PROCEEDINGS, 46th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 15-17, 2021
SGP-TR-218

Death by Injection: Reopening the Klaipėda Geothermal Cold Case

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Keywords: Clastic Rock, Injection, Failure, Case History

ABSTRACT

In 2017 the Klaipeda geothermal plant in Lithuania was shut-down and the operating company declared bankruptcy. Between 2001 and 2017, the low enthalpy project was supplying heat to a local heat loop. That project was part of the Lithuanian energy transition plan and as such had received substantial public funding. From the beginning, the injector wells were unable to accommodate the desired rate, while producers had excellent delivery. A string of studies identified a string of damaging mechanisms and suggested as many remedial actions. These remedial actions included: drilling a second injector, acidization, side-tracking and radial jet drilling (RDJ). They all resulted in disappointments and had at best short-lived impacts on the issue.

We conducted a post-mortem review, admittedly limited to the amount of data publicly available in the related literature. Nonetheless, after a thorough analysis of observations, petrophysical and production logs, injection and production data, we can explain the most prominent damage mechanism plaguing the Klaipeda injector wells. Along, we identify the major flaws pertaining to the injector well design. Based on these conclusions, we propose remedial actions to revive the Klaipeda geothermal project, hoping that the present work will also serve as a basis for best practices to all who want to drill and complete efficient injector wells in clastic reservoir rock.

1. INTRODUCTION

Klaipeda is the third largest city in Lithuania with an estimated population of 147’898 on January 1st, 2019 (*www.citypopulation.de*). Located on the Baltic shore, it hosts an ice-free port protected by the northern tip of the Curonian Spit and controls the entrance of the Curonian Lagoon, thus making the site a geostrategic hub. The city and port of Klaipeda have therefore been coveted over the years by the various surrounding empires until she was eventually returned to Lithuania at the end of World War II.

Klaipeda is less known for its geothermal plant that declared bankruptcy in 2017 (Sliaupa, 2019). In Klaipeda, 88% of the population is supplied in heat by a district heating system (Radeckas, 2000). The heat feeding that loop is subject to a yearly bidding process between several providers (Brehme, 2017), such as the combined heat and power plant (CHPP) in Klaipeda, and in which the Klaipeda geothermal demonstration plant (KGDP) used to compete.

Because a substantial amount of public money has been injected into the project, because the reasons for bankruptcy have not yet been clearly stated, and because the location and geological settings seem almost ideal, we thought that the case of the geothermal project in Klaipeda was worth reopening. Along that journey, we discovered that the problems encountered there should have been identified much sooner, understood much better, and that technical solutions for repair existed. We are not in a position to assess the economic viability of fixing the issues and making that plant operate again, but we provide herein enough data to help the authorities and potential investors consider turning the odds around and making it a technical and environmental success.

2. THE KLAIPEDA GEOTHERMAL PROJECT’S BACKGROUND

Preliminary investigations for establishing a geothermal project in the Baltic basin - North-Western part of Lithuania - were initiated in 1992 (Radeckas B., 2000). After a number of earth science studies, the city of Klaipėda located on the Baltic shores was eventually selected for the project that started in 1996. The location was also ideally equipped, because 88 % of the 200’000 population at that time was connected to the district heating system (Radeckas, 2000).

The primary objective of the project was to demonstrate the feasibility of using the Lower Devonian sediments aquifer at 963m MSL known as the Kemeri formation as an energy source for district heating. The initial program included two production wells expected to produce 600m^3/hr each and one injection well. The heat was to be extracted from the geothermal water using absorption heat pumps. The water was then returned to the aquifer via the injector well (ibid).

The Klaipeda geothermal plant was initiated as a contributor to the Lithuanian energy transition plan and as such received public - national and international - funding by the world bank (5.9 M$), the government of Denmark (3 M$), The Government of Lithuania (3.6 M$) and the Global Environmental Facility Trust Fund (6.9 M$) for a total of 19.5 M$, converted from Lithuanian Lira at their December 1998 US$ value (ibid).

The three wells were drilled in 1997 (Petrauskas, 2018) with mixed results (Radeckas, 2000):

- The production rates were better than expected, around 800 m^3/hr for each producer KGDP-2P and KGDP-3P;
- the wellhead temperature was 38°C (below the expected 42°C); and
- the injector well KGDP-1I showed considerable damage.

Despite the poor injectivity, the communication between the injector and the producers could be established. However, because all the produced water could not be reinjected, it was decided to drill a second injector in 1998: KGDP-4I

Early results showed that with a reservoir permeability ranging between 1 and 3 Darcy, a thickness of 50 to 60 m and rock porosity of 23 to 27 %, the Kemeri formation was perfectly suitable for the low enthalpy project.

Based on these encouraging results, the geothermal plant was sanctioned. The producers were equipped with downhole pumps to lift the water at the expected rate of 300-400 m^3/hr per well with a static fluid level maintained at 20 m, for a total expected production of 700 m^3/hr at the wellhead temperature of 38°C (ibid).

3. SUMMARY OF THE INDUSTRIAL GEOTHERMAL OPERATIONS IN KLAIPEDA

In 1998, the final development included four wells, two producers (2P and 3P) and two injectors (1I and 4I), all targeting the Lower Devonian sandstone at a vertical depth of 1000 m (Petrauskas et al., 2018). The Klaipeda geothermal plant was built between August and November 2000 and started in December of that same year (ibid).

Since the beginning, the geothermal plant operation was plagued with a series of problems. Gypsum precipitation in the surface installation caused an additional delay and the geothermal plant could only be commissioned in June 2004 (ibid). Then, continuous decrease of the injectivity was observed in the dedicated wells (Klimas, 2010). After commissioning, the throughput (production and injection) was about 450 m3/h (Petrauskas et al., 2018), well below the expected rate.

In 2002, because of the alarming injectivity decrease, a remediation operation was performed in both injector wells. The injectivity index was multiplied by a factor of 3 to 5 in both wells. These results, even though encouraging, were insufficient at securing the plant's economic viability; injectivity declined again as soon as injection was resumed.

In a radical attempt to remedy the injection issues, it was decided to side-track well KGDP-1I. The operation took place in 2009. The kick-off point was at 897 m and a 3° to 5° from vertical slanted section was drilled down to 1116 m (all depths from ground level) (Sliaupa, 2016). The side-tracking of KGDP-1I resulted in a disappointing reduction of injectivity from 2.3 to 1.7 m^3/hr/bar.

Because the lack of injectivity was considerably hindering the plant operation, a number of studies were produced, each one supplying a string of remedial suggestions (Klimas 2010, Nowak, 2017, Brehme 2017), including various chemical treatments and even radial jet drilling (RJD) in 2014 (Petrauskas, 2018). Eventually, 12 laterals were jetted in KGDP-1I in December 2014. 9 of them reached 40 m, 2 reached 35 m and 1 only 28 m (ibid). Tests performed three months after these operations showed a positive but marginal improvement, resulting in only a 14% increase of the injectivity (Nair 2017). A series of acid injections followed, resulting in a 39% improvement of the injectivity in total (ibid).

Between October 2015 and May 2016, the Klaipeda Geothermal Plant was delivering 41 MWth to the local heating network. The competitive environment imposed by the heat distributor and the technical struggle translated into great financial difficulties, leading the geothermal plant operator to shut down operations and declare bankruptcy in 2017 (Sliaupa, 2019) with over 3 million euros debts[1].

4. A BRIEF OVERVIEW OF THE KLAIPEDA GEOLOGY

In the Baltic sedimentary basin where Klaipeda is located, a geothermal anomaly had been identified; the heat flow of 70 to 90 mW/m^2 compares favourably to the 40 mW/m^2 normally found in the East European platform (Petrauskas, 2018). The geological sequence of the basin has been presented by Ma et al. (2018) and is reproduced in Figure 1.

As already mentioned, the targeted geothermal formation is the Kemeri, a shallow and poorly consolidated sandstone in the Lower Devonian sequence. The sandstone's cementing material has been found to be clay, carbonates, gypsum and quartz (ibid). The top of the Kemeri formation is at 980 m (963 m MSL) and the bottom around 1110 – 1118 m below ground level, within a 2 km sedimentary cover (ibid).

The hot water reservoirs are of multi-Darcy (around 4 D) permeability and high porosity: 26 %. (Table 1) (Brehme, 2017). These high permeability sand layers are interbedded with siltstone and shale layers and exhibit a net-to-gross ratio of 0.63 to 0.68. The net sandstone reservoir thickness is therefore in the 100 m range and holds highly saline water at a temperature of 39°C (Brehme 2019).

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[1] Personal communication with the plant's management on December 29, 2017. The geothermal facilities were due to be auctioned on January 31st, 2018 for the cost of de debts.

