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Geothermal Reinjection Problems from a Basin-scale Hydrogeological Perspective

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ABSTRACT

Fluid injection into overpressured regimes is only possible with an injection pressure higher than the aquifer pressure. The elevated aquifer pressure eventually prevents fluid inflow through reinjection. Elevated pressure (much higher than hydrostatic) in an aquifer under exploitation, however, can also evolve naturally due to overpressure dissipation from underlying units. The suggested basin-scale hydraulic evaluation complements the traditional geothermal potential and risk analysis. A pressure-regime analysis can be also used to estimate the injection capacity and reinjection problems.

As a case study, we evaluated the hydraulic conditions surrounding the Mezőberény doublet system (40x50 km in SE Hungary). This site faces reinjection problems since 2012, which resulted in stopping geothermal production. The overpressure was assumed to be among the potential reasons for reinjection problems at that site. The analysis was carried out by 1) analyzing the properties of the underlying aquitard unit, 2) defining the pressure regime and the vertical driving forces, 3) modelling the influence of the overpressure on the hydraulic conditions of the reservoir, 4) evaluating the temperature state, 5) characterizing the water chemistry.

Results show that overpressure is present in the underlying units beneath the reservoir with extreme pressure values, dynamic pressure increments (e.g. Δp=11.21 MPa) and superhydrostatic pressure-gradient (indicating ascending flow). Moreover, in the wider study area, the overpressure is likely dissipating into the aquifer indicated by positive dynamic pressure increments (Δp=0.77 MPa and Δp=0.14 MPa) and superhydrostatic pressure gradient (y=11.43 MPa/km). However, at the closer surrounding of the study system, this effect could not be observed: neither the pressure regime nor is the vertical pressure gradient (9.7 MPa/km) superhydrostatic within the reservoir. The reason can be that – based on seismic and well data – the underlying aquitard units are thick and continuous below the study site. Thus, the dissipation of overpressure by vertical leakage through aquitards is likely blocked by them. This is supported by the numerical modelling which suggests hydrostatic conditions at the study site. The numerlical modelling also showed the possible presence of elevated hydraulic heads in the reservoir due to overpressure beneath the aquifer in case of thinned aquitard and/or conduit fault.

Consequently, injection problems due to an overpressured regime is not expected close to the well of Mezőberény. However, based on the results, this effect is proposed to be considered in the farther part of the study area as well as in other overpressured regions. We also propose to take hydraulic conditions into consideration and to apply the approaches of this study during geothermal exploration, risk and problem analyses.

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1. INTRODUCTION

The regional hydraulic evaluation in geothermal exploration in sedimentary basins complements the traditional geothermal potential and risk analysis. In addition to the potential (exploitable) resources, injection capability is also assessed. Unlike the quasi-hydrostatic regimes, injecting fluid into overpressured regimes is only possible with an injection pressure higher than the reservoir overpressure (Mádl-Szőnyi & Simon, 2016). Elevated pressure in an aquifer can originate from an underlying region through dissipation of overpressure by fluid transport as well (Czauner and Mádl-Szőnyi 2013). Consequently, the increased pressure in the overlying aquifer pushes against the reinjection (Mádl-Szőnyi & Simon, 2016; Mádlné Szőnyi, 2019). A pressure-regime evaluation can therefore also be used to estimate the injection possibilities and provides basic knowledge for planning the required injection pressure (Mádl-Szőnyi & Simon, 2016).

In this study a possible negative effect of hydraulic conditions is examined in the Pannonian Basin on the injectivity of Mezőberény well (SE Hungary). This a new approach beside the traditional ones, for revealing the reasons for unsuccessful reinjection. To this end, we analyzed the type of the pressure regime, the possible propagation and presence of the overpressure based on data analyses and numerical simulation.

2. STUDY AREA, STUDY SITE

2.1. Location and geology

The study area is located in the Körös-Maros interfluve and covers the broad surrounding of the town Mezőberény with the edge-points of SW: EOV Y: 774000; EOV X: 146000; NE: EOV Y: 823000; EOV X 185000 (Figure 1). The study area lies between 80-100 m above sea level with a relatively small relief (1,5-3 m/km^2) (Dövényi, et al., 2008).

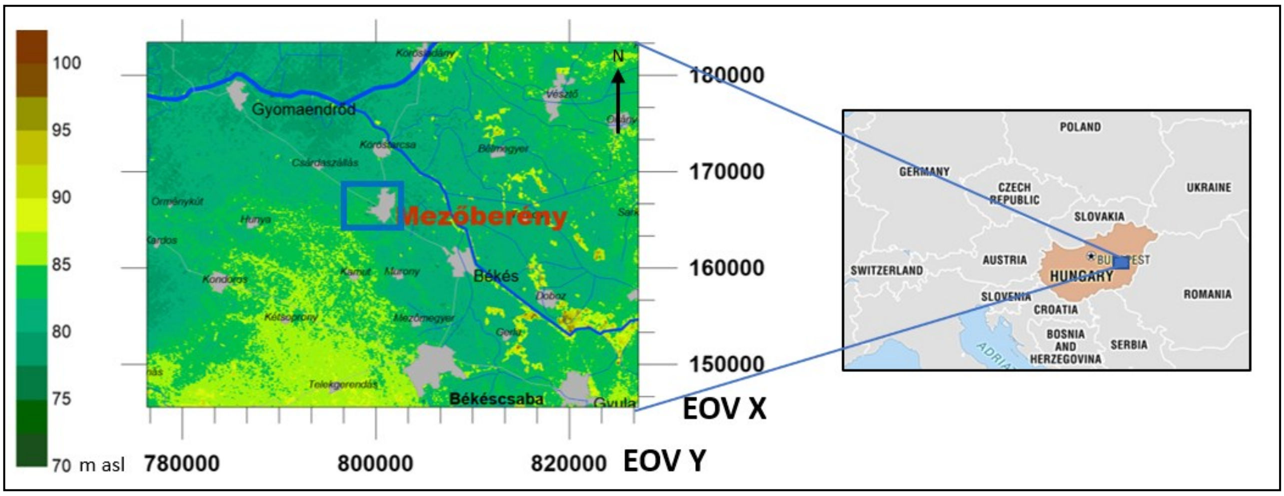

Figure 1: Location and extension of the study area

The Pannonian Basin and its Békés Subbasin are filled with siliciclastic deposits. While Deep-water Pannonian sediments (Endrőd, Szolnok, Algyő Formations) are less permeable; the Shallow-water Pannonian (Újfalu, Zagyva) formations contain vast porous, permeable sandy and sandstone beds. Thickness of these beds varies between 1 and 30 m (Bobok, et al., 1984).

