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Geothermal Exploration in Chukotka, Far East Russsia

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ABSTRACT

The Chukotka region in Russia has several low-temperature geothermal prospects. The Government of Chukotka has plans for harnessing the Kukun hot springs for a hot water supply system for the Lorino village 14 km to the southeast. Kukun hot springs discharge large quantities (45 l/s) of thermal waters, with temperatures up to 58°C. Chemical analysis indicate temperatures at depth in the range of 105-110°C. Orkustofnun Geoscience (now Iceland Gesurvey, ISOR) was engaged to carry out exploration at Kukun hot springs aiming at getting hotter water and to make a reconnaissance survey of geothermal resources 6 km south of the village Uelen, which is on the NE tip of the Chukotka peninsula. In a mission in the summer of 2002, geology and thermal anomalies were mapped at Kukun hot springs and geophysical investigations (TEM resistivity and gorund magnetic surveys) were carried out. An exploratory drilling program was set up to locate the feeding fractures in the plutonic granite basement. Samples of the up to 69°C hot thermal waters were collected at Uelen showing high salinity and abnormally low silica content, indicating carbonate sedimentary origin, and with high radioactivity. Five wells have been drilled at Kukun hot springs, two of which are productive with large amount of thermal waters (48 and 74 l/s respectively). The geothermal system is associated with a complex system of open fractures. The thermal waters are interfering with colder groundwater as indicated by chemical analysis. The highest temperature obtained so far is 64°C. In a mission in the summer of 2003 a flow and interference test was made for the wells at Kukun. A second visit was made to Uelen to map geology and thermal anomalies in detail, and an exploratory drilling program was set up.

1. INTRODUCTION

Chukotka, the easternmost Autonomous Region in Russia (Figure 1), has several low-temperature geothermal prospects. A few of these prospects are relatively close to villages. Houses in Russian towns and villages are generally heated by water from central heating stations. In Chukotka the central heating stations are coal fired. It is therefore of great benefit, both economically and environmentally, to replace coal by geothermal heating.

This paper describes work that the authors have performed in East Chukotka at two geothermal sites, the Kukun hot springs which are about 14 km from the village Lorino, with about 800 inhabitants, and the Uelen geothermal area which is about 6 km from the village Uelen, which is the easternmost settlement on the Eurasain continent, with about 500 inhabitants.

Figure 1: Map of Far East Russia. The Chukotka peninsula is the eastern most part.

In 2001 the Government of Chukotka engaged Kamhnit Ltd. in Iceland to render engineering design services for the harnessing of the Kukun hot springs and a for a hot water supply system for the Lorino village. Kamhnit made a geodetic survey and designed a pipeline for piping the 58°C hot water to Lorino. During the field mission in 2001, the water from the springs was sampled and later analyzed in the laboratories at Orkustofnun Geoscience.

Figure 2. Location of the villages near the two geothermal prospects.

The chemical content indicated reservoir temperature in the range of 105-110°C and mixing with cold groundwater (Ólafsson, 2001).

This indicated that hotter water could be obtained by drilling instead of harnessing only the natural flow from the hot springs. The Government of Chukotka and Kamhnit therefore asked Orkustofnun Gescience (which later became Iceland GeoSurvey, ISOR) to perform geothermal investigations aiming at drilling for hotter water. ISOR was also asked to perform investigations at the Uelen geothermal field and in the Chaplino hot spring area. Investigations at Shaplino were later abandoned due to difficult logistics and because the geothermal resource is un-economically far from the nearest village Novaye Chaplino.

Previous research on geothermal resources in Chukotka seems to be limited, and an attempted literature survey gave meager results. All necessary data had therefore to be collected by field missions. To date, four field visits have been made. Two five week missions have been made, in the summer of 2002 and 2003 and two short visits late 2002 and early 2003. This paper describes the findings and results of the work performed so far (Árnason and Franzson, 2002; Franzson and Richter 2002, Richter and Thordarson, 2003; Árnason et.al., 2003).

2. KUKUN HOT SPRINGS

The Kukun hot springs are located in the NNV-SSE trending Kukun river valley (Figure 3), about 14 km NE of the village Lorino. At the hot springs there is a little guesthouse, greenhouses and a popular bath pool.

The geothermal manifestations consist of a main hot spring which discharges trough the sedimentary filling of the valley at least 27 l/s of 58°C water. It is difficult to measure the natural flow from the spring accurately because about 3 m high concrete cistern has been built around the hot spring to elevate the hot water for piping to the greenhouses and residences. About 45 m west of the main hot spring is another hot spring and several smaller outlets discharging at the bottom and at the banks of a bath pool. Only the total outflow from the bath pool can be measured and is about 14-16 l/s. The highest temperature measured at the inlets at the bottom of the pool is 54.3°C, but some of the inlets have considerably lower temperatures. In addition to these main springs small seepages of warm water (20-35°C) are found in an N-S trending area, extending some 150 m south from the main hot spring.

2.1 Geological settings

The Kukun hot springs are situated within an area of large syenitic intrusion bodies (plutons) of Middle Cretaceous age, probably a part of the Okhotsk-Chukotka volcanic belt that has been interpreted as being a former Andean type active continental margin under which the Pacific Basin crust subducted (Stavsky et al. 1990, Natal'ina et al. 1999).

The rock formation in the geothermal area is therefore considered to be rather homogeneous and monotonous. Repeated glaciations have carved the strata forming shallow U-shaped valleys, and the Kukun hotspring area is situated on the bottom of one such valley. Tectonic fractures weaken the rock and result in that glacial carving often preferentially follows these structural weaknesses. At the end of the glaciation the landscape is characterized by meticulously scraped and polished bedrock, and in the low part of the valleys glacial river sediments and glacial end-moraines are the last remains of the retreating glaciers. Figure 3 shows schematically how river gravel occupies the bottom of the Kukun River valley and minor remains of glacial end-moraines are located (in this paper, coordinates on maps are hereafter in UTM/UPS, zone 2W, WGS-84 datum, coordinates in kilometres). The thickness of the river gravel, filling the bottom of the valley, is about 5-10 m at the hot springs and could be tens of meters in the central part.

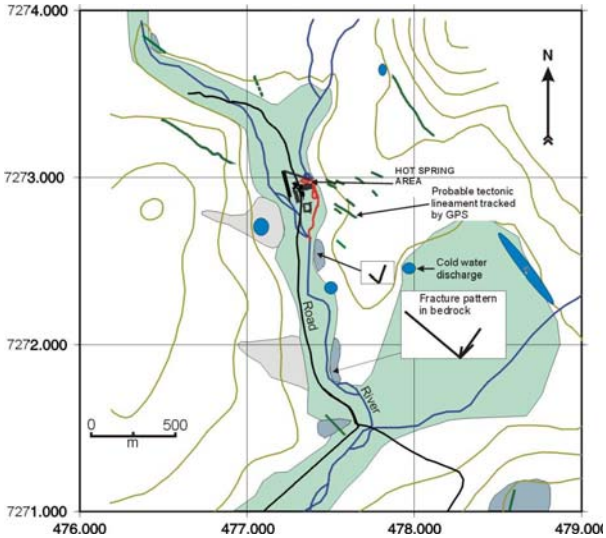

Figure 3. Sediments in the Kukun River valley and surroundings (light green areas), glacier end-morains (light grey), fracture rose diagrams of cracks and lineaments tracked by GPS (dark green lines).

The bedrock is composed of coarse grained and apparently homogeneous syenite intrusion(s). These have undergone in situ postglacial granulation as a result of the frost and thawing action. This granulation may have extended a number of meters into the bedrock, but due to the relatively low altitude topography there has been little movement of the granulated material.

2.2 Tectonics

The plutonic rocks in the Kukun area are highly impermeable and the geothermal activity was therefore believed to be associated with fracture permeability. An emphasis was therefore put on studying relatively young tectonics.

