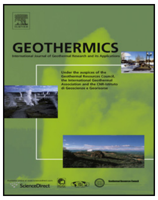
Geothermics 65 (2017) 222–233

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics



On the connectivity anisotropy in fluvial Hot Sedimentary Aquifers and its influence on geothermal doublet performance

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ARTICLE INFO

Article history:
Received 7 July 2016
Received in revised form
30 September 2016
Accepted 5 October 2016

Keywords:
Direct-use
Low enthalpy geothermal
West Netherlands basin
Process-based facies modelling
Fluvial sandstone
Reservoir modelling

ABSTRACT

This study finds that the geothermal doublet layout with respect to the paleo flow direction in fluvial sedimentary reservoirs could significantly affect pump energy losses. These losses can be reduced by up to 10% if a doublet well pair is oriented parallel to the paleo flow trend compared to perpendicular. The chance that flow paths are formed perpendicular to this trend strongly depends on the net sandstone volume in the reservoir. Detailed fluvial facies architecture realisations which are used in this study, are generated with a process-based approach utilizing geological data from the Lower Cretaceous Nieuwerkerk Formation in the West Netherlands Basin. Finally, this study emphasizes the importance of detailed facies architecture modelling for the assessment of both risks and production strategies in Hot Sedimentary Aquifers.

1. Introduction

Hot Sedimentary Aquifers (HSA) are commonly exploited by a doublet system, consisting of a hot-water production and a cold-water reinjection well. Downhole well distance typically is 1000 to 2000 m, and both wells target the same aquifer to maintain pressure support in the reservoir. In fluvial reservoir rocks the doublet connectivity is via a network of permeable fluvial channel sandstone bodies embedded in non-permeable floodplain mudstone. Detailed knowledge of the size, shape, spatial distribution and connectivity of the fluvial sandstone bodies (or: fluvial reservoir architecture) is required to assess the risk of pressure communication loss between the wells and the inherent economic risk of the geothermal energy production projects (Fig. 1).

The effect of the fluvial reservoir architecture on the recovery of hydrocarbons has extensively been studied (e.g. Jones et al., 1995; Larue and Friedmann, 2005; Larue and Hovadik, 2006, 2008; Pranter et al., 2007; De Jager et al., 2009). To a much more limited extent, this topic is addressed for geothermal energy production (e.g. Hamm and Lopez, 2012; Crooijmans et al., 2016) and for CO_2 sequestration (e.g. Issautier et al., 2014). Larue and Hovadik (2008) identified 'connectivity' as one of the main parameters that control the recovery efficiency of hydrocarbon reservoirs. Connectivity could be defined as the ratio of the volume of the largest sandstone body cluster and the total sandstone body volume (e.g. Larue and Hovadik, 2006). If the connectivity is high, less isolated clusters occur and therefore fewer wells are required to drain the reservoir (e.g. Geel and Donselaar, 2007). Previous work on connectivity in sedimentary reservoirs identified several main factors that control the chance that sandstone bodies connect: (1) the net-sandstone volume or net-to-gross (N/G); (2) the sandstone body geometry, and (3) the range in paleo- flow direction, which determines the reservoir trend (King, 1990; Larue and Hovadik, 2006, 2008; Geel and Donselaar, 2007; Ainsworth, 2005; Pranter and Sommer, 2011). Connectivity of reservoir bodies is also influenced by post-depositional faulting (e.g. Bailey et al., 2002), by diagenetic processes, and by depositional permeability heterogeneity within in the sandstone bodies (Willis and Tang, 2010; Henares et al., 2014). To date, studies into the risk assessment of connectivity are dominantly focused on the optimization of hydrocarbon

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http://dx.doi.org/10.1016/j.geothermics.2016.10.002
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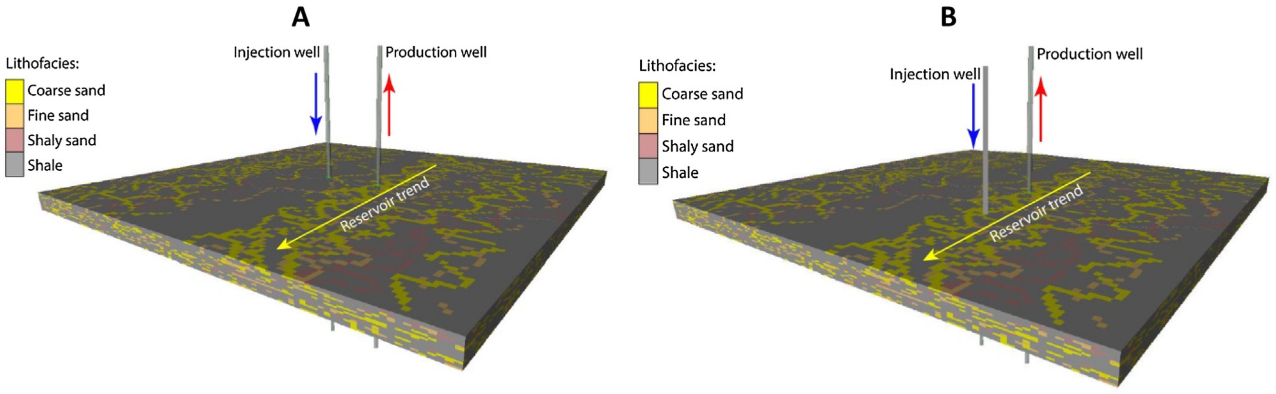

Fig. 1. Example of the effect of doublet layout with respect to the orientation of sandstone bodies in the reservoir. Example (A) shows a perpendicular layout and (B) a parallel layout.