Considering the flow regimes, the subsurface of the Pannonian Basin can be divided into upper and lower hydrodynamic regimes. In the upper, regionally unconfined, topography driven system, elevation differences and topographic relief serve as driving force for the fluid flow (Tóth & Almási, 2001; Almási, 2003). Below this zone, regionally confined, overpressured regimes can be found. In this particular case, regionally effective sources of overpressure are the lateral tectonic compression and burial compaction (Almási, 2003). These force the vertical flow direction upwards. Communication between the two regimes can happen by diffusion through geological strata, and through the conduit structural discontinuities having high permeability. Conduit faults can help in pressure dissipation, causing anomalies in the flow patterns of the gravitation driven regime (Czauner & Mádl-Szőnyi, 2011). Due to the communication of the two regimes, a transition zone has been formed between them. Depth and thickness of this zone vary in the basin, and do not correlate either with hydrostratigraphic boundaries or concrete elevation values (Tóth & Almási, 2001).

We applied a general hydrostratigraphy based on Tóth and Almási (2001) and Almási (2003): This involves the Great Plain Aquifer (GPAF) which consists of the Shallow-water Pannonian (Zagyva and Újfalu) Formations and the Quaternary sediments with an average hydraulic conductivity (K) of 10^{-5} m/s. They are underlain by the Algyő Aquitard ($K=10^{-8}$-10^{-7} m/s), the Szolnok Aquifer ($K=10^{-7}$-10^{-6}) and the Endrőd Aquitard ($K=10^{-9}$-10^{-8} m/s). In elevated positions Algyő Aquitard can be characterized by less effective aquitard properties and higher conductivity (Tóth & Almási, 2001). At the area of Békés Basin, Szolnok Aquifer has a lower grain size and lower permeability due to the long transportation route. Thus, it can be less conductive with aquitard characteristics (Juhász, 1992; Czauner, 2012).

2.2. Study site and problem statement

The study system – constructed in 2011-2012 – consists of one production well (B-115) and one reinjection well (K-116) (Table 1). Wells are fully cased until 2003 and 2001 m depth, respectively, and screened to the sandstone bodies of the Shallow-water Pannonian Sandstones.

Table 1: Basic data of the Mezőberény geothermal doublet

	Mezőberény	
	Producer	Injector
Number	B-115	K-116
Year of drilling	2011	2012
Elevation asl (m)	85,440	85,320
Bottom depth (m)	2003	2001
Reservoir rock	Shallow-water Pannonian Sandstone	
Filtered interval (m)	1826-1947	1643-1931
Length of screened section (m)	27,5	75,5
Static water level	-9,53 m	-7,56 m
	75,91 m asl	77,76 m asl
Bottom hole temperature (°C)	109,7 (at 1995,5 m)	111,3 (at 1989 m)
Outflow temperature (°C)	76,9	83,2
Initial operational flow rate (l/min)	350 (producable)	250 (injectable with 1,5-2 bar)

Thermal water was supposed to support the district heating system with schools, offices, and other public facilities. Due to the fast injectivity decline – experienced after start of operation – the operation of the system had to be stopped. Potential problem sources have been proposed and investigated covering inadequate reservoir properties and clogging processes (fines migration, mineral precipitation, biofilm formation). However, a viable long-term solution for increasing the injectivity has not been found yet

(Brehme, et al., 2019). Influence of basin-scale hydraulic has not yet been taken into consideration. Therefore, in this study, the potential role of overpressure and possible proof of its presence are investigated.

3. APPROACHES AND METHODS

The analysis was performed using five different approaches: 1) describing the aquitard properties 2) evaluating the pressure conditions, 3) numerical simulation 4) characterizing the temperature state, 5) interpreting the water chemistry.

3.1. Examining the aquitard properties

We examined the properties of the underlying aquitard to obtain information about the structural and lithologic properties and thus estimate its regional hydraulic conductivity. This input can help in assessing the potential overpressure dissipation by vertical leakage.

3.1.1. Interpolated maps

We used the lithology data from the surrounding wells to define the relations of (Deep-water Pannonian) aquitard. On the one hand, we constructed an elevation map for the Shallow-water Pannonian– Deep-water Pannonian boundary (top of Algyő Aquitard) for the study area, using 22 well-data. On the other hand, we compiled an interpolated an isopach map for Algyő Aquitard from 16 wells. Interpolation was performed by *Golden Software Surfer* using kriging method. Maps could not be interpolated for the total extent of the broad study area.

3.1.2. Seismic interpretation

We used 2D seismic profiles to obtain information about the structural and lithologic properties of the subsurface, especially of the underlying aquitard unit(s). The seismic interpretation was implemented using *Kingdom Seismic and Geologic Interpretation Software*. As a first step, time-depth conversion had to be done to have a meter scale seismic section. For this reason, we used VSP (vertical seismic profile – measurement made in the vertical wellbore for correlation with surface seismic recorded in Köt-3 (Köröstarcsa) hydrocarbon well. After the conversion, we interpreted the horizons of the Algyő Top (Great Plain Aquifer Bottom), the Szolnok Top, Endrőd Top, and the pre-Tertiary basement. The outcome gave information about the thickness and the structural state (thus about the potential heterogeneities of the aquitard, which contributes to the estimation of the formation-scale hydraulic conductivity.

3.2. Investigating the pressure state

In groundwater/thermal wells, the stabilized water level was measured after the well completion, being referred to the middle of the screened depth interval (23 data points). In case of hydrocarbon wells, pressure values were obtained during DST (drill stem test) measurements (during the shut-in) and represent the pressure at the measurement point (9 data points). Hydraulic head (h) and aquifer's pore pressure (p) were calculated using water density, and the wellhead elevation where standing water level was measured from.

To describe the hydraulic and pressure conditions, we created fluid-potential maps for different elevation-intervals using the hydraulic heads, constructed pressure-elevation profiles by plotting the gathered pressure values against the elevation and calculated their deviation from the hydrostatic value.

3.2.1. Fluid-potential map - hydraulic head

The maps were constructed to three different elevation gaps using the *Golden Software Surfer* program and kriging method. The elevation gaps are: z1=(-894) - (-1290) m (asl); z2=(-1611) - (-2094) m (asl); z3=(-2175) - (-2661) m (asl). By evaluating the fluid-potential maps, we derived the direction of horizontal driving forces. Moreover, as the elevation of the ground surface determines the range of hydrostatic hydraulic heads, a positive anomaly (indicating overpressure) is explorable through the fluid-potential maps (Mádlné Szőnyi, 2019). Elevation at the area varies between 80 and 100 m (asl), therefore the hydraulic heads in hydrostatic state can be expected within this range.

3.2.2. Pressure profile, vertical pressure gradient

Pressure-elevation profiles allow the examination of the vertical component of fluid flow directions. The deviation of the vertical pressure gradient from the ideal hydrostatic gradient indicates the hydrodynamic state.

A pressure-elevation profile was constructed on the close (5*5 km) study area of Mezőberény, using the available data from 6 wells (including the doublet of the study system) screened to the Great Plain Aquifer. As within this close (5*5 km) surrounding area, data from the underlying units were not available, we chose one other area (within the study area, about 15 km from Mezőberény) to be able to examine the whole domain. From this area, we plotted pressure values from Békés-3 drilling measured at 6 different elevations in the Szolnok Formation, together with four available data points from the Great Plain Aquifer.

