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1. Executive Summary

In November 2014, radial jetting technology was identified as a possible solution for enhancing injectivity of the wells. RJD (radial jet drilling) is the technology which uses equipment with high pressure water jets. The water jet nozzle used for jetting the laterals has an exact number of forward and backward jets and is conveyed on mini coiled tubing. The forward-facing jets provide the required erosion of the rock surface and the backward facing jets causing the forward motion by pushing the nozzle forward. Those high-pressure water jets are deconsolidating and washing out sandstone particles making round holes (till 2 cm in diameter) with three or five beams (5 to 8 cm in diameter depending from the jet used) to form the laterals beams. Depending on the well depth water pressure could reach 770 bars in the injection area. Theoretical calculations have shown that injection surface which could be created in this way should double or even triple the existing injection surface and consequently with increased injection surface should increase injection rate in the chosen injection well.

After the quite long negotiations period with “Coil services” company from Netherlands, JSC “Geoterma” finally decided to use this new technology. The detailed program of actions (approved from both sides) was prepared to execute this project in one of existing injection wells. The injection well No. 1I was chosen as the best candidate. The main objective of RJD project was to create the highly conductive channels perpendicular to the new borehole which has inclination from 3 to 5° of old vertical borehole. The duration of the project on site was planned for five working days. The channels were created in the middle of the most productive zones in three different productive layers.

- 1st layer (1037,5 - 1040,0 m) start depth: - 1039,0 ±0,5 m
- 2nd layer (1095,0 - 1097,5 m) start depth: - 1096,5 ±0,5 m
- 3d layer (1104,0 - 1107.5 m) start depth: - 1106,0 ±0,5 m

In each layer were drilled four radial holes at 45°-50° phasing (fig. 25, page 40). Corresponding to the scheme the length of each lateral should be drilled 40 ±0,5 m, but in reality nine of them were drilled 40,0 m length, two 35,0 m length and one of them 28,0 m of length.

Table 1: Economic effect evaluation on post radial drilling project in injection well No.1I after three month of operation.

Injection rate in 2014 November-December (before RJD), m^3/h	43.1
The injection rate in 2015 February-March, m^3/h	49.2
Injection rate increase, m^3/h	6.1
Injection rate increase, %	14.2

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Production of additional heat energy per month, MWh	138,0

Table 2: Economic effect evaluation on post radial drilling project in injection well No.1I after two Years of operation.

Injection rate in 2014 November-December (till RJD project), m^3/h	43,1
Injection rate in 2016 November-December and in 2017 January – February (till geothermal plant was stopped), m^3/h	60,0
Injection rate increase, in m^3/h	16,9
Injection rate increase in, %	39.2
Production of additional heat energy per month, MWh	328,5

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2. Introduction

Klaipeda is a city in Lithuania on the Baltic Sea coast. Cooperating with experts from the “Petroleum Geology Investigators” and the “Danish Environmental Protection Agency“ funding from the Danish Kingdom was prepared the Baltic geothermal energy project, which assessed the possibility of geothermal energy usage in Lithuania, i.e. to use low temperature (35-40ºC) from highly mineralized geothermal water for municipal buildings heating. According to this project as the optimal model for geothermal plant construction was chosen Klaipeda city. It is the third largest city in Lithuania and the capital of Klaipeda County. The place for Klaipeda Geothermal Demonstration Plant was chosen in western part of Klaipeda city. Geologically Klaipeda’s area is part of the Baltic Basin, occupying the major Baltic Sea as well as the Estonian, Latvian and Lithuanian land areas. The Baltic Basin is bounded by the Fennoscandian Shield in the north and west and by the Tornquist-Tesseyre main tectonic zone in the south. Towards the east the Baltic Basin appears separated from the major Russian Platform area by a series of north-south trending elevated basement features, sometimes referred to as the Latvian-Lithuanian saddle. The main objective of geothermal installations comprises the Lower Devonian D_1km (Kemeri) geological section from 963 m MSL to 1100 m MSL formation, also referred to as “the aquifer zone". The two wells producers, - 2P (55°41’03”.85 North 21°12’07”.95 East) and 3P (55°40’58”.30 North 21°12’12”.40 East) and two wells injectors, - 1I (55°40’24”.65 North 21°13’18.19 East) and 4I (55°39’41”.46 North 21°13’18”.70 East) were drilled during the end of the Year 1997 till the end of the Year 1998. The Klaipeda Geothermal Demonstration Plant was launched on December 2001. After quite long period due to arising problems with gypsum precipitations the plant was commissioned just on June 2004. The production and injection after commissioning was about 450 m^3/h of geothermal water.

Since the Year 2001, when JSC “GEOTERMA” started its main activities, it has faced injection rate sustainability problems. Were executed a lot of geothermal water analysis, injection wells were treated with several acidizing procedures. In 2009, a collateral borehole was drilled in injection well No.1I. Despite all these efforts, sustainable injection rates were hard to maintain. In the end of the Year 2014 JSC “GEOTERMA” was the first to apply laterals holes drilling using the radial jet drilling technology (RJD) in the geothermal well.

3. Production history and injection problems

The Klaipeda geothermal project started in 1996 and the production began in 2000. The injectivity of the wells has been deteriorating ever since this point. The countermeasures taken in 2002 and 2003 could not help this situation. In June 2007, the injectivities were so bad that the sense of the further operation of the plant was discussed.

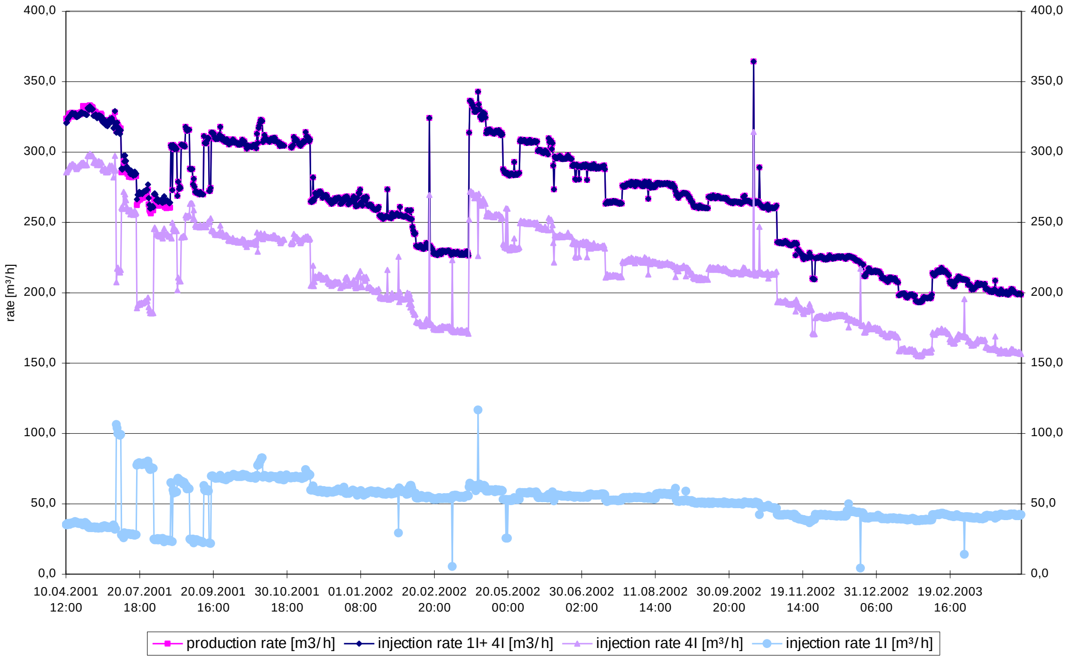

*Fig.1. Production and injection flowrates within the period from 04/2001 – 03/2003; the injection flowrates are known for 1I and 4I by 30.07.01, for the following period the lacking values were calculated. Please note much higher injectivity of well KGDP 4I compared to well KGDP 1I. It is primarily related to different formation damage during drilling operation. The injectivity of the 4I well is > 250 m³/(h*MPa) at the beginning, while only 40 m³/(h*MPa) in well KGDP 1I*

It is necessary for the proper assessment of the investigations to know the chronology of the construction and operation of the geothermal plant. The following data are relevant:

1996 Start-up of the demonstration project „Klaipeda Geothermal Plant “
1997 Drilling of the wells KGDP 1I, 2P, 3P
1998 Drilling of the well KGDP 4I
08 - 11/2000 Completion of the Klaipeda Geothermal Heating Plant (GHP)
12/2000 Start-up of commercial production
2001 Trial run
11 - 12/2001 Video inspection shows clogging in the screen section of the injection wells
11/2001 Proof of gypsum crystals in the surface system
03 - 04/2002 Cleaning work in the injection well

01/2003 Precipitation of gypsum in the adsorption-type heat pumps
02/2003 GHP has 1/3 of its capacity only, removal of gypsum is decided on
08/2003 Cleaning of the adsorption-type pumps
11/2003 Cleaning of the adsorption-type pumps and surface piping systems
12/2003 Installation of an inhibitor system and successful test of the system on 30.12.2003
03/2004 Minor leakages in the LiBr piping system of the adsorption-type pumps
04 - 05/2004 Repair of the geothermal system by 13.05.2004
05 - 06/2004 Test of the geothermal system (25.05. - 07.06.2004)
09/2004 Injectivity is decreasing continuously down to the state in 10/2001
2005 Injectivity is restricted to 150 m^3/h (state as of 16.03.2005)
2007/2008 Investigations by GTN into the deteriorated injectivity
12/2008 Completion of a side track at the KGDP 1I well
01/2009 Test of the KGDP 1I (PI: 38 – 50 $m^3/h/bar$, II: 2.6 $m^3/h/bar$)
09/2009 Test of the KGDP 4I (PI: 31 $m^3/h/bar$, II: 2.7 $m^3/h/bar$)
10/2009 Chemical „work“ on the KGDP 4I with HCl
2010 Operation while the injectivities are further decreasing
July 2010 GTN carried out a sampling campaign

Table 3: Measures to identify the causes of the deterioration of the injectivities and validation of the respective hypotheses.

Measure	Hypothesis: Damage due to
Water sampling and analysis	Precipitation of gypsum, baryte, Fe hydroxide, dolomite
Gas analysis	Corrosion/corrosion products Proof of microbial activity (H_2S), precipitation of carbonate (due to degassing), etc.
Microbiology	Microbial activity, formation of sulphides and carbonate
O2 measurements at the surface	Entry of oxygen
Determination of the „artificial“ final depth and video inspection	Up sanding in the well, clogging of the screen section, corrosion
Downhole sampling incl. analysis	Proof of scaling and corrosion as well as clay migration --> statements on what gets into the aquifer or is formed there
Assessment of all available test data	Validation of all hitherto available reservoir data
Gamma-log, temperature-log	Entry of particles into the sandy screen sections, proof of the screen system

	connection to the rock, identification of the actual inflow zones

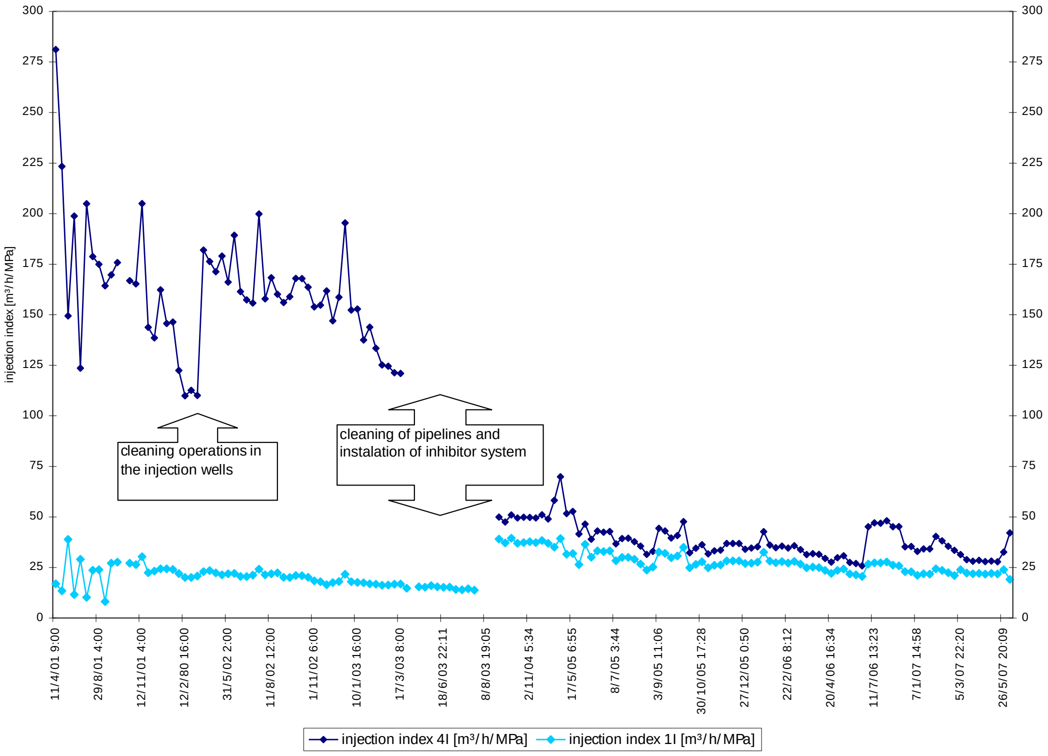

Fig.2. Injectivities of 1I und 4I throughout the period 03/2001 – 06/2007

- The Kemeri aquifer is characterised by very high productivity index (30-50 m^3/h/atm)
- It has initially much lower injectivity index systematically decreases in a course of well exploitation.

Possible reasons

  - Fines migration under high rate water flow. They can be of different nature:
  - pollution by drilling mud (proved in drill cores).
  - mobilisation of the original clay minerals presents in sandstones (illite, kaolinite).
  - erosion of the walls of shaly layers and injection of fines into sandy layers during exploitation (suggested by GR logging).
  - gypsum precipitation (during the initial stage of the plant exploitation)
  - pyrite precipitation facilitated by bacterial activity (proved during pumping of injection wells that show very high pyrite content in the water during the first stage of well test)
  - bubble clogging due to high gas (nitrogen) content in the formation water (may be important during sudden stops in pumps operation)
  - Fe mineral precipitation (during short time when pipe system got unclosed for oxygen input)
  - large sized bacteria growth (fostered by application of the phosphatic inhibitor)

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  - Soft acidization campaigns were of little effect in Klaipėda geothermal wells so far.

4. Geology of the geothermal Reservoir

4.1. Geological setting

The Klaipėda plant is situated in the Baltic cratonic sedimentary basin comprising only weakly tectonized sediments of the Late Vendian to Quaternary age. In west Lithuania, where Klaipėda City is located, the geothermal anomaly is identified where the heat flow attains 70-90 mW/m^2, against the background value of 40 mW/m^2 of the East European platform The thickness of the sedimentary cover of west Lithuania is about 2 km. It comprises several regional-scale geothermal aquifers. The Kemeri Formation of the Lower Devonian age was identified as a target for the Klaipėda Geothermal Plant. The depth of top of the formation is 980 m, the bottom depth is 1110-1118 m. Some lithological variations are recognized in the site area that have an impact on the reservoir properties.

Table 4. Geological column of Klaipėda geothermal wells (depths of a base of the layers are indicated)

4I	1I	3P	2P	Stratigraphy	Lithology
+4	+5	+4.7	+5	Ground level	Flat
134	87	85	85	Quaternary	glacial deposits, sand, clay, gravel
286	265	262	262	Lower Triassic (T1nm-pl)	red clays, gypsum-bearing towards bottom
350	297	295	295	Upper Permian (P2)	limestone, dolomite
607	608	608	608	Upper Devonian (D3pm-D3zg)	predominantly compacted, hard dolomite with marl interbedding's, some gypsum
707	728	722	722	Upper Devonian (D3sv)	sandstone with clay and siltstone interbedding's
799	818	820	820	Middle Devonian (D2up)	sandstone with clay and siltstone interbedding's
925	945	945	945	Middle Devonian (D2nr)	marlstone, dolomite, sandstone
981	980	980	990	Middle Devonian (D2pr)	sand and clay
1118	1110	1118	1118	Lower Devonian (D1km)	sandstone, light-grey, fine and medium grained
1128	1217	1225	1128	Lower Devonian (D1gr)	siltstone and claystone
	1228			Upper Silurian (S2dn)	siltstone, claystone with dolomite stringers

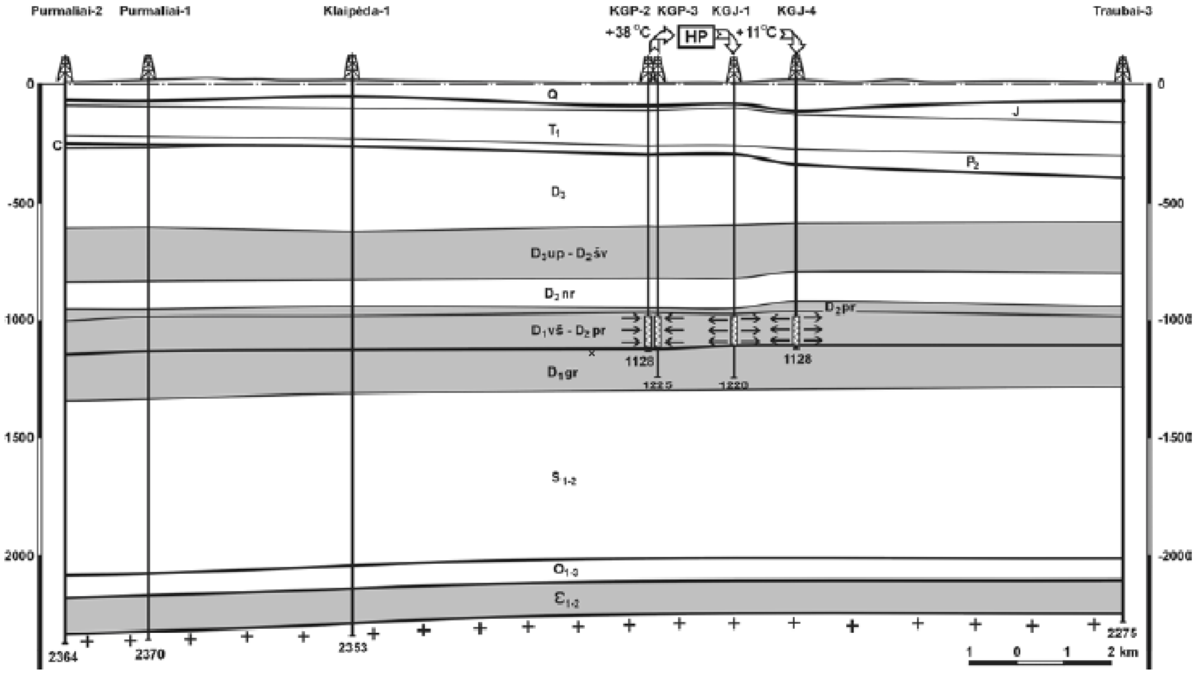

Fig.3. Geological cross section of the Klaipėda area. Production and injection wells and adjacent oil exploration wells are shown (Cambrian is a prospective oil reservoir)

