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Hydraulic Connectivity in Pannonian Sandstones of the Mezőberény geothermal doublet

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ABSTRACT

The geothermal doublet at Mezőberény in SE Hungary has suffered from poor productivity and injectivity since it began operation in 2012. The injection and production wells of the doublet are near vertical and have ~400 m production interval, consisting of few thin sandstone bodies in a shale matrix. Previous studies have considered chemical factors, such as scaling and clay mobilisation, as possible causes of injectivity and productivity limitations. So far, however, the possible impact of poor hydraulic connectivity on these limitations has not been considered. Therefore, a geological model describing the geometry of the sandstone bodies in the aquifer and its net sandstone content have been derived in this study. The model is based on a geological dataset from the Békés Basin including core samples, 2D seismic lines and Gamma Ray logs of nearby petroleum wells. Dozens of aquifer realisations of this model were generated, which capture the sedimentary architecture of the aquifer utilising an object-based modelling approach. For each realisation, the volume of sandstone bodies that both wells intersect was calculated. We found that only a small percentage of the total sandstone volume in the realisations was intersected by both wells. This indicates that the net aquifer volume is most likely much smaller than the net-sandstone content of 11% that was derived from the well logs. Therefore, these results suggest that it is likely that hydraulic connectivity is poor between the injection and production well in the doublet, limiting injection and production rates. In addition, our results highlight the importance of sedimentary facies analysis as a tool for successful exploitation of geothermal resources.

1. INTRODUCTION

Hundreds of geothermal wells have been drilled in Hungary in past decades for direct-use applications. Approximately half of these are used for spas and the other half for district-, agriculture- or industrial heating (e.g. Nador et al., 2016). Deltaic and turbiditic sandstones deposited during the Pannonian stage of the Late Miocene form one of the main geothermal targets in the Pannonian Basin (e.g., Nador et al., 2016; Szanyi and Kovács, 2010; Toth, 2015). These rocks were deposited during a time of dramatic environmental change, resulting in rapidly-changing sedimentary environments: the ancestral southward drainage of the Pannonian Basin to the Aegean Sea became disrupted, creating an endoreic lacustrine environment, before the modern drainage to the Black Sea via the River Danube became established (Csato et al., 2007; Olariu et al., 2018; Sztanó et al., 2013). Despite the long experience with geothermal heat production from these aquifers, reinjection issues are common and fewer than 10% of all Hungarian geothermal wells are reinjection wells in the past decades; most projects discharge at the Earth's surface (Szanyi and Kovács, 2010; Toth, 2015). Without reinjection, aquifer pressure has reduced significantly in recent decades at most geothermal sites, limiting efficient and sustainable exploitation of these geothermal resources (Szanyi and Kovács, 2010). Chemical factors, such as scaling and clay mobilization have previously been discussed as causes of the injection problems (Balint et al., 2010; Nador et al., 2016).

In this study, the impact of the sedimentary aquifer architecture on injectivity is evaluated, the geothermal doublet at Mezőberény, SE Hungary, being used as a case study. The wells of this doublet have a depth of ~2000 m and a large production interval of approximately 400 metres with a low Productivity Index (PI) of 2 to 4 [L/s/bar]. The Gamma Ray (GR) logs of the doublet indicate that the sandstone content (net-to-gross, N/G) of the aquifer is low. In addition, the thickness of the individual bodies is low, ranging from several tens of centimetres to up to 7m (Fig. 1). According to (Phillips et al., 1994) the depositional environment of rock at similar depths of a nearby petroleum Hunya-1 is delta-plain to alluvial-plain. Sandstone bodies are therefore most likely deposited as mouth-bar lobes or channel shaped bodies with limited lateral extent. Multiple studies have highlighted the risk of low hydraulic connectivity between such sandstone bodies in sedimentary reservoirs, especially with N/G below 30% (Ainsworth et al., 1999; Larue and Hovadik, 2006; Manzocchi et al., 2007; Willems et al., 2017; Willis and Tang, 2010; Zhang et al., 2013). Therefore, the possibility exists that the sandstone bodies in the Mezőberény aquifer also have limited lateral extent, reducing the formation of flow paths between the wells. To illustrate this, two extreme possibilities of flow path formation are sketched in Figure.1. Figure 1-A shows a ‘tramline’ configuration, were the sandstone bodies have sheet-like geometries with lateral extent of several kilometres. In Figure 1-B, another extreme aquifer architecture scenario sketched whereby sandstone bodies have a width of several hundred metres and therefore do not directly connect both wells. While some sandstone bodies might connect further up- or downstream of the paleo-flow direction, injectivity would be reduced in this last scenario because all the reinjected water will have to flow through a smaller aquifer volume, and through longer flow paths.