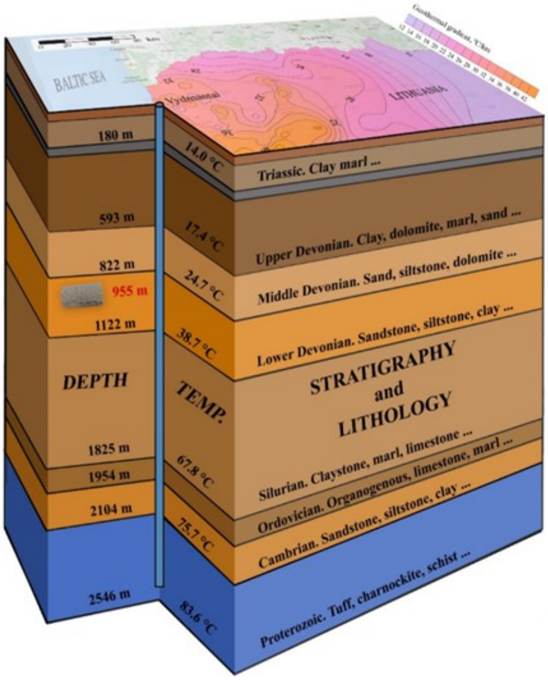

Figure 1: Stratigraphic sequence of the subsurface in the Klaipeda region after Ma J. et al. (2018)

Characteristic	**Injection Well 1I**	**Injection Well 4I**	**Production Well 2P**
Porosity	26%	-	-
Permeability	4 D	-	-
Total reservoir thickness [m]	112	111	94
Injectivity 2002 [m^3/h/bar]	5.7 (160 m^3/h, 28 bar)	30.9 (266 m^3/h, 9 bar)	-
Injectivity 2015 [m^3/h/bar]	1.3 (51 m^3/h, 39 bar)	1.1 (46 m^3/h, 42 bar)	-
Productivity 2012-2014 [m^3/h/bar]	36 – 44 (~50 m^3/h, ~1 bar)	27 – 35 (~50 m^3/h, ~1 bar)	20 – 35 (~300 m^3/h, 2 bar)
Productivity calculated [m^3/h/bar]	60	60	60

Table 1: Wells and reservoir characteristics after Brehme M. (2017)

5. KLAIPEDA INJECTORS WELLS DRILLING AND COMPLETION

The only wellbore schematics that we have had access to (Figure 2) is the one presented by Novak (2017). It is a simplistic view of the initial vertical injector KGDP-1I well and of its side-track.

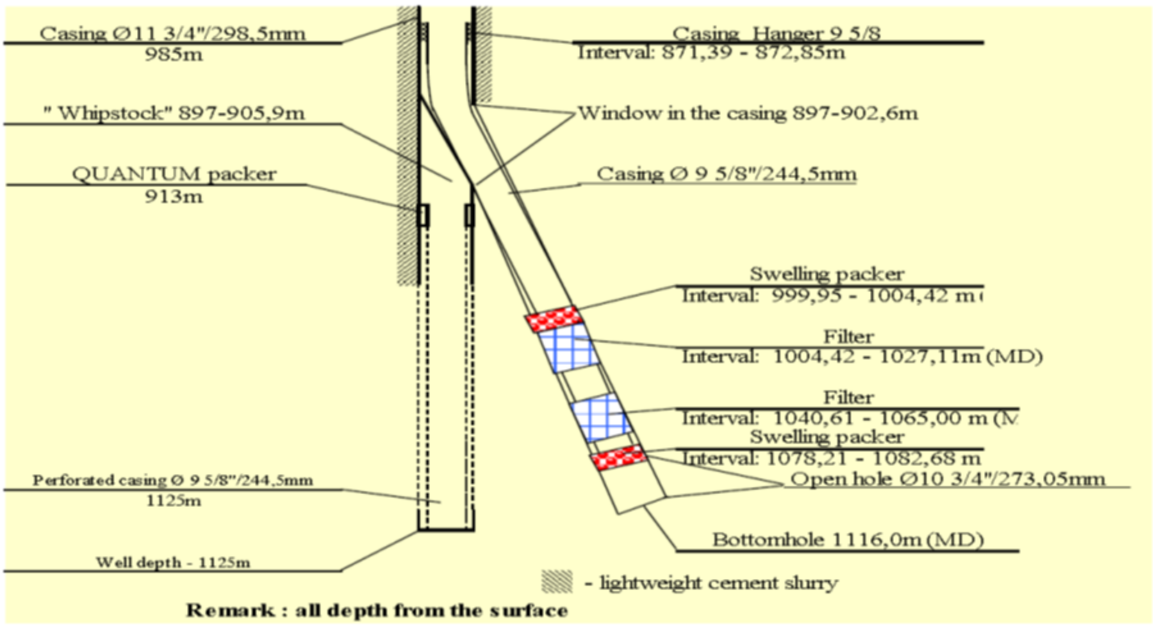

Figure 2: Injector well 1I diagram after Nowak (2017).

We note that the original drain as well as the side-track were completed open hole from around 900 m to around 1120 m, with some sort of sand control: initially an uncemented perforated casing in the main bore and then standalone screens (SAS) in the side-track.

The Figure 3 below presented by Petrauskas (2018) shows the parallel gamma ray tracks along with completion elements of 1I and 4I injector wells, suggesting that both wells were completed with combinations of standalone screens and blank pipes. In KGDP- 1I side-track, swell packers have been run above and below the screen section; however, there was no attempt to isolate the various silt, clay and sand layers along the gross reservoir thickness. It is unclear whether the casing hanger holding the blank and screen string inside the side-track bears any sort of packing elements.

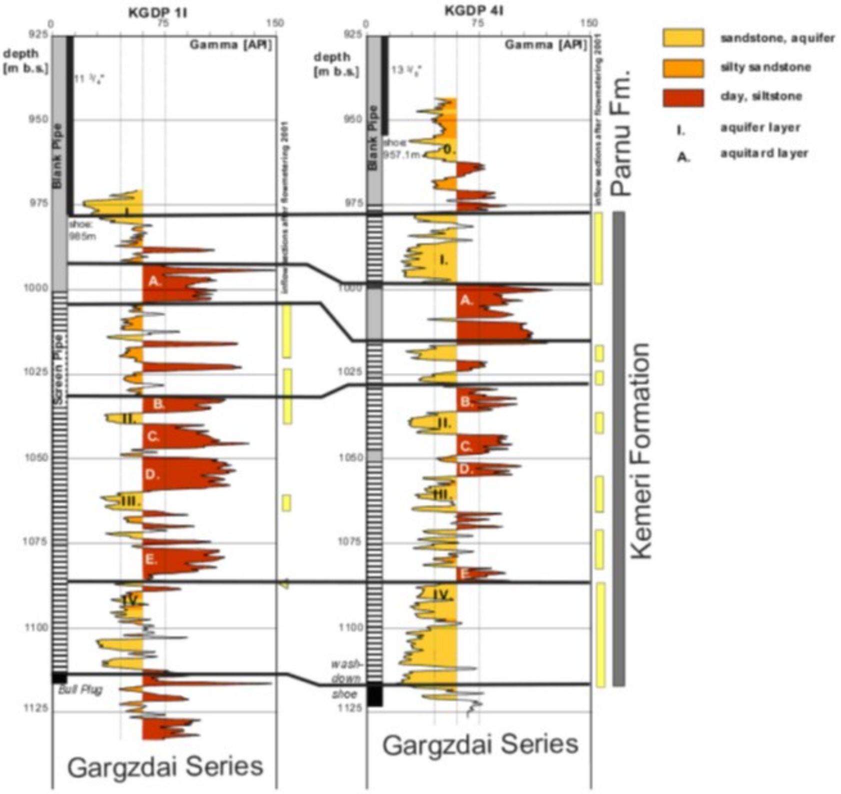

Figure 3: Gamma ray logs and open hole completion of wells KGPD-1I and 4I after Petrauskas et al. (2018)

6. STUDIES, DIAGNOSIS, STIMULATION TREATMENTS

The injection difficulties experienced in Klaipeda since the beginning of the project and the following rapid injectivity decline have been the attention of many reports. Hydrogeology studies concluded that the high salinity of the re-injected water and subsequent precipitations were to be blamed. Klimas et al (2010) developed a computer model to validate that assumption; their paper also recognises that the applied countermeasures had only "partial and temporary effects". A bactericide injected in an attempt to reduce sulphate reducing bacteria (SRB) activity was also reported not to have had any noticeable effect (ibid). Other authors identified chemical precipitation, fines mobilisation and scaling (Nair 2017) and proposed radial jet drilling (RDJ) as a remedial option. When tried, that technology had a limited impact on injectivity improvement (Petrauskas, 2018) while Nair (2017) recognized that the modest impact of RJD was short lived; here again the disappointment was blamed on scaling, fines mobilization, and precipitation of minerals. Brehme (2018) identified also bacterial activity and corrosion in a medium with *spatially correlated poroperm properties*. In her conclusions, the damage would be a combination of fines migration, mineral precipitation, biofilm, and corrosion.