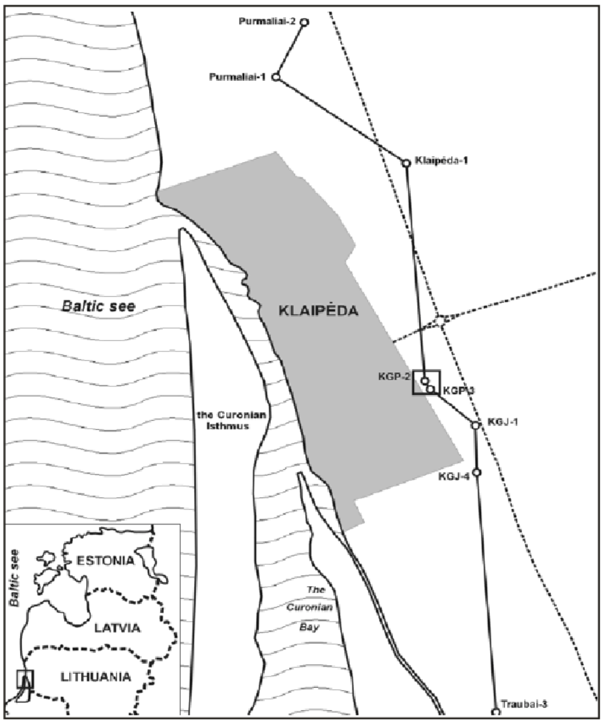

Fig.4. Location of geological cross section shown above

The Kemeri Formation represents one of three (Cambrian, Lower Devonian, Upper-Middle Devonian) major geothermal aquifers of Lithuania. Temperature ranges from 15°C in the east

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to 50°C in the west. This trend is due to deepening of the aquifer and increase in heat flow to the west. Klaipėda geothermal plant utilizes reservoir that has temperature of 40°C.

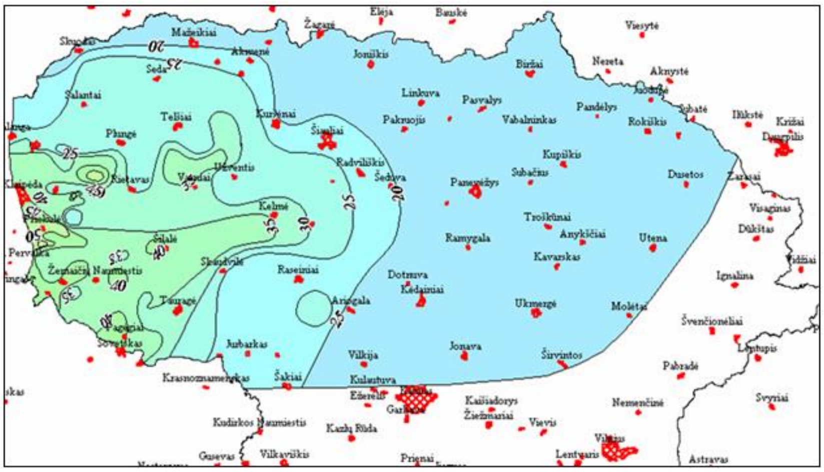

Fig.5. Temperature map of Kemeri Fm.

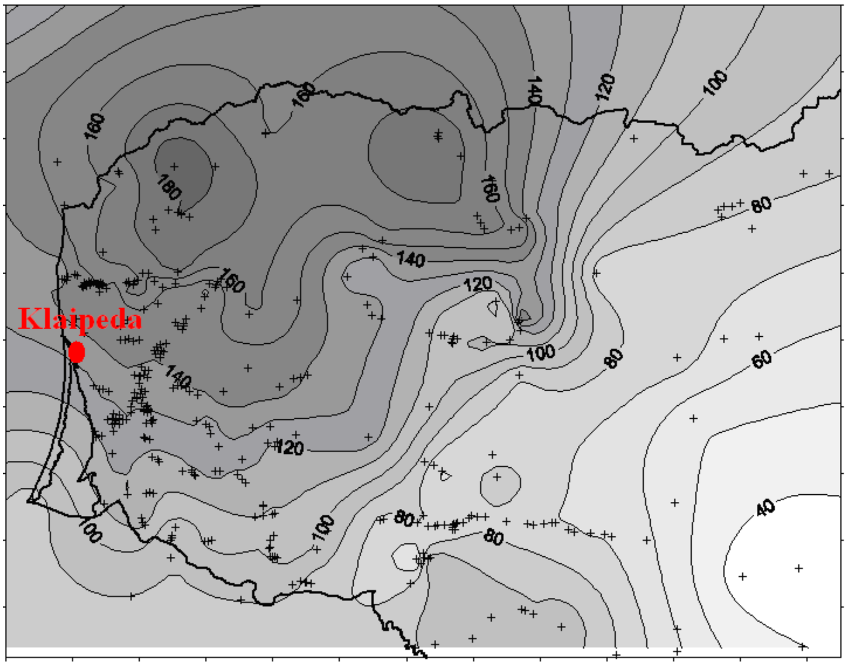

Fig.6. Isopach map of Kemeri Fm. of west Lithuania

The thickness of the aquifer increases from the south (90 m) to the north (180 m) in west Lithuania. The thickness of the Kemeri formation is 130-138 m in Klaipėda.

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4.2. Reservoir Architecture

The Klaipėda geothermal reservoir is formed by the Lower Devonian sandstones of the Kemeri formation. It is hit at depths 981-1118 m in the well KGDP II and 980-1110 m in the well KGDP 4I. The Kemeri Fm. is overlain by the Middle Devonian marlstones, dolomites, and strongly cemented sandstones. It is underlain by the Gargždai Series of the Lower Devonian age, dominated by siltstones and shales with subordinate sandstones and dolomites.

The Kemeri Fm. is represented by friable sandstones (sometimes strongly cemented sandstones) cemented by clay, carbonates, gypsum, and quartz; with siltstone and shale interlayers. Net-to-gross is 0.63-0.68.

The aquifer is characterized by rather complex architecture. No consistent sedimentological model was presented so far. Those can be shallow marine sediments with sandy bars, deltaic complex, alluvial deposits. The latter model seems the most reasonable, assuming the shale domainted parts of the succession reflecting the meandering river environment, while sandy parts could be indicative of the braiding river stage of the alluvial system evolution. Due to complexity of the reservoir architecture there is no consistent model also on a connectivity of the individual sandstone layers.

There is a good correlation of the individual layers between production wells KGDP-2P and KGDP-3P located only 200 m apart (Fig. 7). Corelation is more complex with injection wells that are located at a distance of a few kilometers from the production wells. There is a remarkable difference in the reservoir architecture between injection wells KGDP-1I and KGDP-4I. The former well is characterized by the lowest net-to-gross value. Some small amplitude fault is suggested between the injection wells, as indicated by sharp increase of the Upper Permian layer to the south, also some differences in the Middle Devonian Parnu Fm overlying the Kemeri Fm. These features can explain different injectivity potential of both wells. Also, important parameter that influenced differences in the injectivity was a more careful application of the drilling mud in the well KGDP-4I.

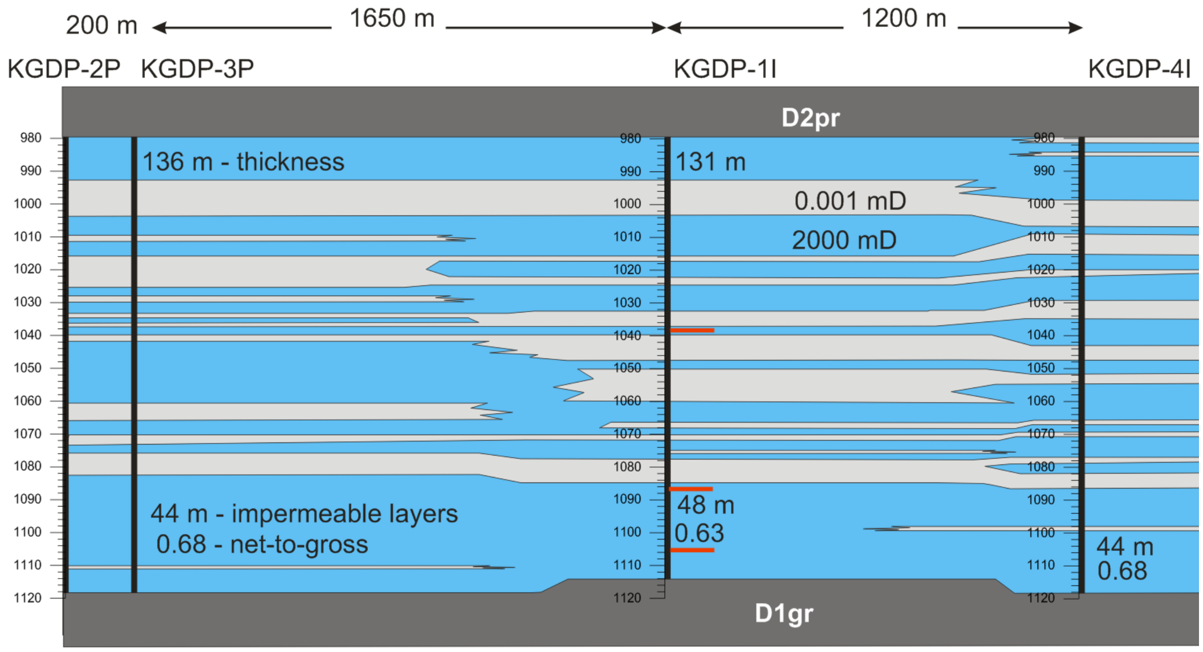

Fig.7. Geological cross section of the Kemeri geothermal aquifer. Grey layers show aquitards, blue are sandstones. The jetted intervals are indicated (red horizontal lines) in well KGDP-1P

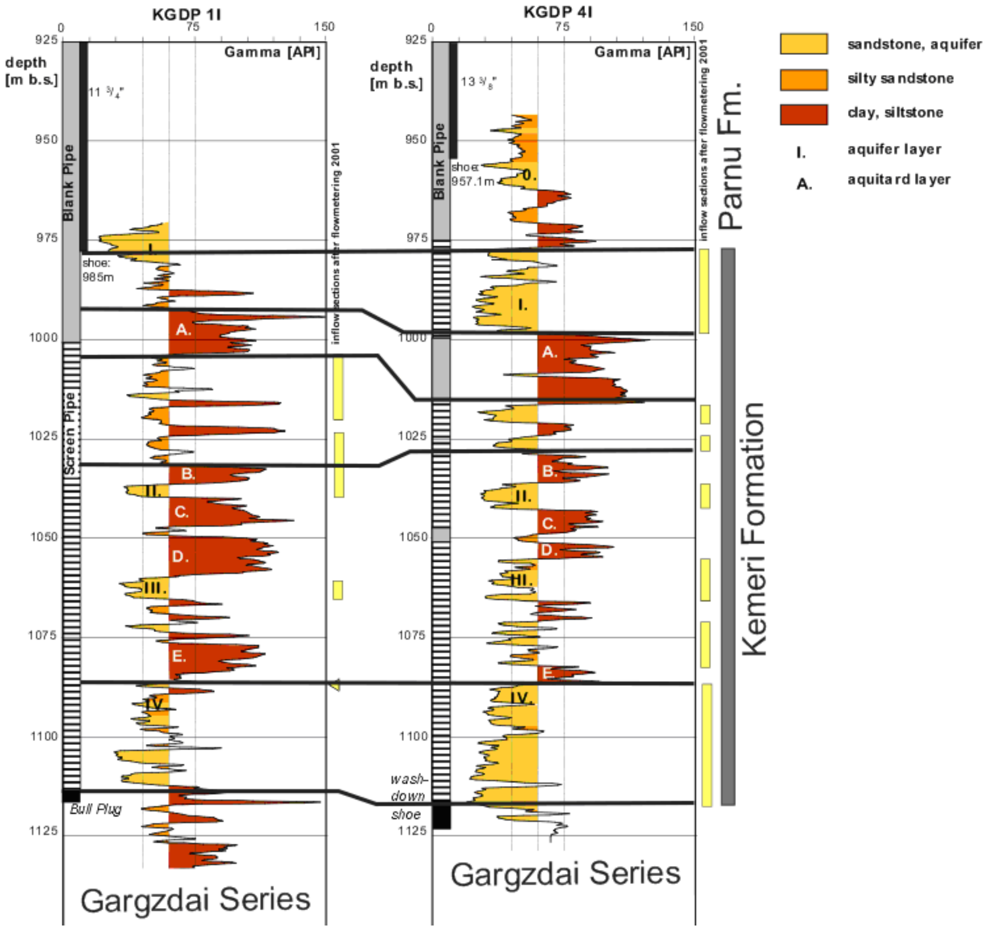

Fig.8. Logging vs lithology and well design of the injection wells KGDP 1I, 4I. Bold lines indicate boundaries of lithological packages

Fife lithological packages can be defined in Klaipėda wells (Fig.8).

Lowermost package. The lowermost sandstone body (indexed IV) of about 30 m thick is well correlated across all Klaipėda geothermal wells. It is also distinct in the rest west Lithuanian wells (Fig.9,10 This package is characterized be the best reservoir properties Larger grain size, low amount of thin shaly interlayers, high porosity and permeability). Latterlas at two levels were jetted in this best part of the Kemeri reservoir (well KGDP-1I).

Lower package. The lowermost grades upwards to intercalation of shales (correlated layers D, C, B), siltstones, and sandstones (correlated layers III, II). It is of about 55 m thick. Well KGDP 4I shows higher sandstone proportion in the section compared to the well KGDP 1I. Laterals were jetted in this part of the section in the well KGDP-1I at the depth 1039 m. This package can also be traced across all west Lithuanian wells (Fig.3,4). It is still difficult to suggest to what extent the individual layers are continuous or discontinuous.

Middle package. It is characterized by increased abundance of siltstones and sandstones. It is as thick as 27 m in the well KGDP 1I, while only 14 m in the well KGDP 4I. Siltstone lithologies seem to be predominant in the well KGDP 1I, while sandstone is dominating lithologies in the well KGDP 4I. This package can also be traced across west Lithuanian wells.

Upper package. Shale package is distinct in west Lithuanian wells, as it is also in Klaipėda area. It is 12-17 m thick. It likely provides and important hydrodynamic barrier in the Kemeri aquifer.

Uppermost package. It is composed of sandstones (with shales and siltstone) in the well KGDP 4I, while siltstones predominate in the well KGDP 1I. It is about 14 m thick. It can be suggested that this package is isolated from overlying sandy packages.

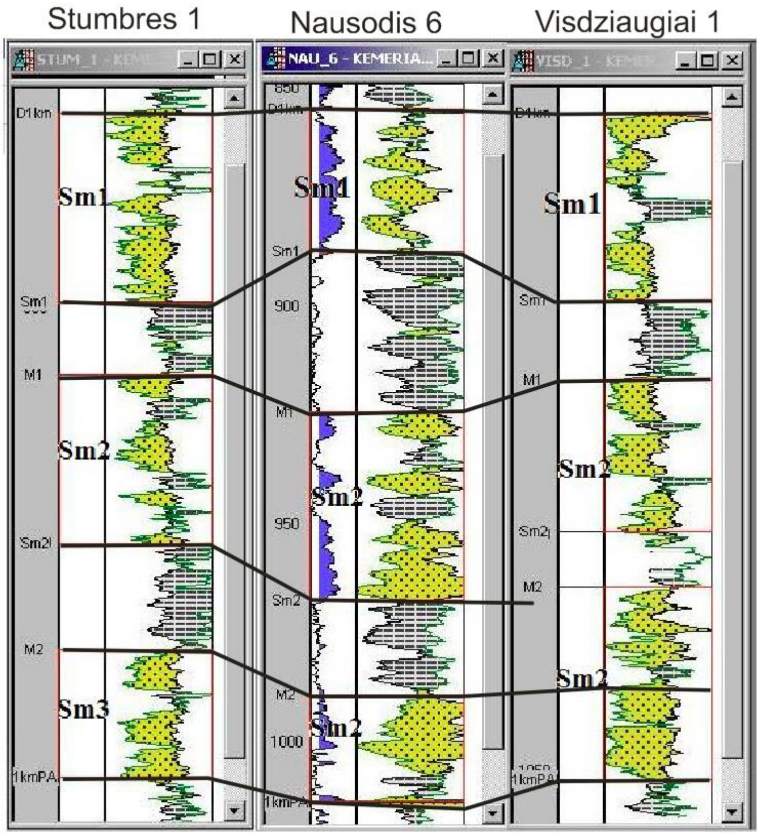

Fig.9. Five packages defined in west Lithuanian wells

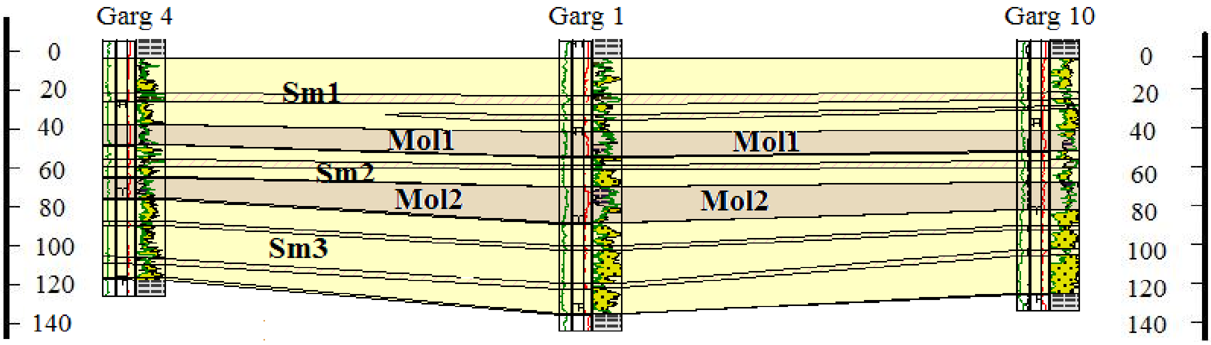

Fig.10 Correlation of five packages of Kemeri Fm., Gargždai zone, west Lithuania (~30 km SW of Klaipėda). Mol - denotes shaly packages, Sm – sandy packages. Scale bar shows thickness (m)

Comparison of wells KGDP 1I and 4I shows that the latter well hit the reservoir of better quality. The Lowermost package is of the best quality in the Kemery Fm. section.

