GEOTHERMAL POTENTIAL OF HOT GRANITES OF LITHUANIA

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INTRODUCTION

The utilization of high-enthalpy geothermal aquifers is well recognized and proved in practice. Still, the combination of favourable conditions, e.g. high content of water vs. high temperatures, is not common that urges to look for alternative geothermal resources. The technology to extract useful amounts of energy from hot dry rock – nehanved geothermal system (HDR/EGS) resource has been under development for more than twenty years. Many field experiments showed that it is possible to extract HDR/EGS energy using techniques originally conceived and tested in the different sites, e.g. Soultz, Urach, Los Alamos, Rosemanowes, Fenton Hill. The process entails drilling a well to reach high enough temperatures $\geq 150^{o}C$, injecting water at high pressure to open artificial and natural fractures in the rock, and returning the water, heated by the rock, to the surface through one or more additional wellbores. After extraction of its thermal energy, the water is recirculated through the hot rock to mine more heat. In this closed-loop process, nothing is released to the environment except heat, and no long-term wastes accumulate. This kind of geothermal energy using HDR/EGS systems is included in the geothermal strategies of other countries. Moreover, they can be used in combination to congenital energy power plants.

The Middle Proterozoic cratonic granitoid intrusions hosted by Lower Proterozoic high-grade metamorphic and igneous rocks are considered to have the highest geothermal potential in Lithuania, essentially in the southwest. They show the increased heat flow that correlates with the high heat production of those cratonic granitoids.

These rocks are still difficult to explore due to great depth of the basement overlain by up to of 2 km thick sedimentary cover. Still, abundant deep industrial wells and potential field data in combination to available geothermal information enables preliminary assessment of those intrusions. The most prospective body is the largest Zemaiciu Naumiestis intrusion (ZNI) identified in southwest Lithuania at the depth of about 2 km.

GEOLOGICAL SETTING

Lithuania is situated in the eastern and central part of the Baltic sedimentary basin. The thickness of the sediments increases from 200-500 m in the east to about 2 km in the west of the country. The Phanerozoic sediments overly the high-grade metamorphic and igneous rocks of the Paleoproterozoic age. The crystalline basement of Lithuania is a part of the East European Craton of the Early Precambrian consolidation (Fig.1).