Due to the aforementioned granulation of the bedrock, direct measurements of tectonic fractures could only be done in exposures, where the Kukun river has cleared the granulated cover off the bedrock (marked in Figure 3). Northeast of the hot spring area a few escarpments that were tentatively interpreted as fractures, were measured and showed mainly a strike of N130°E. The bedrock exposure just south of the hot spring did not show intense tectonic lineaments, and it is suspected that some of the fractures there are associated with cleavage planes of the intrusive body, rather than being of tectonic origin. Two directions were observed as indicated in Figure 3, a minor one striking N120-130°E and the other striking from N0-40°E but with directions of about N20°E most abundant. The dip of the latter fracture trend was generally towards west and the average was within 10° from vertical. It is suspected that some of the fractures with large deviations from vertical may not be of tectonic origin, but a cooling phenomenon. If the fractures are largely tectonic, however, they indicate that the general dip of N-S trending fractures is towards west.

At the south end of the valley, a good exposure was found in very fractured bedrock. The N130°E fracture direction is by far the most notable as shown by the rose diagram on Figure 3. Northeast fractures (N35-50°E) are also conspicuous, while near north trending fractures (N5°E), which are parallel to the valley, are few. A series of measurements was likewise done on the inclination of these fractures. Fractures trending N130°E, are generally inclined towards southwest of well within 10° from vertical.

As stated earlier the topography of the area is rather gentle and there has been little movement of the granulated material. This means that major tectonic features manicured by the glaciers can probably still be observed, evidenced as vegetated linear terraces or depressions in the hilly landscape. Such linear structures were tracked by GPS (green lines on Figure 3). One linear vegetated depression is clear in the northern slopes of the hill west of the hot springs. This structure is parallel to the western branch of the valley, where it splits, north of the hot springs. Vegetated terraces are also found in the hill east of the hot springs. All these structures are oriented about N130°E. A more N-S oriented lineaments were tracked in the slope of the hill north of the hot springs and under the mountain slope in the NE.

According to surface investigations, N130°E seems to be the dominant fracture direction around the hot spring area. It is most common in the bedrock exposures and in tracked lineaments. Where the valley splits, north of the hot springs, the western branch takes up this same direction. In bedrock exposures, fracture directions form due north to N50°E are observed, but these directions are not seen as lineaments in the landscape. It is possible that these fractures are largely due to cleavage of the plutonic rocks rather than of tectonic origin. As was mentioned in section 2.1, it is believed that the valley hosting the hot springs is a structural weakness carved out by the glacier. This direction (about N170°E) is hardly seen in outcrops, but a terrace in the slope north of the valley has similar direction supporting that the valley is a carved out fracture zone.

2.3 Soil temperature survey

In the first mission in 2002 the intention was to make a soil temperature survey in the area. This was, however, not possible because the temperature measurement sticks were lost by the airlines on the way from Iceland. Only mapping of surface manifestations by maximum thermometer was achieved. The distribution of the manifestations strongly suggested that the geothermal activity is associated with an almost due E-W fracture through the main hot spring and the bath pool and a N-S trending fracture. The intercept of these fractures seemed to be in the main hot spring.

In the mission in the summer of 2003 a soil temperature survey was performed. Large parts of the area have compact gravel (roads and parking spaces). The distribution of data points is therefore in some places rather uneven.

Figure 4 shows a map of the soil temperature (at the depth of about 40 cm). The figure shows a very clear thermal anomaly which has a very sharp and well defined northern margin and a clear E-W trending anomaly between the main hot spring and the bath pool. A clear anomaly extends towards south (N170°E) from the main hot spring. Even though it is not very clear from the picture, E-W profiles showed two maxima just south of the main hot spring. A localized maxima are also found about 60 m SSE of the hot spring in the bath pool and at 120-130 m SSE of the main hot spring.

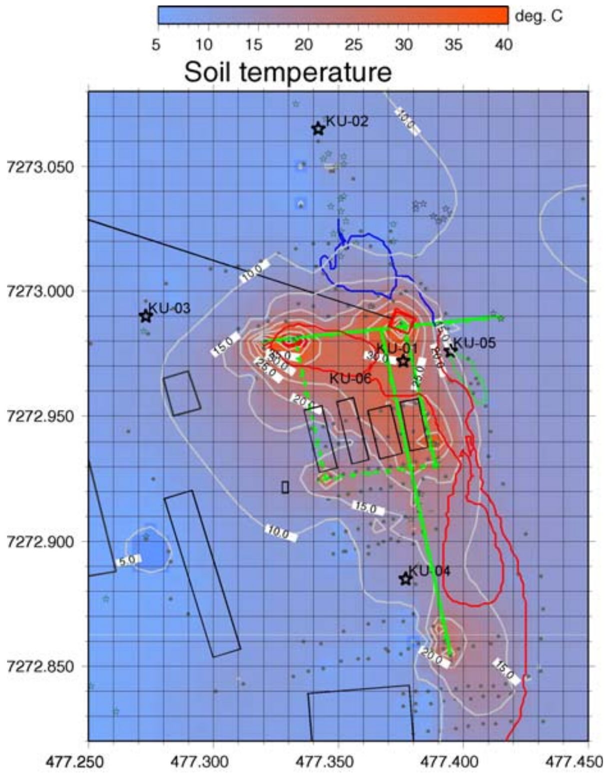

Figure 4. Soil temperature around the Kukun hot springs, inferred possible faults (green lines) and wells (black stars). (Black squares are old concrete foundations of buildings).

The thermal anomalies are interpreted as being due to up-flow of thermal water from fractures in the crystalline basement and up through the sedimentary filling. Figure 4 shows location and orientation of fractures that would explain the thermal anomalies (green lines). Fairly certain fractures are shown with solid lines and more uncertain fractures with broken lines. According to this interpretation, both of the main up-flows, the main hot spring and the inflow into the bath pool are at an interception of E-W and N-S fractures.

The N-S fractures on Figure 4 are roughly parallel to the valley and the lineament tracked in the slope north of the valley, so this fracture direction was to be expected. The N130°E direction, which seemed to be dominant in the tectonics (section 2.2 and Figure 3) does not show up in the temperature distribution. Instead a nearly E-W (N85°E) fracture is seen. This fracture direction is not seen on the surface, except as lining up the hot springs and gas outlets in the hill east of the hot springs (grey stars on Figure 4).

2.4 Geophysical survey

Two types of geophysical surveys were attempted in the first mission. A ground magnetic survey which did not give any useful results because of large quantities of metallic trash is buried and scattered around the hot springs. Due to the homogeneity of the bedrocks, no large anomalies were expected and in the hot spring area any such anomalies were drowned in metallic noise. The only consistent anomaly was found under the western slope of the valley. This anomaly, which does not seem to be of any relevance to the geothermal exploration, was found where massive quartz deposits are found and might be associated with some metallic deposits

Prior to the first mission, information on conditions at the Kukun hot springs was sparse. It was therefore decided to bring necessary equipment in order to make resistivity soundings in case they might be of use to delineate the subsurface structures of the system. The geothermal system at the Kukun hot springs is probably due to a deep circulation of water in localized tectonic environment. The thermal water in the system is therefore unlikely to generate a detectable resistivity anomaly, on its own. The Kukun springs are, however, surrounded by permafrost, and due to the hot water, the permafrost must be locally absent in the vicinity of the hot springs.

Laboratory and in situ measurements (Hoekstva and McNeil, 1973) show that the resistivity of frozen rocks is at least an order of magnitude higher than in un-frozen rocks. The absence of the permafrost around the hot springs should therefore show up as an anomaly of relatively low resistivity.

The resistivity measurement at the Kukun hot springs were not meant as a primary exploration tool in this mission but meant as a backup and support for the surface mapping. Another objective was to learn how permafrost and its local absence show up in resistivity measurements. This knowledge is vital for the design and planning of more blind geothermal exploration at other places.

The method chosen for this study was the central-loop TEM (Transient Electro-Magnetic) method), which, in the resistive environments in the survey area, gives a depth of penetration of about 400-500 m.