After reviewing the available literature on Klaipeda injectivity issues, it is clear that none of the remedial attempts has produced anything other than short-term gains in injectivity; however, it is worth noting that the most successful remediation was the acidization of both injector wells in 2002 (Brehme 2019). During that operation, the injector wells were treated through coiled tubing, each of them receiving 20 m^3 of 18 % hydrochloric acid (HCl). Immediately after, noticeable injectivity gains could be measured, even though these gains were also short-lived and followed by an inexorable decline. In summary, the injectivity indices at the start of the project in 2001 were of 3 m^3/h/bar in well 1I and 10 m^3/h/bar in well 4I, and started to decline immediately. The 2002 acidization resulted in well performance increasing from 1 to 6 m^3/h/bar for 1I and from 5 to 31 m^3/h/bar for 4I. These improvements were so short-lived that they are barely noticeable on Figure 4 from Petrauskas (2018) below, especially for KGDP-1I well (more detailed information is available in Brehme et al. (2019)). Injectivity resumed its decline, reaching 1 m^3/h/bar in both wells in 2018 (Brehme 2018).

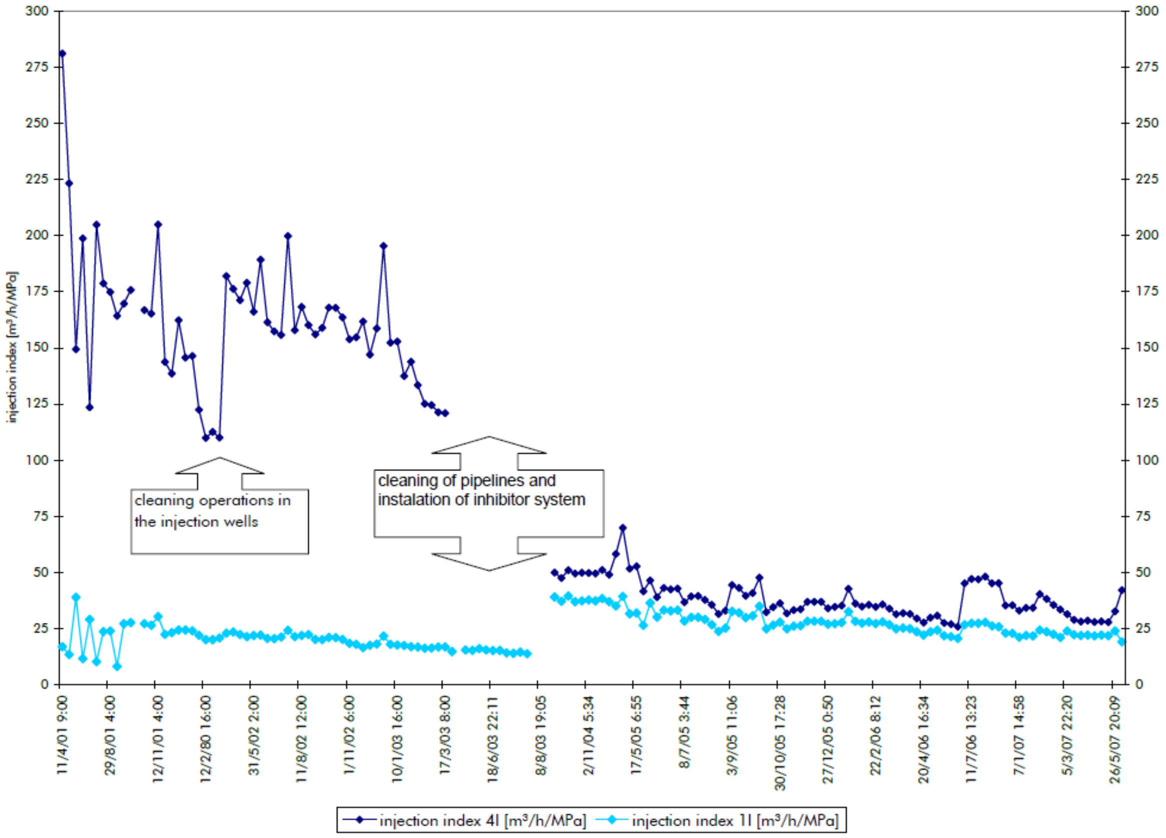

Figure 4: Injectivty index vs. time after Petrauskas et al., 2018

A notable specific of Kaipeda wells is the dramatic difference between the injectivity and productivity indices with productivity indices being 30 to 40 times higher than the injectivity indices (Figure 5 by Brehme, (2017)). This phenomenon was also identified in the nearby Vilkyčiai oil exploration well in formations at similar depths (table 2) (Petrauskas et al., 2018).

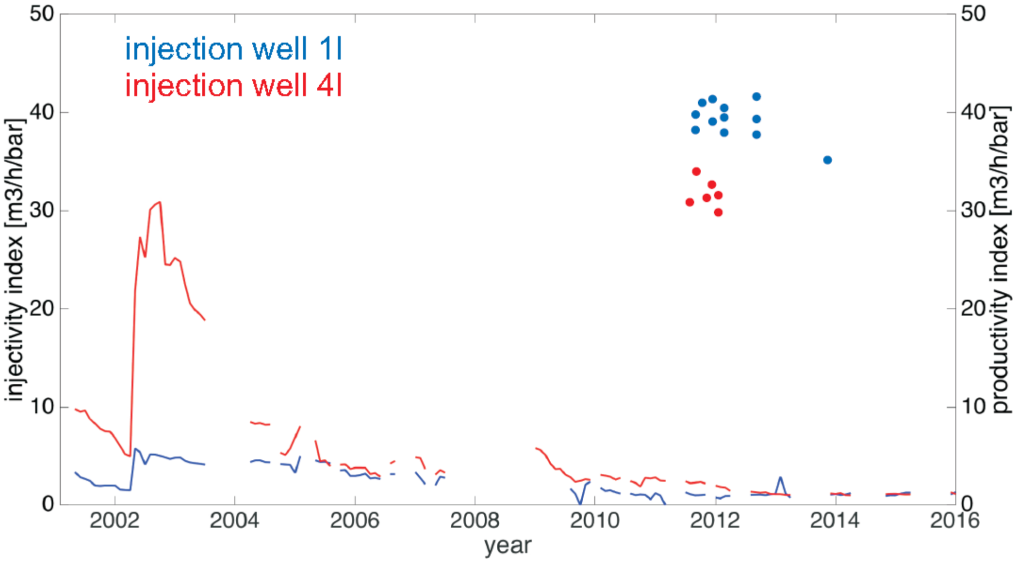

Figure 5: Comparative evolution between injectivity indices (lines) and productivity indices (dots) presented by Brehme et al. (2017)

Well	Interval depth (m)	Injectivity Index (m^3/h/at)	Productivity Index (m^3/h/at)
Vilkyčiai-3	946 - 1029	0.86	51.1
Vilkyčiai-3	1050 - 1074	0.76	33.64
Vilkyčiai-5	965 – 1024	1.17	40
Vilkyčiai-5	1053 - 1077	0.81	29.4

Table 2: differences between injectivity and productivity indices found in Vilkyčiai oil exploration well after Petrauskas et al. (2018)

In the latest attempt to model the injectivity impairment, authors have estimated a skin value of 120 (Petrauskas, 2018). For their purpose (RJD), they decided to model that impairment using a combination of skin value and permeability impairment around the wellbore. They themselves recognise the weakness of that model (ibid); meanwhile, they do not address the reasons for the – dramatically - different skin values during injection and production.

7. REOPENING THE CASE

Because of the perceived mystery around the injection issues in Klaipeda, and because substantial amounts of public money have been used directly and indirectly (through publicly funded research programs), it is important to dig into the reasons of that project's failure and to ensure that lessons are learnt and taken into account in future similar developments.

7.1 The 2002 Acidization

The 2002 coiled tubing acidization was the only remedial attempt that resulted in sizeable improvements. Unfortunately, that operation has not been closely investigated in the different technical papers available to us. It is quite troubling that an operation that generated substantial positive results was overlooked. Today, because of the bankruptcy of the operating company, the archives are inaccessible. However, we could access the technical requirements provided in the call for tender documents generated by a Danish technical partner. In that document (UAB Geoterma), the injectivity problems are described the following way: "[…] mechanical cleanup and opening of clogged up portions of the injection screens located between 970 - 1113 m GL […]". It was then understood that some material was clogging the screens and that this material had to be removed. For a service company, and as described later in the same tender document, that means providing a treatment that will both act chemically and mechanically, through the use of a coiled tubing (or a specific workstring), to remove the plugging material. We assume that the acid was placed with the use of a jetting bottom hole assembly designed to mechanically dislodged the clogging material around the screens. Therefore, it is possible that the chemical nature of the 20 m^3 of 18 % HCl injected in each well was less important than the mechanical effect of the jetting assembly used to place that treatment.