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4.3. Reservoir properties

No samples are available for petrophysical studies of Kemeri sandstones from Klaipėda wells. The well logs provide some information on density and porosity of Kemeri lithologies. The density of sandstones, siltstones, and shales is mainly in the range of 2.2-2.3 g/cm^3. The calculated average porosity of sandstones is about 28% showing minor variations between 25-32%.

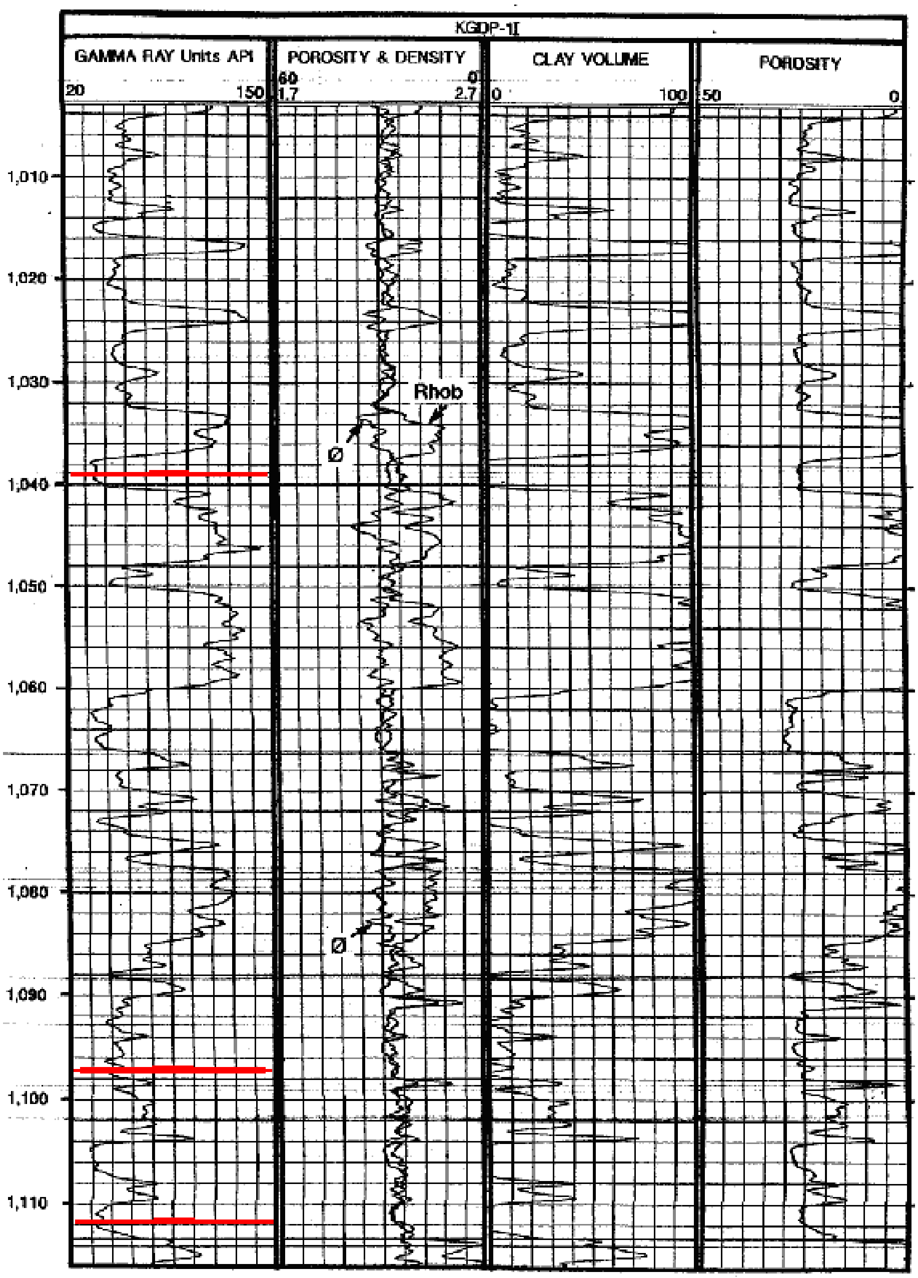

Fig.11. Logging data and interpretation of jetted well KGDP 1I. Depths of jetting are indicated (red lines)

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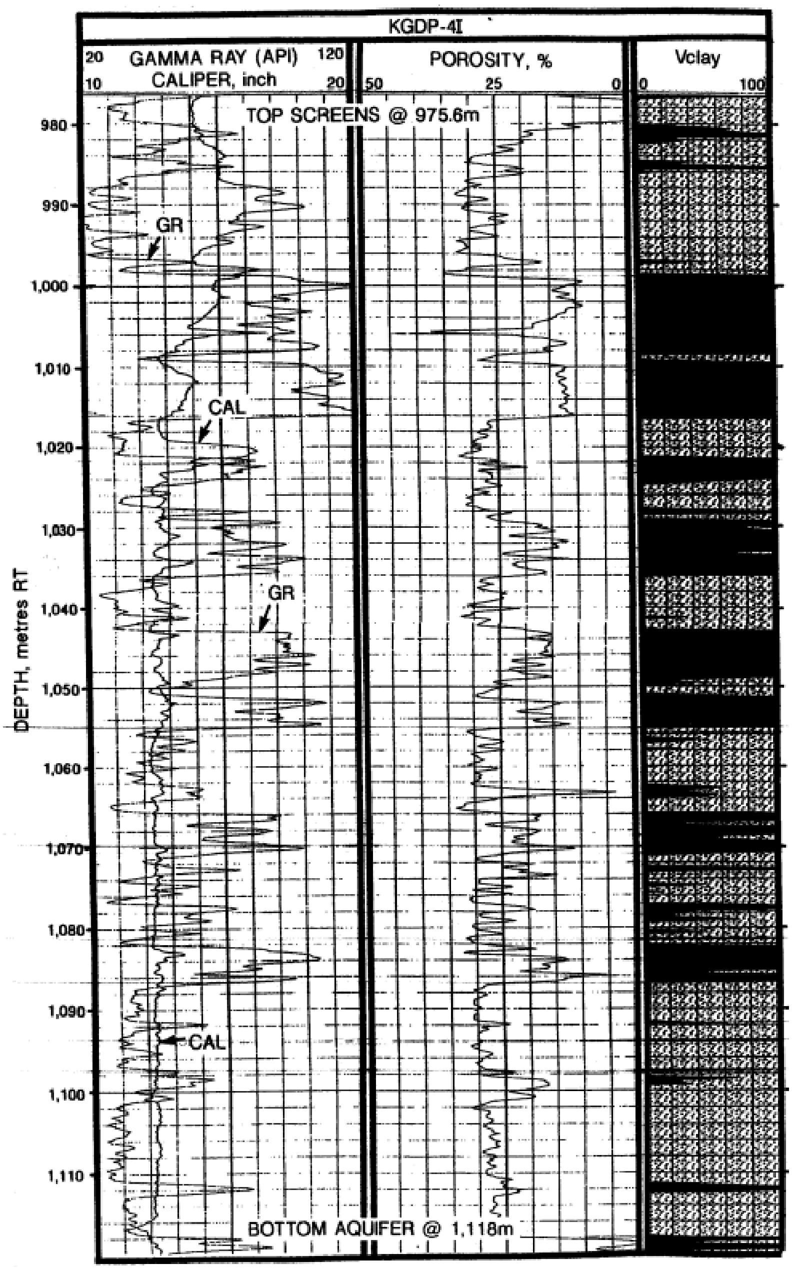

Fig.12. Logging data and interpretation of well KGDP 4I

The average permeability was assumed 1.0-1.3 D when designing Klaipėda geothermal wells. It is in concert to well testing data of Vilkyčiai-3, 5 oil exploration wells located 20 km to the SSE of Klaipėda plant. These old oil exploration wells were re-opened in mid-nineties for injection of Cambrian waste water produced during the oil exploitation. The permeability of the lower sandy package was defined by well testing as high as 4 D, while permeability of the upper sandy package was evaluated 2 D. These data confirm the best reservoir quality of the Lowermost package. It should be noted that the Kemeri reservoir was likely strongly affected by drilling mud as it was considered as not prospective body for oil industry. The perforation of the wells was related to necessity of disposing the Cambrian waste water. It should be stressed that productivity ranges from 29 to 51 m^3/h/at, while injectivity was only 0.76-1.17 m^3/h/at. Those are still high values of injectivity.

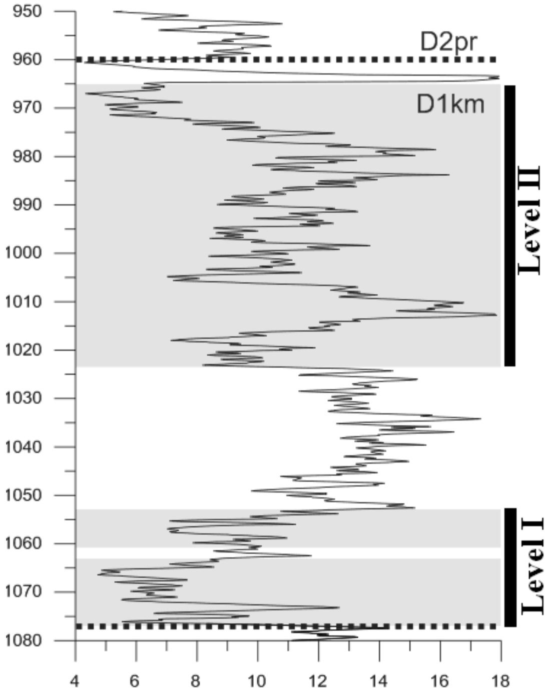

Fig. 13. Gamma-ray log of well Vilkyciai-5. Perforated levels I and II are indicated. Level I corresponds to the Lowermost package, Level 2 correlates with the Middle-Uppermost packages.

Table 4.1. Well testing results in wells Vilkyciai-3,5 (year 1993)

Parameters	Results
Water density	1.043
Pressure	10.9 (1065 m)
well Vilkyčiai-3, level I, depth 1050-1074 m	
Productivity k_{ef}, *m^3/h/at*	33.64
Hydraulic conductivity k*h/M, *mkm^2*cm/MPa*s*	11872
Permeability k, *mDd*	4950
Injectivity, *m^3/h/at*	0.76
well Vilkyčiai-3, level II, depth 946-1029 m	
Productivity k_{ef}, *m^3/h/at*	51.1
Hydraulic conductivity k*h/M, *mkm^2*cm/MPa*s*	18033
Permeability k, *mD*	2280
Injectivity, *m^3/h/at*	0.86
well Vilkyčiai-5, level I, depth 1053-1077 m	
Productivity k_{ef}, *m^3/h/at*	29.4
Hydraulic conductivity k*h/M, *mkm^2*cm/MPa*s*	10391

Permeability k, *mD*	4720
Injectivity, $m^3/h/at$	0.81
well Vilkyčiai-5, level II, depth 965-1024 m	
Productivity k_{ef}, $m^3/h/at$	40
Hydraulic conductivity k*h/M, $mkm^2*cm/MPa*s$	14118
Permeability k, *mD*	2206
Injectivity, $m^3/h/at$	1.17

Laboratory studies show close correlation between the permeability and porosity measured in Kemeri sandstone samples. Fig.14 presents an example of this correlation defined for Kemeri Fm. of the well Vydmantai 1 (located close to Palanga resort) that is about 35 km to the north of the geothermal plant. Porosity ranges from 10% to 31%, while permeability is in the range of 0.8 to 6295 mD. Average porosity 28% corresponds to 2000 mD permeability. It is in good concert to well testing data. The minimum porosity values were measured in strongly carbonate or gypsum cemented (amounting about 11%) sandstones interlayers. In most samples, the carbonate/gypsum content is in the range of 0.3-3.2% (Fig.13). There is no correlation between the porosity and carbonate content in this range.

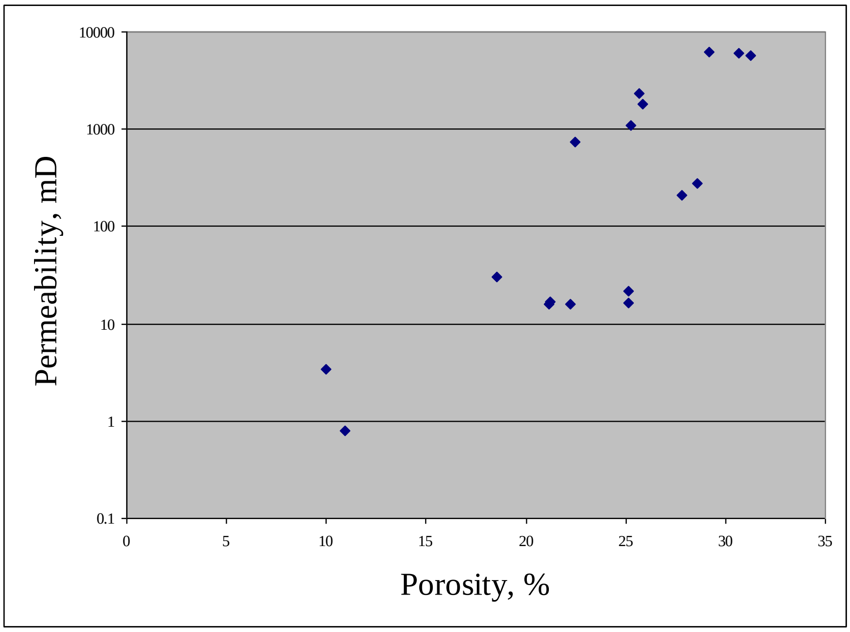

Fig.14. Porosity vs. permeability of Kemeri sandstones, well Vydmantai 1

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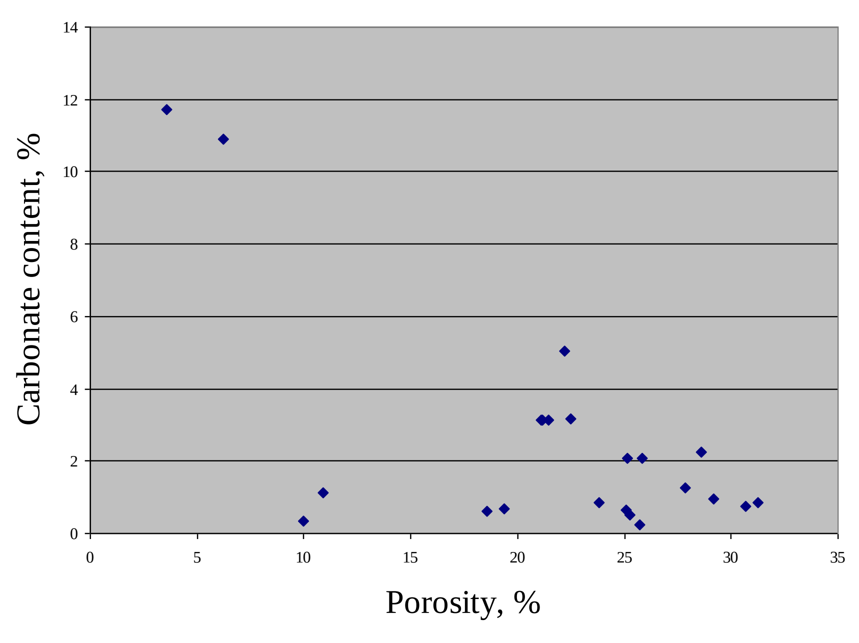

Fig.15. Porosity vs. carbonate content of Kemeri sandstones, well Vydmantai 1

The figure bellow represents summary of all Kemeri Fm. samples collected from west Lithuanian wells. The results are close to those obtained in Vydmantai 1 well.