Like for the magnetics, the applicability of the TEM soundings was limited by buried metallic trash, especially in the immediate vicinity and to the south of the hot springs. A total of 12 soundings were made and their locations are shown on Figure 5. Figure 6 shows two E-W oriented resistivity cross-sections, based on 1D inversion of the data (for location, see Figure 5).

The westernmost sounding on Line I is distorted, showing sign reversal of the transient. This turned out to be the case for all the soundings under the western slope of the valley, where the magnetic field showed an anomaly. The most plausible explanation is that magnetized and polarizable ore bodies are present in the heavily quartz veined rocks found there.

Apart from this anomaly, Figure 6 shows that below a thin surface layer of about 1000-3000 Ωm, there is generally a layer of considerably higher resistivity (generally at least by a factor of two) which is considered to reflect the permafrost. Below is a layer with an order of magnitude lower resistivity and finally a resistive basement. Figure 6 shows that the permafrost layer is absent north of the hot springs, reflecting the absence of the permafrost due to the geothermal activity.

This demonstrates that resistivity soundings can be used to map areas with anomalously high heat flow or geothermal activity at depth but without clear surface manifestations, by mapping the thickness and possible absence of the permafrost.

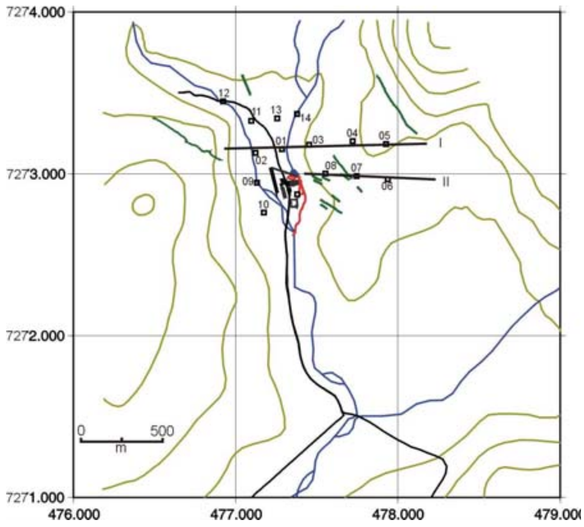

Figure 5. Location of TEM soundings at the Kukun hot springs and lines of cross-sections.

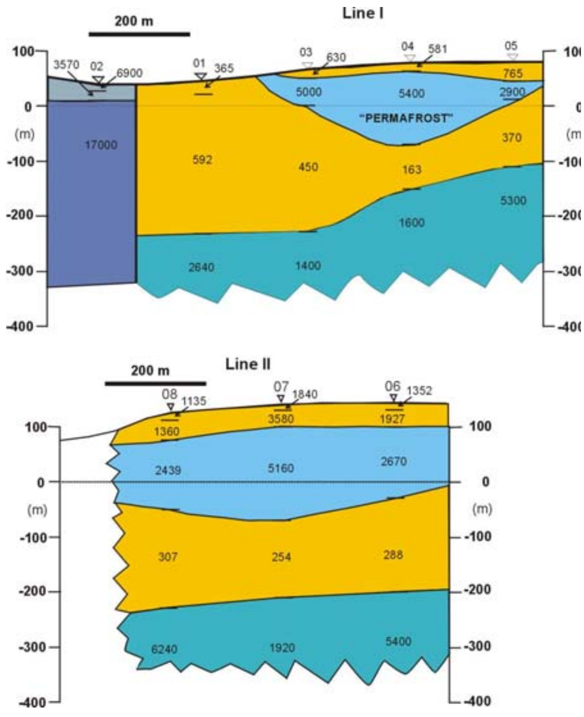

Figure 6. Resistivity cross-sections along lines I and II. For location, see Figure 5.

2.5 Exploration drilling

Even though a detailed soil temperature survey could not be carried out in the first visit in the summer of 2002, the fracture pattern shown in Figure 4 was anticipated. Five exploration wells were then sited to investigate which of the fractures control the flow of the geothermal waters. The locations of the five exploration wells are shown in Figure 4. One well was sited close to the intersection of the suspected fractures and four wells away from the hot springs, close to the suspected fracture lines in order to check if the hot water was channeled to the hot springs along one of the fractures. Well KU-05 was originally sited up in the hill east of the hot springs, but it turned out to be impossible to get the drill-rig to that location so the well was re-sited at the foot of the hill.

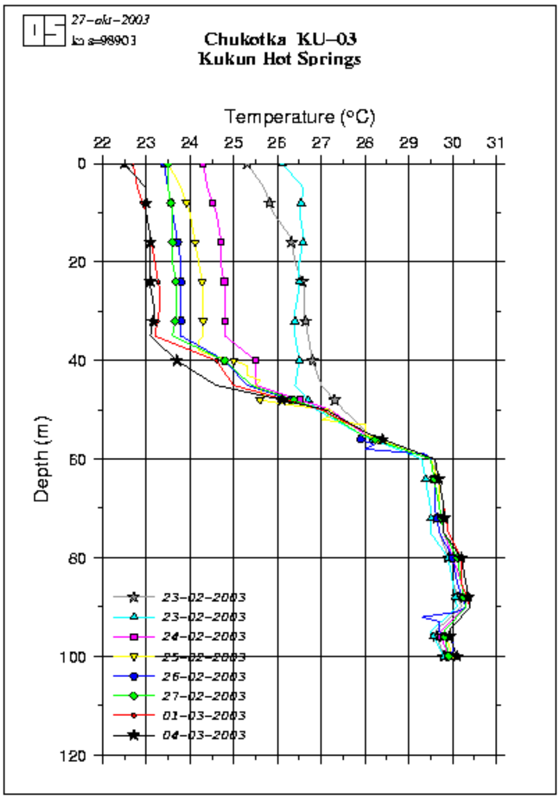

Figure 7. Temperature measurements in well KU-03.

The drilling started in November 2002 and well KU-03, west of the hot springs, was the first well drilled, to the depth of 100 m. Figure 7 shows temperature logs in the well.

Before these measurements were made, the well had been closed for ten days and was opened on 23rd of February. The casing in the well is not well cemented and some water seeps up outside the casing.

The figure shows that as the well flows, it cools considerably down in the upper part but heats a little up in the lower part. This is interpreted to indicate that the feed-zones in the well are related to two groundwater systems. Feed-zones in the lower part of the well are connected to the geothermal system but the colder feed-zones in the upper part are in the shallow colder groundwater system. The deeper and warmer system has higher pressure and when the well is closed, warm water from the lower part of the well flows up and partly into the feed-zones in the upper part and some seeps to the surface, outside the casing. When the well is opened and the pressure lowered, the colder feed-zones in the upper part start to flow into the well and the discharging water cools down. When the pressure is lowered, the inflow of warm water in the deeper feed-zones increases and the temperature rises a little bit.

The next well to be drilled was KU-01, about 15 m south the main hot spring. At a depth of 43.5 m, a fracture was cut and the well started to flow vigorously, and at the same time the water level in the concrete cistern of the main hot spring fell rapidly. The drilling was then stopped and the well closed to maintain flow of hot water to the greenhouses. Three temperature logs had been measured before this feed-zone was cut (short segments on Figure 8). They showed increasing temperature with depth and approaching about 55.5°C. During a flow test, the temperature of the water from the feed-zone at 43.5 m was above 59.5°C.