7.2 The Gamma Ray Logs

7.2.1 Measurement and analysis principles

The gamma ray (GR) tool consists of a scintillation counter that passively receives the gamma rays from the environment (borehole, mud cake, invaded and virgin zones) and converts them to a recorded electric signal. When the disintegration of radioactive atoms (e.g. uranium, thorium, potassium, etc…) emits gamma photons, these propagate through the rock and the borehole fluid before reaching the detector and being counted. While traveling through the rock and borehole, the gamma rays are absorbed by the medium thus attenuating the signal. This attenuation follows an exponential decay with the traveled distance. Hence, attenuation is mostly a function of the traveled length and the bulk density of the medium through which the gamma photons propagate, independently of the GR tool.

The GR signal is not deep reading. It is widely admitted that, of the GR signal received by a logging tool, half comes from a distance of less than 180 mm (7 in.), and 90 % from less than 450 mm (18 in.) (Serra O. and L., 2004). The signal strength is also depending on tool centralization and other environmental parameters such as mud density and its KCl content; those can be corrected for enhanced analysis.

In Klaipeda, the operating company acquired gamma ray (GR) response logs in both injector wells at different times (Figure 6).

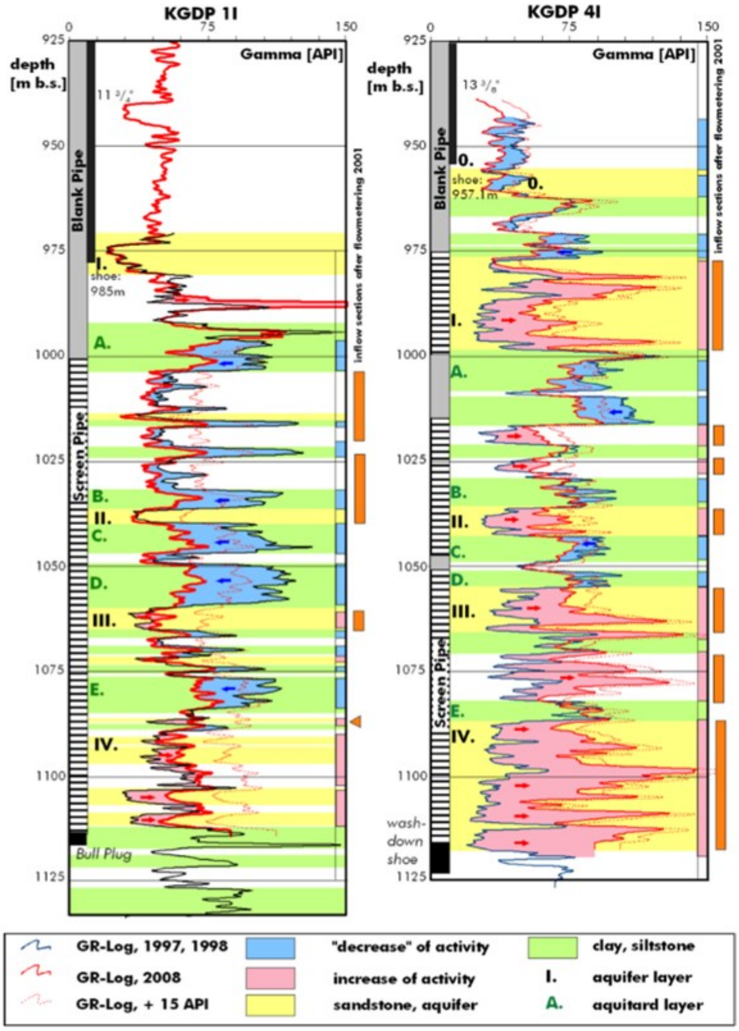

Figure 6: GR logs comparison 10 years apart

7.2.2 Case of KGPD-1I

On the left track of Figure 6, the GR logs run in the original KGDP-1I well are presented. The black GR line was acquired in the open hole, before completion (1997), and the red one was acquired eleven years later (2008), inside the completion string (blank pipes and sand control screens). The initial GR log shows a succession of plurimetric, high GR layers up to 120 GAPI, identified as claystones and siltstones, and low GR intervals between 20 and 40 GAPI, regionally known as poorly consolidated sandstones. These sandstones are the targeted geothermal aquifers; they have excellent petrophysical properties with porosity up to 26 % and permeability up to 4 Darcy. The reservoir sand sections are highlighted in yellow and labelled from I. to IV. Between these reservoir sections, shale and silt interbeds identified by their higher GR response are colored in green and labelled from A. to E.

The two GR logs run eleven years apart show significant differences.

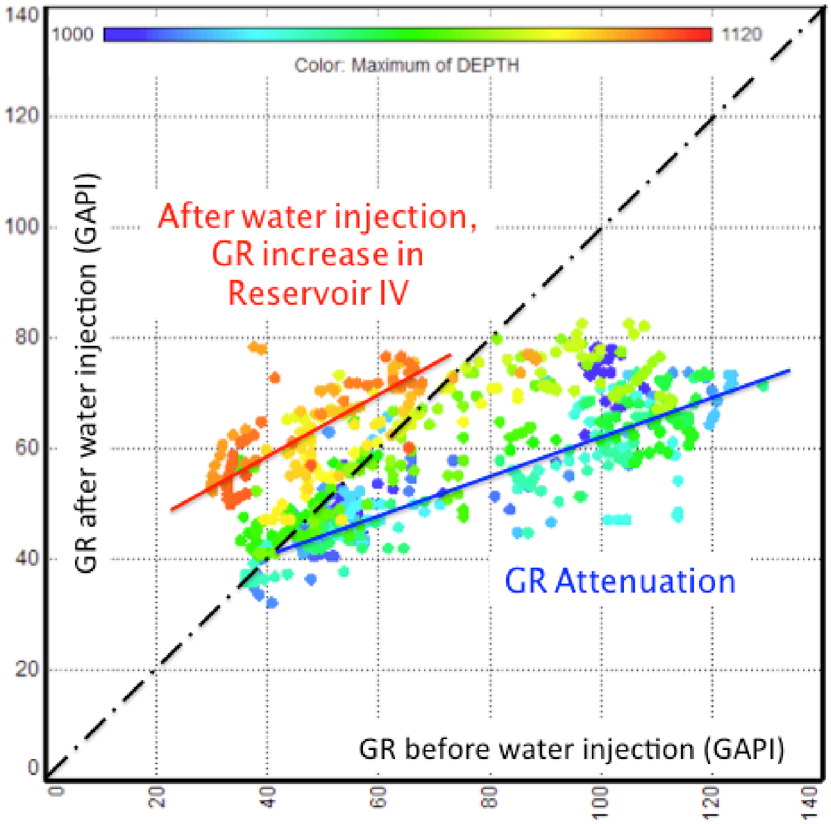

Figure 7: Crossplot of GR after injection versus GR before in KGPD-01I

The crossplot presented as Figure 7 compares the GR readings prior to and after water injection. The black dashed line represents the point where GR would be unchanged, while the blue line shows a lower GR after injection and the red one an increased GR after injection.

- In the top part, above 1085 m (or down to layer E.), the GR after completion is very attenuated in the shales and silts when compared to the open hole acquisition (blue shading, blue line in Figure 7): the 115-120 GAPI base line in the open hole run has decreased to 70-80 GAPI after completion and the injection period. This attenuation could result from a combination of: gamma photons being absorbed by the completion steel, washouts developed in the shaly formations thus increasing the distance to the tool, but also potentially a different tool centralization or environmental corrections.

  Down to layer E., the low radioactive layers are slightly attenuated, likely due to similar effects.

- In the lowermost part of layer E. and in reservoir IV., while an attenuation should also be expected, the GR readings have increased from 30-35 to 50-55 GAPI (pink shading and red line on the crossplot in Figure 7). This indicates that in the water injection process, radioactive material was transported and accumulated in front (or in the immediate surroundings) of reservoirs IV.

Using the following observations and hypothesis:

1. Half of the GR contribution comes from inside a 7 in. radius extending from the borehole wall.
2. The GR after water injection was 55 GAPI in the lower sandstone layer; while
3. The initial sandstone radioactivity was 30 GAPI in that layer.
4. The centralization and attenuation from steel are unknown and arbitrarily neglected.

It appears that the radioactive material in front of the sand face is at least of 80 GAPI, and higher if the radioactive material is plated in a sheet thinner than modeled, or if the steel attenuation were accounted for.

This high GR reading is fully compatible with shale material destabilized and washed from the above sections during water injection, and deposited at the borehole wall where the permeable layers filtered it out of the liquid.