3.2.3. Dynamic pressure increment

Dynamic pressure increment causes the positive or negative deviations from the hydrostatic value expected at the particular depth. We calculated the pressure increment for the two wells of the Mezőberény study system. Moreover, we provided these values for the wells of the analogue "Békés" area and the other wells of the study area as well.

To calculate the hydrostatic pressure ($p_{hydrotatic}$), we used the average elevation of the study area ($z_{(Wt(avarage)}$=90 m) as an assumed average elevation of the water table:

$p_{hydrotatic}=[z_{(Wt(avarage))}-z] x\ \rho\ x\ g\ x10^{-6}$ [MPa] (1)

where z=elevation of the reference point (m asl), ρ=density of the water (1000 kg/m^3), g=gravitational acceleration= 9.81 m/s^2

Using this value, dynamic pressure increment (Δp_{dyn} = deviation from the hydrostatic value) can be calculated:

$\Delta p_{dyn} = p_{observed} - p_{hydostatic}$ (2)

To evaluate the pressure increments we calculated the quasi-hydrostatic pressure range based on the approach of Mádlné Szőnyi (2019) specific for the study area.

$p_{hydrostatic} + [\rho\ x\ g\ x\ (z_{Wt(max)}-\ z_{Wt(min)})/2\ x10^{-6}] \leq p_{dynamic}$ [MPa] (3)

$p_{hydrotatic} - [\rho\ x\ g\ x\ (z_{Wt(max)}-\ z_{Wt(min)})/2\ x10^{-6}] \geq p_{dynamic}$ [MPa] (4)

Where $z_{Wt(max)}$=the maximum elevation=100 m (asl) and $z_{Wt(min)}$=the minimum elevation=80 m (asl). If the pressure of the reference point exceeds these limits, it is abnormal, either underpressured or overpressured.

3.3. Numerical modelling of the theoretic influence of the overpressure

Numerical modelling was carried out to complement the specific analyses for the study area by gaining information about the theoretical influence of overpressure on the hydraulic state with the given geological conditions. *COMSOL Multiphysics Modelling Software* – a general finite element modelling environment (Li, et al., 2009) – was applied to solve Darcy's Law in a stationary state.

The model set up was a simplified 2D regional section from the study area, with the following model structure: horizontal length: 20 km; vertical extension: 2720 m; no-flow side boundaries; upper boundary: sloping water table from west to east with limits of 90 and 80 m (asl). Bottom boundary of the aquitard was defined by a 2000 m (asl) hydraulic head representing the overpressure. A 1000 kg/m^3 value was used as water density. We modelled two scenarios:

The first one was a simplified domain of the studied reservoir with two homogeneous isotropic units. Extension of the top layer was 2120 m [85 – (-2035) m asl] with a hydraulic conductivity of K=10^{-5} m/s (given by Czauner & Mádl-Szőnyi (2013) as the average value for Great Plain Aquifer = GPAF). This unit was underlined by a 600 m thick layer [(-2035) – (-2635) m asl] with a conductivity of K=10^{-8} m/s (representing the Algyő Aquitard). Both units had a porosity of 10%.

Using a similar model set up, in the second scenario, we presented possible phenomena which might contribute to elevated hydraulic heads in the aquifer in presence of the overpressure underneath that. Thus, in a combined model we simulated the effect of I) a reduced hydraulic conductivity of the aquifer in a specific extent (representing a siltier section of Zagyva Formation of GPAF); II) a local thinning of the underlying aquitard unit; and III) a conduit fault within the aquitard. Where I) the "interbedding" section's conductivity was one magnitude lower (10^{-6} m/s) compared to the 'aquifer' and it had a thickness of 1020 m [(-515) – (-1535)] m asl); II) the thinning of the aquitard was present at the central 2 km of the domain, from 600 m to 300 m; and III) the conductivity of the 10 m thick fault was two magnitude higher (10^{-6} m/s) than the aquitard (10^{-8} m/s).

3.4. Evaluation of temperature state

Temperature data originate partly from the temperature database of Hungary (Lenkey, et al., 2002), further data came from the thermal well register and hydrogeological logbooks. We constructed a temperature-elevation profile for the broad study area (Figure 1).

A positive temperature anomaly (compared to the average geothermal gradient – Békés Basin: 50°C/km (Dövényi & Horváth, 1988)) can indicate upward flow with higher temperatures. Furthermore, a significant positive deviation of the bottom hole temperature values measured in the well of the study system Mezőberény can indicate local ascending flow.

3.5. Characterization of the chemical character of water

To know more about the chemistry of water components we used the evaluation approach of Varsányi & Ó.Kovács (2009). They investigated the fluids from wells screened to the Shallow-water Pannonian aquifers in respect to their chemical and isotopic composition. Samples were classified concerning the $Cl^-/(Cl^-$ + alkalinity) ratio against the specific electric conductivity into Cl^- (Group 1) and HCO_3^- type water groups. HCO_3^- type waters are further grouped based on HBO_2 and Br^- content into high boron, bromide, iodide (Group 2) and low boron, bromide, iodide contents cluster (Group 3). Classification of the waters from the studied wells gives information about their origin and these can connect to the pressure regimes.

4. RESULTS AND INTERPRETATION

4.1. Examining the aquitard properties

4.1.1. Interpolated lithology

Based on the lithology from available boreholes in the study area, the top elevation of Algyő Aquitard varies between z= (-2400) and (-1650) m (asl), tilting towards E-SE direction. Below Mezőberény Algyő Top elevation is between z= (-2000) and (-2035) m (asl) (Figure 2/A).

The thickness of the latter Algyő Aquitard shows thickening into the north direction, having a thickness between 100 and 800 m. Near Mezőberény, it is between 590-610 m thick, also thickening towards the north (Figure 2/B).