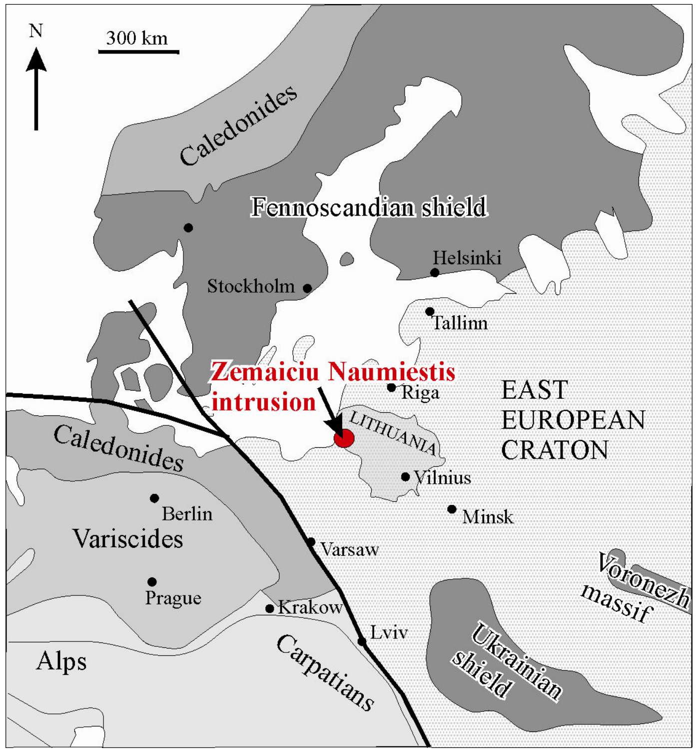

Fig.1. Tectonic scheme and location of Zemaiciu Naumiestis intrusion

The basement is composed of different lithotectonic domains that were established in the Palaeoproterozoic time. The eastern part of Lithuania is attributed to East Lithuanian Domain, composed mainly by mafic metavolcanic and felsic metasedimentary rocks metamorphosed in amphibolite to granulite facies conditions and heavily migmatised. Most prominent structural feature of this domain is domination of lenticular belts of different lithology reflected in the gravity and essentially magnetic fields by alternation of NNE-SSW oriented magnetic and gravity lows and highs of a few dozens of kilometres long and few kilometres wide, interpreted as the fold-and-thrust-sheet structures. The western half of Lithuania is comprised by the West Lithuanian Granulite domain (WLGD). The domain is characterised by high position of Moho discontinuity (40-45 km), thick (up to 30 km) upper crust, and thin and comparatively light lower crust. The oldest representatives of WLGD are supracrustals formed in the time span between 2.15-1.85 Ga, most probablty 1.87-1.86 Ga. These are mainly felsic and metapelitic gneisses. They are interpreted as primary psammites, pelites, felsic and intermediate volcanics, while mafic metavolcanics are very rare. The supracrustals are strongly metamorphosed in the granulite facies conditions and migmatised. Intrusive charnockites and S-type, garnet and cordierite bearing granitoids comprise a major part of the WLGD. Several generations, formed between 1.85 Ga and 1.815 Ga, are defined. The highly variable, contrast mosaic style potential field anomalies are characteristic for areas composed by migmatised supracrustals, probably reflecting their relic stratified structure. In contrast, the bodies of plutonic rocks corresponds to more homogeneous slightly variable, non contrast patterns of gravity and magnetic fields.

During the Mezoproterozoic the lithosphere of Lithuania and adjacent territories was subject to intense cratonic igneous activity. The largest multiphase Riga pluton of rapakivi and related gabbroic and ultramafic rocks intruded the northern part of WLGD. The diameter of this batholit is of 200-250 km. Maffic lithologies formed 1576 Ma ago, the rapakivi granites yield 1584 Ma. Numerous cratonic intrusions were mapped in the west of south Lithuania, in the north Poland and north-east Belarus. The main activity took place at 1.56-1.47 Ga. With granitoids are associated charnockitoids, gabbroids and anorthosites. They compose 250-300 km long west-east striking Mazury belt. The cratonic granitoids are also abundant in west Lithuania, the most prominent Zemaiciu Naumiestis intrusion is as large as of 30*45km (Fig.2).

In terms of the geothermal potential, the cratonic granitoids of the west Lithuania are considered to be the most prospective that is related to (a) generally high heat flow and (b) high heat production of the granitoids. The cratonic intrusions located in the shallow periphery of the Baltic basin are less prospective due to twice as low background heat flow. The most prospective geological body is the Zemaiciu Naumiestis intrusion in southwest Lithuania.

