic setting is determined. The stacked sandstone beds may then constitute secondary gas plays which will help postpone the end of field-life in mature production areas.

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