7.2.3 Case of KGPD-4I

Similar to KGPD-1I, KGPD-4I experienced a low and declining injectivity while maintaining a good productivity when reversing the flow. The initial GR log was acquired open hole in 1998, prior to running the sandface completion. After years of declining injectivity, another GR log was acquired in 2008. Both logs cover the entire reservoir section. These GR logs are shown on the right track of Figure 6. On that plot, the blue line depicts the GR before injection and the red line is the GR after several years of injection, both on a 0-150 API scale. The pink shading highlights the intervals where the GR has increased while the green shading emphasizes those where the GR has decreased during these ten years.

After ten years of injection, the high claystone and siltstone GR have slightly decreased (by 15-30 GAPI or 30 % decrease), likely attenuated by the completion steel, a possible better centralization of the tool inside the completion screens and the further developed washouts. A similar attenuation ratio would be expected across the reservoir intervals. Unexpectedly, the GR readings in the sand intervals, far from being attenuated have significantly increased. For example, in the clean sandstone at 1109 m, the GR counts has increased from 26 to 128 GAPI. The GR evolution shows that the injection into the permeable layers has brought a large quantity of radioactive elements that were deposited at the sandface or in the very near wellbore volume.

Using the following observations and hypothesis:

1. Half of the GR contribution comes from inside a 7in. radius extending from the borehole wall.
2. The GR after water injection was 128 GAPI in the IV. sand reservoir; while
3. The initial IV. sandstone radioactivity was 26 GAPI.
4. The centralization and attenuation from steel are unknown and arbitrarily neglected.

and focusing on the 1109 m readings, we can approximate the post-injection average GR in the wellbore and first 7 in. of formation of up to 230 GAPI. Because this estimate does not account for steel attenuation and because the radioactive material is probably deposited in a thinner layer, the actual GR value is likely higher. In any case, this value is much higher than that of the claystone, ranging from 100 to 120 GAPI. Nonetheless, we believe that the GR element transfer is likely due to the destabilization and transport of the argillaceous and silty material by the injection flow and the creation of a filter cake across the highly permeable sandstone. The segregation mechanism causing the highest GR material (higher than the original claystone formation GR reading) to plate onto the sandface is still to be investigated. Access to the reports from the logging company, to the core from the Klaipeda reservoir section and dedicated laboratory experiments would greatly help understanding this mechanism.

7.2.4 Summary of the GR analysis

These GR logs indicate that in the span of ten years, the GR intensity across the reservoir sands has increased dramatically, and that in the meantime, the GR reading has lowered in the shales. That clearly shows that radioactive material has built-up across these sands, near the wellbore, while the GR reading was attenuated across the shale layers.

Further investigation has not pointed toward the formation of radioactive precipitate and we found no report of radioactive tracers being ever injected in these wells. Additionally, foreign radioactive precipitate would have had no effect on the GR reading across the shale layers Therefore the changes of radioactive activity along the Kemeri formation in the injector wells is most likely endogenous. The natural suspect is a shale and silt accumulation at the permeable sand face that would undoubtedly increase the GR reading across these layers meanwhile the GR decrease across the shale layers is likely resulting from a phenomenon attenuating the signal between the shale and the logging tool. This attenuation could be caused by:

- the metal installed into the wellbore - namely blank pipes and screens - between the open hole and the cased hole logging runs thus partly shielding the logging tool from the formation emissions. This effect works for both shale and sand layers, though;
- some caving in the shale that may have increased the distance between the rock face and the logging tool (run inside the screen); and
- some sand may have collapsed into the voids left by the hole enlargement across the shale layers, thus providing additional attenuation of the GR emitted by these.

7.3 Gypsum Precipitation

Gypsum precipitation has been found in surface facilities and thus making it a potential culprit of downhole problems, in part because of its retrograde solubility. However, gypsum solubility exhibits a low sensitivity to temperature and pressure in the range experienced in the Klaipeda facilities. On the other hand, gypsum solubility is strongly sensitive to salt dissolution (Klimchouk, 1996); gypsum precipitation is likely linked to the variations in salt content across the geothermal system. The reader is invited to refer to Brehme et al. (2019) for discussing precipitations from hydrothermal water in Klaipeda.

However, the increase in the GR response across the sand layers cannot be explained by gypsum precipitation. Gypsum is recognized for having a very low gamma-ray response (KGS, 2017). The positive effect of the 2002 HCl injection is also unlikely due to a chemical dissolution of gypsum given the low temperature environment, from the surface down to the injection depth.

7.4 Injectivity vs. Productivity Indices

One of the critical elements of Klaipeda injector wells' damage is the difference between injectivity and productivity, with indices varying by a factor of 30 to 50 in favour of productivity. Petrauskas (2018) reported a skin value of 120, but that is only an "injection skin". Using Hawkin's formula (equation (1) below), such a skin value would require a huge permeability reduction over a substantial damage radius. Such a damage would also be seen in the production direction using conventional reservoir engineering wisdom.

$$S = \left(\frac{k}{k_d} - 1\right) \ln(\frac{r_d}{r_w}) \quad (1)$$

In Hawkin's formula, S is the skin factor, k the reservoir permeability k_d the damaged zone permeability, r_d the radius of the damaged zone and r_w the wellbore radius.

Precipitation in the porous medium would also be seen in both production and injection directions unless a miraculous dissolution happens upon production and instantaneously reprecipitates upon reversing the flow. The difference in productivity and injectivity, or “check-valve” effect is typical of particle moving in the plugging direction and being dislodged when the flow is reversed. If these particles were inside pores - as frequently experienced in unconsolidated sandstone producers (Ezeukwu et al. 1998) - this difference is observed, but never to the extent seen in Klaipeda.

The Klaipeda observation is typical of a filter cake, i.e., a layer that builds right at the borehole wall and that has virtually no permeability. This layer is pressed against the porous medium when injection pressure is applied and is lifted when a differential pressure moves it away from the borehole wall. When the filter cake is lifted, the well produces with no apparent damage. When the cake is removed and free to move to surface, then the wellbore can be cleaned and ready for injecting again. However, when the cake is trapped downhole, between the sandface and a screen for instance, reversing the flow presses the cake back onto the borehole wall, and the injection is greatly impaired again. Ironically, the lower the injectivity, the higher the pressure and the more effective the sealing against the sand, thus further impairing the injection.

7.5 Injection Wells’ Flowmeter Measurements

Petrauskas (2018) shows flowmeter logs ran by the operating company in both injector wells in 2008 (Figure 8). Despite the alternation of very high permeability sands and very low permeability silt and clay layers, the spinner survey shows an almost constant rate decline (i.e., uniform injectivity) along the reservoir section, where huge heterogeneities should have been found. This behaviour of uniform filtration over an otherwise heterogeneous wellbore section is typical of a cake build-up onto the wellbore wall. When solids are carried within the injected fluid, they deposit wherever the filtration occurs; a sandface cake is then created and a homogeneous impairment is eventually built at the filtration locations.

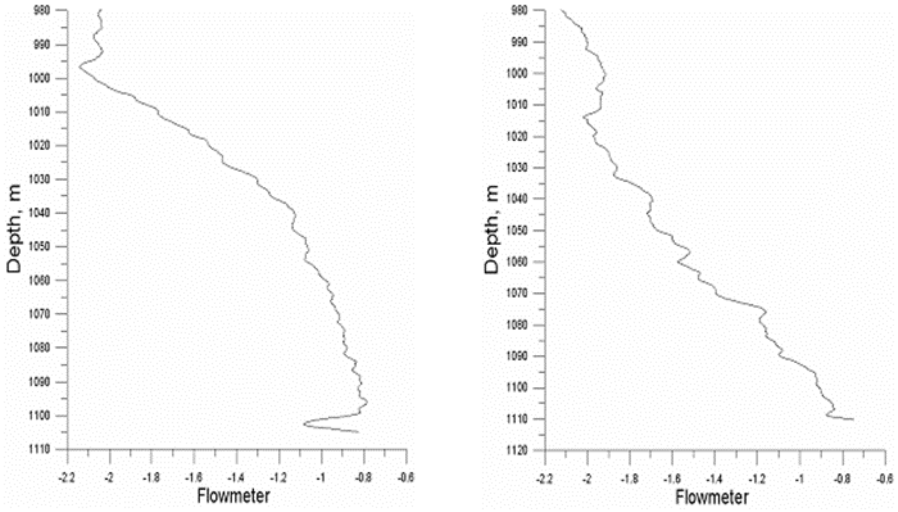

Figure 8: Flowmeter records during injection in wells KGDP-1I (left) and KGDP-4I (right) after Petrauskas et al. (2018)

8. THE FORGOTTEN WORLD OF WELLBORE COMPLETION

Unfortunately, we did not enjoy complete access to the Klaipeda wells’ archives. However, Petrauskas et al. (2018) note *a more careful application of the drilling mud in the well KGDP-4I*, without giving more details. Apparently, the drilling fluid used when drilling the first wells caused problems. The sub-optimal drilling fluid is likely to have translated into hole stability issues, hence the “more careful application” when drilling KGDP-4I. Indeed, the open hole logs of KGDP-4I (Figure 9) show a well pretty much in gauge, especially in the bottom part of the reservoir section. In the KGDP-4I, the top sand was more affected by the caving, similar to situations observed when using oil-base drilling fluid systems. Here again, getting access to the Klaipeda drilling reports could provide very interesting information and important lessons, should the geothermal project be revived.