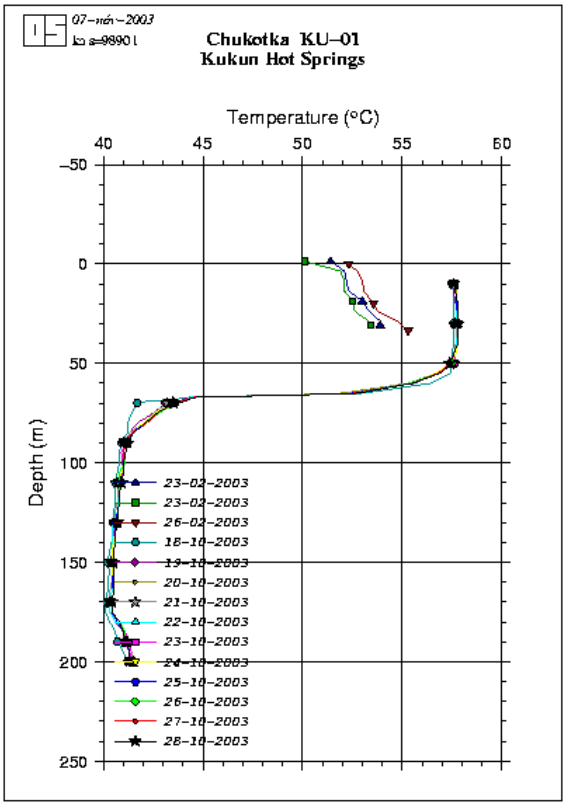

Figure 8. Temperature measurements in well KU-01.

After finishing the other wells and flow tests, KU-01 was deepened to 230 m. Figure 8 shows several temperature logs made after the well was completed. The well was flowing when the temperature measurements were made. All these logs show the same character. The temperature in the uppermost 50 m is about 57.7°C. Between 50 and 70 m, the temperature drops sharply to about 43.5°C.

Well KU-01 clearly intercepts a fracture system in the depth range of 43.5 to 50 m with water at temperature about 59–60°C. The well then penetrates much colder rocks below. The sharp drop in the temperature between 50 and 70 m indicates that this fracture system does not, under undisturbed conditions, conduct about 60°C water vertically from depth. Either the fracture system is far from vertical or, what is more likely, that it conducts hot water nearly horizontally towards the well, from the fracture feeding the main hot spring.

After the drilling of KU-01 topped at 43.5 m depth, wells KU-02 and KU-04 were drilled, to the north and south of the hot springs respectively. Figure 9 shows temperature logs from KU-02. The well was completed on the 25th of April 2003, and the figure shows how the temperature in the well approaches equilibrium. The well was drilled with hot circulation fluid from the hot springs, so the rocks around the well got heated up while the well was drilled, and then cool with time back to the ambient rock temperature. The temperature increases with depth and is about 27°C at the bottom (100 m depth). There are indications of minor inflow at 25 and 75 m depth.

Figure 10 shows temperature measurements in well KU-04. The well is 100 m deep and was completed on the 23rd of May. In the beginning, 29°C hot water flowed from the well. The flow rate was not measured. In two weeks time the well heated up by about 1°C from top to bottom. Figure 10 shows that the main feed-zone is at about 40 m depth, delivering water of about 30°C. Below that, the temperature rises considerably to about 37.5°C at the bottom, which means that there is only minor inflow to the well below 40 m.

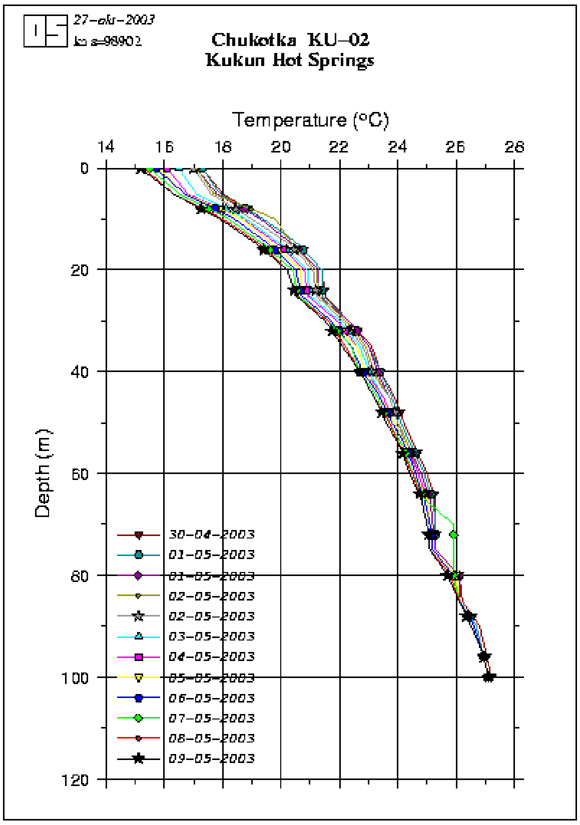

Figure 9. Temperature measurements in well KU-02.

Drilling of well KU-05 started around the middle of June 2003. As stated earlier, the well was originally sited on the slope east of the hot springs but had to be re-sited at the foot of the hill.

Figure 11 shows temperature measurements in the well. The first measurement is from 24th of June, when the well is about 45 m deep, and shows increasing temperature with depth to about 38°C at the bottom. The next measurements, from 25th of June to 1st of July, show that undisturbed rock temperature increases rapidly with depth.

On July 2nd the well cut a fracture at a depth of 83.7 m and started flowing about 50–60 l/s of 56–57°C water. The temperature log from July 2nd (yellow line with small circles on Figure 11) shows that the water from the fracture is 58°C hot when it enters into the well and is slightly mixed with colder water on the way to the surface.

After this fracture was cut, the well was closed for a while. Drilling was resumed on July 12th but no temperature measurements were made until July 25th. In the meantime the outflow from the well had cooled down from 56°C to about 53°C. The temperature log from July 25th (grey line and crosses on Figure 11) shows nearly constant temperature to a depth of about 80 m, where it drops suddenly to about 46°C, at about 86 m depth. Right below that, the temperature rises rapidly again and then nearly linearly down to the well bottom, which was at that time at 139 m. This sharp temperature drop at 86 m depth can be explained such that the well cut a second fracture just below the feed zone at 83.7 m, and that this fracture is in connection with a much colder groundwater system.

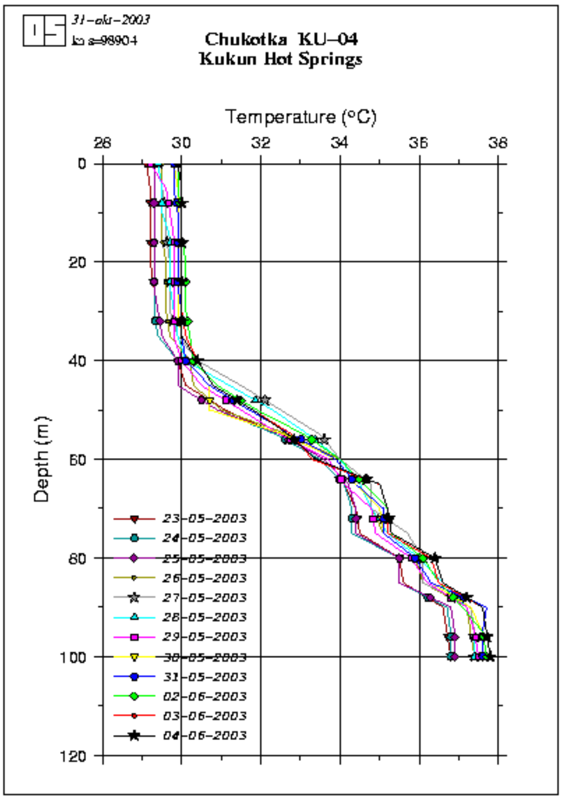

Figure 10. Temperature measurements in well KU-04.

After this measurement, the temperature measurement reel broke down and no continuous measurements could be obtained until a new reel had arrived from Iceland. The drilling of KU-05 continued while the ISOR experts visited Uelen. When they returned the depth of the well was 175 m. The outflow from the well had heated somewhat. A maximum thermometer which was lowered inside the drill string, showed 64.1°C, confirming that a hotter feed-zone had been intercepted.