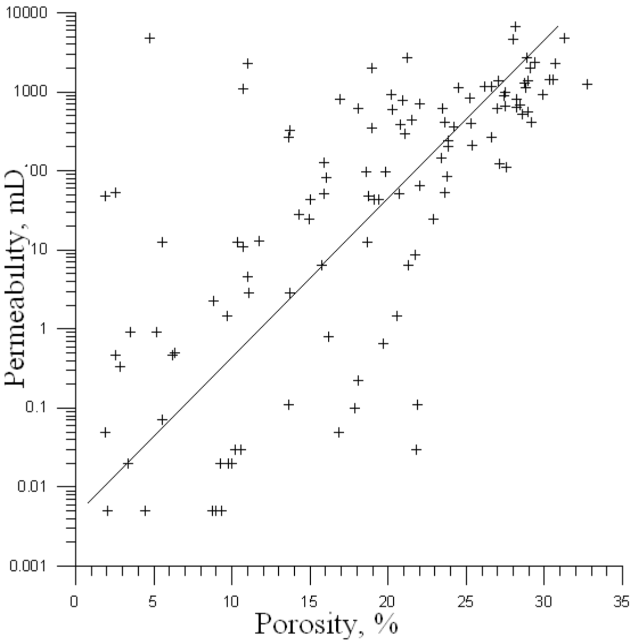

Fig.16. Porosity vs. permeability of west Lithuanian KemeriFm. sandstones and siltstones

Flowmeter was applied in the well KKGDP 1I in 2008 to investigate the state of the reservoir layers after some years of exploitation. An example of flowmeter results at an injection regime is presented in Fig.18. It shows no spinning rate changes in the interval 980-1000 m within the cased zone. A high gradient interval is defined at the depths of 1000-1035 m that roughly correlates with the Middle sandy package. It shows increased injection within this zone. The gradient of the spinning rate considerably decreases in the rest of the well section that is attributed to the Lower and Lowermost packages. It is surprising that the Lowermost package, considered as the best quality part of the Kemeri Fm. section, does not show any significant injection that suggests severe damage of this part of the reservoir.

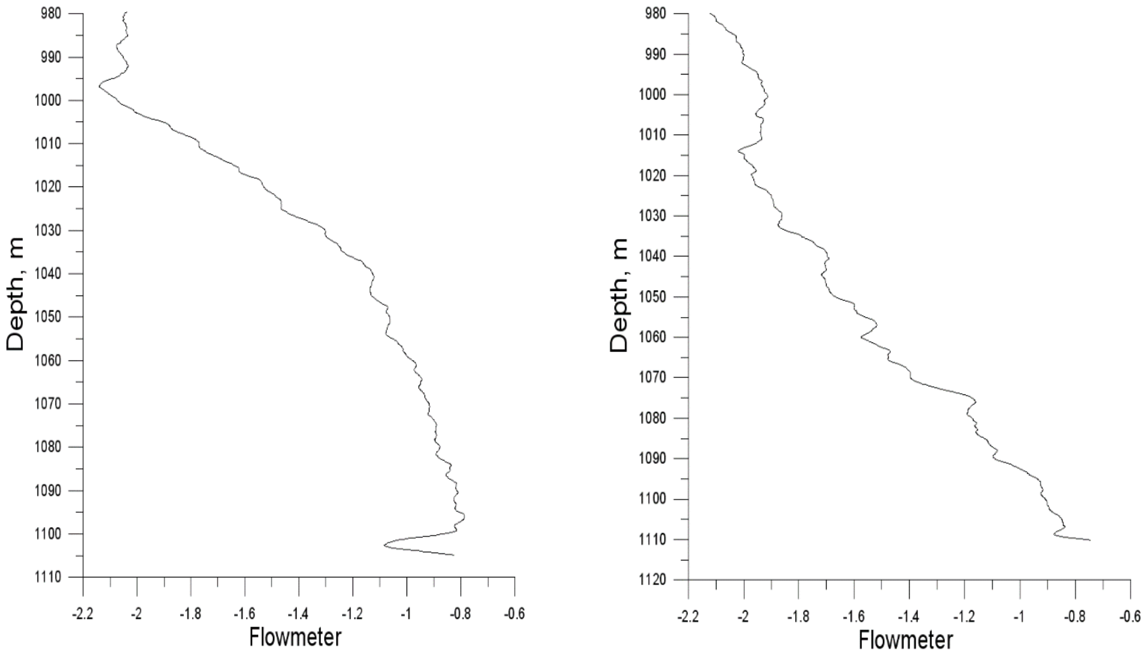

Fig.17. Flowmeter records during injection in wells KGDP1I (left) and KGDP4I (right)

Flowmeter data indicate somewhat different situation in the well KGDP4I. Low gradient zone is defined in the sandy Uppermost package (981-999 m), while no injection is recorded in the shaly Upper package (999-1016 m). The Middle and the Lower packages (1016-1085 m) are characterized by a rather uniform average gradient with some high injectivity zones. Similar average gradient is defined in the Lowermost package suggesting no anomalous formation damage of this part of the section in this well.

4.4. Petrography

Adjacent well data

For the determination of the composition of the Klaipėda aquifer sandstones, only drill cores of nearby wells could be used (Vydmatai-1, Plunge-1, Nida-1). Only one sandstone sample was provided from the bottom part of the well KGDP 1I.

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Sandstones predominate in the Kemeri Fm. They are mainly of fine and medium grain size, massive and cross-bedded structure. Sandstones are quartzes and quartzes with feldspar, of grey and red colors. The typical composition is as follows: 81–96 % of detrital quartz (mean value 92 %), 3–12 % detrital potash feldspars (mean value 8 %), 0.2–2.0 % detrital micas (muscovite), 0.2–2.0 % chlorite and partly glauconite with contents < 2.0 %. Heavy minerals (tourmaline, garnet, etc.) are represented by contents < 2.0 %. Moreover, excessively decayed clasts occur (0.2–5 %). Carbonates and clay are the main cementing fractions. Gypsum cement is rather variable both in the lateral and vertical distribution. For example, the gypsum is present at 1-2% in the well Palanga-318a, whereas no gypsum was identified in the well Vydmantai-1 located only a few kilometers away. The investigation of the drill cores of those wells revealed some differences, such as higher content of organic matter in the Kemeri shales of the well Vydmantai-1, more intense weathering of the potassium feldspars in the same well. The gypsum cement is still present in most of west Lithuanian wells. It is more common in the lower and upper parts of the Kemeri section. These lower and upper parts are characterized by the red color of shales, whereas shales are of gray and dark gray color in the middle part of the section. These differences can have an effect on the mineral precipitation in the vicinity of an injection well.

Siltstones are of similar mineral composition.

Shales are of grey and red colors. No mineralogical studies were carried out to characterize the mineral composition of shales.

Fig.18. Transition of the grey and red coloured shales, Kemeri formation, well Vydmantai-1. This colour transition can be prognosed in Klaipėda wells in the upper part of the Shale E and continues down to the bottom of the Kemeri Fm. (including Sandstone IV)

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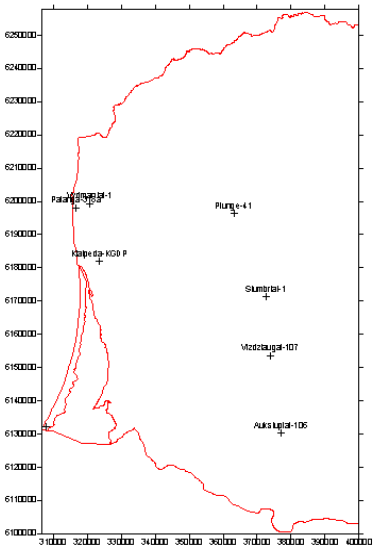

Fig.19. Location of the Klaipėda and adjacent wells with drillcore sampling

Fig.20.Vidmantai-1 drill cores the Kemeri Fm.

Mineral composition of sandstones and siltstones is illustrated in Fig.22. Two distinct parts are defined in the well Vydmantai 1. The upper part of the section is characterised by low feldspar/quartz ratio about 0.07, while he increased ratio about 0.15 is defined for the lower part of the section. Two distinct parts are identified in the Kemeri Fm. The upper part of the formation contains average 6-7% of the potassium feldspar and sharply increases to 11-12% in the lower part. It is likely related to increase of the chemical weathering in the denudation zone during the latter part of the Kemeri time. Sandstones are more mature than siltstones that contain a higher content of feldspar grains.

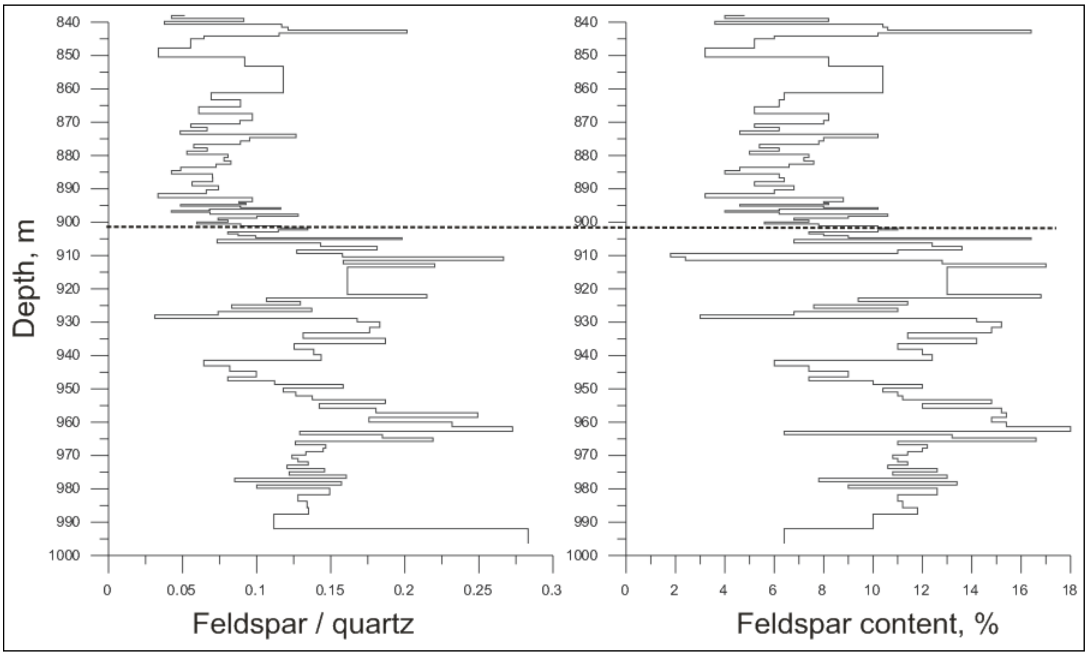

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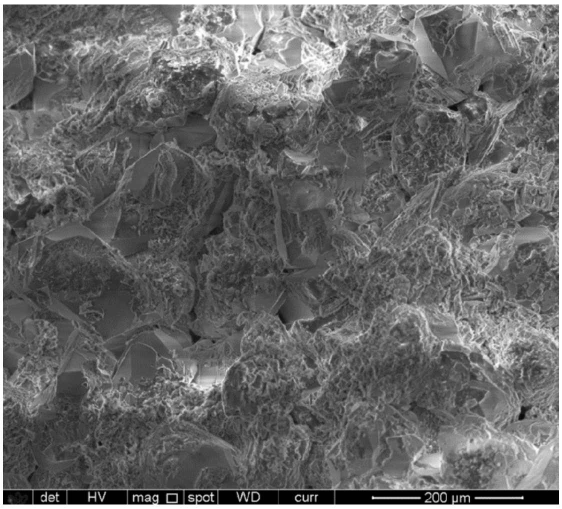
Fig.21. Quartz / potassium feldspar ratio and feldspar content in Kemeri sandstones and siltstones of well Vidmantai-1

Petrography of sandstone sample of well KGDP 1I

Sandstone sample (depth 1111.2 m) was obtained from the bottom part of the well KGDP 1I (Lowermost package). Sample was studied by *SEM QUANTA 250* with EDX extension. Plain rock fragments were studied.

Summary comments on petrographic study results of KGDP 1I sample
The studied sample is represented by fine/medium sandstone.
Quartz is the major detrital mineral. Regular shape of grains is a peculiar feature that is accounted to authigenic quartz overgrowths formed during the late diagenetic stage.
Potassium feldspar is of characteristic platy shape. Some grains are affected by corrosion. Feldspar ratio to quartz is about 1:10.
There is rather significant part of **clay** in the studied sample. The following minerals were identified: illite (with smectite interlayers) and kaolinite. Drilling mud predominates in pores. Illite (with smectite) is presumably of diagenetic origin by transformation of smectite in a course of deep burial. Two generations of kaolinite are present, of platy and wormy shapes. Drilling mud is composed of smectite, illite and defragmented detrital minerals.



General view of studied sandstone
Sandstone is composed of euhedral (crystalline shaped) quartz grains due to authigenic quartz overgrowths. Please note sharp shape of pores between quartz grains. There is abundant drilling mud covering grain surfaces. It suggests heavy formation damage in the well

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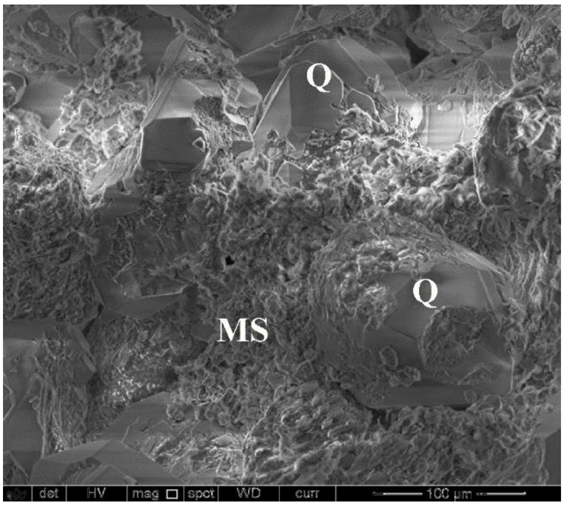
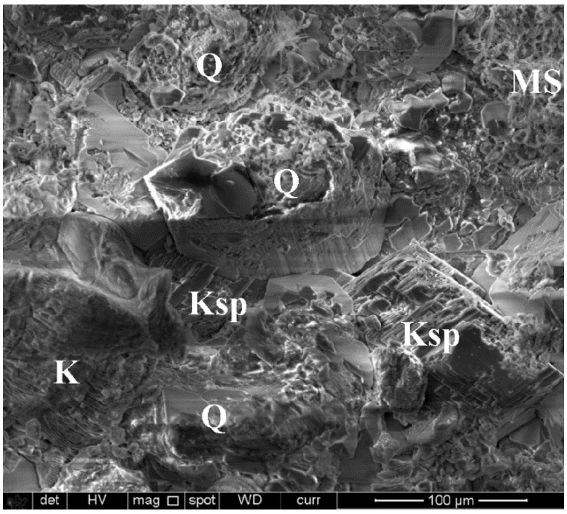
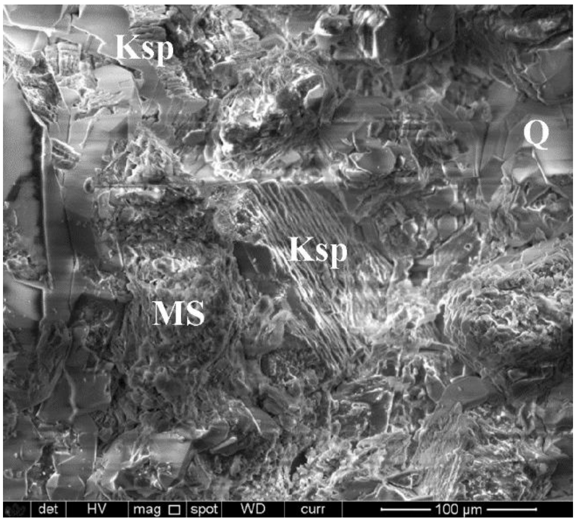
Detrital minerals



Quartz grains (Q) and abundant drilling mud (MS). An ideal (crystalline) shape of quartz grain is a distinct feature



Compacted arrangement of quartz (Q) and potassium feldspar (Ksp) grains. Large kaolinite (K) crystal is located in the left lower corner of photograph. The rest mass is represented by drilling mud



Quartz (Q) and potassium feldspar (Ksp) grains. Pores are filled by drilling mud

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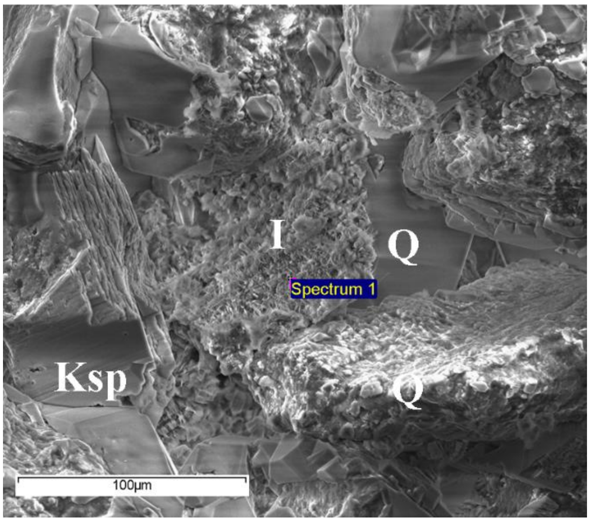
Clay minerals

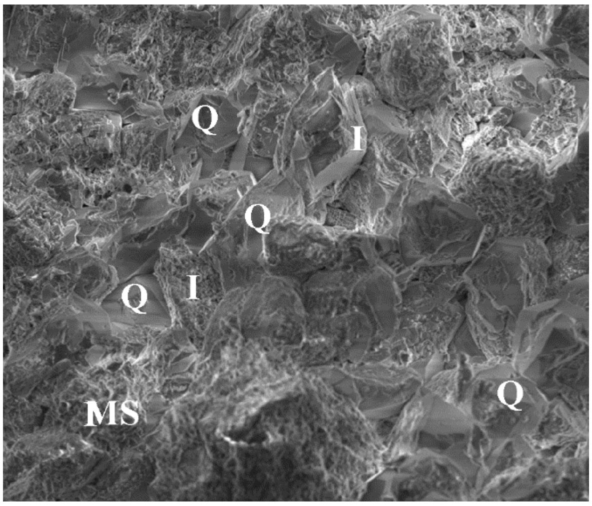


Diagenetic illite (I) between quartz (Q) and potassium feldspar (Ksp) grains

Element	Weight%	Formula
Mg	1.14	MgO
Al	13.72	Al2O3
Si	25.81	SiO2
K	10.05	K2O
Fe	3.34	FeO
O	45.36	
Totals	100.00	