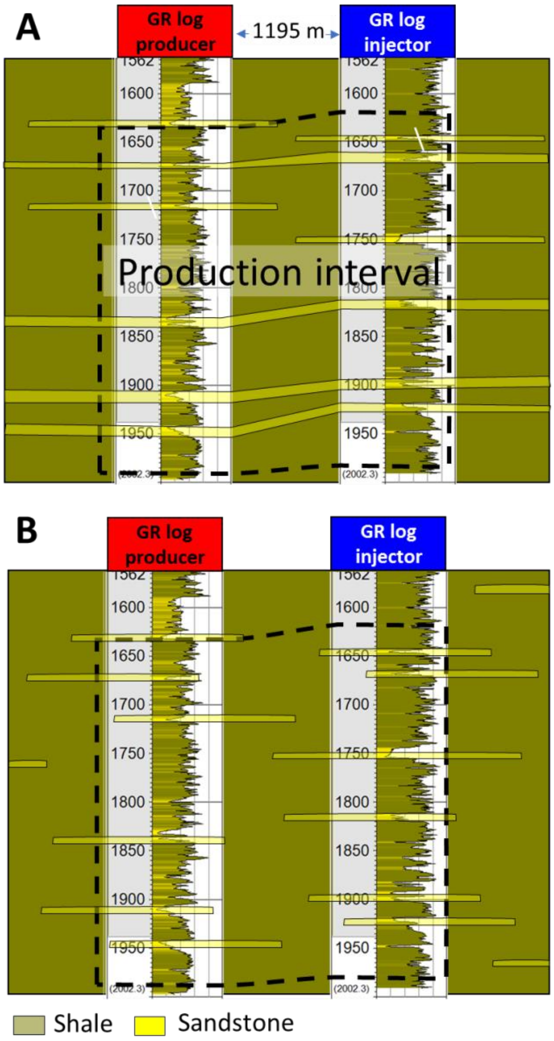

Figure 1 Cartoons illustrating the impact of different sandstone architecture on hydraulic connectivity of the doublet in Mezőberény. In (A) sandstones are extensive sheets and hydraulic connectivity is high. In (B) sandstone bodies have limited width and are embeded in an impermeable shale matrix, resulting in lower hydraulic connectivity. Low Gamma Ray (GR) readings indicate sandstone, and high readings indicate shale. Depth indication is every 50 m.

The risk of low hydraulic connectivity in the Mezőberény doublet is assessed in this study in two phases. In the first phase, a geological model was derived that describes the geometry of sandstone bodies and the net-sandstone content of the aquifer of the Mezőberény doublet. The geological model is based on a geological subsurface dataset from the Békés Basin. In the second phase, detailed 3D realisations were generated of the geological model, width an object-based modelling approach. For each realisation, the volume of sandstone is calculated that both wells intersect. This volume is expressed in percentage of total sandstone volume in each realisation. A high connected volume percentage is associated to good hydraulic connectivity and a low percentage to poor hydraulic connectivity.

Using this statistical approach, we aim to support the hypothesis that poor hydraulic connectivity limits injectivity of the Mezőberény doublet. This work highlights the need for establishing the importance of sedimentary facies analysis as a tool for successful exploitation of geothermal resources.

2. METHOD AND DATA

2.1 Geological dataset

A subsurface dataset from the Békés Basin in southeast Hungary formed the basis for the geological model. The dataset comprised of two Gamma-Ray (GR) logs of the Mezőberény doublet, three vintage GR logs of nearby petroleum wells, core fragments from the Gyoma-1 well and six 2D seismic lines (Fig. 2). Core fragments from five intervals of the Gyoma-1 well were available. Originally, some 5 m sections were cored at these intervals, but only few fragments of several centimetres in height and up to 8 cm in diameter were actually recovered.

2.2 Derivation of depositional environment and sandstone body geometry

The core- and GR log interpretation provided estimates of ranges of sandstone body thickness, which were parameters for the geological modelling. The GR logs were also used to derive the N/G of the aquifer. Values for sandstone body width cannot be derived from 1D well log data. Estimates of sandstone mouth-bar width were derived from a study by Richards et al., 2014, describing the Holocene Volga Delta. Because of the uncertainty in this assumption, we used a wide range values for sandstone body width, ranging from 100 to 400 m, width 250 as mean. Because the proto-Tisza and the proto-Danube were probably smaller than the Holocene Volga delta (Olariu et al., 2018), this assumption could overestimates the actual mouth-bar width. Larger width enhances the chance on hydraulic connectivity (e.g. Larue and Hovadik, 2006). Therefore this assumption might lead to more positive hydraulic connectivity in the realisations. Estimates of the delta-plain sandstone body width were derived from Amplitude Versus Offset (AVO) seismic attribute horizons published by Sztanó et al. (2013) and Balázs et al. (2018). These studies visualise narrow fluvial sandstone on seismic attribute horizons with low amplitude of ~1km, widths of up to ~300 m, and with wavelengths of approximately 3000 to 5000. In addition, they visualise small mouth-bar lobes just upstream of the palaep shelf edge of several hundred meter in width.