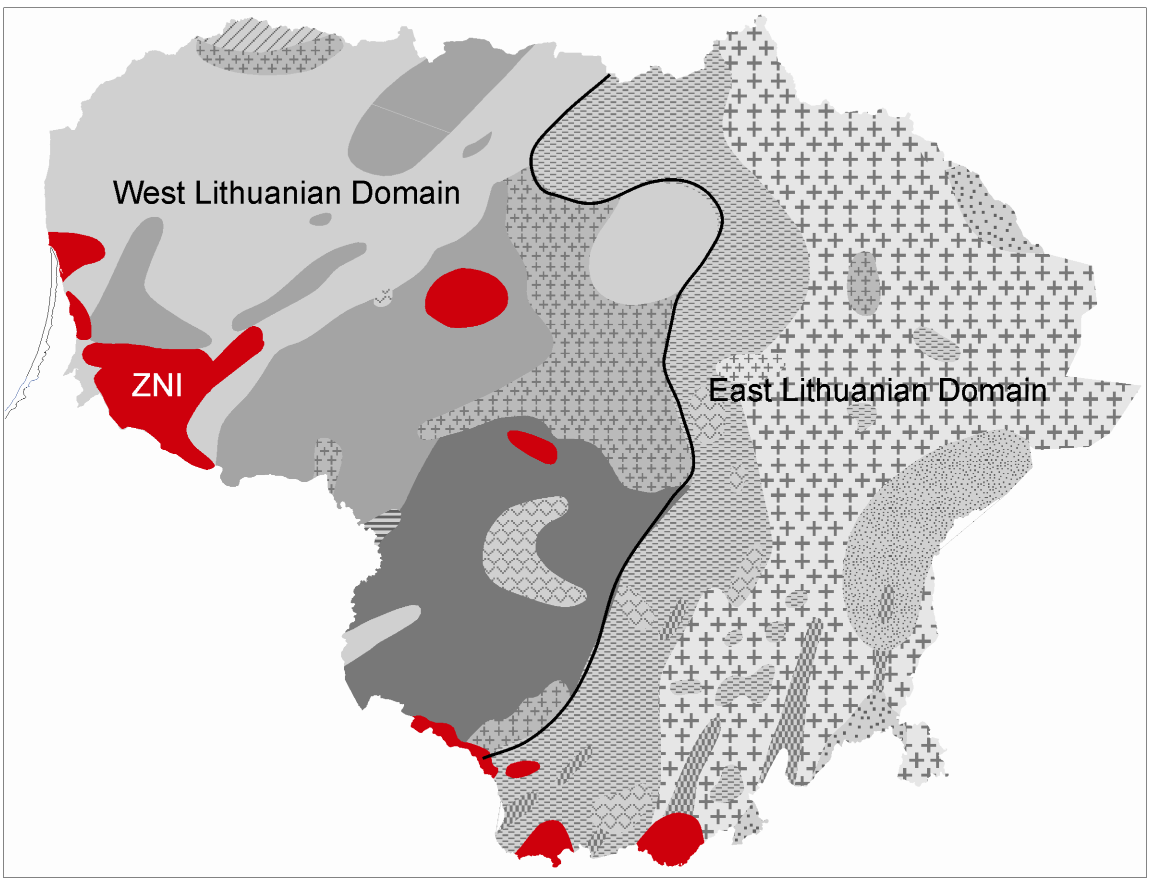

Fig.2. Geological map of crystalline basement of Lithuania (after Motuza,2005). Cratonic granitoids are shown in red. ZNI – Zemaiciu Naumiestis intrusion.

GEOLOGY OF ZEMAICIU NAUMIESTIS INTRUSION

ZNI is characterised by drill cores of 29 wells drilled for the oil exploration of the overlying Cambrian rocks (Motuza at al., 2004). The hosting rocks of the pluton consist of migmatised supracrustals – metapelites and felsic gneisses of metapsammitic origin. In the north it borders to the Kursiai charnockitoid pluton, while the geology of the southern contact remains rather obscure due to lack of the drilling data. Within the ZN pluton a few occurrences of small enclaves of migmatites were mapped (e.g. well Ramuciai-3) (Fig.3).