Element	Weight%	Formula
Al	9.97	Al2O3
Si	26.81	SiO2
K	15.12	K2O
Fe	4.35	FeO
O	43.75	
Totals	100.00	

Illite containing smectite layers chemistry



Illite (I) and drilling mud (MS) fill pores between detrital grains. The hairy shape is characteristic for drilling mud clay minerals. Two generations of illite is noted, i.e. fine crystals and larger platy crystals

Element	Weight%	Formula
Mg	0.60	MgO
Al	10.35	Al2O3
Si	31.61	SiO2
K	9.81	K2O
O	47.62	
Totals	100.00	

Illite containing smectite layers chemistry

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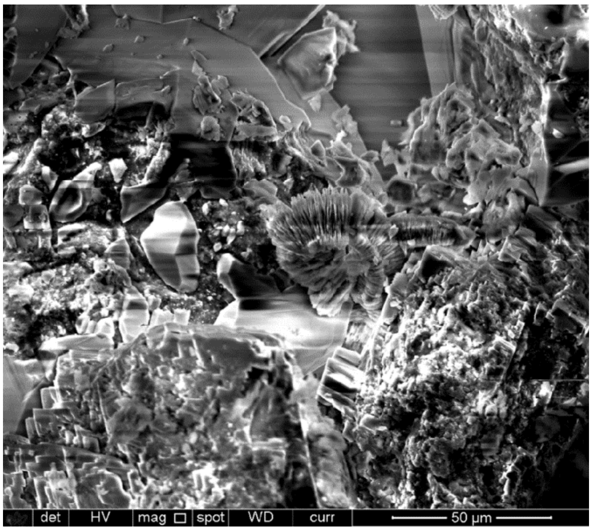
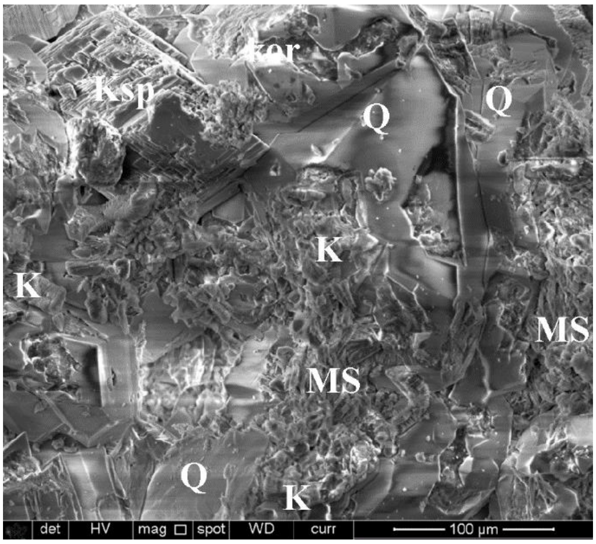
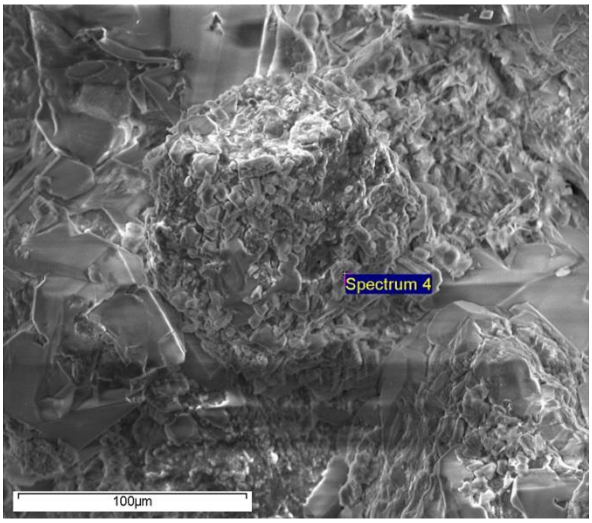


Wormy kaolinite (second generation) in the centre of photograph

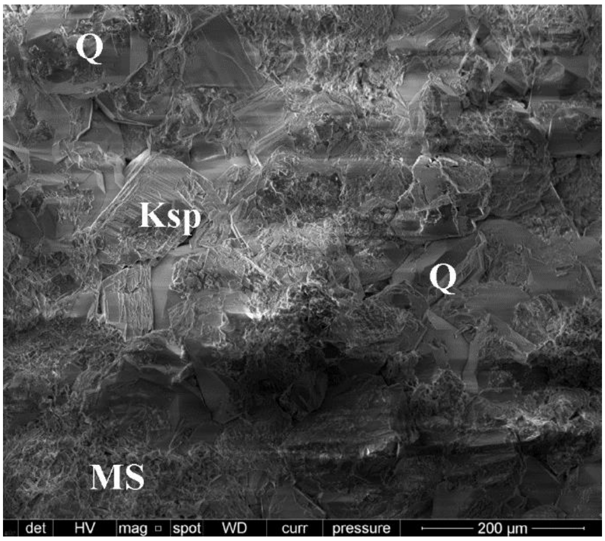


Wormy kaolinite (K) mixed to drilling mud (MS), filling pores between quartz and potassium feldspar grains

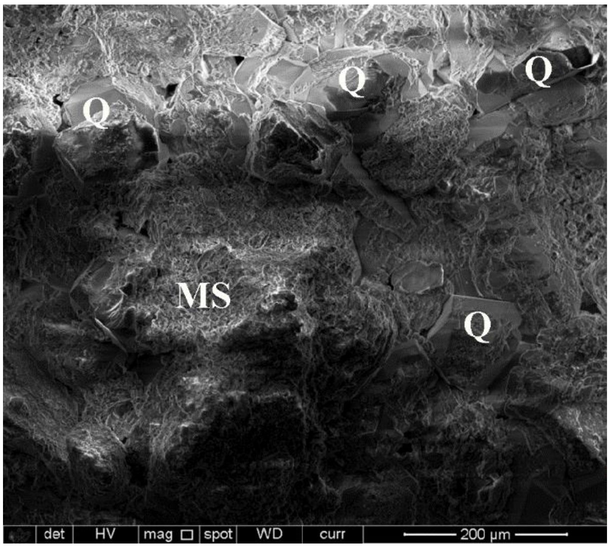


Quartz grain covered by platy kaolinite (first generation

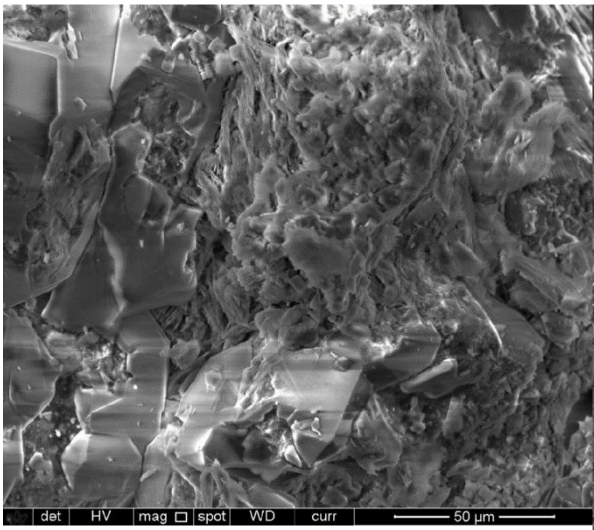
Formation damage



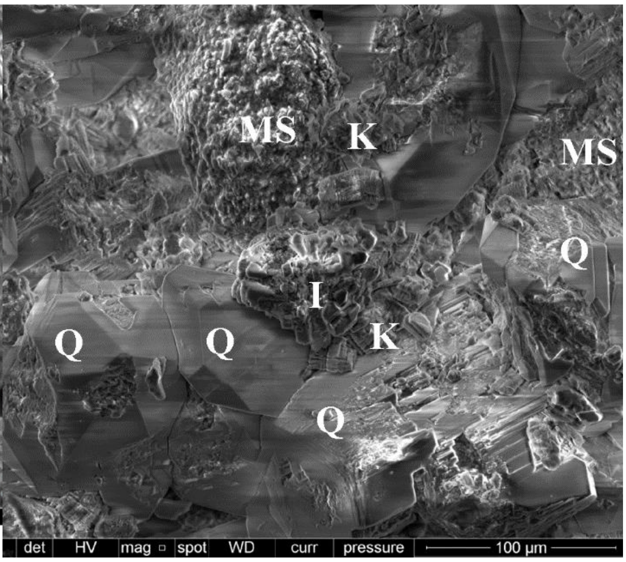
Drilling mud (MS) totally blocks pores between quartz (Q) and potassium feldspar (Ksp) grains



Drilling mud totally fills pores



Drilling mud fills pores



Photograph showing displacement of diagenetic illite (I) and kaolinite (K) by drilling mud

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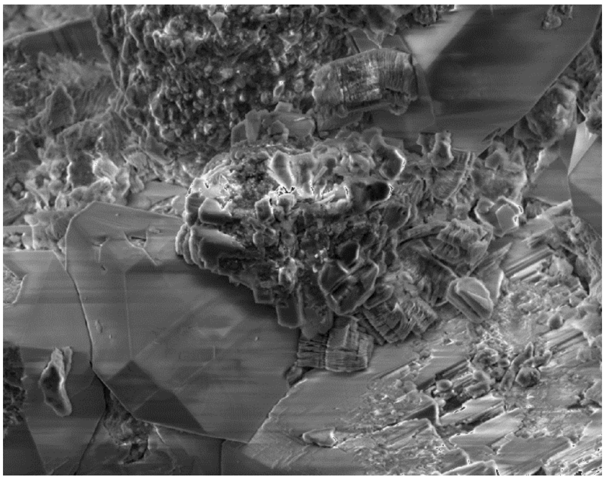
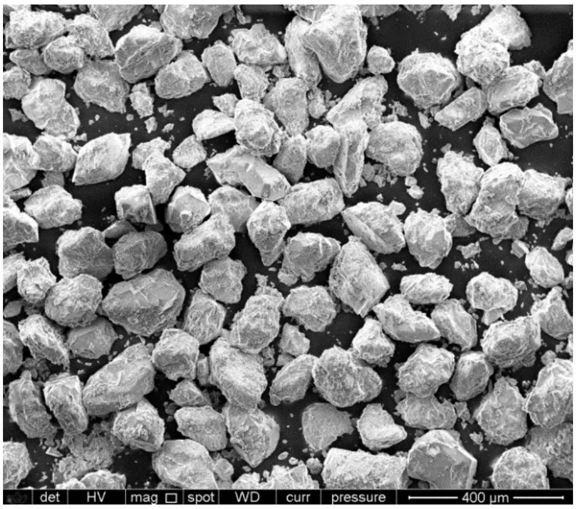
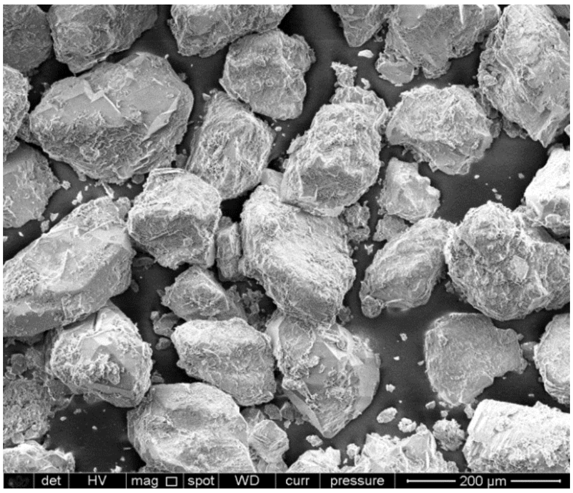


Zooming of central part of the same photograph as above with a higher resolution

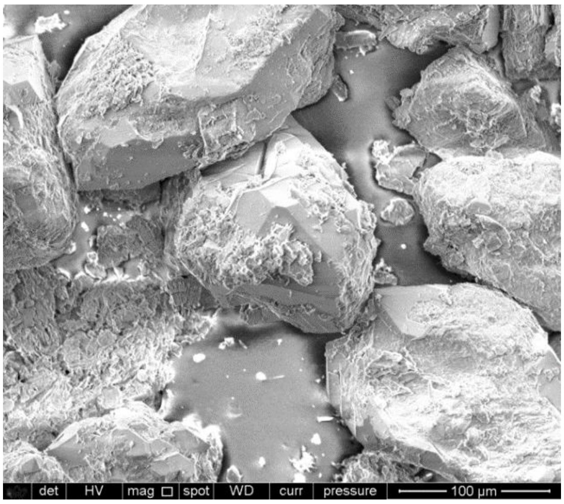
Grain size and shape (disintegrated sample study)



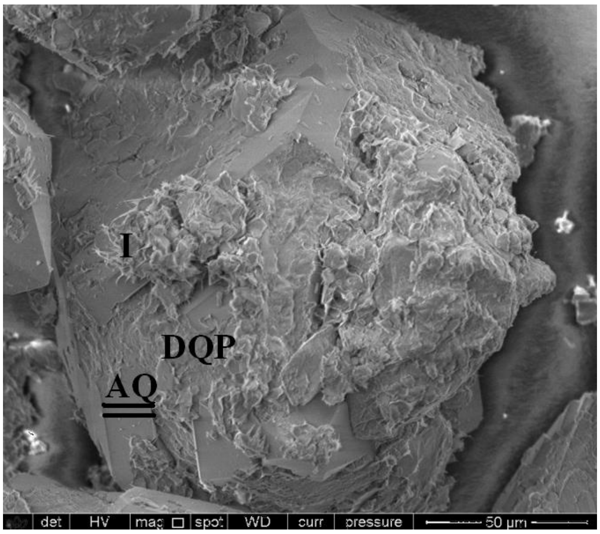
Disintegrated sandstone. Please note that surface of all grains is covered by drilling mud



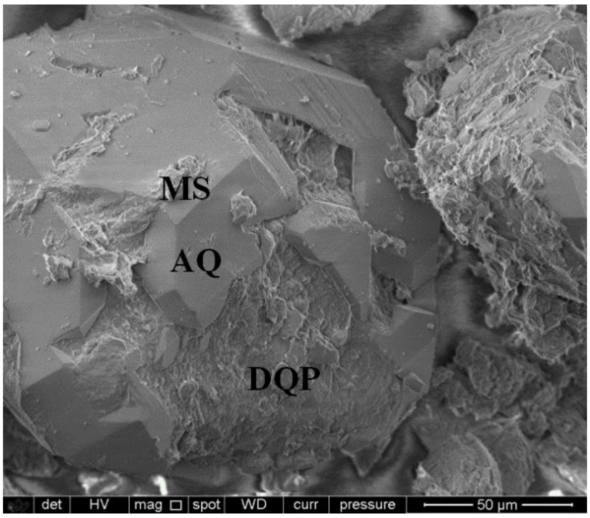
Larger magnification of disintegrated sandstone. Grain size is mainly in the range 0.1-0.3 mm (fine and medium sandstone)



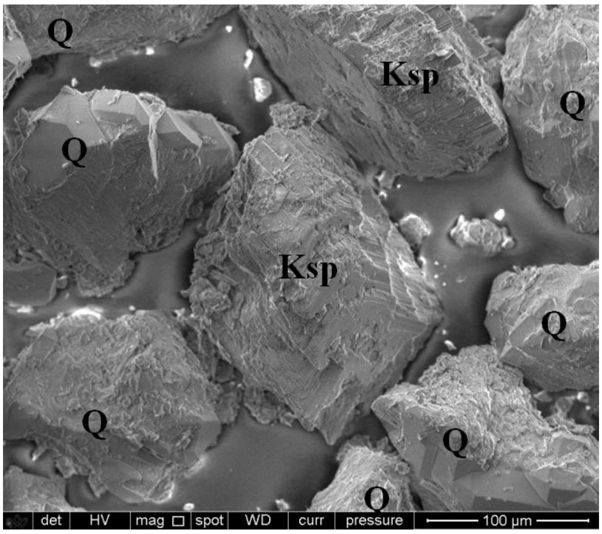
Crystalline shape of quartz grains. Abundant drilling mud on grains surfaces



Quartz grain. DQP marks original surface of detrital quartz grain. AQ denotes quartz overgrows, thickness 10-16 µm. (I) marks illite)



Detrital quartz grain (DQP) overgrown by authigenic quartz (AQ) (10 µm thick). Drilling mud is visible on the surface



Two grains of potassium feldspar (0.15-0.20 mm large)

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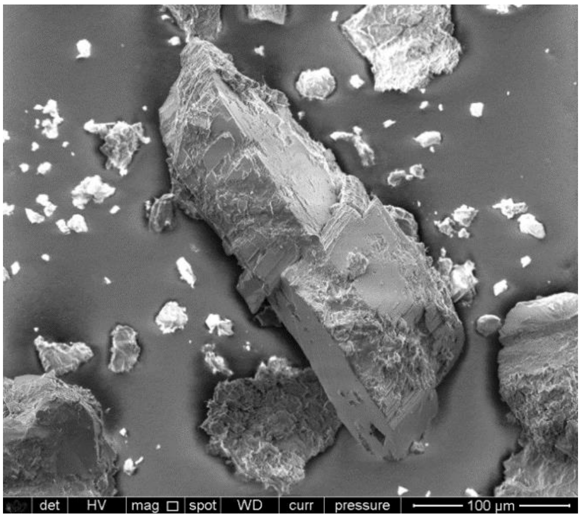
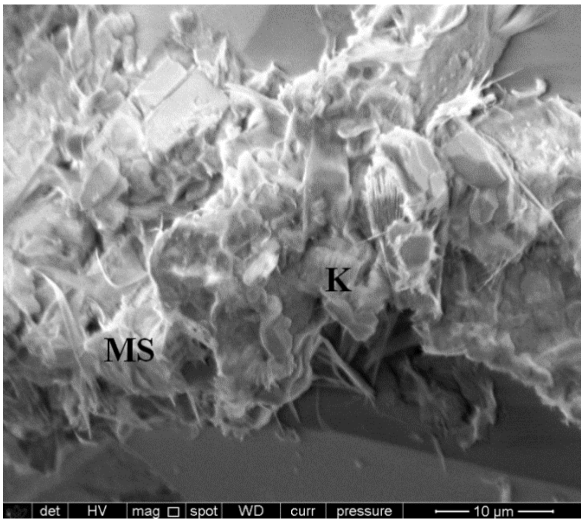
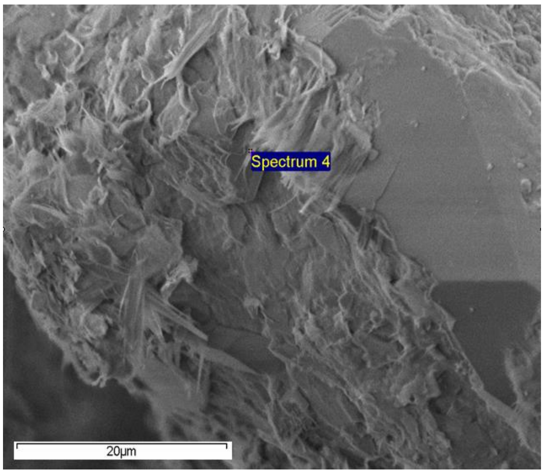