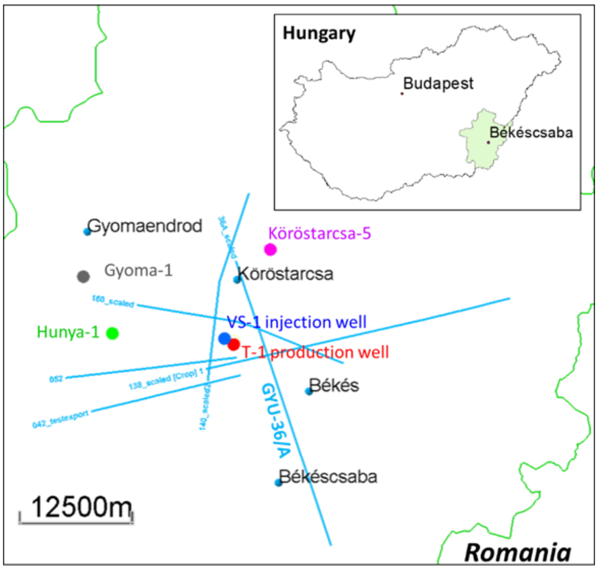

Figure 2: Location of the Békés Basin in Hungary, and the outline of our study area with the location of the seismic lines, the doublet and nearby petroleum wells. Core fragments of the Újfalu Formation were available from the Gyoma-1 well.

2.3 Seismic interpretation

The seismic lines were used to interpret guiding surfaces in TWT for the top and base horizons of the geological model. We followed seismic interpretation by (Csato et al., 2015; Sztanó et al., 2013) to interpret the base of the alluvial sediment interval of the Zagyva Fm. (Fig. 3), by recognising a difference in seismic facies. Without well control and access to density and porosity data, we were not able to depth convert these surfaces and compensate for differential compaction (Lamb et al., 2017). Nevertheless, we assume that these factors will largely average out on overall basin scale and that therefore the TWT surface can be used as guiding surfaces for the top and base horizon in the geological modelling process. The depth of the top of the aquifer model was constrained at the well locations.

Epoch	Stage	Formation	Depositional environment
Late Miocene	Upper Pannonian	Zagyva Fm.	terrestrial
		Újfalu m.	↑
	Lower Pannonian	Algyö Fm.	
		Szolnok Fm.	Lacustrine

Figure 3 Schematic regional stratigraphy.

2.4 Geological modelling

The detailed facies realisations were generated using an object-based modelling approach in Schlumbergers Petrel 2018 software suite. To focus on hydraulic connectivity between the wells through sandstone bodies, only sandstone and shale facies were distributed in a shale matrix (Fig. 4). Facies distribution was constrained by facies interpretations on the well logs. Input parameters for the geological modelling include (1) N/G, (2) ranges of sandstone body width and thickness and (3) a range of palaeo-flow directions. We assumed that the main palaeo flow direction was from the northwest (Csato et al., 2015), with a 15° range. Thirty realisations were generated. The realisations had dimensions of 3 km x 3 km x 400 m (Fig. 4). Grid blocks were 50 m x 50 m, width a maximum thickness of 3 m. The top and base of the production interval formed the top and based on the aquifer model. The topography of these surfaces was made utilising dipping trends of the seismic interpretations.

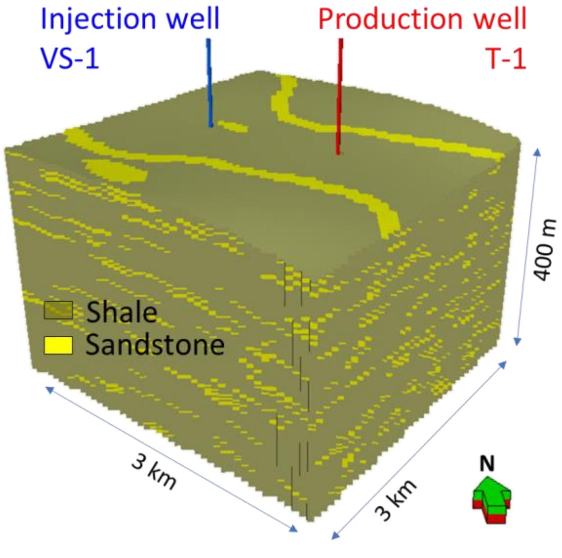

Figure 4: Example of facies realisation.

2.5 Hydraulic connectivity calculations

In the 'connected volume' application of Petrel 2018, a group of adjacent sandstone grid blocks was defined as a sandstone cluster. These clusters were formed by individual sandstone mouth bars or channel bodies, or by amalgamations of these bodies. The clusters were numbered, and the number of grid blocks per cluster was derived for each realisation. Subsequently, a 3D matrix was generated for each realisation whereby each element corresponds to a grid cell and its associated sandstone cluster. Shale grid blocks remained undefined in the matrix. Two vectors were extracted from this matrix of grid blocks at the locations of the trajectories of the injection and production well. The vectors contain the values of the clusters that the wells intersect. By comparing the two vectors, the sandstone clusters were identified that both wells intersect. The number of grid blocks that formed these clusters was divided by the total number of sandstone grid blocks in the realisation to express hydraulic connectivity in percentages.