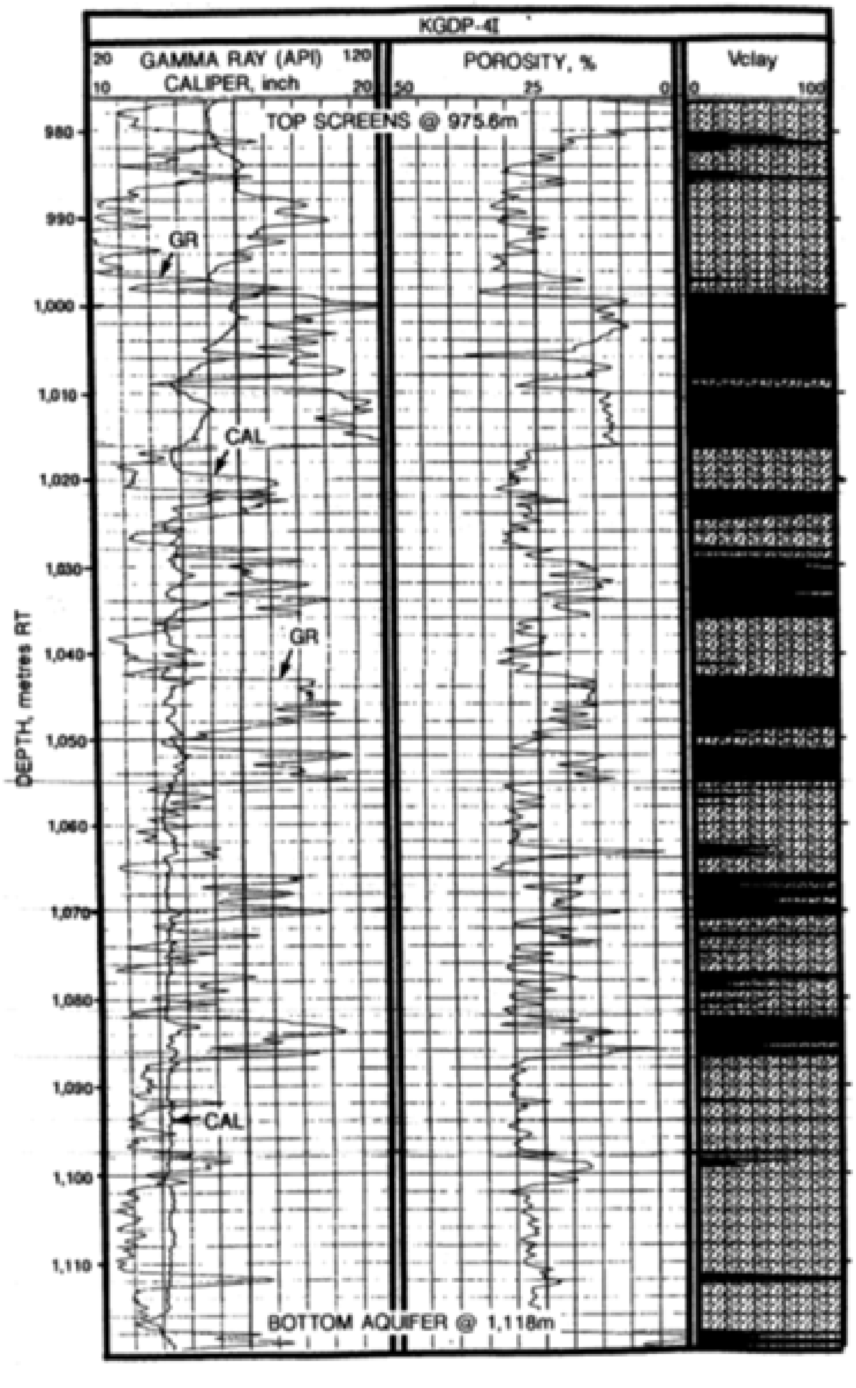

Figure 9: Open hole log data and interpretation of KGDP-4I

Since the reservoir section sensitivity to the drill-in fluid had been identified early, the upcoming issues when injecting water into openhole sections could also have been anticipated as early as 1997, right after drilling the first well in Klaipeda. Since the water-base fluid used for drilling destabilized clays in the reservoir section, the water injected during the plant operation was likely to have a similar effect, unless properly treated to ensure that the process catered for shale/clay inhibition upstream the injector wells.

Apparently, the lesson learnt in 1997 about drilling fluid and hole stability was lost when side-tracking KGDP-1I in early 2009. Figure 10 is a portion of the open hole log acquired in 2009 just before running the completion. The GR log is in red on the left track, while the bit size (10 ¾ in., in red) and the caliper log (in blue) are presented on the right track. This measurement clearly shows severe hole stability issues, more pronounced across the high GR sections.

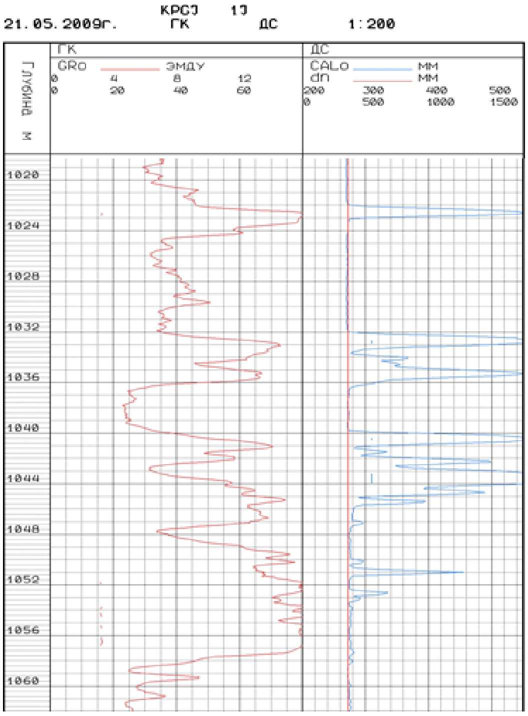

Figure 10: Gamma ray example log in Klaipeda reservoir section from KGDP-1I side-track (May 21st 2009)

The hole is pretty much in gauge across the sand sections, while caving is observed across the shale layers. This is commonly observed in wells drilled using water-base drilling fluids; when the reservoir section drill-in fluid is not properly engineered, clays react with the fluid and are destabilized, thus causing hole enlargement. This is even more severe when drilling formations such as the Kemeri that Brehme (2019) describes as hypersaline with water salinity circa 90 g/L. As a result, in KGDP-1I side-track, for a 273 mm drilled hole, caving caused hole diameter enlargements up to 500 mm across shaly layers.

The core retrieved in Klaipeda (Figure 11) shows the alternation of sand and shale, and also confirms the low level of consolidation of both species.

Figure 11: Cores sampled in Klaipeda geothermal reservoir section

In the side-track of well KGDP-1I, two gamma ray logs were acquired 9 days apart (Figure **Error! Reference source not found.**12). The first one was likely part of the initial open hole logging suite, aiming at identifying the permeable layers and planning for the final completion length and position. The second one was run after installing the completion string in the open hole. Unlike for cased hole completions were perforating guns must be correlated, it is quite unusual to run such logs after running sand screens in open hole completions. Because of the limited information available to us, we must make an educated hypothesis: something may have gone wrong while installing the screens and the operator ran that log as part of the investigation, as well as to ensure that the well could be used despite the operational difficulties. The only daily drilling report that we have in hand is dated May 25. At that moment, a clean-up trip had been performed and the crew was preparing to turn the well to geothermal water before running the completion string.