After the completion of the well at the depth of 242 m, a new temperature measurement reel arrived from Iceland. A series of temperature logs were run on October 6th to 12th. The well was almost closed and only delivering a small amount of water during these measurements. As is seen on Figure 11, all these logs show identical temperature profiles. From the well bottom, the temperature is 53.6°C and is almost constant, but slightly decreasing up to 180 m depth. Between 179 and 177 m depth the temperature rises sharply and is 63.7°C at 177 m depth. Above 177 m the temperature stays nearly constant. Between 85 and 80 m depth the temperature drops considerably, and above that, it decreases smoothly up to the wellhead.

This is interpreted in such a way that between 140 and 179 m depth, there is a feed-zone (or zones), feeding water into the well with temperature about 64°C. This water flows out into fractures in the depth interval of 80–85 m

One further and important thing can be inferred from the temperature logs after the well was completed. Undisturbed rock temperature from 179 m and to the bottom is hardly higher than 54°C. The sharp rise in temperature of 10°C over a two meters interval (from 54°C at 179 m and to

64°C at 177 m) cannot represent the undisturbed rock temperature. Such a sharp temperature gradient would relatively rapidly (on the time scale of a few years) be smeared out by heat conduction.

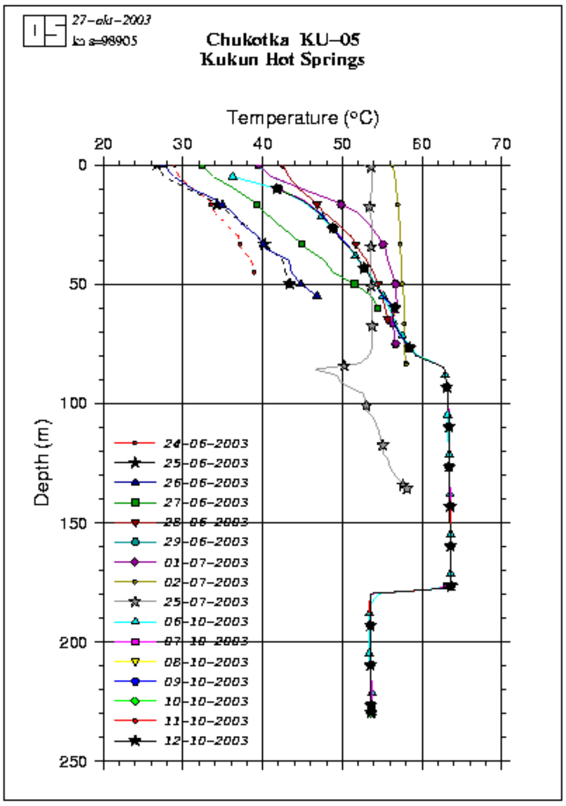

Figure 11. Temperature measurements in well KU-05.

The most plausible explanation for the sharp rise in the temperature above 179 m is that the well has cut a fracture system, which is in good hydrological connection with a hot-water system sideways of the well. When the well cut the fractures, a new flow path was opened and the higher-pressure hot water starts flowing laterally along the fractures and into the well. If this is the case, it implies that the well is near to a relatively high pressured geothermal up-flow with temperature higher than 64°C.

2.6. Flow test of wells KU-01 and KU-05

One of the main objectives of the visit to Kukun in the summer of 2003 was to perform flow tests of wells KU-01 and KU-05. At the time the flow tests were performed KU-01 was 43.5 m deep and KU-05 175 m deep. Both wells had hit feed-zones in good hydrological connection with the main hot spring.

The main purpose of the flow-test was to find out how much the wells can produce at different well-head pressures. Another purpose was to study how pressure changes in the flowing well are reflected in the other wells, as well as in the water level of the main hot spring and the flow from the bath pool. This gives valuable information on the hydrological connections in the system.

During the flow-tests the following parameters were recorded digitally by a data logger: The pressure and flow rate of the flowing well, (water height in the V-notch container; see Figure 12), the temperature of the discharged water, the pressure in the other well close to the hot spring (KU-05 when KU-01 was flowing and KU-01 when KU-05 was flowing), the water level in the concrete cistern of the main hot spring and the flow rate in the outlet from the bath pool. These parameters were also recorded manually from analogue meters. The pressure in wells KU-02, KU-03 and KU-04 was recoded manually. The pressure in all the wells that were not flowing was recorded for some time before the start of the flow-tests, in order to monitor the initial pressure state of the system.

Figure 12. Flow-test installation mounted on well KU-01. The well is flowing fully open (47.5 l/s) to the V-notch container (the bath pool is seen behind the well and the greenhouse furthest away).

Flow-test was first performed for well KU-01. KU-05 had been flowing more or less continuously for some weeks before the flow-test and some pressure draw-down had occurred in the geothermal system. When doing a flow-test, it is considered favourable to start from a nearly steady state. It was therefore decided to start the flow-test with KU-01 fully open and close it gradually in five steps.

The results of the flow-test of KU-01 are summarized in Table 1 and Figure 13 shows the flow rate as a function of pressure.

Table 1. Flow-rate, wellhead pressure and temperature of well KU-01 during flow-test.

Step no	Time interval	Flow l/s	Press. mb	Temp. °C
1	08/09/00:00-08/09/12:00	47.5	0	58.4
2	08/09/12:00-08/09/16:00	41.5	90	58.6
3	08/09/16:00-08/09/20:00	30.0	278	58.9
4	08/09/20:00-08/10/00:00	4.8	560	58.3
5	08/10/00:00-08/10/12:30	0.0	625	

Figure 13 shows that the flow increases linearly with decreasing pressure and the well itself is therefore not limiting the flow. Table 1 shows that the temperature rises by 0.5°C in the first three steps. This is most likely due to reduced cooling as the rock surrounding the well is heated up. In the last step the temperature drops again, most likely due to cooling in the well, when the flow is little.

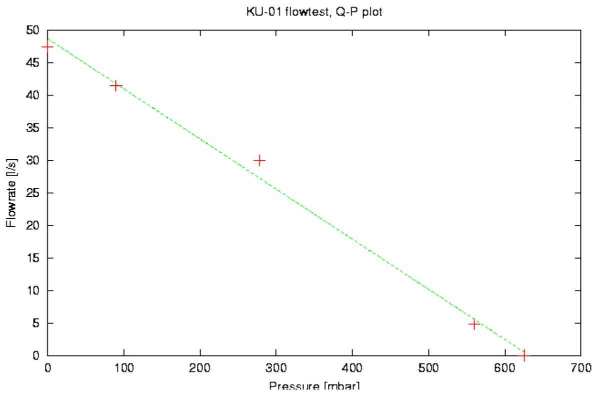

Figure 13. Flow-rate of well KU-01 (l/s), as a function of wellhead pressure (mbar).

When KU-01 was flowing fully open, the water level of the main hot spring was stable at 35 cm below the edge of the cistern, which is about 3 m above the horizontal outlet from the well. As the well was partially closed in the second step the water level rose almost to the edge and started flowing over in the third. The outflow from the bath pool was about 8 l/s when the well was fully open and increased to about 14 l/s when the well was fully closed. As for the flow of the hot springs, the pressure in well KU-05 responded almost instantaneously to the pressure changes in KU-01. This showed that wells KU-01 and KU-05 and the hot springs are in very good hydrological connection. This interplay will be further demonstrated below.

After the flow-test of KU-01, the installation was moved to KU-05 and a similar flow-test performed, except that the well was opened in four steps. Table 2 summarises the results of the flow-test of KU-05. Plot of the flow-rate versus pressure shows linear relationship as for well KU-01 (Figure 13) but with considerably higher flow-rates.

Table 2. Flow-rate, wellhead pressure and temperature of well KU-05 during flow-test.

Step no	Time interval	Flow l/s	Press. mb	Temp. °C
1	08/11/00:00-08/11/09:00	0	655	
2	08/11/09:00-08/11/13:00	16	565	64.0
3	08/11/13:00–08/11/17:00	32	390	60.5
4	08/11/17:00–08/11/21:00	57	165	58.0
5	08/11/21:00–08/12/12:45	74	-30	56.5

Table 2 shows that when the well flows under considerable pressure in step 2, the temperature is 64°C and it is only the hot feed-zones between 140 and 179 m that produce into the well. As the well head pressure is lowered the colder aquifers around 85 m depth start producing too and the temperature drops.