3. RESULTS

3.1 Core interpretation GYOMA-1

Sedimentary structures and ichnofacies in core fragments from the Gyoma-1 well suggest that the sediments of the interval between 2000 to 1600 m depth are a mix of delta-front and delta-plain deposits. Examples of subaerial delta plain deposits can be recognised in core fragments at 1995 m depth and 1600 m depth (Fig. 5-d and e) as rootlets cutting through ripple structures and laminations of light grey, fine grained sandstone and darker siltstone laminations in the deepest core section. Oxidized siltstone in Fig. 5-a also suggests a subaerial delta-plain origin of this section. Several fining upward sequences can be recognised on the GR logs of all wells in Fig. 5 at depths above ~1650. These were associated to distributive channel bars on the delta-plain (dotted-lined squares in Fig.5). Also, several coarsening upward sequences can be recognised on the GR log (blue squares in Fig. 5), which are associated to prograding delta-front mouth-bars. The lower part of one particular coarsening upward sequence was cored at 1710 m depth. The core sample of this sequence shows thin laminations of layers of very fine-grained sandstone and darker grey siltstone to claystone. These darker siltstone laminations contain abundant fine-grained lignitic fragments of less than 1 mm size (Fig. 5-b and c).

3.2 Regional well log correlation

In the well log correlation panel of Fig. 6, two distinct intervals can be recognised based on GR log trends. One heterogeneous interval with a 'ratty' GR signature up to depths of ~1950 and another interval with more homogeneous GR readings at larger depths. The latter is associated to a more distal delta slope deposits of the Algyö Formation. The heterogeneous interval is associated to the delta-front to delta plain Újfalu Formation. The well log correlation scheme in Fig. 6 is based on the recognition of a large regional N/G trend on the GR logs. Black arrows in this figure highlight this trend between the base of the Újfalu Formation marker and a correlation marker at the base of a low N/G interval. This trend is associated to a relative drop in lake level, prograding delta-front deposits with high N/G, followed by lower delta plain deposits with lower N/G. Based on this correlation scheme, we deduce that the depositional environment of the aquifer rocks at Mezőberény is similar to the cored interval of the Gyoma-1 well (Fig. 5). The GR log scales vary for each well because the logging took place in difference decades, by different companies, and most likely through partially cased well intervals or past casing shoes. Using the lithological description of drill cuttings of these wells, a GR cut-off value was chosen for each well. With these GR cut-off values, N/G was calculated in each well for Újfalu Formation at depths below 1600m, which is the top of the production interval of the geothermal doublet. The average N/G of this interval is 11%. Only the GR log of well Kot-5 has API, the other ones have vintage Roentgens/hour units. These values are multiplied with 10 to approximate API GR units.