The landing string tally that was produced on May 28 (reproduced in Table 3Table 3: KGDP-1I Sidetrack sandface completion string tally reproduced from field data and from top to bottom) reveals that the shoe ended down at 1086.80 m. However, Petrauskas (2018) reports that the most promising layers with the largest sand grain size in KGDP-1I sidetrack were found at the following depths:

1st Layer: 1037.5 – 1040 m

2nd Layer 1095 – 1097.5 m

3rd Layer: 1104 – 1107.5 m

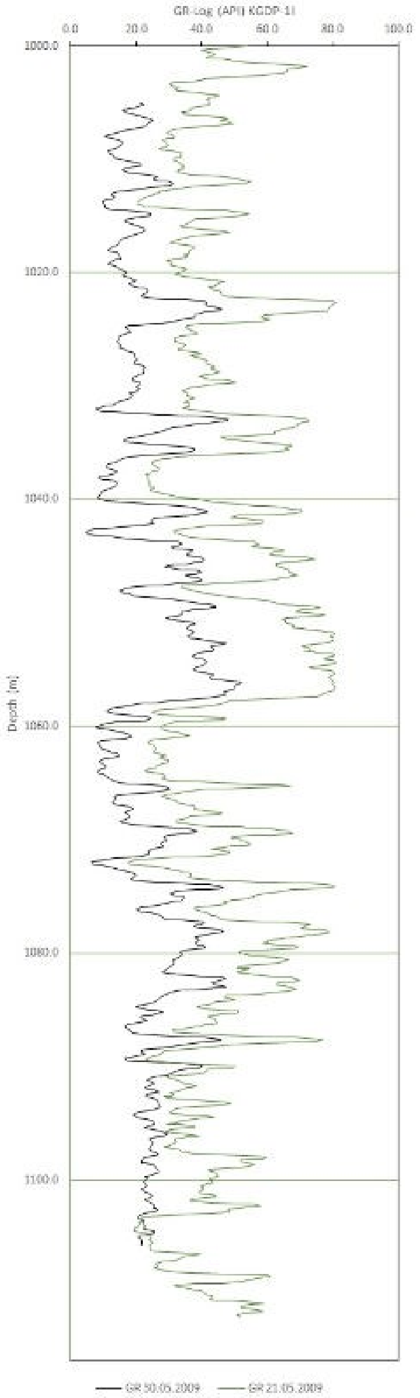

Figure 12: Gamma ray logs ran in KGDP-1I side-track on May 21st (green line) and 30th (black line) 2009

It seems strange that two of the best layers were left below the bottom packer and not part of the screened completion, with the risk of collapsing into the wellbore. When the remedial option through RJD was contemplated, then 7 of the 12 laterals were jetted in these two bottom layers thus confirming their attractiveness.

Sandface completion elements	**Top** *(m)*	**Bottom** *(m)*
Swell packer	1003.77	1008.24
Screen	1008.24	1030.93
Blank pipe	1030.93	1044.43
Screen	1044.43	1068.82
Blank pipe	1068.82	1082.03
Swell packer	1082.03	1086.5
Shoe	1086.5	1086.8

Table 3: KGDP-1I Sidetrack sandface completion string tally reproduced from field data and from top to bottom

The distance open to flow between the two packers is 78.26 m. It is therefore highly probable that the operator wanted to run this completion string across the three best layers above described and covering a gross interval of 70 m. Therefore, it is suspected that:

1. The completion string did not reach bottom and was stuck above the two best bottom layers.
2. A gamma ray log was run after getting stuck to confirm the completion string actual position and evaluate the risks of operating as such.

Based on the above evidences, the probable mechanism that led to the final KGDP-1I side-track configuration is speculated below:

- during drilling the open-hole section was affected by the drilling fluid thus causing caving and instability in the silt and clay layers;
- at TD, viscous pills were used to clean the wellbore and the well was turned to geothermal water increasing the wellbore instability because of the lack of inhibition and the ionic disequilibrium of the geothermal water, and possibly the reduced hydrostatic pressure;
- the completion string, with its swell packer at bottom (low clearance) acted like a piston that pushed all the swollen and destabilized material at bottom;
- the completion string got stuck at some point in a poorly calibrated hole; and
- The operator decided to run a GR log to investigate the problem and locate the exact position of the stuck string.

When looking back at the completion sketch (Figure 2) while keeping in mind the previously explained technical issues, it appears that:

1. The swellable elastomer devices, (commonly referred to as swell packers) were likely unable to provide sealing when located in a caved section. When exposed to large voids, the absorption of water by the polymeric material included in the elastomer eventually destroys the material supposed to provide sealing.
2. Because the swelling process of water swellable elastomer is an osmotic one, its utilization in a highly saline environment such as the Kemeri formation requires a specific fluid management procedure (Guinot and Meier, 2019).
3. If the liner hanger does not include packing elements, a flow path exists all along the open hole, thus leaching and destabilizing clay and shale during the injection operations. Unfortunately, the type of hanger used to suspend the blank pipes and screen assembly are not yet available to us.
4. The long screen string across the reservoir section, without sealing element, provided un unrestricted pathway to the injected fluid that could keep on leaching the clay and shale layers to further destabilize those and carry solids onto the permeable sandface.

9. THE LETHAL INJECTION AT WORK IN KLAIPEDA INJECTOR WELLS

The injector wells situation in Klaipeda in grossly sketched in Figure13 and can be described as follows:

1. during drilling, the fluid did not provide the appropriate inhibition and the shale (especially in the most damaged well KGDP-1I), clay and siltstone sections were destabilized, thus providing a poorly calibrated hole and mobilizing solids;
2. the open hole completion design did not provide isolation between these sensitive shale and clay layers and the high permeability sands targeted for injection;
3. the injected fluid leached and further destabilized the silt and clay layers through the multiple flow paths in the open hole;
4. the shaly material plated the sand face across the permeable layers, thus creating efficient filter cakes; and
5. the filter cakes are now trapped between the sand face and the downhole screen, thus unable to be flowed back to surface when the wells are reversed to production mode;

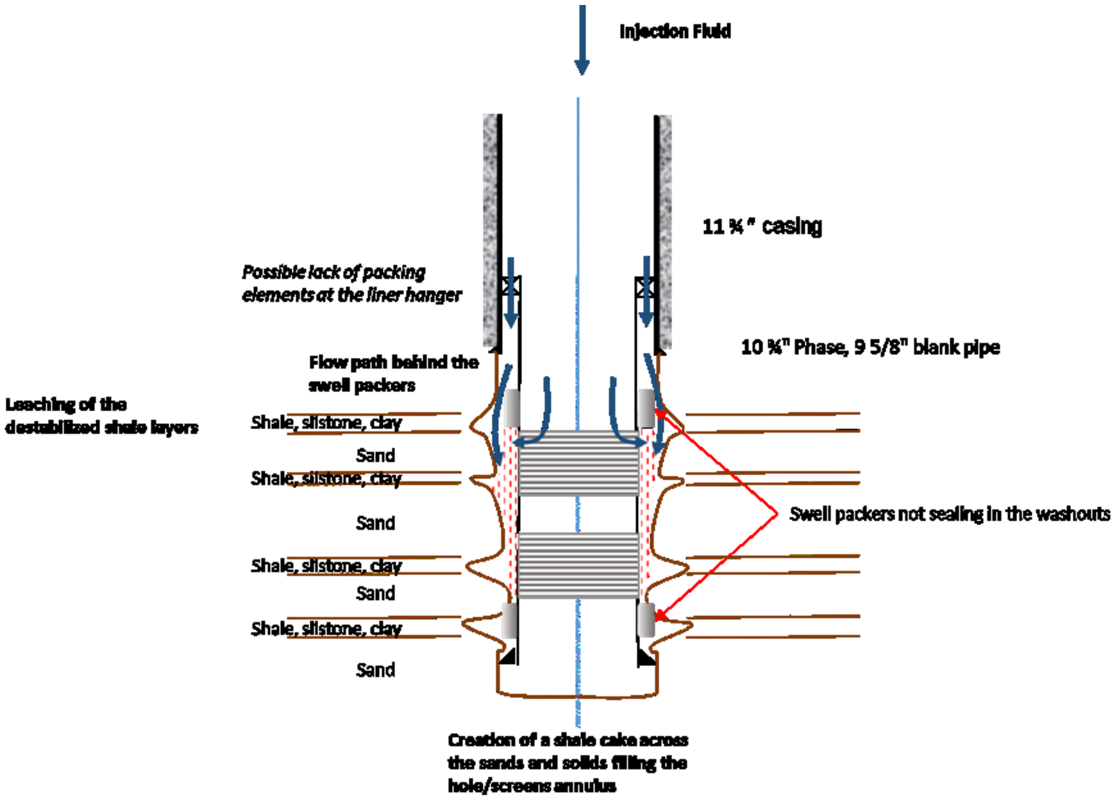

Figure 13: Klaipeda mechanism of formation damage

To illustrate the point as well as raise awareness, Figure 14 shows a filter cake artificially created in the laboratory on the face of a sand plug. That one was created with water-base bentonite drilling fluid and is a good example of the type of material that has built up against the sandface and is plaguing the Klaipeda injector wells.

Figure 14: Example of a filter cake created in the laboratory by filtering water-base drilling fluid onto a permeable sand, courtesy or Schlumberger

10. DISCUSSION:

The drilling fluid literature is full of examples showing shale destabilization with fluid contact and stabilization with chemical additives (Griffin et al. 1986, Weaver and Nguyen 2011, Friedheim et al. 2011).