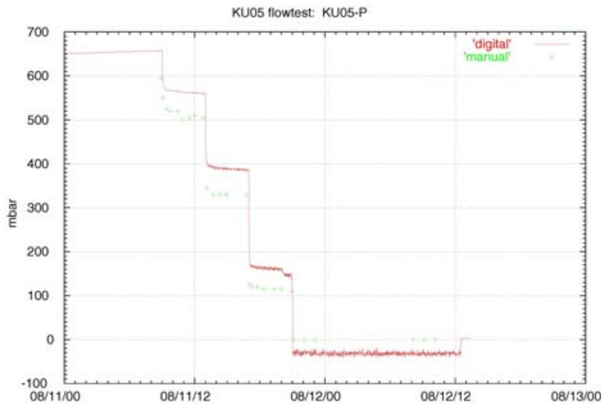

Figure 14. Wellhead pressure of KU-05 during its flow-test. The analogue pressure gauge (green crosses) gives consistently too low values.

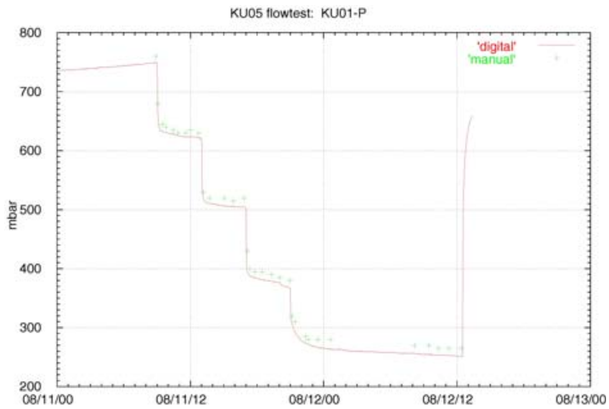

Figure 15. Wellhead pressure in KU-01 during flow-test of KU-05

It is instructive to see how the wells KU-01 and KU-05 and the hot springs interplay. Figure 14 shows the pressure in KU-05 during its flow-test and Figure 15 shows the pressure in KU-01. The figures show that the pressure in KU-01 responds almost immediately to the pressure change in KU-05 and stabilises within about two hours.

Figures 16 and 17 show changes in the water level in the concrete cistern of the main hot spring and the flow from the bath pool respectively. Figure 16 shows that the cistern around the main hot spring stays full while the well flows 32 l/s but the water level starts to fall when it flows 52 l/s, and when the well is fully opened the water level falls quite rapidly and seems to be leveling out at about 1 m, but then keeps on falling slowly till the end of the flow test. This might indicate that the original high flow-rate is sustained by a reservoir close to the hot spring, but that after some time the inflow to this reservoir, from a deeper reservoir, will be limiting in the long run. Figure 16 further shows that when the well was closed, the water level rises rapidly and the cistern starts flowing over. Close inspection shows that this takes about 30 minutes

Figure 17 shows how increasing flow from well KU-05 decreases the flow from the bath pool, from 13-14 l/s when the well is closed down to about 5.5 l/s when it is fully open. When the well is closed again, the flow increases rapidly again (the recording was stopped while the flow was still increasing)

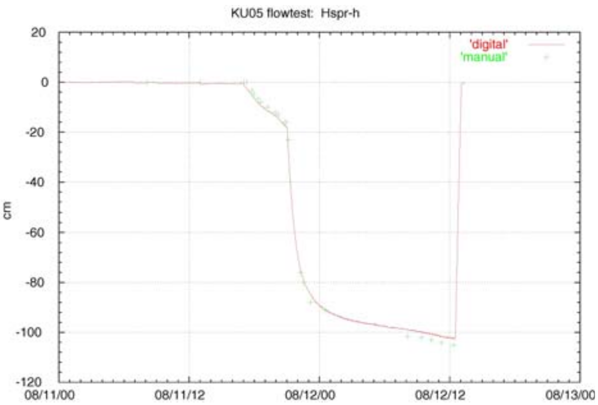

Figure 16. Depth to the water level in the concrete cistern of the main hot spring during the flow-test of KU-05.

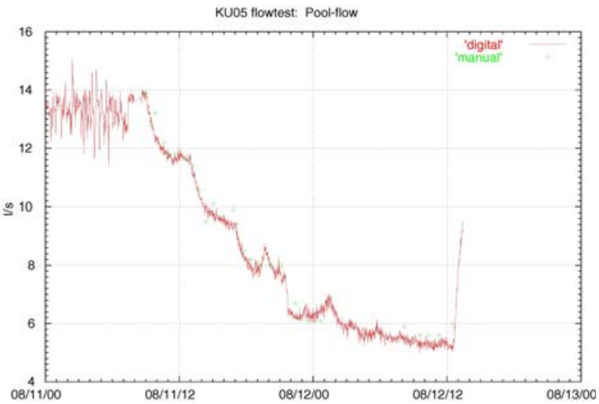

Figure 17. Flow from the bath-pool during the flow-test of KU-05.

Figures 14 to 17 show that there is a very good hydrological connection between wells KU-01, KU-05 and the hot springs, both the main hot spring and the spring in the bath pool.

The pressure in the surrounding wells was monitored by analogue pressure gauges during the flow tests. KU-03 to the west and KU-04 to the south showed clear pressure variations that harmonized with the pressure variations in the wells close to the hot springs. These wells even show a short interval transient when both KU-01 and KU-05 were open for about two hours while installing new flange and master valve on KU-05. Well KU-02 in the north shows only minor pressure variations. KU-04 in the south seemed to respond more strongly to pressure changes in KU-01 than in KU-05. This lends further support to the hypothesis that they are both close to a N-S trending fracture as indicated on Figure 4.

An estimate of the natural flow from the main hot spring can be obtained by analysing the rate of the rise of the water level in concrete cistern after KU-05 was closed. By multiplying the surface area by the rate of rising, right before it starts flowing over, a flow rate of 27 l/s was obtained. The flow from the bath pool was measured about 13 l/s when both wells were closed (Figure 17). The flow to the greenhouses and leakage from the cistern were estimated about 5 l/s. All this amounts to a total of about 45 l/s. This is most likely an underestimate of the undisturbed natural flow, because well KU-05 had been flowing more or less continuously for about three weeks before the flow tests, causing considerable pressure draw-down in the system.

The flow tests showed that there is a very good hydrological connection between the wells KU-01, KU-05, the main hot spring and the spring in the bath pool. They are most likely all connected to an E-W oriented and well open fracture or fracture system, which is a major flow channel in the system. It is not clear whether KU-01 and KU-05 cut this fracture directly or if they cut N-S oriented fractures that intercept the E-W fracture. The sharp drop in temperature in the wells (at about 60 m depth in KU-01 and 177-179 m in KU-05) indicates that they do not cut the main up-flow fracture, but more likely N-S fractures in connection with the main E-W fracture. The wells probably open new flow paths for hot water laterally from the E-W fracture and to the surface through the wells. These sharp drops can hardly reflect the steady state thermal distribution because heat conduction would have smeared them out.

The geothermal system is in contact, and interacting with the surrounding cold groundwater system. This is seen in well KU-05 where low temperature water entered the well at the depth of 86 m. The geothermal water at depth is at higher pressure than the cold groundwater system because KU-05 flows 64°C water under pressure and the temperature drops when the pressure is lowered. The fact that the temperature of the main hot spring (58°C) is considerably lower than 64°C indicates mixing with cold groundwater near the surface.

The limited time span of the mission in 2003 did not allow for a long term flow-tests, but the results of the tests performed showed that wells KU-01 and KU-05 can produce enough water and at temperatures high enough to meet the criteria set in the design of the district heating system for Lorino. It would however be highly advantageous to eliminate the cold feed zone above 90 m depth in well KU-05.