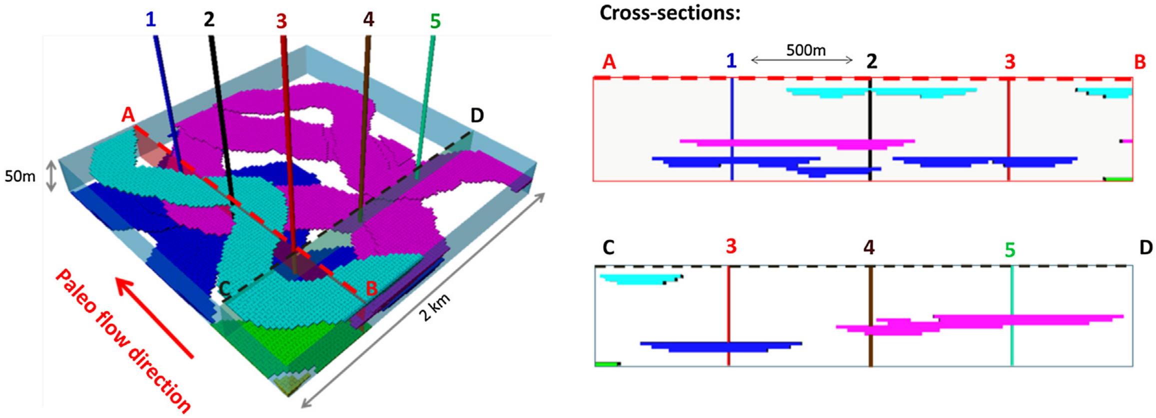

Fig. 2. Conceptual fluvial reservoir model with 5 wells. Floodplain fines are transparent; sandstone bodies have the same colour if they are connected.

recovery efficiency. A main goal of connectivity analyses was to identify a N/G threshold below which isolated bodies start to occur. In meandering fluvial reservoirs, this N/G threshold is often recognized between 20 and 30% N/G, depending on the sandstone body geometries (e.g. Larue and Hovadik, 2006). Because in geothermal exploitation well pairs are used, a new directional component in connectivity analyses is required. This can assist engineers to design geothermal doublet systems with the largest possible heat exchange surface between two wells in order to minimize pump energy losses and to delay cold water breakthrough. A conceptual fluvial reservoir model illustrates the difference between the hydrocarbon and geothermal exploitation objectives (Fig. 2). The model contains five wells in an L-pattern with a 500 m spacing and an alignment parallel and perpendicular to the paleo flow direction. In terms of drainable volume, these wells are efficiently placed and intersect most of the sandstone bodies in the reservoir. However, if the wells included geothermal doublets, the distance and orientation of the well pair layout would significantly influence the chance that flow paths are formed between well pairs. Please note that the well spacing in the model is a third to one half of the 1.5 km spacing commonly used in HSA doublets (Lopez et al., 2010; Mottaghy et al., 2011). A larger well spacing would increase the risk of connectivity loss. The chance that sandstone bodies form flow paths parallel and perpendicular to the paleo flow direction (i.e., the connectivity anisotropy) has so far not been investigated.

The West Netherlands Basin (WNB) is an example of an area with fluvial HSA exploitation. Six doublets currently produce from the fluvial Nieuwerkerk Formation (DeVault and Jeremiah, 2002; Van Heekeren and Bakema, 2015). In three of them the doublet layout is parallel to the paleo flow trend. In the other three doublets, the layout is oblique or perpendicular. Productivity and injectivity vary considerably in the WNB (Van Wees et al., 2012). The reduction in injectivity could be related to well layout but also to other factors such as scaling or skin formation. Van Wees et al. (2012) pointed out that unfortunately it is not possible to identify a single cause of this variability because of limited available data. The uncertainty in injectivity and productivity, limits the growth of HSA development. In the Netherlands this is reflected by the fact that approximately 100 exploration licences are granted, while only 14 doublets are actually realised in the past 10 years. Such a gap between HSA potential and actual exploitation exists worldwide (Boxem et al., 2011). Other examples of sedimentary basins with large HSA potential but limited exploitation are the Perth Basin, Australia (Pujol et al., 2015), and the Idaho thrust belt (Welhan, 2016). A better understanding of connectivity anisotropy could reduce the risks associated with HSA exploitation and hence support its growth. Therefore, the first goal of this paper is to evaluate connectivity anisotropy and its dependence on N/G. Secondly, the possible effect of this anisotropy on doublet performance is evaluated. The results should contribute to fluvial HSA development strategies that increase the efficiency and decrease the risks of exploitation.

For this purpose, hundreds of detailed facies architecture realisations have been generated. This stochastic approach, in which reservoir heterogeneities are taken into account, is standard in hydrocarbon exploitation (e.g. Keogh et al., 2007). In contrast, geothermal reservoirs are often modelled as homogeneous layers (e.g. Mottaghy et al., 2011). The realisations are based on a geological dataset of the Lower Cretaceous Nieuwerkerk Formation (DeVault and Jeremiah, 2002). Sediments in this interval were