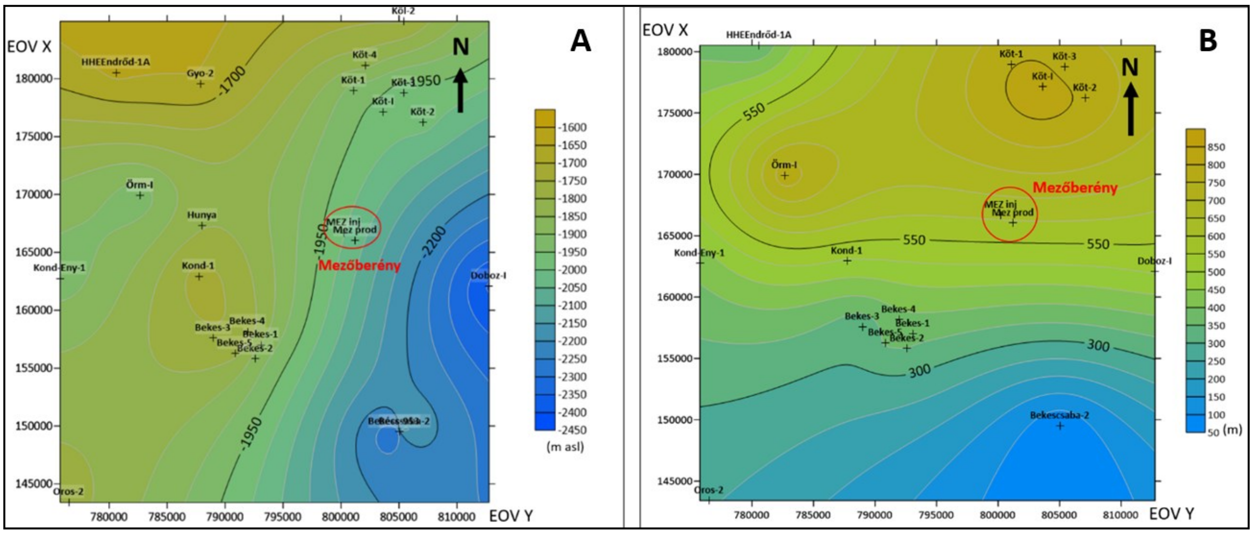

Figure 2: Elevation map of the Algyő Aquitard Top (A) and isopach map of the Algyő Aquitard (B), interpolated from surrounding well data

Seismic sections

We interpreted three 2D seismic sections from the study area (one of them: Figure 3). Interpretation was done with respect to the top horizons of the aquifer and aquitard units and the structural elements if present. Top of Algyő Aquitard, Szolnok Aquifer, Endrőd Aquitard and the pre-Tertiary basement top were interpreted. Sections show the pre-Tertiary basement with various depth between 3450 and 2950 m. Below the town of Mezőberény (MEZ in Figure 3) the basement top lies most likely at 3300 m depth. The Endrőd Aquitard has a thickness of 100-150 m, while the overlying Szolnok Aquifer– represented by strong reflections – is 100-300 m thick, thinning towards North. The depth of Algyő Aquitard Top varies between 2100 and 1950 m. Structural elements were not seen in the Algyő Aquitard and Szolnok Aquifer, both are present by continuous reflections.

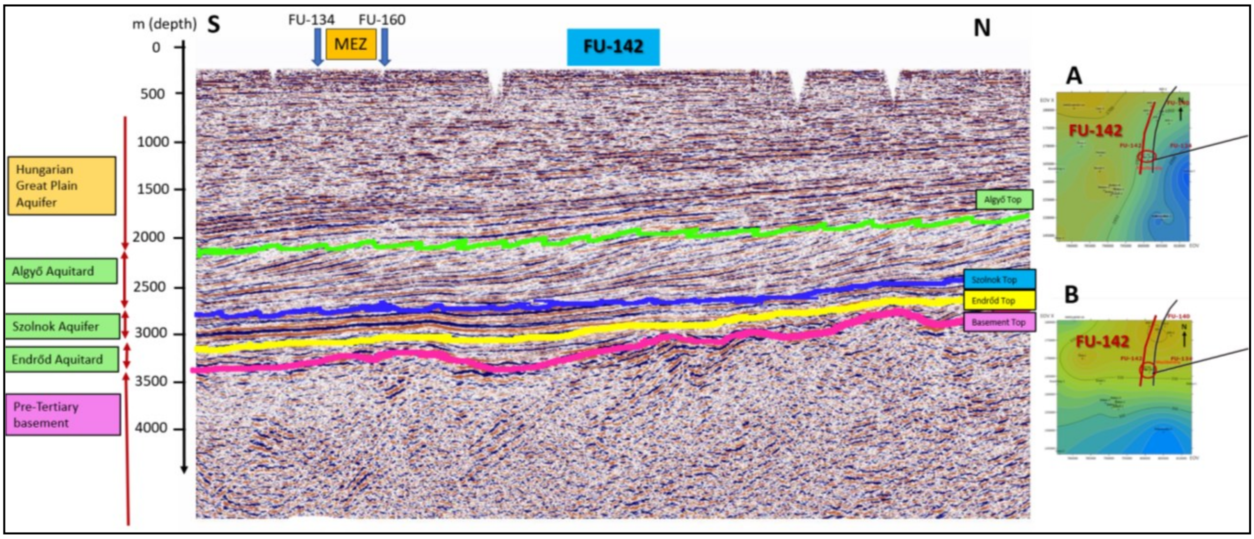

Figure 3: Interpreted seismic section - FU-142 with the location of Mezőberény (MEZ) and the location of the seismic sections

4.2. Investigating the pressure conditions

4.2.1. Fluid-potential maps

Fluid-potential map of the first elevation interval [z1=(-894) - (-1290) m (asl)] was compiled using the values coming from wells screened to the Great Plain Aquifer. Compared to the surroundings, K-106 well shows an elevated 'h' value with 106 m (asl) (Figure 4).

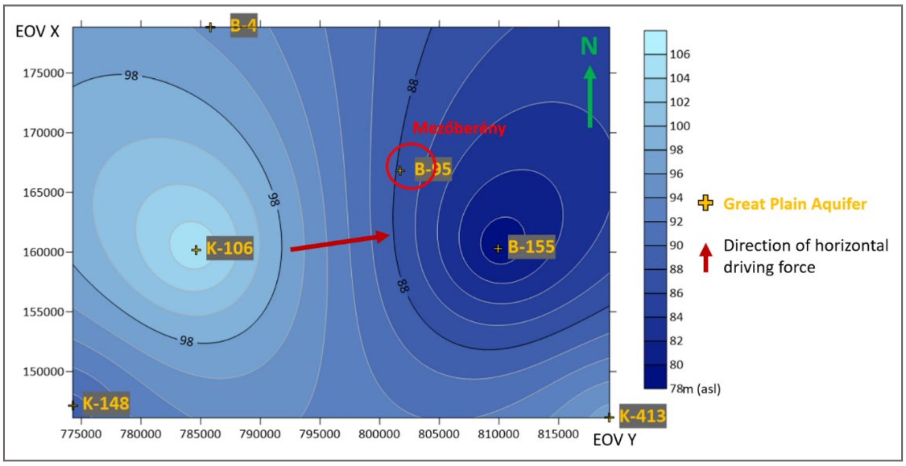

Figure 4: Fluid-potential map at the elevation gap: z1=(-894) - (-1290) m (asl)

The map of the second elevation interval [z2=(-1611) - (-2094) m (asl)] – that includes the wells of Mezőberény site as well – also shows the values from the Great Plain Aquifer (Figure 5). Due to lack of data, it was not possible to construct the maps with the same extent. Kond-1 (situated at the west part of the area) has an elevated 'h' with a 170 m value.