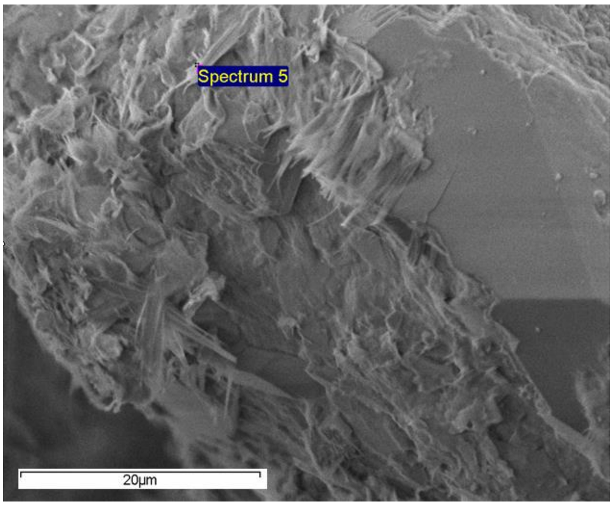
Two potassium feldspar crystals, not rounded



Drilling mud (MS) and kaolinite buckets (K)



Drilling mud covering quartz grain surface. Spectrum 4 points to illie (with smectite)



Same photograph. Spectrum 5 marks smectite

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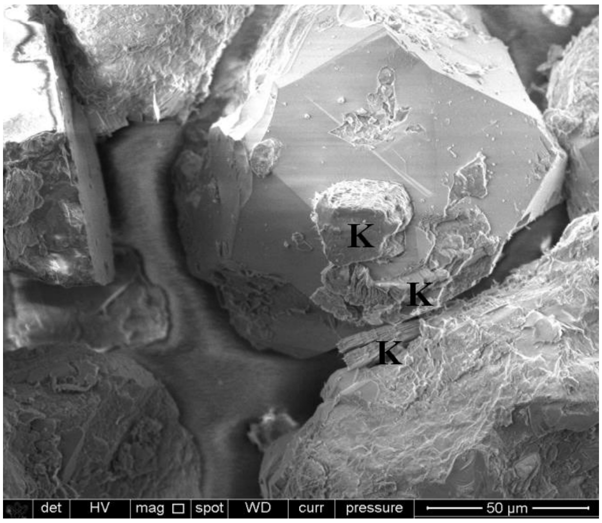
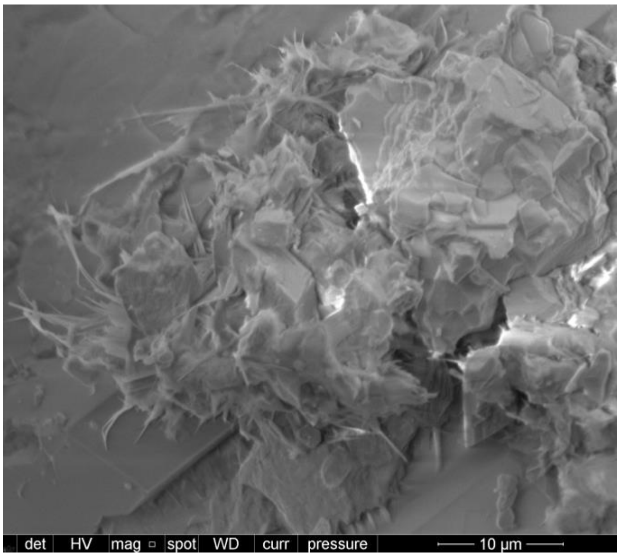


Quartz grain and kaolinite (K) buckets



Illite on quartz surface

4.5. Grain size composition

There is abundant grain size database available from west Lithuanian wells. The well Vydmantai 1 is the best studied well represented by 110 sandstone and siltstone samples. Sandstones are classified as a silty fine and a silty medium sandstone. Fraction 0.10-0.25 mm predominates. The average value of measured samples is 0.11 mm. The average grain size composition is shown in Fig.22. Five packages are discernible in grain size distribution that can be correlated to aforementioned sediment packages defined based on lithological variations up the section.

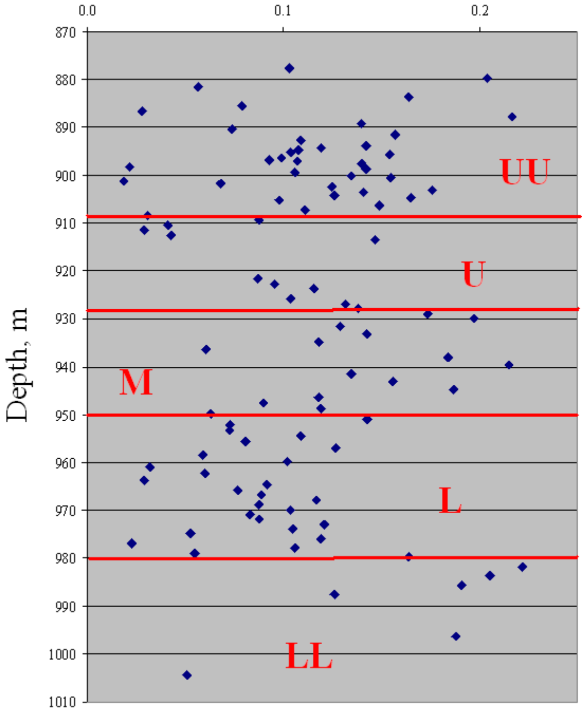


Fig.22. Geometric mean of grain size (mm) of sandstones and siltstones of Kemeri Fm., well Vydmantai 1. LL-lowermost package, L-lower package, M-middle package, U-uper package, UU-uppermost package

Sandstones are poorly sorted. Sorting very closely correlates with the grain size (Fig.23). It ranges from 0.03 for siltstones to 0.22 for larger grained sandstones.

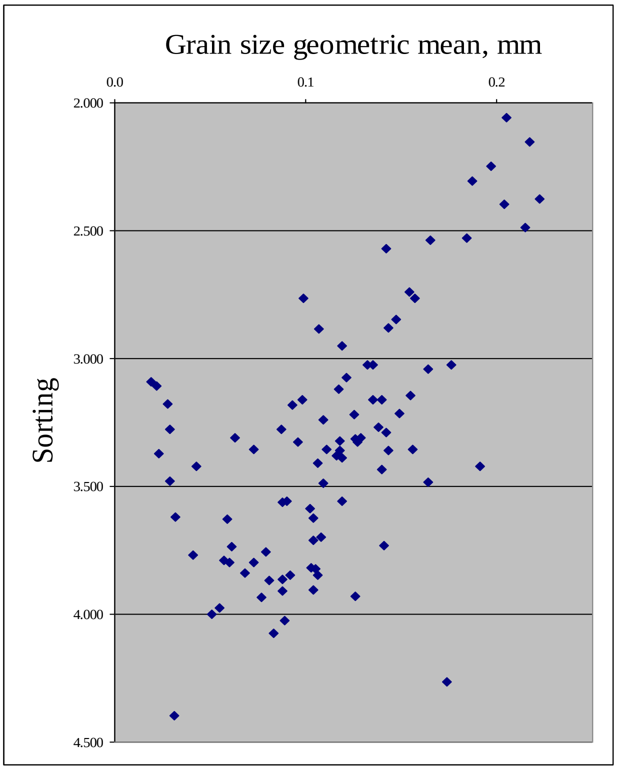


Fig.23. Grain size vs. sorting of sandstones and siltstones of Kemeri Fm., well Vydmantai 1

Sandstones and siltstones are characterized by negative skewness values (asymmetry towards small grain size).

4.6. Concluding remarks

Reservoir characteristics

- The Kemeri geothermal aquifer is composed of sandstones with shale and siltstone interlayers. Net-to-gross ratio is in the range of 0.60-0.65 in west Lithuania.
- The upper and lower parts of the Kemeri section are of reddish colour, while greyish in the middle part; it results in high Fe content in the formation water.
- Three sandy packages are defined in the Kemeri succession, separated by two shaly packages. The correlation of individual layers is rather complex and hydrodynamic communication between reservoir layers is not clear.
- Sandstones are classified as medium and fine sand, the average grain size is 0.11 mm; composed of quartz with some admixture of potassium feldspar; sandstones are cemented by clay minerals (illite, kaolinite), carbonates and some gypsum; the latter is variable laterally.
- average porosity of sandstones is 26-28%, permeability exceeds 1 Darcy.
- sandstones are loosely (rarely strongly) cemented by carbonates, gypsum, and quartz.

- well KGDP 1I has lower lithological characteristics compared to the well KGDP 4I.
- reservoir of the well KGDP 1I seems to have been severely damaged by the drilling mud, essentially the lower part of the section that initially had the best reservoir properties.

5. Horizontal jetting and sustainability

In November 2014, radial jetting technology was identified as a possible solution for enhancing injectivity of the wells. With radial jet drilling (RJD), several open hole laterals of 100 m maximum length and with a diameter of 1 to 2 inch are jetted from the main well bore in order to enhance the connectivity of the well to the rock and thereby the well productivity or injectivity (Buset, et al., 2001, Ragab & Kamel, 2013, Peters, et al., 2016). The jet nozzle used for jetting the laterals has a number of forward and backward jets and is conveyed on mini coiled tubing. The forward-facing jets provide the required erosion of the rock surface and the backward facing jets cause the forward motion by pushing the nozzle forward. The laterals are created with a 90° or 45° angle from the main well bore and its azimuth can be controlled at the start. However, once the jet nozzle is in the formation, it is not steerable and relies on the stiffness of the jetting hose and the symmetry of the forward thrust generated by the backward facing jets to maintain inclination and azimuth. Experience with RJD comes mostly from the petroleum industry (Peters, et al., 2016) with limited applications in geothermal wells. The production increase resulting from using this technology is highly varied (Peters, et al., 2016) and there are still some clear questions regarding the technology, its performance in different geological settings and also long term (>5 year) performance.

At the Klaipėda site, well No.1I was selected for RJD. The original well No.1I was drilled in 1997. The well was vertical and plugged back at 1125 m MD RT. In 2008/2009 the original backbone was abandoned and a new side track 1I(A2) was drilled with an inclination of 3° to 5° with respect to the vertical (S.Šliaupa, 2016) and azimuth around 180°. The side track was completed in December 2008. In this side track, 12 horizontal laterals of around 40 m in length were planned in a number of highly permeable layers present in the aquifer. The planned laterals were set to kick off in the middle of the most productive reservoir intervals in three different productive layers:
- **1st layer** (1037.5 - 1040.0 m) start depth: 1039.0 ± 0.5 m
- **2nd layer** (1095.0 - 1097.5 m) start depth: 1096.5 ± 0.5 m.
- **3rd layer** (1104.0 - 1107.5 m) start depth: 1106.0 ± 0.5 m

For each layer four laterals with a length of 40 ± 0.5 m and a separation of 45° - 50° were planned (Figure 24).

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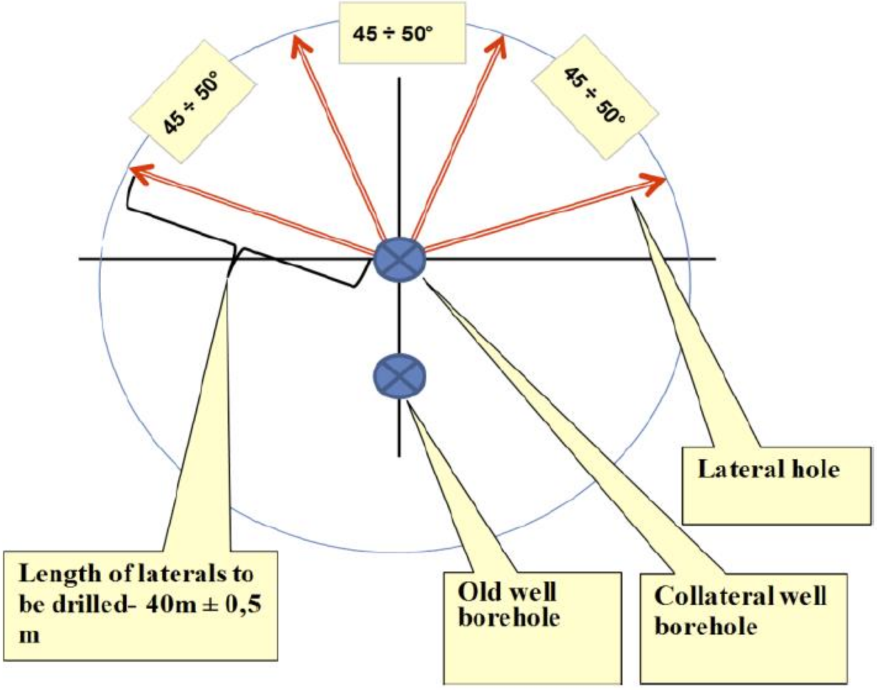

Fig.24.Schematic of laterals to be jetted in well No.1I at Klaipėda (Blöcher, et al., 2016)

In December 2014, the RJD job was carried out. In total 12 laterals were jetted of which nine reached 40 m, two reached 35 m and one reached 28 m. In deviation from the workplan, 5 laterals were jetted at the intermediate depth and only three at the deepest kick-off point.

Production data after jetting suggests an improvement in injectivity of approximately 14% based on the production data from three months after preceding the RJD. The increase didn't give the expected results for overall injection flow rate increase, what contradicts with initial project presumptions, surprises project customer and project contractors as well.

Possible reasons which during Radial Jetting Drilling works with high pressure geothermal water jet might influence or even stipulate almost the same injection flow rate level as that which was expected:

- Enormous migration of micro particles;
- The porous layer channels clogging with generated micro particles during RJD;
- The porous layer channels clogging stipulated by reactions between minerals in geothermal water with clay minerals deconsolidated and washed out during RJD;
- Drilled laterals clogging with particles from deconsolidated sand, the slumps and failures inside the drilled laterals;

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- The porous layer channels clogging with precipitations being inside of the wellbore surface and channels;
- Deviations from the perfect geometry as simulated in Chapter 6.
- The complex impact of all above named factors.

According to the project program after RJD was done back flashing (1040 m³ were pumped out with pump with 50 m³/h flow rate). Injection rate after final project completion for well No.1I was just slightly positive; the rate was increased by 4.5 m³/h.

Soft acidizing procedures. JSC "GEOTERMA" has decided to execute two types of soft acidizing after the jetting (Fig. 26). Those soft acidizing procedures were often executed after electrical power supply breaks for injection pumps in order to regain previous injection rates in the wells. During this soft acidizing procedure 1 m ³ of 18% HCl acid solution is injected in the geothermal water main flow with about 100 L / hour injection rate.

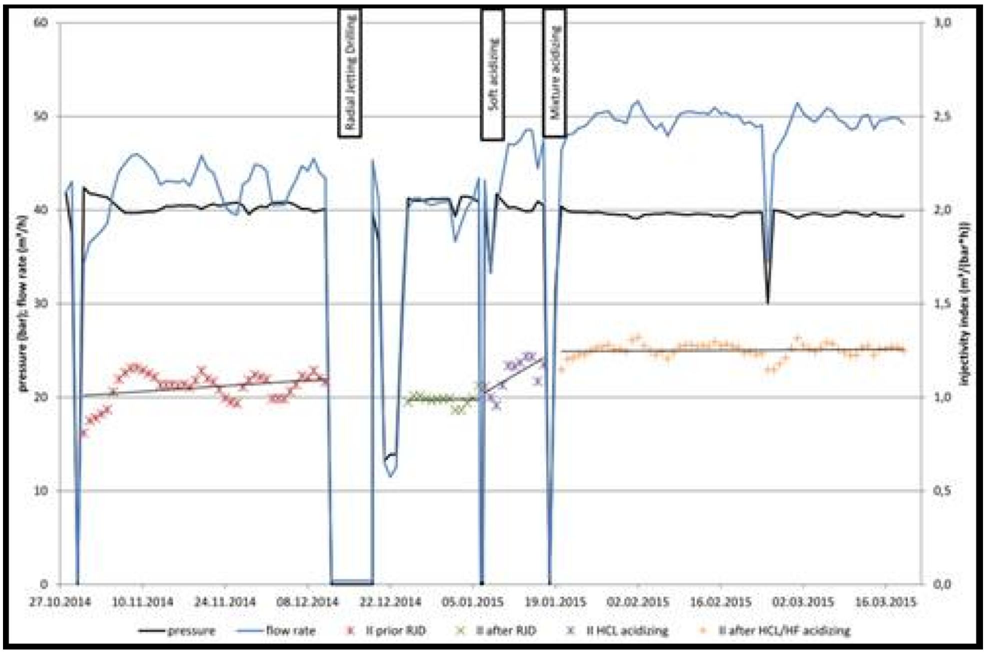

Fig. 25. Production history after jetting and two soft accidisation campaigns

First soft acidization. It was carried out 17 days after the jetting. The well No.1I was acidized with 1 m³ of 18% HCl acid solution. Injection rate after final treatment of well No.1I was positive, injection rate was increased by 3.9 m³/h.