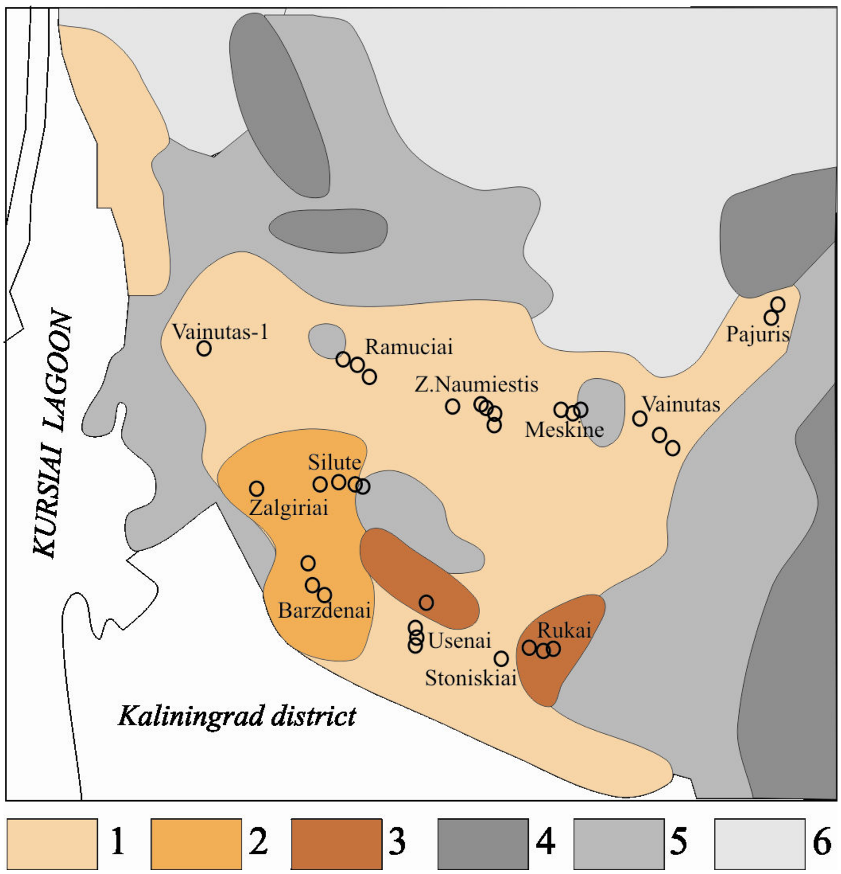

Fig.3. Geological map of ZNI. Deep wells within ZNI are indicated (open circles). ZNI: 1-moncogranites, 2-syenogranites, 3-quartz moncodiorites; hosting rocks: 4-metasedimentary granulites, 5- migmatites, 6-charnockitoids (after Motuza et al., 2004).

The main part of the ZN pluton consists of biotite monzogranites. The southwestern periphery is composed of sillimanite-bearing biotite syenogranites. Also, small bodies of porphyritic quartz monzodiorites occur locally, located mainly in the southern and south eastern periphery of the pluton.

The monzogranites are medium- to coarse-grained, often porphyry with phenocrysts of microcline (up to 3-4 cm long) and plagioclase (up to 2 cm in length). Biotite is interstitial, forming aggregations, often containing accessories such as magnetite, pyrite, zircon, apatite, allanite, sphene. Remarkable is sporadically high amount of apatite and alanite forming crystals as large as up to 2 mm. Secondary minerals are muscovite, epidote, and chlorite. The sienogranites are more fine grained, the porphyritic texture is less distinct. Microcline grains are usually microperthitic. Often appears sillimanite, in form of aggregates, sized up to 2 mm and swarms of fine needles. Chemically sienogranites are mainly peraluminous, while monzogranites - metaluminous. In general, all of the ZN granitoids are dominantly alkali-calcic and shoshonitic, based on criteria by Frost et.all 2001. Enrichment in incompatible elements, particularly K, REE, U, Th is remarkable.

GEOMETRY OF ZNI

The drilling and potential field data are employed to identify geometry of the ZNI in a plan view and to the depth. As mentoned above, ZNI was identified in 29 deep oil exploration wells. The mapping of the gravity and magnetic fields at the scale of 1:200 000 was performed in early sixties as a part of the whole-Lithuanian mapping survey.

The ZNI is very well discernable in the gravity and magnetic field maps (Fig.4). It is confined to the gravity low and the magnetic high. Such the negative correlation between the gravity and magnetic fields is a characteristic feature of the Mezoproterozoic granitoids (Marfin et al., 1994) therefore they are easy to map even in the areas that lack the drilling information. The intensity of the gravity field above ZNI is in the order of -10 to -14 mgal, whereas the surrounding lithologies associate with the gravity field of -10 to 0 mgal with a distinct positive anomaly marking the Taurage block in the east. The magnetic field ranges from +4 to +8 nT that is much higher than the background +2 to -4 nT.