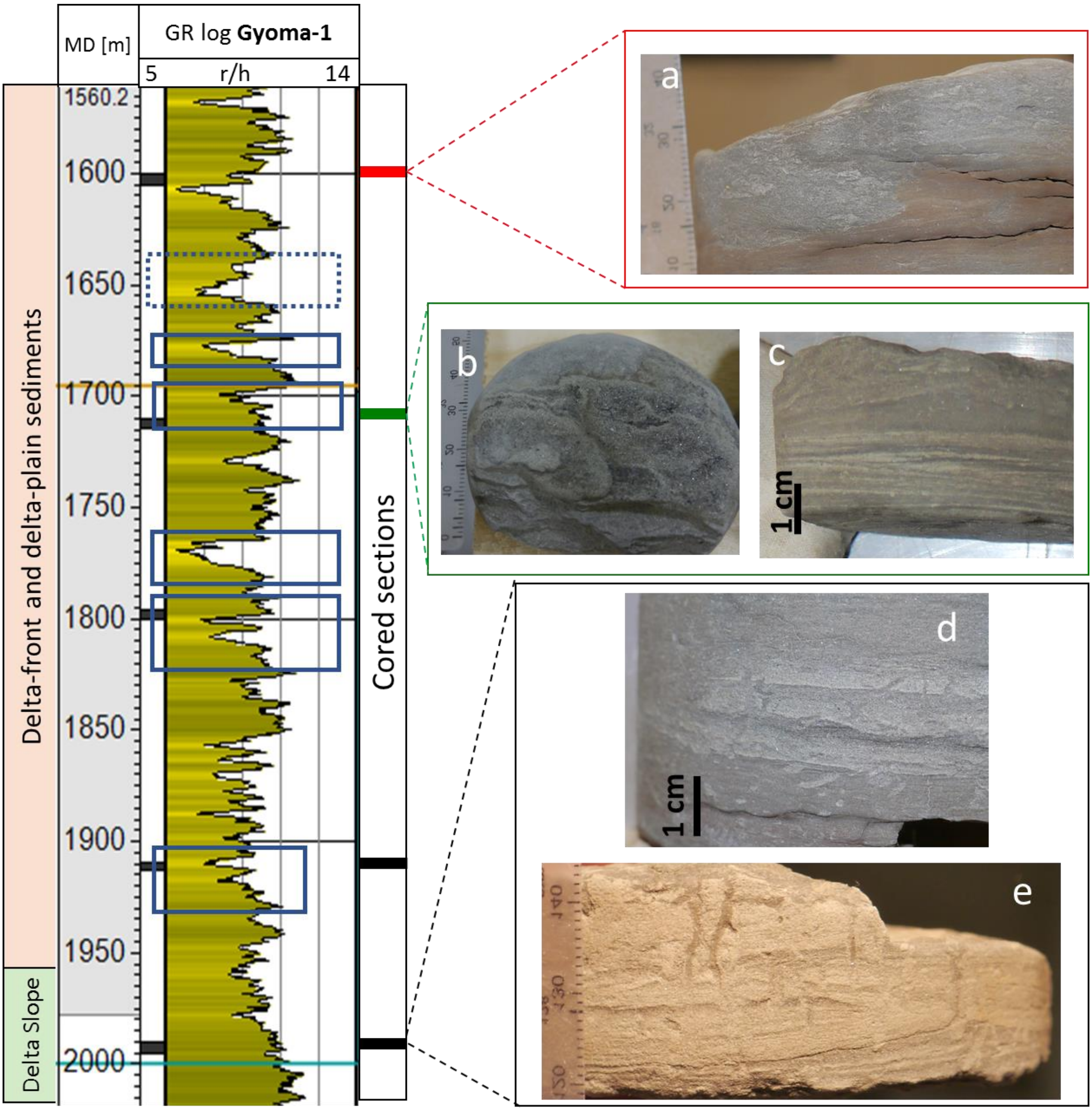

Figure 5: Gyoma-1 vintage GR log in roentgens/hr and cored intervals on the left, with examples of core fragments on the right. Boxes projected on the log with solid line highlight coarseing upward sequences, dotted line boxes indicate fining upward sequences on the GR log. Our interpretation of depositional environment is indicated on the left side of the log. Sedimentary features and ichnofacies that were recognized in the samples include: (a) oxidized soil, eroded by light grey sandstone. (b and c) fine grained sandstone with thin, darker gery silty laminations with abundant lignitic fragments, (d and e) rootlets in fine grained sandstone with ~1 cm ripple structures.

3.3 Estimation of sandstone mouth-bar geometries

The largest complete coarsening upward signal that was recognised in the logs was approximately 7 m (Fig. 5). This was associated to a maximum thickness of the mouth-bar lobes in the aquifer. Small gamma ray peaks within coarsening upward sequences are interpreted as fine grained, distal deposits that cover mouth-bar lobes during rises of the relative base level in different parasequences (as sketched in Fig. 7-A) or delta avulsions. Sandstone sections on the well logs with a larger thickness than 7 m are assumed to be stacked mouth-bar complexes. The estimated lobe width is 100 to 400 m, which is derived from visual interpretation of Amplitude Versus Offset maps by (Sztanó et al., 2013). Several fining upward sequences can be recognised on the GR logs Figure 4 with a maximum height of 4 m (e.g. at ~1660 m Gyoma-1, 1665 m Hunya-1, 1645 VS-1, 1900 m Köt-1). They were associated to palaeo bank-full flow depth of fluvial deposit (e.g. Fielding and Crane, 1987). The relation between fining upward sequence, point-bar height, sandstone body thickness and channel body width is sketched in Figure 7-B. A thickness distribution of sandstone bodies for all wells is presented in Figure 8. The distribution shows that only three mouth-bar-complexes of more than 8 m thickness occur in the aquifer interval. Most likely this is because many of the sandstone bodies are isolated lobes and the mouth-bar lobe thickness tapers rapidly away from the mouth-bar source. Figure 8 shows that most of the sandstone bodies that were intersected by the wells in in Figure 6 have a thickness of less than 2 m.