Second Soft acidization. 12 days after the first accidisation campaign, the second accidisation was performed. The well No.1I was acidized with 1 m³ of 12% HCl and 6% HF acids mixture. Injection rate after final treatment of well No.1I was with a less significant result; the rate was increased by just 2.2 m³/h.

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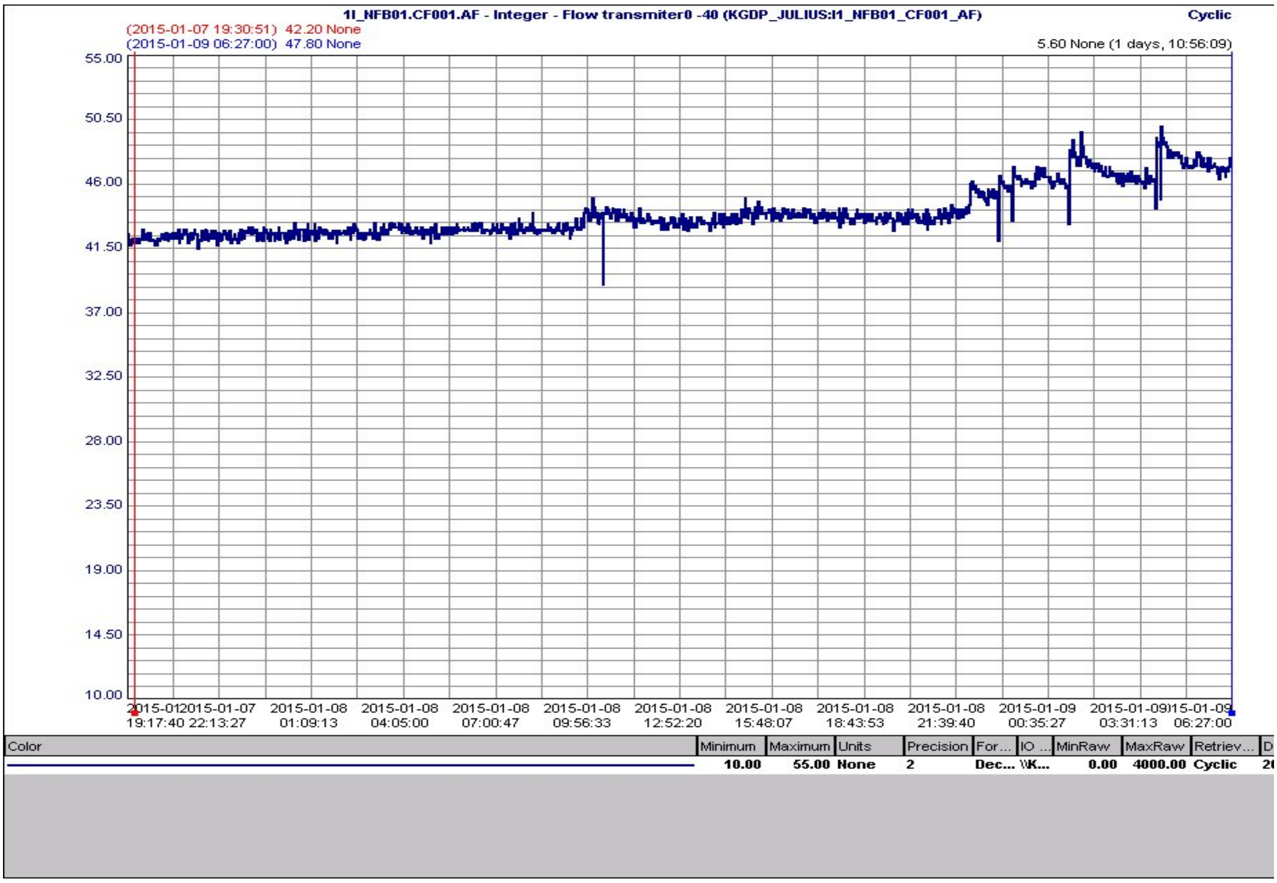

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Fig. 26.Injection after RJD

Interpreting the results of post injection right after RJD it worth to mention that during this period was unusually warm winter period. Geothermal plant was forced to work below full geothermal capacity because of the limited heat requirements of the Klaipeda city district heating network.

Looking at the longer working periods after post RJD during Year 2016 and Year 2017 heating seasons the injection rates in the well No. 1I were very sustainable and became less sensitive for electrical power supply breaks for injection pump. Unfortunately, those data can’t be shown in the graph form “SCADA” system, because of the breakdown of injection flow rate indicator in injection well No.1I. In order to define injection rates of well No. 1I JSC “GEOTERMA” was using deduction method. The injection rate of well No. 1I was calculated from overall injection rate deducting the injection rate of well No. 4I. The calculated injection rate of well No. 1I was sustainable and has reached 50 m^3/h.

With the start of the heating season of Year 2017 JSC “GEOTERMA” engineers have noticed that injection pressure in well No. 1I is significantly lower than in injection well No. 4I. After checking the injection tubing was find out that check valve of rim piping is functioning not properly and some part of geothermal water is not injected but runs in closed loop in the rim piping. JSC “GEOTERMA” management decided to change check valve as soon as possible.

After check valve was changed the calculated injection rate of well No. 1I was sustainable and has reached about 60 m³/h.

Conclusion. Despite comparably first insignificant injection rate increase after short period of time post RJD in the well No. 1I, the injection rates of well No. 1I remains sustainable during long period of time, became less sensitive for electrical power supply breaks and injection pump stops and even slightly increasing without any additional treatments. Comparing injection rates before RJD and post RJD after two years the overall injection rate increase is about 39 %. Injection problems in the Klaipeda injection wells are most likely related to the skin effect. Therefore shorter but more numerous laterals, connecting the wellbore to an undamaged reservoir, should have a higher effect for a high porosity formation compared to long laterals design.

6. Modelling of the horizontal jetting

(*based on publication by Rohith Nair, Elisabeth Peters, Saulius Šliaupa, Robertas Valickas and Sigitas Petrauskas. 2017. A case study of radial jetting technology for enhancing geothermal energy systems at Klaipėda geothermal demonstration plant. PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 13-15, 2017 SGP-TR-212. https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2017/Nair.pdf*)

The goal of this chapter is to evaluate the injectivity increase resulting from the RJD job taking into account the uncertainty arising from both the geology and the RJD process. This will help in understanding the injectivity and productivity from the laterals. First a base case is simulated in which the laterals are implemented based on the drilling reports and are assumed to be according to specifications. Next, the main uncertainties are evaluated by conducting a number of parameter sensitivity experiments.

The base case scenario was constructed based on the specifications of the radial jetting job at Klaipėda, assuming the laterals were all jetted according to the specifications. An uncertainty analysis was carried out to investigate the impact of uncertainties in the length, positioning, diameter, inclination, and pre-existing near wellbore damage of the laterals on the water injection rate.

6.1. Model Setup

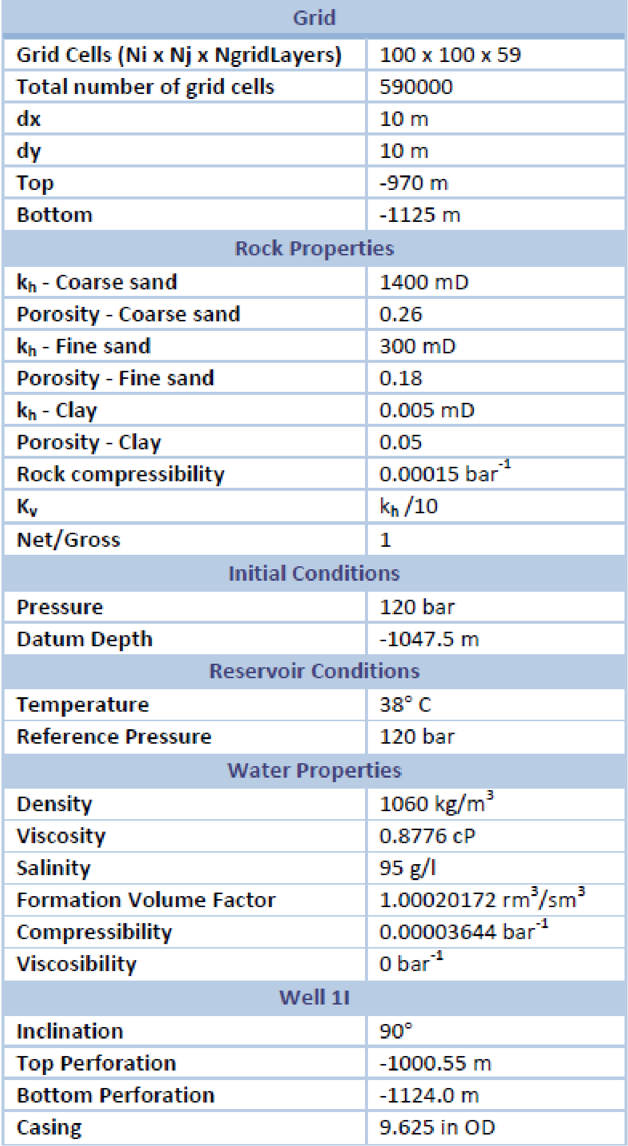
To evaluate the changes in injectivity of the well resulting from stimulation by radial jet drilling, a single well model suffices. By setting a constant pressure condition at the reservoir boundary and a constant pressure boundary condition in the well, the well productivity and/or injectivity at a constant drawdown can be evaluated. The geological model was generated using Petrel and reservoir simulations were conducted using ECLIPSE 100.

The single well model was set up with the following assumptions:
- Since the deviation of the new side track is very small, we simulate the laterals as if they were drilled in the original, vertical well.
- We assume the layering to be perfectly horizontal, perpendicular to the well and laterally extensive over the size of the model.
- Three facies are identified: coarse sand, fine sand and clay. Permeability and porosity are constant per facies (Table 6), because it is assumed that the variability between the facies is much larger than the variability within facies. The vertical distribution of the facies is modelled based on the gamma ray log.

Table 6 shows an overview of the values used for the model. Most of the values are derived from logging and well test reports from the operator.

Table 7 lists the parameters values for the laterals jetted at Klaipėda and implemented in the base case.

Table 6. Overview of the Klaipėda model properties



Grid	
Grid Cells (Ni x Nj x NgridLayers)	100 x 100 x 59
Total number of grid cells	590000
dx	10 m
dy	10 m
Top	-970 m
Bottom	-1125 m
Rock Properties	
k_h - Coarse sand	1400 mD
Porosity - Coarse sand	0.26
k_h - Fine sand	300 mD
Porosity - Fine sand	0.18
k_h - Clay	0.005 mD
Porosity - Clay	0.05
Rock compressibility	0.00015 bar^{-1}
K_v	k_h /10
Net/Gross	1
Initial Conditions	
Pressure	120 bar
Datum Depth	-1047.5 m
Reservoir Conditions	
Temperature	38° C
Reference Pressure	120 bar
Water Properties	
Density	1060 kg/m^3
Viscosity	0.8776 cP
Salinity	95 g/l
Formation Volume Factor	1.00020172 rm^3/sm^3
Compressibility	0.00003644 bar^{-1}
Viscosibility	0 bar^{-1}
Well 1l	
Inclination	90°
Top Perforation	-1000.55 m
Bottom Perforation	-1124.0 m
Casing	9.625 in OD

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Table 7: Overview of the laterals jetted in well 1I.

Lateral	Kickoff depth (mTVD RT)	Length (m)	Azimuth (°)	Inclination (°)	Radius (m)
1	1105.3	40	105	90	0.019
2	1105.0	40	150	90	0.019
3	1104.5	35	195	90	0.019
4	1104.16	40	240	90	0.019
5	1038.6	40	105	90	0.019
6	1038.3	40	150	90	0.019
7	1038	40	195	90	0.019
8	1038	28	240	90	0.019
9	1039.3	35	180	90	0.019
10	1097.6	40	105	90	0.019
11	1097.3	40	150	90	0.019
12	1097	40	195	90	0.019

6.2. Model Validation

Well 1I has shown high variability in both productivity and injectivity since it was drilled. The first production test just after well completion showed a flow rate 22.3 m3/hr at a drawdown of 1.2 bar (186 m^3/hr/MPa). The production logging tool observed most inflow over the interval 1085 to 1000 m MD RT. The model results for the same drawdown with initial estimates of permeability were 19.4 m^3/hr, which is a difference of 13% with the well test result. Since for purposes of this paper, we evaluate changes rather than the absolute productivity/injectivity, this difference is acceptable.

An issue is that the laterals were jetted a few years after the side track was drilled and injectivity had deteriorated considerably by the time the laterals were jetted, which was probably caused by scaling, fines mobilization and chemical precipitation of minerals (possibly also in the formation) as was discussed in previous chapters. At the time that the laterals were implemented, injectivity had reduced to around 5 to 10 m3/hr/MPa. For the purpose of comparing the increase in injection rate achieved at Klaipeda by radial jetting stimulation, with the model results, the model needs to reflect the state of the formation (formation damage) near Well 1I, at the time radial jetting stimulation was carried out.

The effects of scaling and precipitation can be represented by a decrease in near-well permeability or a skin factor. If the formation damage is purely represented by skin, a skin factor of approximately 120 in the backbone would be required to represent the drop in injectivity (Figure 2) which is extremely large. If the reduction in injectivity is represented by a decrease in permeability, an overall decrease by a factor of 20 would be required. For a good representation of the formation damage a combination of both skin and permeability reduction near the well is required. However, we have no information on which to base such a model. But for the injection or production resulting from laterals, it is very important how far the formation damage extends into the reservoir. If the reduction in permeability is very close to the well (<1 m), it can be represented by a skin and the initial injectivity or productivity from the laterals would be expected to be very high. If the reduction is in the permeability, then the laterals are subject to the same decrease in permeability as the main well. Thus, it was chosen to do the evaluation of the effect of the laterals on a reservoir without skin and formation damage.

Due to this choice, the direct interpretation of the results for the Klaipėda well 1I is limited. Still the order of magnitude is expected to be relevant. The laterals would be likely to suffer from a similar decrease in injectivity as the backbone. If that happens, the relative contribution of the laterals compared to the backbone should be in the same order of magnitude as in our model (i.e. without skin and formation damage).

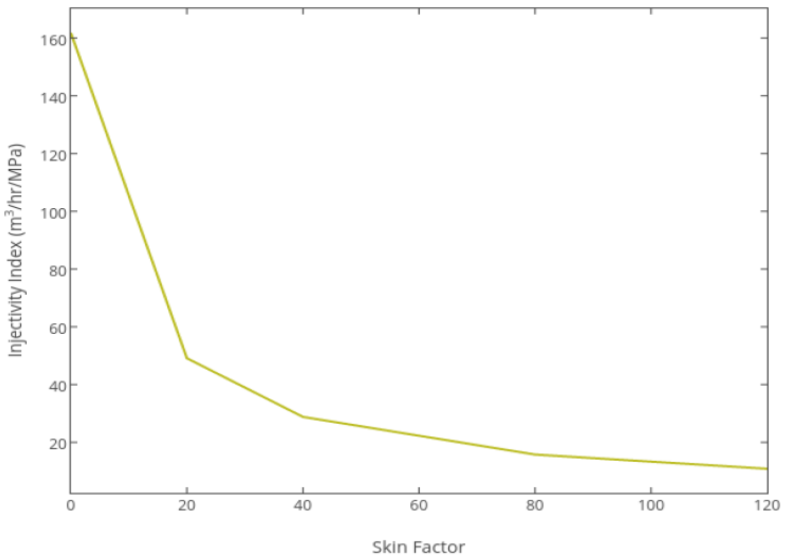

Fig. 27. Impact of varying backbone skin on the injectivity index of the backbone

6.3. Setup of the uncertainty Analysis

Uncertainty about the injectivity in the laterals depends mainly on two aspects: geological uncertainty and uncertainty on the actual location and dimensions of the laterals. The main geological uncertainties for the productivity/injectivity of the jetted laterals are the permeability and the distribution of the high and low permeability layers. Additionally, lateral variations in the thickness of the high permeability layers may affect the injectivity of a lateral. Since the effect of this variability on the injectivity is similar to the effect of changes in kick-off depth, this uncertainty is captured in the sensitivity of the injection rate to the kick-off depth of the laterals.

All uncertainties are summarized in kick off depths, length, diameter and inclination of the laterals. These will be discussed in more detail below.

The uncertainty analysis was conducted with a total of 40 simulations for each uncertain parameter. The perturbations in the lateral design parameters were carried out randomly and sampled from a uniform distribution. The value of the uncertainty parameter for each of the 12 laterals has been perturbed independent of the other laterals. An automated workflow is utilized for the purposes of this uncertainty analysis.

Kick off depth

Uncertainty in the kick-off depth results from uncertainty in the positioning/depth of the deflector shoe (Elliott, 2011). The deflector shoe determines the position at which the lateral is jetted. The deflector shoe is connected to the tubing thus the uncertainty in depth measurement is relatively small (+/- 0.5 m). The geological uncertainty in the layering is incorporated in this parameter as explained before, making the final uncertainty range larger.

Numerical reservoir simulations have been carried out to quantify the sensitivity of the model to uncertainties in kick off depth of -2 to +2 meters.

Lateral length

At the Klaipėda geothermal plant, the laterals jetted have lengths in the range 28 – 40 m. However, like all wells, laterals are susceptible to cave-in's, clay swelling etc. and thus the actual length of the producing lateral might be smaller. Furthermore, the coiled tubing on which the jetting assembly is conveyed can expand or buckle during operations making the measurement of the length of the laterals uncertain (Pesin & Boyle, 1996).
The uncertainty range in lateral length is taken from 8 to 45 m.

Lateral diameter / Skin

The diameter of a jetted lateral is uncertain because it depends on the strength of the formation and how much the back jets enlarge the hole. Based on surface measurements, a diameter of 0.03 m to 0.05 m can be expected (Ragab, 2013, Abdel-Ghany, et al., 2011). The diameter depends on the effectiveness of the back jets in increasing the size of the hole. The minimum diameter achieved is the diameter of the nozzle, which is 0.0127 m (0.5 inch) in most applications. The diameter of the jetted hole probably varies over the length of the lateral.