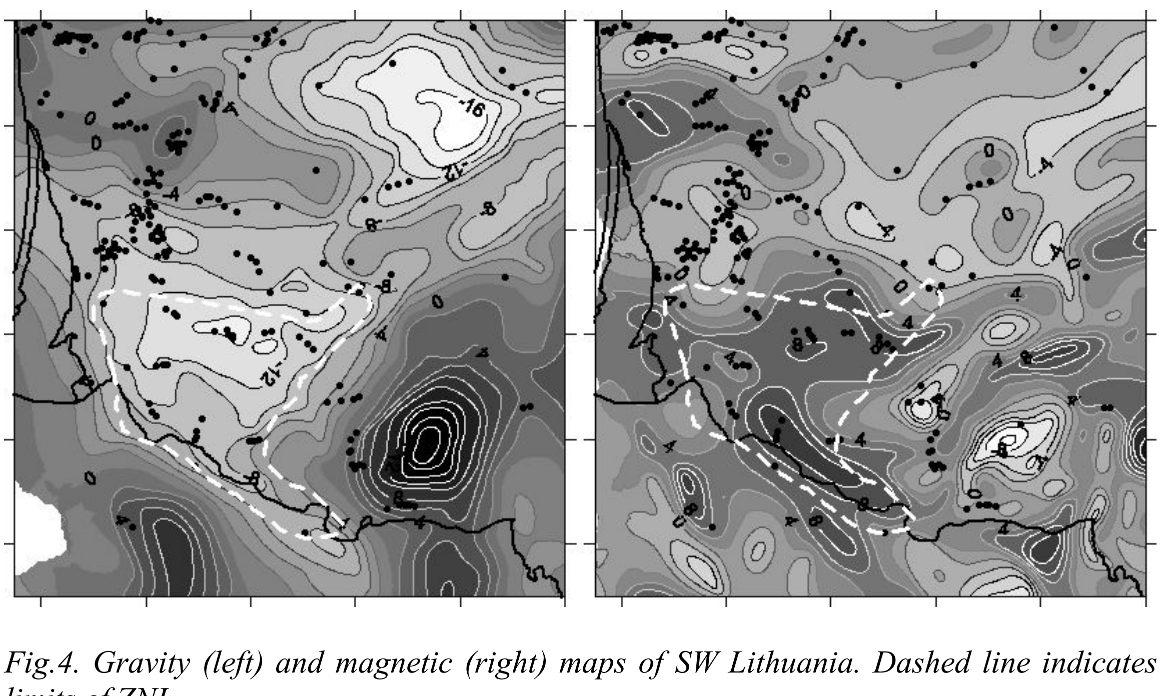

Fig.4. Gravity (left) and magnetic (right) maps of SW Lithuania. Dashed line indicates limits of ZNI.

The potential fields reveal the complex geometry of ZNI. The major body is elongated west-east with a distinct axial anomaly extending from the well Vabalai-1 in the west to Vainutas area in the east (Fig.3). This trend coincides with the deep seated Silute fault crossing the whole Lithuanian territory from the west to the east. South of the major intrusion, a smaller appendix extending northwest-southeast is mapped. It is controlled by the large-scale Nemunas tectonic zone. The northern appendix (Pajuris area) was accommodated by the first-order Taurage-Ogre tectonic zone striking NE-SW. Accordingly, the ZNI originated at the intersection of three large-scale shear zones.

The modelling of the gravity and magnetic fields is applied to identify the deep geometry of ZNI. GM-SYS $2^3/_4$D software was employed (Korabliova et al., 2000; Sliaupa, Korabliova, 2000). The effectiveness the potential field modelling is related to high petrophysical contrast of the cratonic granitoids to the hosting lithologies. The average magnetic susceptibility of ZNI rocks is about $30*10^{-5}$SI (ranges from $6*10^{-5}$S in the Silute area to$136*10^{-5}$S in the Usenai area), whereas it is much lower in the hosting rocks (0.2-$20*10^{-5}$S) (Sliaupa et al., 2004). The average density of ZNI granitoids is 2.73 g/cm^3, while the average density of the hosting rock is 2.78 g/cm^3.

Regardless to high density and magnetic contras of modelled rocks the modelling is inevitably invariant, in other words, alternative solutions equally well fitting the observed potential fields are possible. Therefore, independent additional information is required to improve the model. The geothermal data provide additional information on the thickness of ZNI that has much higher heat production than the surrounding lithologies. Heat production vs. heat flow intensity relationship suggests 4-5 km thickness of ZNI.