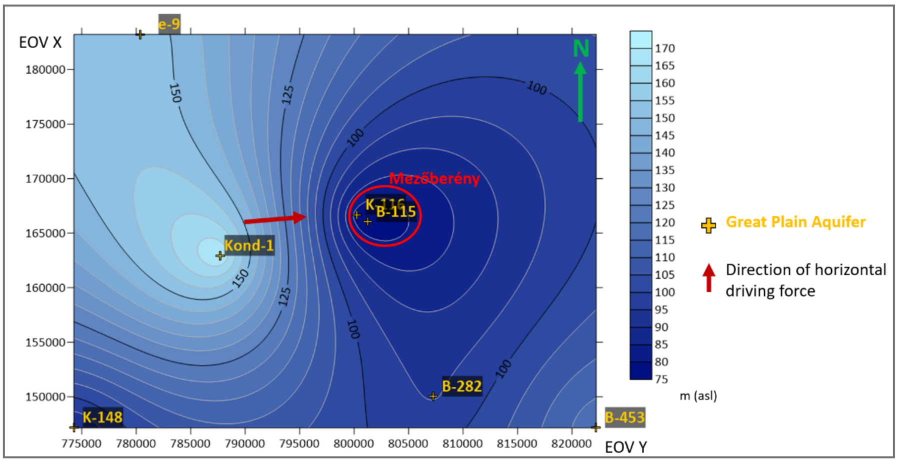

Figure 5: Fluid-potential map at the elevation gap: z2=(-1611) - (-2094) m (asl)

The third map shows values from both the Great Plain Aquifer (GPAF) and the Szolnok Aquifer covering the elevation interval of z3=(-2175) - (-2661) m (Figure 6**Error! Reference source not found.**). Values from the latter Szolnok Aquifer are by two magnitudes higher compared to the GPAF, representing hydraulic heads of 2000 m.

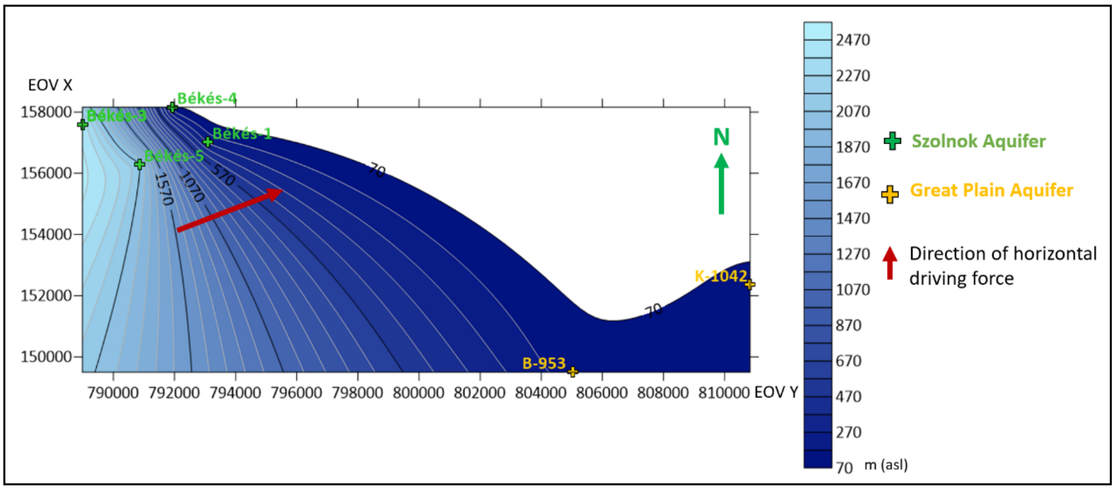

Figure 6: Fluid-potential map at the elevation gap: z3=(-2175) - (-2661) m (asl)

Based on the fluid-potential maps, a horizontal driving force is directed towards the east. In the first (Figure 4, Figure 5) and the second map, anomalous high values can be observed in Kond-1 and in K-106 well. In case of the third map, values from the Szolnok Aquifer show a clear hydraulic head anomaly indicating the presence of the overpressure.

4.2.2. Pressure-elevation profiles

A pressure elevation profile was constructed for the Mezőberény town (Figure 7/A) and for the analogue “Békés” study area (Figure 7/B); their location on the Pre-Tertiary basement map is shown on (Figure 7/C). Basement elevation is in between -3500 and -4000 m asl.

Pressure-elevation profile of the Mezőberény area was compiled, using the data from wells screened to the Great Plain Aquifer (Figure 7/A). Vertical pressure gradient in the Shallow-water Pannonian (dotted orange line) has a value of 9.65 MPa/km, while in Great Plain Aquifer’s including the Quaternary deposits it is y=9.75 MPa/km (yellow line). Pressure elevation profile of the “Békés” study area consists of the values from the Szolnok Aquifer and the Great Plain Aquifer (Figure 7/B). Vertical pressure gradient in the Szolnok Aquifer has a value of 58.43 MPa/km (green), while in Great Plain Aquifer y=10.29 MPa/km. Considering only the Shallow-water Pannonian formations it is y=11.43 MPa/km (Figure 7/B).