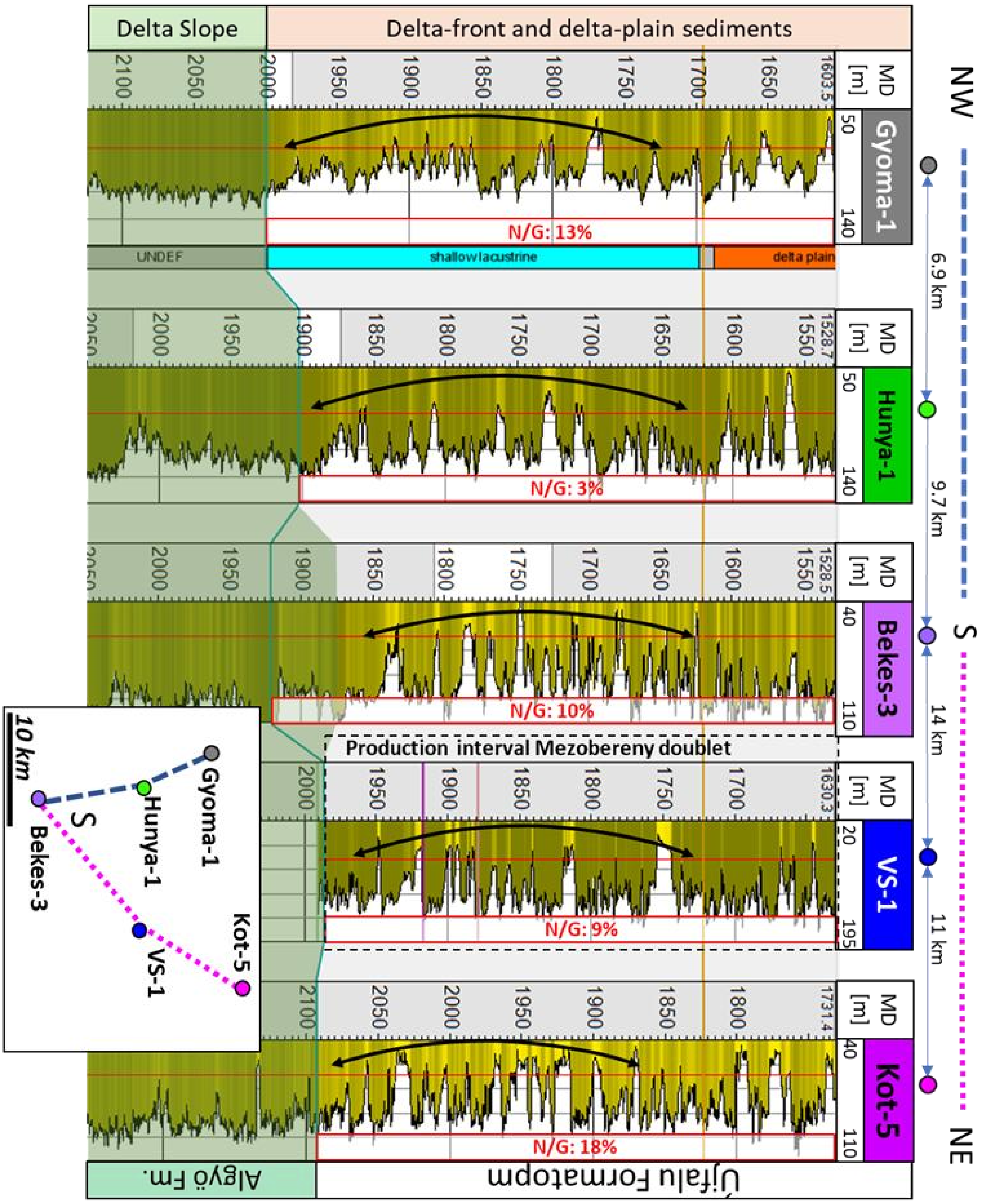

Figure 6: Regional GR well log correlation. Only one well of the Mezobereny doublet is displayed (VS-1). The black arrows highlight a regional GR log trend in the Ujfalu Fm. The map indicates the locations of the wells in our study area. GR cutoff values were: 75 for Gyoma-1, 80 for Hunya-1, 60for Bekes-3, 75 for VS-1 and 60 for Kot-5.

Sandstone bodies in this thickness range may also include crevasse splays and small distributive channels in the Delta plain, especially in the upper part of the aquifer. Furthermore, a small peak in sandstone thickness is recognised around 4 m. Table 1 summarises the estimations of sandstone body geometries that were described in the sections above. Half of the sandstone grid blocks in the realisations formed mouth-bar lobes, the other half formed fluvial sandstone bodies.

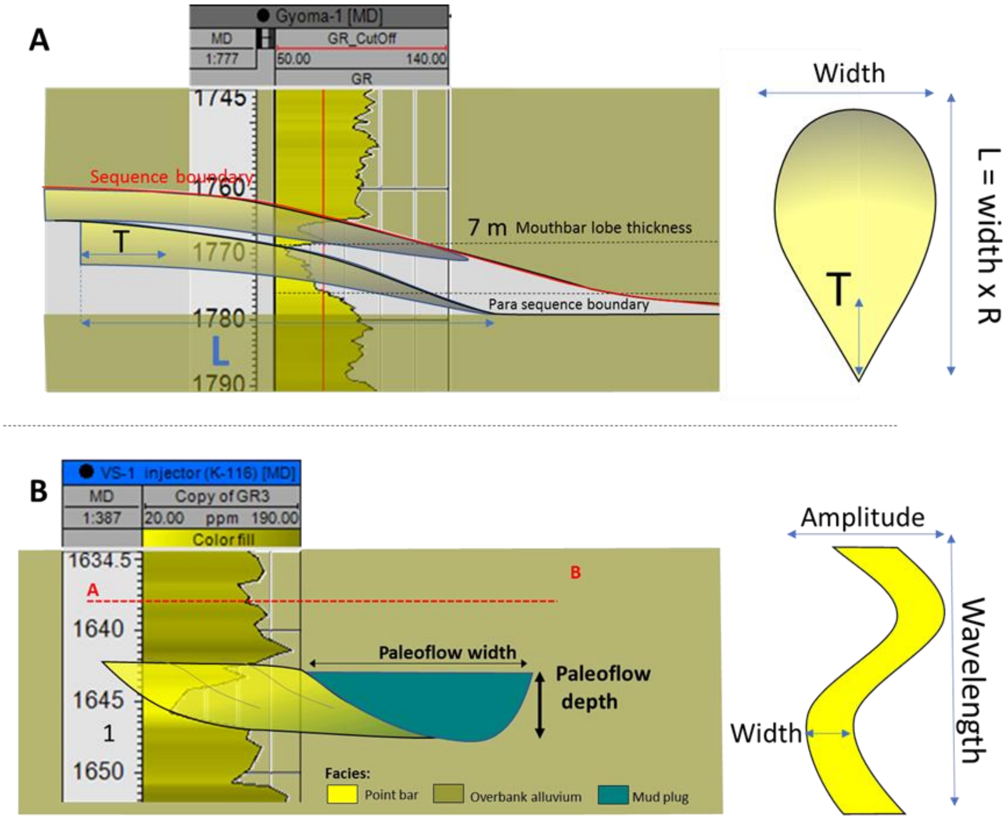

Figure 7: Schematic two-dimensional depiction of the relation between the GR log of the Gyoma-1 well and (A) mouth-bar stacking (inspired by Ainsworth et al., 1999) and (B) Fluvial sandstone bodies. On the right, map views of the two types of sandstone bodies associated object-based modelling input parameters (Table 1) is sketched. In (A), T indicates distance from the base of the lobe where tapering starts reducing lobe thickness and R is the length to width ratio (see Table 1).