3. THE UELEN GEOTHERMAL AREA

The Uelen geothermal area is around 6 km due south of the Uelen village (see Figure 18), at an altitude of about 60 m a.s.l. It is located at the mouth of a small valley, on the south bank of a small river. It is on the fluvial deposits of the river, which is characterised by coarse grained gravel and big boulders. The geothermal area is elongated east-west and its size is only 200 x 50 m^2. The natural discharge of geothermal water has been estimated to be about 5 l/s. That is the visible run-off but a part of the water is assumed to seep through the river gravel underground. A primitive swimming pool and well-constructed hot pot are in the geothermal area. The mineral water from the springs is transparent and clear with a bitter salty taste.

Geological investigation and drilling had been performed in the area, probably in 1965, but reports on this activity were not attainable. A total of 9 exploration wells were found, and seven of them are in the geothermal area (see Figure 19). The wells were apparently drilled with a percussion drill, but a few cores have been taken. The core fragments found are all of granite and show a layering in the rock formation but little indication of fracturing or hydrothermal alteration**.** The wells have not been capped after drilling and are all filled with stones. Three of the wells, UEL-1, UEL-2 and UEL-4 (for location see Figure 19) discharge a minor flow (< 0.5 l/s) of hot water with temperatures 53°C, 60°C and 69°C, respectively

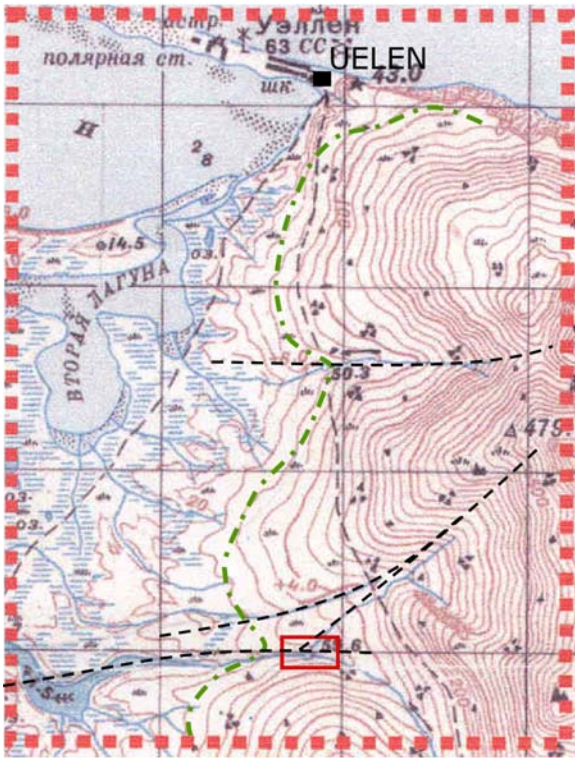

Figure 18. The village of Uelen, the geothermal area (red sqare), the borderline of the intrusion (green broken line) and tectonic lineaments (broken black lines).

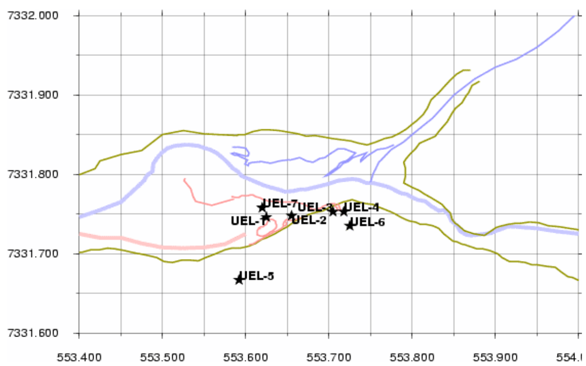

Figure 19. Simple map of the Uelen geothermal area. Green lines are escarpment of river bed, blue lines are rivers and brooks, light red lines are warm brooks and bath pool and black stars are old boreholes.

3.1 The chemistry of the thermal water

During a mission in 2002, thermal water was sampled from wells UEL-1 and UEL-4, and brought to Iceland for analysis. The Uelen thermal water is highly mineralized, with almost 20,000 mg/l of total dissolved solids. It is very high in chloride content (over 10,000 mg/l) but abnormally low in silica (23.5 mg/l and 28.4 mg/l in UEL-1 and UEL-4 respectively). The thermal water in Uelen is also high in magnesium content.

Conventional silica geo-thermometers give lower temperatures than measured in the wells. This might indicate that the water originates from carbonate sedimentary rocks, which are very low in silica. Other geo-thermometers indicate that the discharging water is mixed with colder ground water and that the deep reservoir temperature could be well above 100°C.

During the mission in 2003 water samples were taken from well UEL-2 and UEL-4 for measuring the radon radioactivity. It turned out to be quite high or about 4200 to 4900 Bq/l. This is 4 to 5 times higher than the allowed maximum value for drinking water in Scandinavia (1000 Bq/l).

The high mineral content and radioactivity make the water unfeasible for direct use, so heat exchangers will be needed. The high chlorine content in the water will make it very corrosive if it is contaminated by atmospheric oxygen. The high level of radioactivity also makes heat exchangers necessary. Disposal of the geothermal water at the surface and the radioactivity in the heat exchanger station might be a matter of concern.

3.2 Thermal manifestations

Because of the coarse gravel and boulders in the area, it was not possible to make a regular ground temperature survey. Instead, emphasis was put on mapping thermal anomalies. This was done by a systematic search for water outlets in the thermal area and its surroundings, and measuring their temperature.

Figure 20 shows the location of water outlets with their temperatures shown by different colours. The figure shows that most of the thermal manifestations are found under the southern escarpment of the river bed. The hottest natural manifestations are found under the escarpment just east of borehole UEL-2, about 40°C. Clear geothermal outlets are found under the southern escarpment to about 50 m east of borehole UEL-4 and slightly elevated temperatures are found about 100 m further to the east. Clear manifestations are also under and in the steep escarpment west of the bath pool. Some warm outlets are found in the river gravel north of borehole UEL-4 and along the southern bank of the river north of UEL-2 as well as north of the warm river emerging in the gravel bed west of the bath pool (closed pink loop on Figures 19 and 20).

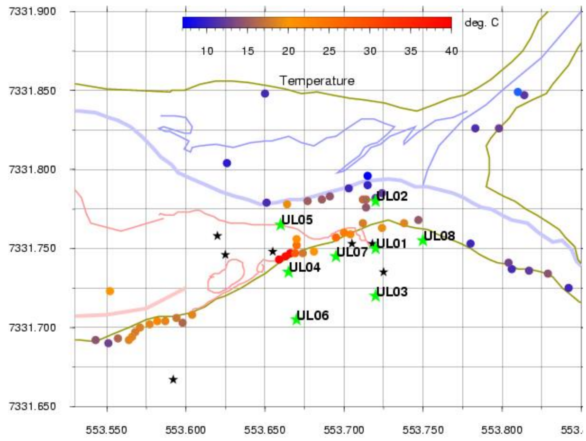

Figure 20. Thermal manifestations (coloured dots), old wells (black stars) and proposed location of new exploration wells (green stars).

No clear thermal anomalies are found north of the main river. Slightly elevated temperature is found along the cold brook running from north-east. Some of these are, however, stagnant pools and could be slightly heated by the sun or the air.

The river bed is covered with gravel and further away the ground is covered with granulated rocks and vegetation. Groundwater and geothermal water can percolate through the loose surface material and mix. The fact that the natural hot and warm water outlets are along the southern escarpment of the river bead suggest that the main up-flow of geothermal water might be at or little further to the south than the surface manifestations.

3.3 Geological setting and tectonics

The Uelen geothermal area is located near to the border of a large granite intrusion of mid Cretaceous age, or 110 million years old (Amato et al. 2001), that makes up the Dezhnyov Massif, the head of the easternmost peninsula of the Eurasian Continent. It intrudes a regionally un-metamorphosed Paleozoic carbonate rocks and therefore appears to have been emplaced at high crustal levels. The highest peak reaches 741 m a.s.l. Altogether the area of the intrusion is around 115 km^2 on dry land. The intrusion is layered and seems rather heterogeneous. The layers are sloping steeply towards east. The crystal size and crystal composition differs from one layer to another. The main body is coarse-grained and has light colours with darker more fine-grained bands. Fracture infillings of quartz or calcite are not pronounced in the granite.