The creation and removal of filter cakes normally created while drilling across permeable sand layers is also a classic of chemical stimulation literature (Morgenthaler et al. 1998, Zain and Sharma 1999, Ryan et al. 1995), as well as the effect of filter cake build-up mechanism in decreasing injectivity (Pautz et al. 1989, Pang and Sharma 1997).

The most efficient way to clean sandface filter cakes is by reversing the flow and producing them to surface. Generally speaking, it is always a good practice to produce all the cuttings, filtration fluid and foreign material present inside the well prior to start injection. For an efficient back production, the flow path between the reservoir sand and the surface effluent collection tank must allow all this material to reach surface. The applied drawdown must be sufficient to lift the cake off the sandface and the production velocity high enough to bring everything to surface. These operations require a sufficient reservoir pressure or the assistance of an appropriate lifting system.

In the case of Klaipeda, when the flow is reversed, the filter cake plates onto the outer diameter of the sand control screens and does not flow to surface. Alfenore et al. (1999) have recommended that when a sand control screen is run in the well prior to filter cake flowback, the latter must be engineered to be able to flow through the screen. In Klaipeda, the cake build-up mechanism described in section 9 is naturally created inside the wellbore, hence not subject to engineering…

Screen plugging in producer wells is often insufficient to observe its effect on production data because plugging a 250-micron nominal opening size screen is more difficult than plugging a sand formation exhibiting a few microns average pore throat. The production flow, can also find alternate pathways and bypass the plugged portions of screens and progress towards the surface (e.g., along the pipe annulus). This allowed Burton and Hodge (1998) to show that as long as a sand screen is more than 10% open to flow, production is not highly impaired by the plugging.

The 2002 CT acidization of the two Klaipeda injector wells was likely performed through a jetting tool that destabilized part of the filter cake that took a few weeks to replenish. Running a PLT (production logging tool) while producing well KGDP-1I could give further clues on damage characterization and on its location; especially if jetting of the screens with an inert fluid can be performed between two PLT logs.

Because cores are available from the Klaipeda reservoir section (Figure 11) the effect described in section 9 could be easily reproduced in the laboratory. The set-up presented in Figure 15 requires only standard equipment available in any core flow test laboratory. In addition, the same or parts of this equipment could be used to identify or dismiss other damaging mechanisms affecting the reservoir formation during injection.

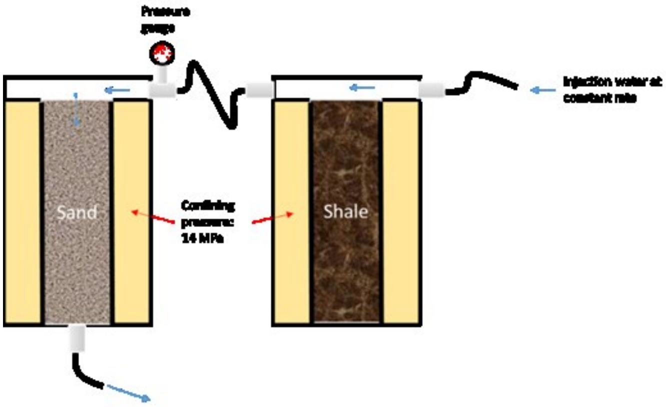

Figure 15: Suggested laboratory test to prove the damage mechanism

11 REMEDIAL SOLUTIONS

The injection impairment in Klaipeda is clearly linked to poor choices in designing and constructing the injector wells. Chemical stimulation attempts in Klaipeda have failed because they do not offer a real sustainable solution to the injection problem. The nature and level of damage in the two injector wells cannot be efficiently removed with well stimulation. The drains jetted using RJD in the unconsolidated Kemeri formation have probably collapsed shortly after they were drilled, offering just a new very limited entrance hole at the wellbore that the damaging material took no time to plug.

Recompleting Klaipeda's injector wells through a workover campaign is probably not worth considering; the liner hangers may not be retrievable, a milling intervention would be costly, and pulling out the swell packers may result in many operational challenges. Additionally, the level of damage and caving cannot be mended with a work-over intervention. Even if the open holes were successfully accessed, the challenge of isolating the high gamma ray layers and the clean sand layers inside an irregular and enlarged wellbore would remain.

Given the shallow nature of the Klaipeda wells, a properly drilled injector is the best technical option to solve the current issues and to give new prospective to the Klaipeda geothermal heat plant. A properly drilled and completed well in Klaipeda should be able to inject and produce between 20 and 40 m^3/hr/bar.

Because of the geological nature of the reservoir section, the shale and sand layers must be properly isolated. Zonal isolation in this type of environment means completing the reservoir section with a cemented pipe. To efficiently cement the pipe, the drilled hole must be properly calibrated, hence the need for a carefully selected drilling fluid and drilling assembly. A properly inhibited water-base, or alternatively a synthetic oil-base drill-in fluid system must be engineered for the specific shale found at the reservoir level and used to drill the targeted section. That drill-in fluid must efficiently build a filter cake across the multi-Darcy formation to limit filtration and formation damage while keeping the siltstone and clay stable. The drill-bit (likely a PDC type) and BHA must be selected for its performance in low strength rock at drilling a well calibrated hole. After reaching the desired depth, a standard triple-combo logging suite must be run to identify the permeable sands. Then, a pipe, either a casing or a liner must be installed in the hole, across the reservoir section and properly cemented. After cementing the casing/liner string, the well will have to be turned to clean solid-free brine.

Because of the poorly consolidated nature of the reservoir sand (Figure 11), a downhole sand control system must be installed for robustness. A properly installed sand control completion would also allow using the well both as an injector and a producer, thus increasing the options in Klaipeda. Therefore, the best sands must be carefully selected perforated with big hole, high shot density guns. It is also a good practice to perforate injector wells using underbalanced or dynamic underbalance technologies. The preferred sand control technique to use in Klaipeda is likely gravel packing using the High-Rate Water Packing (HRWP) technique. With such a robust completion, would insufficient injectivity occur, the pressure can be increased slightly above the fracturing pressure in the sands to recover the needed injection parameters.

Additionally, next to the Klaipeda geothermal site is a refuse incineration plant. That plant produces heat that competes with the Klaipeda geothermal plant in feeding the district heating network during the wintertime. However, during the summertime, part of the heat generated there is dispersed into the atmosphere. A properly designed well could be turned into an injector in the summer time, inject the lost heat from the incinerator and be reversed as a higher temperature producer during the winter. A robust well architecture would therefore not only solve the low injection problem in Klaipeda, but also bring additional value to the site by using it as an underground thermal energy storage (UTES) site thus increasing the amount of energy available in winter, at no additional cost.

12 AND WHAT NOW? A SORT OF CONCLUSION.

This review evidences major flaws in Klaipeda injector wellbore drilling and completion. In sedimentary covers such as the one found in North-Western Lithuania, best practices should always consider isolating geological layers that behave differently under mechanical and/or chemical actions. This is particularly true for injector wells in which any solid picked during injection will irremediably plug the receiving formation. In the specific case of Klaipeda, the completion technique made remedial actions impossible. This eventually killed the project after engulfing a substantial amount of (public) money.

But it may be the beginning of a renewed project in Klaipeda. Because, the problem has been clearly identified herein, because the technology to drill a proper injector well exists, because the target formation is fairly shallow and because the geothermal plant is already connected to a district heating loop craving for heat in the long winter time, there is hope and necessity of reviving the plant.

The debt of the company (around 3 Meuros) must be erased by the competent authorities. The reasonable cost of drilling and properly completing an injector well can be sourced from a benevolent investor with public support. Eventually, the plant can later be coupled with an underground heat storage system fed with the lost heat generated in the summer time by the incineration plant next door. At a very reasonable cost, a low emission district heating system can be revived to the benefit of the largest population and make the geothermal industry in Lithuania great again.

ACKNOWLEDGEMENTS

This work received no funding whatsoever and was performed on our spare time. It was made possible because of the help of individuals who kindly provided access to data: Maren Brehme, Kerstin Nowak, Kong Xiang-Zao and Philippe Quero. Thanks to Pierre-Eloi Ragettli for his kind and thorough review of this article, to Dieb Hammami for his suggestion of bringing Serge into the project, Benjamin Sallier who accepted that contribution and Thomas Driesner whose praises were much appreciated. The encouragement of Michel Meyer and the SIG as well as Philippe Michel and Vulcania Energy SARL are here as well recognized.

GLOSSARY

BHA	Bottom hole assembly	MD	Measured Depth
GL	Ground level	MSL	Mean sea level
GP	Gravel pack	PLT	Production logging tool
GR	Gamma ray	SAS	Standalone Screen
HCl	Hydrochloric acid	TD	Total Depth
HRWP	High rate water pack	UCS	Unconfined Compressive Strength

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