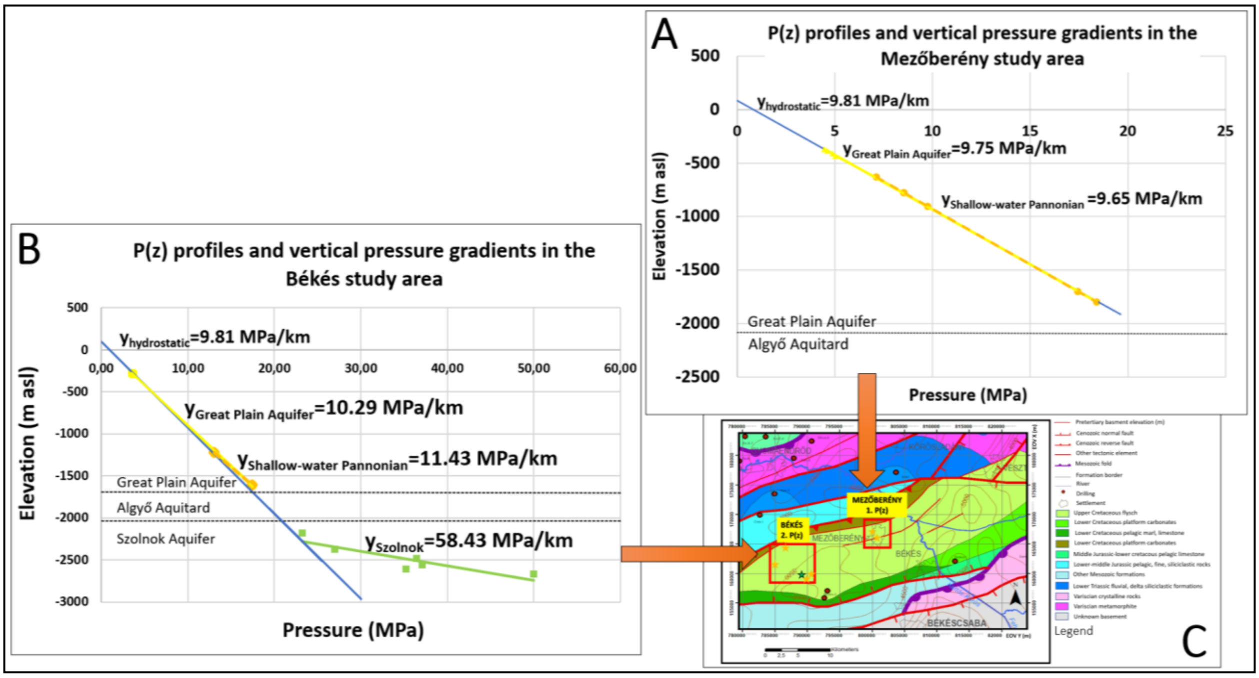

Figure 7: Pressure elevation [p(z)] profiles and vertical pressure gradients in the Mezőberény (A) and in the analogue Békés study area (B) (blue: hydrostatic vertical pressure gradient, yellow: Great Plain Aquifer, orange (dotted): Shallow-water Pannonian, green: Szolnok Aquifer) and their location on the pre-Tertiary basement map (C)

4.2.3. Dynamic pressure increment

We calculated the dynamic pressure increments for the pressure data in the study area (Figure 1) and plotted against the elevation. There are both positive and negative increments. Pressure increment of the Mezőberény injector is: Δp= -0.12 MPa while in the producer: Δp=-0.14 MPa. In case of the “Békés” study area (defined above) Δp=0.14 MPa and Δp=0.77 In case of the “other” values from the study area, Δp varies between -0.24 and 0.63 MPa. Pressure increments from the Szolnok Formation show much higher values (between 0 and 23 MPa) (Figure 8/A).

For the evaluation we defined the range of the quasi-hydrostatic pressure increment based on the elevation of the study area: +/- 0.1 MPa (Figure 8/ B). The values of the Mezőberény injector and producer show a light negative deviation. Contrary, several other data points exceed the positive limit, e.g. the two values at the ‘Békés’ study area and all the values from Szolnok Formation.

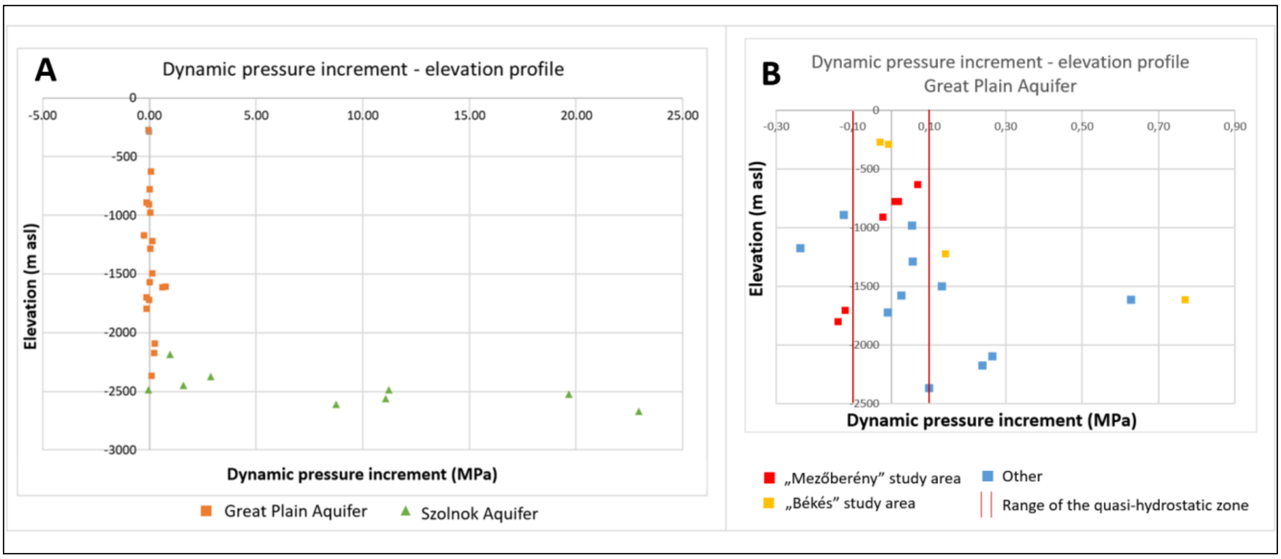

Figure 8: Dynamic pressure increment - elevation profile: A: Great Plain Aquifer and Szolnok Aquifer; B: Great Plain Aquifer with the quasi-hydrostatic range

4.3. Numerical modelling of the theoretic influence of the overpressure

Simplified numerical modelling was carried out to understand the potential influence of the overpressure on the hydraulic state of the aquifer underlain by an overpressured region. To this end, by using the geological-hydrogeological conditions in Mezőberény hydraulic heads ('h') were simulated and displayed.

In the case of the first scenario (Figure 9), model shows that the elevated heads (~2000 m) are present in the bottom 'aquitard' unit. At the top of the 'aquitard' a quick drop of hydraulic heads can be observed. In the overlying unit, the pressure state is hydrostatic with heads between 80-90 m (asl).

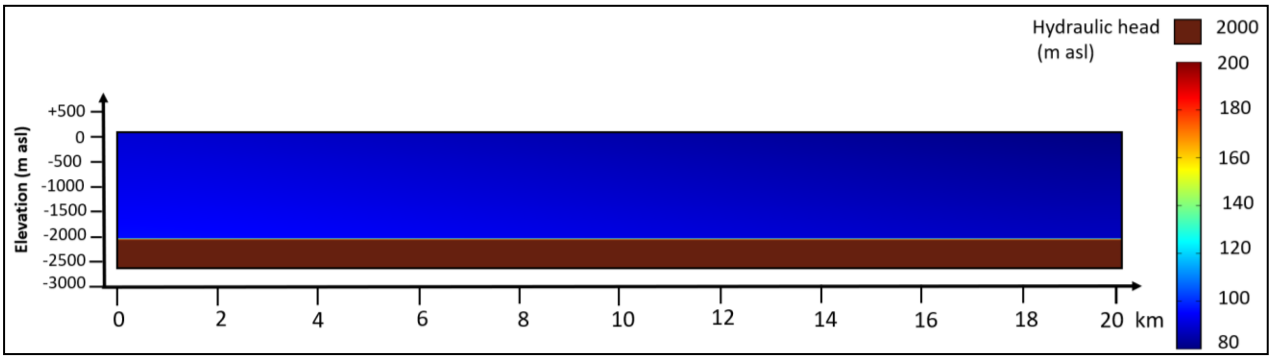

Figure 9: First model scenario: homogenous isotropic domain with no flow side boundaries (left: h=90 m; right: h=80 m), bottom boundary: h=2000 m (color legend range between h=80-200 m and additionally 2000 m)

In contrast to that, the second scenario showed elevated heads in the upper region as well (Figure 10, Figure 11). Considering the effect of the three investigated phenomena, I) the low conductive section within the aquifer caused a general increase of the 'h' values in the aquifer with approximately 30-40 m, II) the thinned aquitard further enhanced the hydraulic heads at a scale in between 10 to 20 m (depending on the distance from the thinned section); and III) the conduit fault rose the heads locally with 10 m; as shown by the combined model.