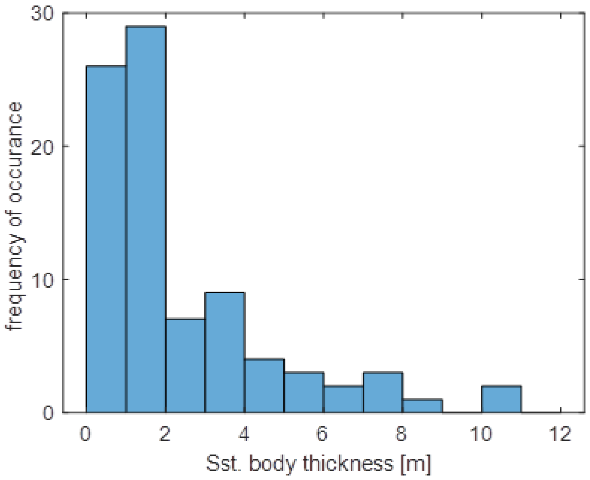

Figure 8: Frequency of occurrence of sandstone body thickness, derived from the GR logs in Figure 6.

Table 1: Sandstone body geometries. W is width and L is length as in Fig. 7.

Mouth-bar lobes			
	Min	**Med**	**Max**
Thickness (m)	3	4	7
Lobe width (m)	100	250	400
Length	1xW	2xW	3xW
(T) Tapering start	0.1xL	0.2x L	0.4xL
(R)Ratio Length/width	1	2	3
Fluvial channel bodies			
	Min	**Med**	**Max**
Thickness (m)	3	4	5
Width (m)	100	200	300
Amplitude (m)	400	800	1200
Wavelength (m)	3500	4000	4500

3.4 Hydraulic connectivity

Only a small fraction of the sandstone bodies in our realisations are intersected by both the production and injection well. Fig. 8-A to C shows this for one particular realisation. In this realisation, many of the sandstone grid blocks form smaller isolated clusters embedded in an impermeable shale matrix (Fig. 8-A).

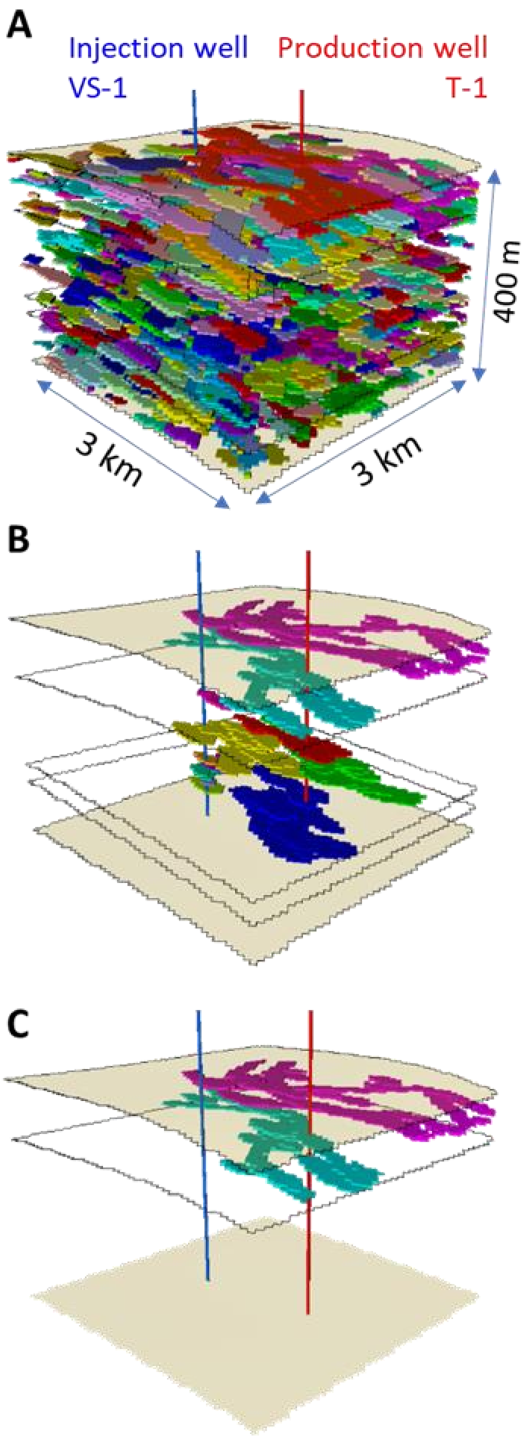

Figure 8 3D examples of connected volume calculations. (A) all sandstone clusters in one realisation with shale. Each cluster has a different colour, shale frid-blocks are transparent. (B) Sandstone clusters that are connected to one or both wells of the doublet, (C) sandstone clusters that are connected to both wells.