West of the intrusion are various sedimentary and metamorphic rocks of Paleozoic age. The borderline between them and the intrusion lies roughly from south to north between the hot spring area and the village of Uelen (Figure 18). Dark metamorphic layers enveloping the intrusion are found just west of the geothermal area. They appear in the riverbed, made of dark grey, or nearly black, fine-grained rock. In the field they look like columnar basalt but in a microscope their sedimentary origin appears.

The main tectonic lineaments in the landscape are east-west trending valleys and river channels (see Figure 18). It is not known whether these tectonic lineaments are still active but according to the local people, earthquakes occasionally occur in the region.

The geothermal activity seems to be connected to a fissure, or a fissure system, trending nearly E-W. The channel of the river seems to be cut into this fissure for two kilometres towards west and still further west a shallow depression in the tundra, with several small ponds, shows the alignment of this fissure and finally a small rivulet marks the western end of the fissure system. Altogether this system can be traced for up to 10 km. It seems to be presently active, otherwise it would not be so easily recognized in the loose overburden and in the tundra.

According to a hydrological map of the Uelen area made available by the Chukotka Geological Survey, a NE-SW trending fissure cuts the geothermal area (see Figure 18). This lineament is very faint in the landscape but its existence might be supported by magnetic measurements (see section 3.4).

3.4 Magnetic measurements

Since the bedrock is not visible in the vicinity of the geothermal area, an attempt was made to map faults and fractures by magnetic measurements.

As discussed in the previous section, features in the landscape suggest that the river west of the geothermal area follows an E-W fault or fracture. Therefore a series of north-south oriented profiles were measured across the river, from the west and with approximately 100 m intervals all the way to east of the thermal area. These profiles did not show any consistent anomalies that could be associated to faults.

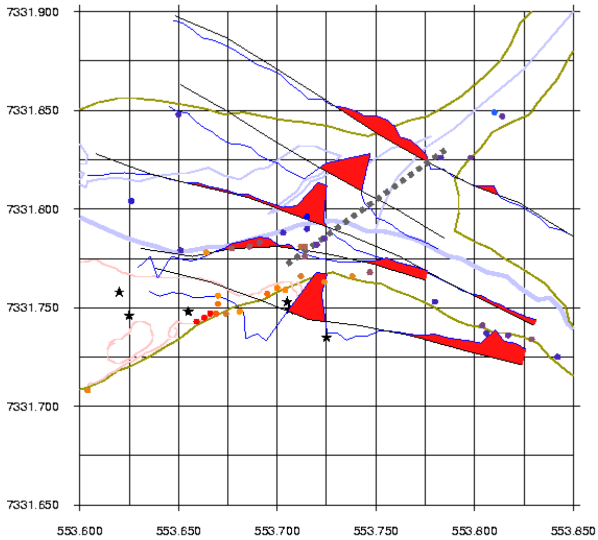

Figure 21. ESE-WNW oriented magnetic profiles at Uelen geothermal area. Black lines are profile traverse lines. The magnetic field is shown as positive (red) and negative (blue lines) deviations form the average value along each profile.

Figure 21 shows ESE-WNW trending magnetic profiles through and to the north of the geothermal area. The southernmost profile is somewhat distorted by metallic trash on the surface. The other four show anomalies which seem to line up. These anomalies are clear in the two profiles in the middle, but weaker in the other two. This might be an indication of a fault with the location as indicated on the figure by a dashed grey line. This line coincides roughly with the fault postulated by the Russian scientists and discussed above.

3.5 The origin of the geothermal water

The geological reasons for the geothermal activity at Uelen are most likely open fissures in the bedrock, caused by recent tectonic movements, allowing the groundwater to penetrate deep down into the crust where it encounters warm deep-seated formations. The high content of radon in the water supports the idea of the relation with active tectonics. Enriched radon in groundwater is common in seismic zones. The chemistry of the water (low silica content) and its high salinity indicates closer relation to the sedimentary rock than to the intrusion. The water is therefore believed to penetrate the intrusive rock and some underlying sedimentary strata of marine origin

3.6 Further exploration

Geological mapping and magnetic measurements indicate that the up-flow is most likely on an interception of an E-W fault along the riverbed, west of the hot springs, and a NE-SW trending fault along the brook NE of the area. The location of these faults is, however, not known precisely enough to locate production wells.

The only option is to try to locate the faults by drilling thermal gradient wells. From the rough estimate of the inferred faults it is expected that they will intercept somewhere around the hottest natural manifestations, east of the bath pool. The temperature of the flowing wells however increases from west to east. Therefore exploration wells were sited from the hottest natural manifestation and towards east. A total of eight wells were sited and arranged such that they will provide three temperature profiles, two N-S trending and one E-W. The proposed locations of the wells are shown on Figure 20.

The wells are located rather close to each other in order to locate the up-flow fracture as precisely as possible. They should be drilled to a depth of 100 m. If the exploration drilling successfully locates the up-flow fracture a production well will then be sited.

4. CONCLUSIONS

The geothermal systems at Kukun and Uelen are both due to deep circulation of water in fractured rocks and mining heat from the general heat flow. The geothermal system at Kukun seems to be connected to an E-W oriented main fracture intercepted by N-S oriented fractures.

The results of the drilling at the Kukun hot springs are as yet two productive wells. Flow-tests showed that the KU-01 can produce about 47–48 l/s of 59–60°C hot water coming from a shallow feed-zone at 43.7 m depth.

Well KU-05 shows much greater complexity in feed-zones. The well intercepts fractures with about 58°C hot water at 83–86 m depth. Temperature drop in one of these fractures, as the well flows freely, indicates a connection to the cold groundwater system. A considerably hotter feed-zone (64°C) is in the interval from 140 to 177 m depth, below that the well is colder again. The hot feed-zone dominates when the well flows under pressure. When KU-05 is fully open, it discharges an enormous amount of water (about 74 l/s), but the temperature drops to about 56.5°C when the colder feed-zones deliver freely. The shallower cooler feed-zones are a problem, but by letting the well flow under some pressure, they can be kept more or less inactive. It is not known how much KU-05 can produce without a drop in temperature, but it can be expected to produce about 20 l/s of about 64°C water.

The amount of water already available from wells KU-01 and KU-05 is sufficient to supply the geothermal heating system for Lorino. by letting KU-05 flow under pressure so that it delivers about 20 l/s of 64°C water and by letting KU-01 produce 59–60°C water as needed.. The fact that the shallow aquifers in the wells interplay with the shallow cold groundwater system means that they cannot be pumped because that would most likely lead to an inflow of colder water with atmospheric oxygen, leading to lower temperature and corrosion problems.

The Uelen geothermal area is located near to the border of a large granite intrusion of mid Cretaceous age which intrudes Paleozoic carbonate rocks. The highest temperature of the geothermal fluid on surface is close to 70°C. The fluid has high mineral content with a bitter salty taste and radioactivity above the Scandinavian sanitary standards.

The geothermal area seems to be connected to a E-W trending fissure, or fissure system, which seems to be presently active. This fracture system probably allows groundwater to penetrate deep down into the crust where it encounters hot deep-seated formations. The chemistry of the water and its high salinity indicates closer relation to the sedimentary rock than to the intrusion.

Drilling was performed in the Uelen geothermal area in 1965. Seven wells were drilled at the hot springs. Three of them flow minor amount of water with substantially higher temperatures (up to 70°C) than the natural springs. Further exploratory drilling is needed. Several 100 m deep pilot wells will be needed to determine the alignment and the dip of the geothermal fissures before production wells can be sited and drilled. A direct use of the geothermal fluid is not possible, and a heat exchanger station will be needed.

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