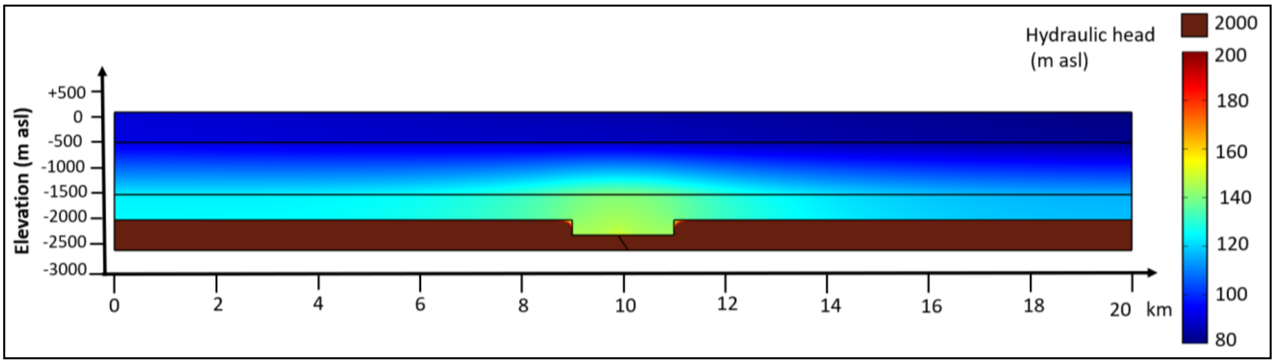

Figure 10: Second model scenario with I) less conductive interbedding section in the aquifer, II) thinned aquitard unit, and III) conduit fault within the aquitard.
No flow side boundaries (left: h=90 m; right: h=80 m), bottom boundary: h=2000 m. (Color legend range between h=80-200 m and additionally 2000 m)

Elevation-hydraulic head profiles shows the change of heads at three points of the domain (Figure 11). It can be observed that in the middle of the section (at 10 km) heads on the same elevation are approximately 20 m higher than at the sides thanks to the effect of the thinned aquitard and the conduit fault.

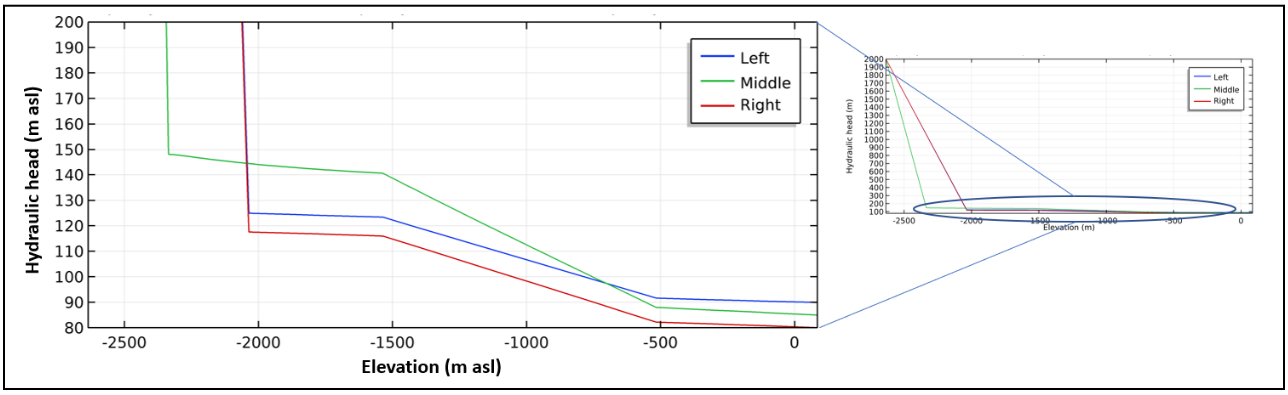

Figure 11: Second model scenario, elevation-hydraulic head (h) profile at three points of the section: left (0 km), middle (10 km), right (20 km) zoomed to the section between h=80-200 m

4.4. Evaluation of the temperature state

The geothermal gradient for the Great Plain Aquifer (GPAF) is 58.73 °C/km, while the gradient of the underlying Szolnok Aquitard is lower with 46.37 °C/km (Figure 12). Compared to the average geothermal gradient in the Békés Basin (50 °C/km (Dövényi & Horváth, 1988)), the geothermal gradient of the GPAF (58.73 °C/km) is even higher. Though most of the temperature values are below the line of the average 50 °C/km gradient. The bottom hole temperature of the Mezőberény wells, they are sitting on the 50°C/km line.

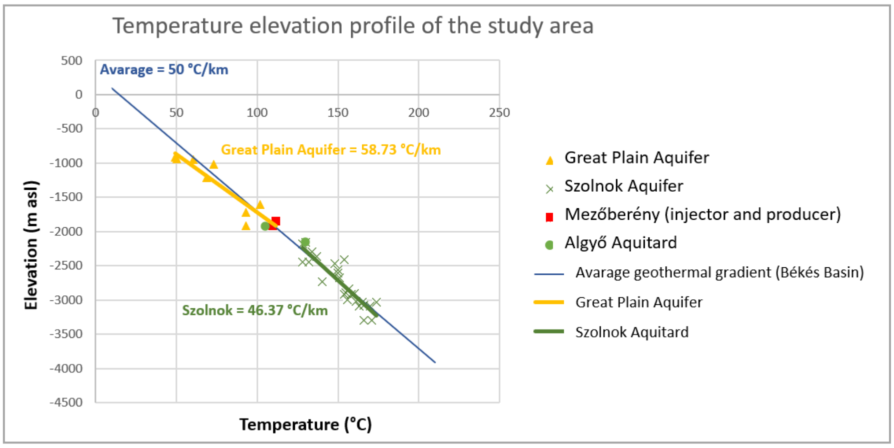

Figure 12: Temperature-elevation profile of the study area

4.5. Characterization of the chemical character of water

We classified the water samples from Mezőberény into the groups based on the approach of Varsányi & Ó. Kovács (2009), to interpret their origin. Considering the Cl^- and HCO_3^- content and the specific electric conductivity, both wells belong to the HCO_3^- type group (Figure 13/A). In case of the second classification, based on the Br^- and HBO_2 content, water samples are closer to the Group 2, thus belong to the high HBO_2 content waters (Figure 13/B). Additionally, the organic components – TOC (total organic carbon), COD (chemical oxygen demand), phenol – have considerably high amounts, which strengthen the similarity to Group 2 (Varsányi & Ó.Kovács, 2009).