The modelled profiles reveal a cone-shaped geometry of the ZNI (Fig.5). The thickness of the intrusion is around 4 km, so that the bottom is suggested at the depth of 6 km. The modelling also confirms the complex geometry of the ZNI represented by main Silute body and smaller appendixes. The thickness of the major body is 4.5 km, the smaller Nemunas appendix is only 2 km thick. The modelling also suggests rather significant petrophysical (and lithological) differentiation of ZNI that is in concert with petrographical observations.

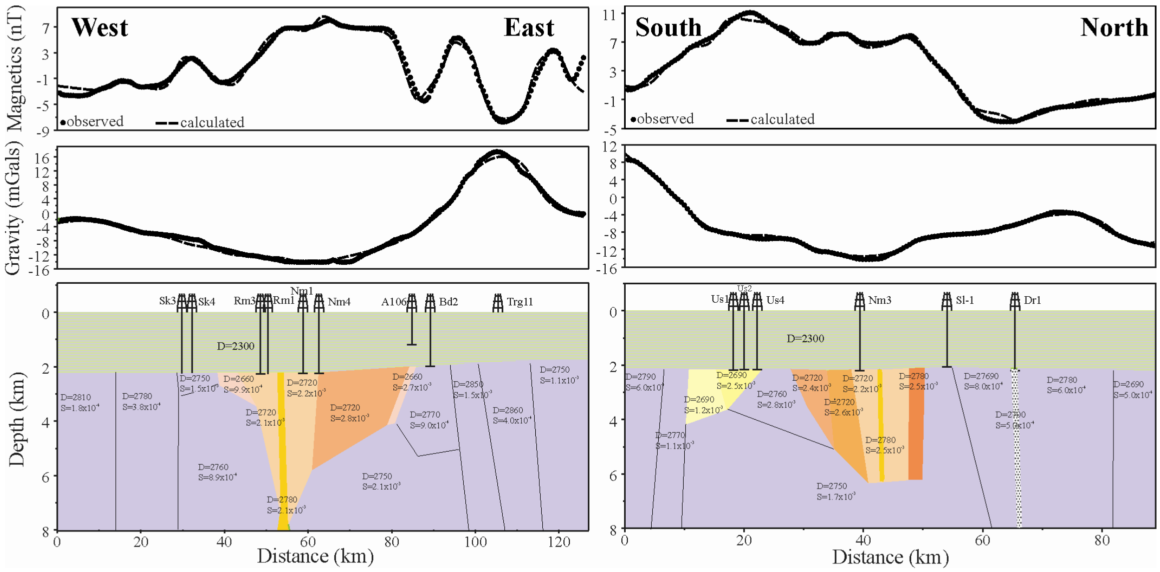

Fig.5. 2$^{3}/_{4}$D models of ZNI. Modelled lines are indicated in Fig.2.

GEOTHERMAL PARAMETERS OF ZNI

Abundant geothermal information was collected during oil exploration and deep mapping drilling throughout the past 40 years in Lithuania (Sliaupa, 2002). The west Lithuania is characterized by the most intense heat flow (Fig.6) (Kepezinskas et al., 1996; Rasteniene et al., 1998) that is attributed to fertile crustal lithologies and anomalous mantle heat flow (Sliaupa, Rasteniene, 2000). The West Lithuanian anomaly has well defined boundaries. The western limit is confined to the aforementioned NE-SW trending Taurage-Ogre shear zone, the northern limit is confined to mafic lithologies of the Riga massif. The southern part of the anomaly extends into the Kaliningrad district and is limited by the Mazury High. The western boundary of the West Lithuanian anomaly is not well defined due to scarce wells available. Still, drilling data suggest the boundary roughly coinciding with the Baltic Sea shore line. The West Lithuanian anomaly is rather heterogeneous, the heat flow ranges from 55 mW/m^2 to nearly 100 mW/m^2. These variations are of short-wavelength nature that suggests their relationship to different heat production of crustal lithologies. The most intense heat flow anomaly is mapped just above the ZNI, the shape of the anomaly follows the geometry of ZNI (Fig.6). The heat flow intensity varies from 83 mW/m^2 to 100 mW/m^2 within the intrusion. The maximum intensity is defined in the axial part of the intrusion.