The laterals might also suffer from skin. The skin factor for individual wells can be modelled as a reduction or increase in well radius (Equation 1), where rw (changed) is the changed wellbore radius and rw (original) is the original wellbore radius.

$$S = -\ln\left(\frac{r_{w\,(\mathrm{changed})}}{r_{w\,(\mathrm{original})}}\right)$$

Based on this, the total uncertainty range in lateral diameter is taken from 0.002 to 0.2 m.

Lateral inclination

The angle the laterals make with the backbone is 90° where the lateral starts from the main well bore, but since the lateral is not steered it may deviate from that angle in all directions affecting both azimuth and inclination. For example, changes in geological properties due to layering, geo-mechanical variability of formations and faults may cause the lateral path to deviate from the straight line. Furthermore, an uncertainty in the inclination of the different geological layers is captured within the uncertainty in lateral inclination. The inclination of the laterals has been varied from 45° to 135°.

Lateral azimuth

The azimuth of the laterals become important if the reservoir geology is laterally heterogeneous and anisotropic. The Klaipėda geological model is essentially a layer cake model with laterally extensive and continuous layers. Preliminary investigations showed that the model is not very sensitive to changes in the azimuth and therefore the azimuth uncertainty was not investigated in detail.

6.4. Simulation Results

Base case results

The base case laterals are the actual laterals as reported in the drilling reports. Not all laterals reached the planned length of 40 m. Also, due to difficulty in jetting in the lower part, 5 laterals were jetted in the topmost layer and three in the middle layer. It is assumed that the laterals follow a straight path and have a uniform diameter of 1.5 inch (0.038 m). Table 2 shows the lateral parameters, which are visualized in Figure 2. The majority of the laterals is located in the coarse sandy facies as planned. This is illustrated in Figure 28. Water injection rate in Well 1I with the base case is 30.4 m^3/hr (728.8 m^3/d) for a pressure difference of 1.2 bar. This is an increase of 57% over the injection rate in the backbone without laterals, which was 19.4 m^3/hr for the same pressure difference (see section on Model Validation).

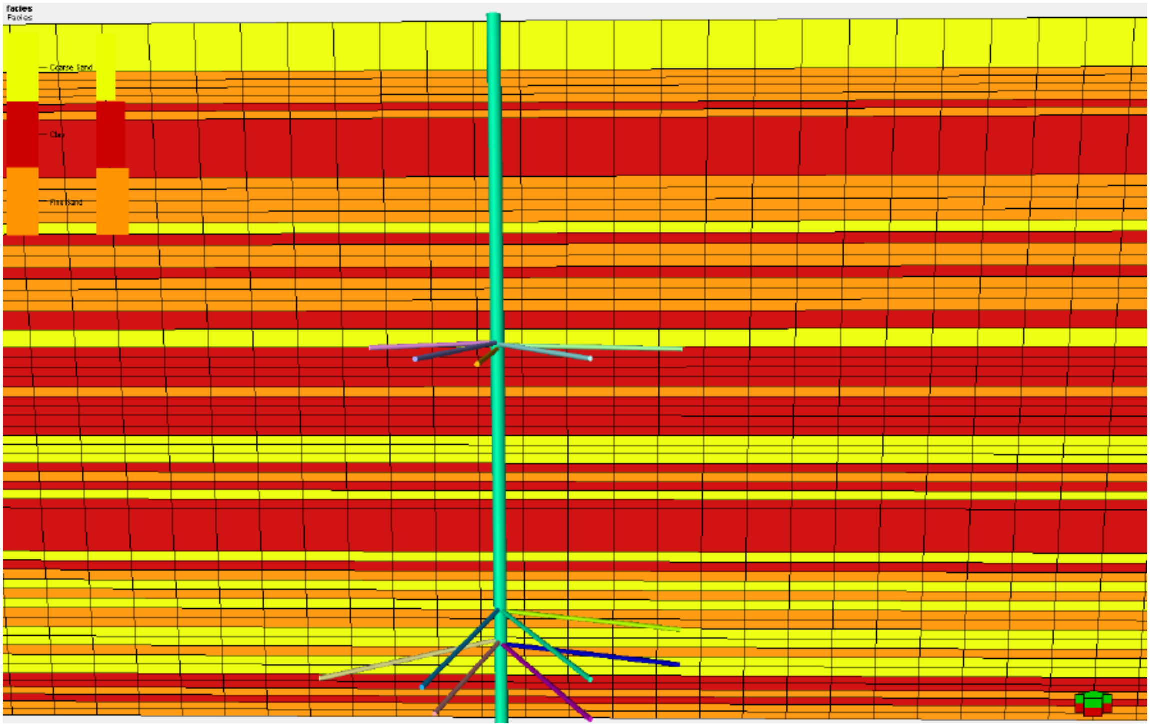

Fig.28. Lateral configuration as jetted in well 1I in the Klaipėda geothermal field (view from south), including the single-well model showing facies: red is clay, orange is medium fine sand, yellow is coarse sand (properties in Table 3).

Results uncertainty analysis

Uncertainty in kick off depth the sensitivity of the water injection rate at Klaipėda to uncertainties in kick off depths is represented by the vertical spread in Figure 27.

There is a difference of 8.2% in the injection rate when the mean of the absolute value of the changes in the kick off depth for each of the laterals is shifted between 0.6 and 1.3 m. This shows that an uncertainty in the kick off depth of approximately a meter can have a significant impact on the effectiveness of the RJD job at Klaipėda. All changes in the kick off depth resulted in lower injectivities compared to the base case, which suggests that the laterals were placed optimally in the base case. The laterals shown in Figure 27 can be seen as two different sets of laterals; one set in a single coarse sand layer at the top of the formation and another set towards the bottom of the formation. The set of laterals at the top of the formation are very sensitive to kick off depths since a small uncertainty in the kick off depth would mean jetting the laterals in a clay layer.

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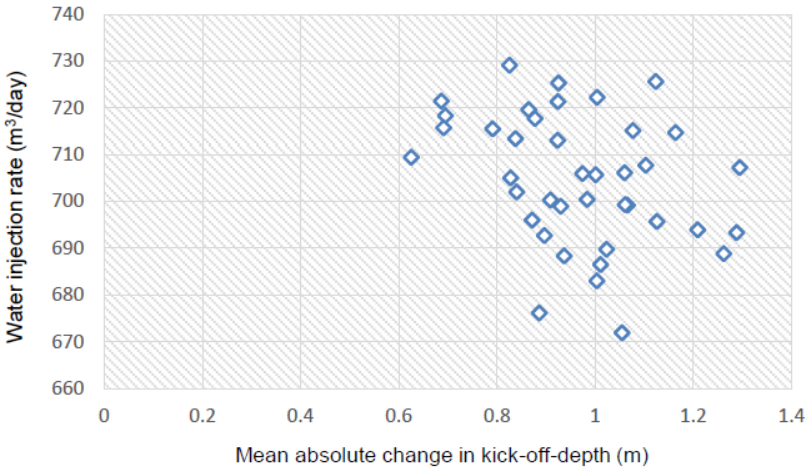

Fig.27. Sensitivity of the water injection rate at Klaipėda to uncertainty in the kick off depths of the laterals

Uncertainty in lateral length

Laterals improve well injectivity/productivity by increasing the connection between the well and the formation. An increase in productivity/injectivity is expected from an increase in lateral length. The trendline in Figure 28 clearly suggests that an increase in the length of the lateral indeed results in an increase in the injection rate in Well 1I. There is a difference of 12.3% in the injection rate when the mean of the changes in the lateral length changes from -18 to -3 m. Realistically, the probability of having shorter radials is higher than the probability of having longer radials; the ranges chosen for the uncertainty analysis reflect these probabilities and is the reason why all the observations in Figure 28 have negative mean changes in lateral lengths.

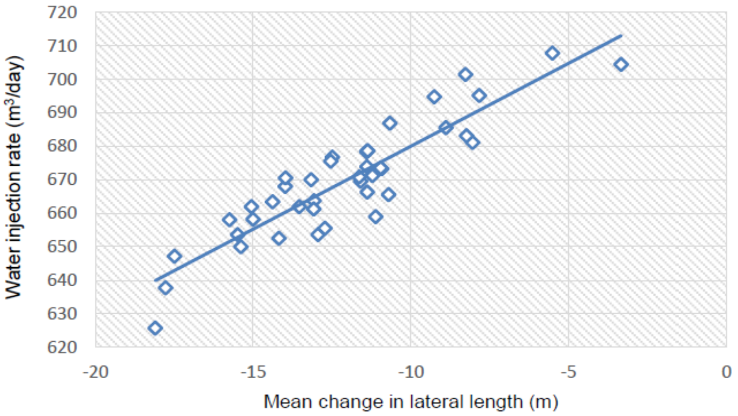

Fig.28. Sensitivity of the water injection rate at Klaipėda to uncertainty in lateral length

Uncertainty in lateral diameter

The SURE project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654662.

The sensitivity of the water injection rate in Well 1I to the changes in lateral diameter is represented by the spread in Figure 29. The trendline in Figure 29 shows that an increase in the diameter of the laterals results in an increase in the injection rate. Injection rate is not very sensitive to changes in diameter; a mean change in the diameter of between 0.02 and 0.09 m results in a difference of 2.3% in the injection rate.

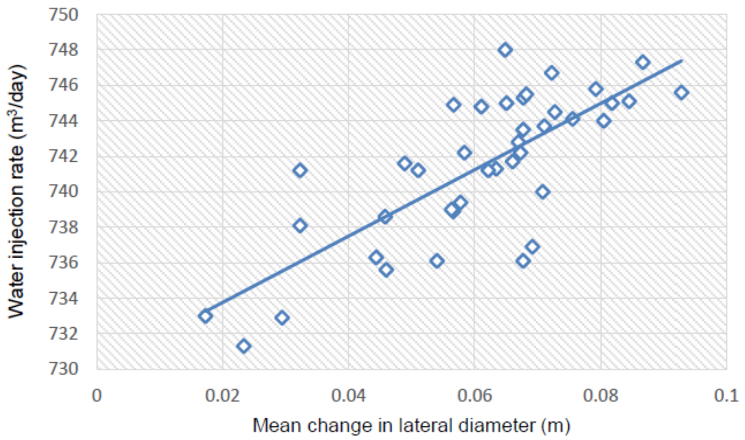

Fig.29. Sensitivity of the water injection rate at Klaipėda to uncertainty in lateral diameter

Uncertainty in lateral inclination

Figure 30 shows sensitivity of injection rate in Well 1I to the mean change in inclination of the laterals at Klaipėda. There is a difference in injection rate of 13.4% when the mean inclination varied from -15.8° to 15.1°. The trendline suggests that laterals inclined slightly upwards with respect to the horizontal result in more favorable values of injection rate.

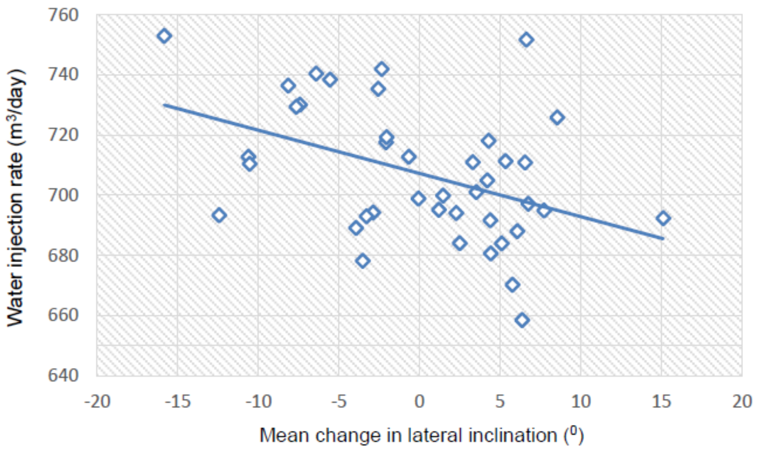

Fig.30. Sensitivity of the water injection rate at Klaipėda to uncertainty in lateral inclination

Overview of results

The SURE project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 654662.

Table 4, Figure 31 and Figure 32 summarize the results obtained from the uncertainty analyses conducted. From Figure 31 and Figure 32, it can be observed that any uncertainty in the kick off depths or the lateral length leads to decrease in injectivity with respect to the base case. Injectivity in Well 1I is most sensitive to changes in the inclination of the laterals, followed by the length. A combination of these uncertainties can lead to a more severe impact on the injectivity.

It is possible to improve production from laterals at Klaipėda by varying the inclination and increasing the lateral diameter. This proves that there exists an optimal combination of the lateral design parameters which can lead to maximized injectivity at Klaipėda. Moreover, due to the observed impact of uncertainties on the effectiveness of radial jetting, a robust optimization is favorable.

Table 8: Uncertainty ranges and results of the analyses conducted

	Uncertainty Range	**Minimum injection rate (m^3/day)**	**Maximum injection rate (m^3/day)**	**Mean injection rate (m^3/day)**	**Variance**	**Percentage difference (injection rate)**
Length	8 m to 45 m	625.7	707.8	666.75	1685.103	12.3
Inclination	45° to 135°	658.4	752.9	705.65	2232.563	13.4
Kick off depth	-2 m to +2 m	671.9	729.1	700.5	817.96	8.16
Diameter	0.002 m to 0.2 m	731.3	748	739.65	69.7225	2.25

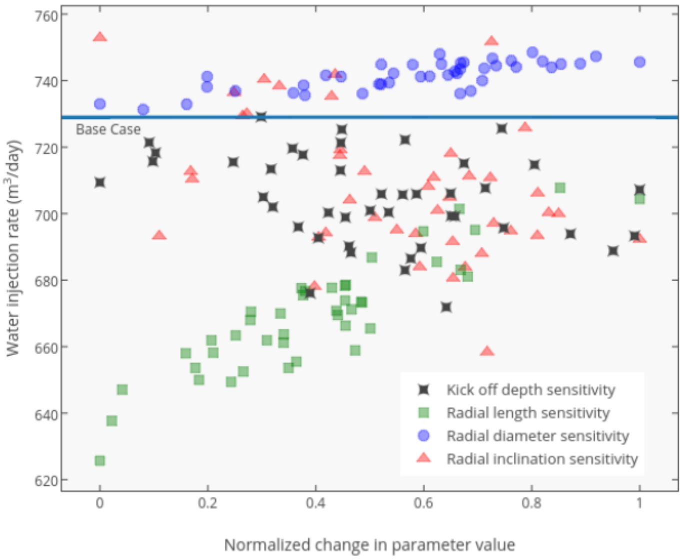

Fig.31. Sensitivity of the water injection rate at Klaipėda to uncertainties in the different lateral design parameters

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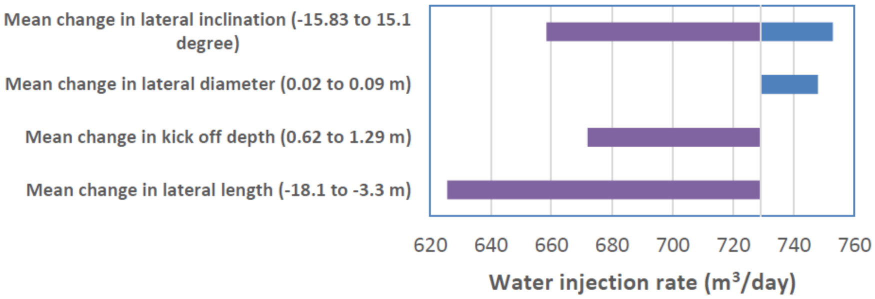

Fig.fig32. Sensitivity of the water injection rate at Klaipėda to uncertainties in the different lateral design parameters

6.5. Summary and Conclusions

The plant at Klaipėda is designed to be a low enthalpy geothermal conversion facility, relying on high injectivity and productivity to achieve the required energy capacity. The injectivity of the injection wells has deteriorated due to a variety of problems (scaling, fines mobilization, sanding etc.). Radial Jet Drilling (RJD) was identified as a technology which could help improve injectivity and subsequently 12 laterals were jetted in well 1I in December 2014, which resulted in an increase in production of 14%.

The geology of the Klaipėda geothermal site consists of very thin, extremely permeable sand layers and moderately permeable sand layers interspersed with nearly impermeable clay layers. This makes the productivity and injectivity and thus the energy produced sensitive to the positioning of the laterals. The position of laterals jetted using RJD is quite uncertain as a result of the jetting process: inclination and azimuth of the lateral are not controlled after the start of the lateral. The diameter of the lateral depends on the efficiency of the backward facing jets in enlarging the hole and the length of the laterals depends on the length measurement using the CT. The effect of these and other relevant uncertainties on the increase in injectivity is evaluated using a numerical model of injection well 1I.

For the base case, the laterals are assumed to be jetted exactly according to the specifications (straight trajectory, located at the specified kick-off depths and with the specified lengths). The base case gave a 57% increase in injection rate compared to the unstimulated well, which is considerably higher than the observed increase of 14%. Most of the uncertainties that were investigated resulted in a decrease in injectivity. The most sensitive parameter (for the ranges chosen here) was the lateral inclination followed by the length. Both these parameters caused changes in injectivity in excess of 10%. Inclination had quite a large impact on the result because for larger inclination, laterals can leave the high permeability layer in which they are jetted. The impact of a change in diameter was limited. All changes in kick off depth and lateral length resulted in a lower injection when compared to the base case, highlighting the inherent risk these parameters represent in achieving expected injectivity and energy production. The observed sensitivity of well injectivity to the aforementioned lateral parameters suggests that proper monitoring of the progress of a radial jetting job is important.

The results from the model should be viewed with caution, because the model used for the simulations represents the original reservoir before injection started rather than the actual situation at the time of radial jetting in which injectivity of the well had decreased considerably due to scaling, chemical precipitation and fines mobilization.

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