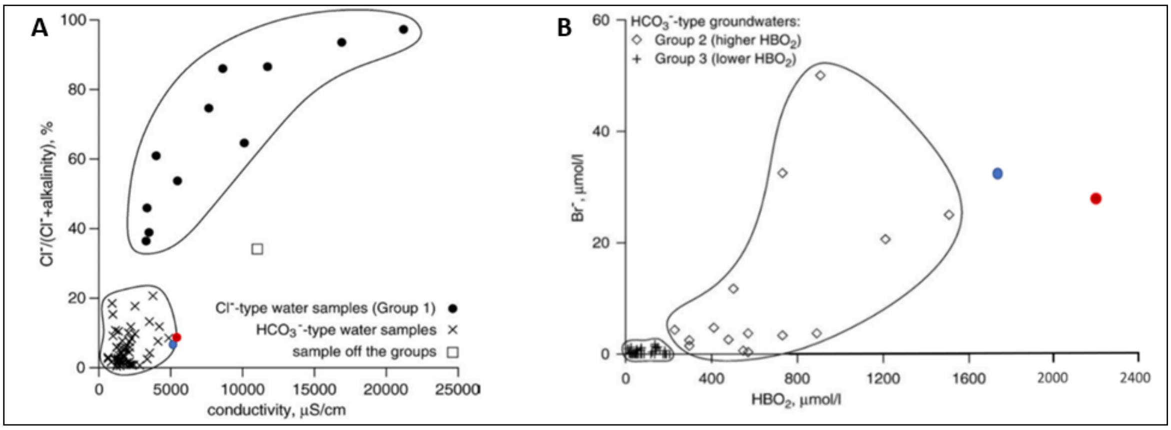

Figure 13: A: Separation of samples on the basis of the relationship between the ratio of Cl^- to Cl^-+alkalinity and conductivity. Cl- and HCO3- type waters are distinguished; B: Grouping of the HCO_3^- type samples based on HBO_2 and Br^- concentrations Clusters are high and low boron content.
(modified from Varsányi & Ó.Kovács (2009), red: production well sample, blue: injection well sample)

5. INTERPRETATION AND DISCUSSION

Based on the interpolated maps and the seismic sections, the Great Plain Aquifer continues by 85-110 m more beneath the 2000 m deep wells in the study area, followed by the underlying Algyő Aquitard. The latter formation has a thickness of 600 m. The underlying Szolnok Aquifer has a low grain size at the area and can be also considered as a less permeable formation. Considering their structural state, Algyő Aquitard and Szolnok Aquifer are continuous and larger structural discontinuities (faults) are not present. Due to their thickness (altogether 800 m) and their continuity, good regional formation scale aquitard properties (i.e., low hydraulic conductivity) can be assumed beneath the study site.

Based on the fluid-potential maps, the p(z) profiles, and the pressure increments it can be stated that the overpressure is present in the underlying Szolnok Formation (Figure 6, Figure 7). The gradient indicates the vertical dissipation of the overpressure. Moreover, the vertical pressure is higher than the lithostatic gradient (25 MPa/km). For this extreme pressure gradient an interpretation was proposed by Czauner (2012) who also investigated the analogue „Békés" area: the overpressure might open fractures in the rock that cause the variable pressure conditions (Czauner, 2012). In this area Shallow-water Pannonian have an increased (11.43 MPa/km) vertical pressure gradient, and Great Plain Aquifer shows also higher value (y=10.29 MPa/km), which indicate upward flow. These gradients, the anomalous hydraulic heads and the positive pressure increments in the area likely shows the effect of the elevated pressure due to vertical leakage. Though this effect cannot be seen in the Mezőberény area, both the pressure values and their gradient are slightly subhydrostatic (Figure 7, Figure 8).

Numerical modelling with the given geology suggests a hydrostatic state in Mezőberény. Additionally, the second model scenario showed the enhancing effect of overpressure dissipation in presence of a less conductive section in the aquifer, thinned aquitard, and conduit fault with a positive deviation between Δh=10-70 m.

Temperature state (values from Mezőberény) does not indicate a local effect of the advective heat transport from upward flow.

Based on Varsányi & Ó.Kovács (2009), as belongs to Group 2, the Mezőberény water's origin can be the mixing of ascending pre-Pannonian $NaCl^-$ type waters (squeezed by the overpressure through a clay membrane) and the trapped freshening Lake Pannonian pore fluids. The decreased Cl^- content indicates the microfiltration, thus the bigger thickness and good aquitard properties of the underlying (Algyő and even Szolnok) formations (Varsányi & Ó.Kovács, 2009). Accordingly, a significant effect of upward flow in chemical character of the water of Mezőberény can be not observed.

Combining the results from regional aquitard conductivity estimation, pressure regime analysis and numerical modelling (second model scenario), it can be assumed that at the "Békés" study area thinner underlying aquitard and/or conduit structural discontinuities within the aquitard might be present. These facilitate the ascending vertical flow that rise the pressure in the aquifer. In contrast to that, beneath the study site, the aquitard is thick and continues (interpolated isopach map). Additionally, the pre-Tertiary basement lies deeper beneath Mezőberény (-4000 m asl) than in the "Békés" area (-3500 m asl). These characteristics likely contribute to the hydrostatic pressure conditions, observed through quasi-hydrostatic pressure increments and vertical pressure gradient in the reservoir, and supported by the numerical modelling as well. Consequently, in contrast to several regions of the Pannonian Basin (investigated by Tóth & Almási, (2001); Czauner & Mádl-Szőnyi (2013); Mádl-Szőnyi & Simon (2016)) unfavorable hydraulic conditions could not be observed close to Mezőberény. Moreover, the slight negative deviation from the hydrostatic conditions is beneficial for reinjection.

6. CONCLUSION

This study proposed a new potential reason for low injectivity at a geothermal site (Mezőberény - SE Hungary). We investigated the hydraulic conditions of its surrounding and the potential proves of the vertical overpressure dissipation from beneath into the aquifer.

The hydraulic analysis explored the extreme pressure values beneath the aquifer, as well as the elevated hydraulic heads and upward vertical driving forces within the investigated broad study area, farther from the study system. These likely indicate the dissipation of the overpressure from underlying units.

Nevertheless, at the close surrounding of Mezőberény site the pressure regime and vertical pressure gradient are slightly subhydrostatic, overpressure and upward flow is not expected. Seismic and well data suggests that underlying units are thick and continuous enough to block the local vertical dissipation of the overpressure. The latter is supported by the water chemistry (which suggests weak ascending flow through poorly conductive units) and numerical modelling. To conclude, drawbacks caused by hydraulics are not expected at the study site.

In addition to the site-specific results, this study provided approaches to reveal a potential overpressure-origin reinjection problem. Therefore, we propose to take regional hydraulic conditions into consideration and to apply the approaches during geothermal exploration, risk and problem analyses.

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