Because sandstone content is low, and because the sandstone bodies have limited width, only some of the all sandstone body are connected to one of the wells (Fig. 8-B). An even smaller percentage of the sandstone volume in the aquifer is intersected by both wells (Fig. 8-C). Only the clusters that are intersected by both wells would contribute to the hydraulic connectivity of the doublet in this realisation. The example in Figure 8 illustrates the importance of considering sedimentary aquifer architecture to assess hydraulic connectivity risk Pannonian Sandstone aquifers.

The average sandstone volume that is intersected by at least one of the doublet wells ranged from 40 to 60%, with an average of approximately 45% (Fig. 9). The percentage of the sandstone volume that both wells intersect, and thus contributes to hydraulic connectivity is on average ~20%. In some realisations, only ~5% of the sandstone volume is intersected by both wells. Assuming that our geological model is representative of the aquifer, these results suggest that hydraulic connectivity could be a significant factor limiting the injectivity of the doublet. Moreover, the results highlight the importance of sedimentary facies analysis as a tool for successful exploitation of geothermal resources, which is common-practise in well planning for hydrocarbon exploitation (e.g. Bridge, 2006; Larue and Hovadik, 2008, 2006).

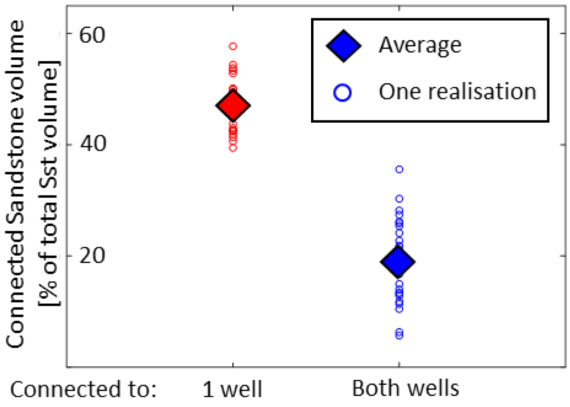

Figure 9: Volume of sandstone that is connected to at least one of the wells (left) and to two wells (right), expressed as percentage of the total sandstone volume in the realisation.

4. CONCLUSIONS.

In this study, we have explored the possibility that poor hydraulic connectivity limits the injectivity of the Mezőberény doublet. Low net-aquifer volume impacts injectivity when all the injected water is forced to flow through a small aquifer volume which increases the required pressure. Ultimately, this would not only affect injectivity but also the life time of the doublet because the reinjected fluid reaches the production well faster when it is injected into a smaller aquifer volume (e.g. Crooijmans et al., 2016). We have used a stochastic approach to make a probabilistic assessment hydraulic connectivity. For this purpose, we derived a geological model of the aquifer describing the depositional environment, the geometry of the sandstone bodies and the net sandstone content. The model was based on a geological dataset consisting of core fragments, GR logs and 2D seismic lines. These data suggest that the aquifer was formed in shallow water lacustrine delta environment. The sandstone bodies in the aquifer therefore predominantly comprise of mouth bar lobes, with some fluvial channel bodies especially in the shallowest interval of the aquifer. The net sandstone content is approximately 11%. Thirty 3D realisations of this geological model were generated with an object-based modelling approach. In each realisation, the percentage of sandstone in the aquifer that both wells of the doublet intersect is determined. The sandstone volume that both wells intersect was not more than on average ~20% of the total sandstone volume of all realisations. This can be explained by the low net-sandstone content and the limited width of the sandstone mouth bar lobes in our geological model. Our results are consistent with previous connectivity analyses on lobate reservoirs (e.g., Manzocchi et al., 2007; Zhang et al., 2013) and channelized reservoirs (Larue and Hovadik, 2006; Willems et al., 2017). The results highlight the likelihood that ‘tramline’ models of the aquifer as sketched in Figure 1-A could overestimate the net volume of the aquifer. Many Hungarian geothermal schemes have injection issues (e.g. Szanyi and Kovács, 2010; Toth, 2015), and most of these were developed based on these simplified tramline aquifer models. This work highlights the importance of detailed analysis of sedimentary facies architecture as a tool for successful design of future doublets in the Pannonian Basin. The geological model that was described in Table 1, as wells as the ‘tramline’ model should be considered as two end members of possible geological models that describe the aquifer. For further work on hydraulic connectivity of Pannonian Sandstones, we recommend a more comprehensive study into appropriate outcrop analogues. Utilizing 3D seismic attributes like Balázs et al., (2018) and Olariu et al. (2018), as well as considering studies on regional N/G trends in delta plain and alluvial environments (e.g. Owen et al., 2018) could also improve the understanding of aquifer architecture in the Pannonian Basin. Furthermore, the results of our study could be refined by utilising process-based facies modelling to generate more realistic facies realisations (e.g. Vegt et al., 2016). Finally, the impact of hydraulic connectivity could be quantified further with numerical production simulations.

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