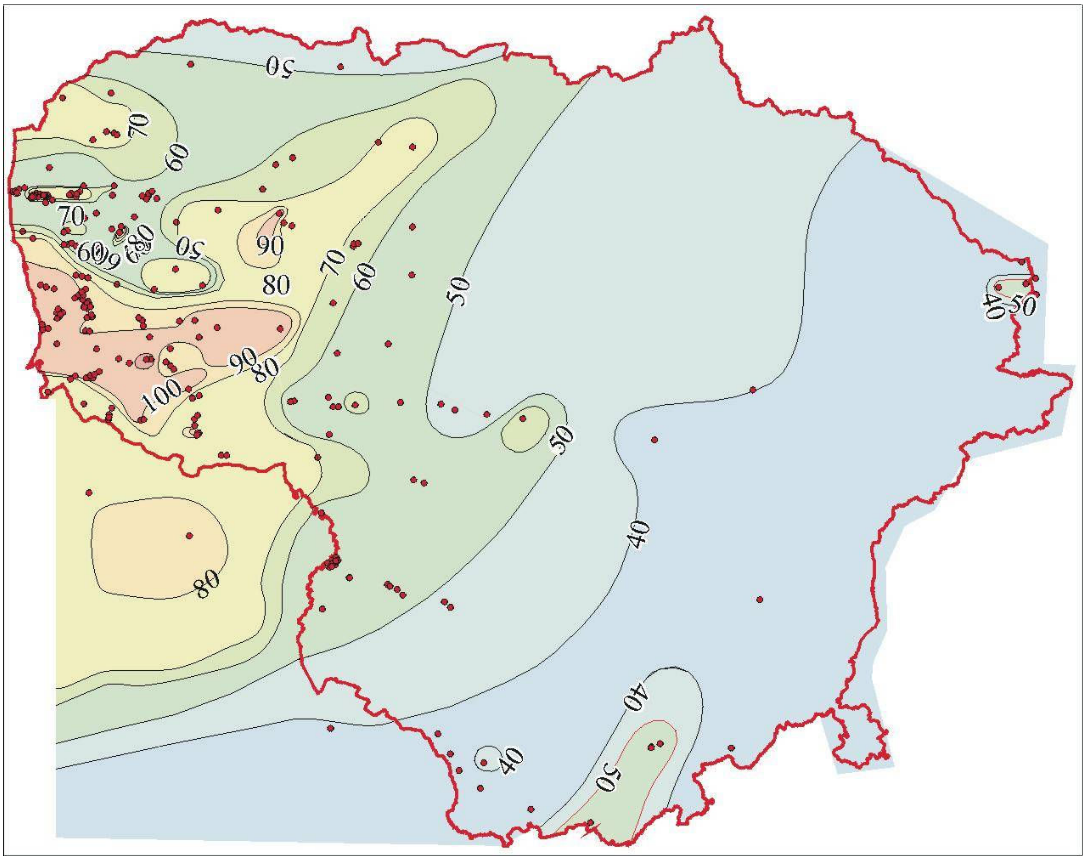

Fig.6. Heat flow map (after Sliaupa, 2002). Dots show studied wells.

The heat production of the crystalline basement rocks is calculated from the geochemical and rock density data as described by (Rybach, 1973):

$$A=\rho(9.52C_u + 2.56C_{th} + 3.48C_k)10^{-5}$$

here A is the heat production (μW/m3), C_u and C_{th} are the U and Th concentrations (ppm) and C_k is the potassium concentration (%), and ρ is the density (kg/m^3). A dozen of measurements are performed on ZNI rocks and nearly 100 samples were measured from the other west Lithuanian wells (Sliaupa, Rasteniene, 2000; Motuza et al., 2003). Furthermore, a good fit between the measured heat production and gamma-ray well logs was recognised that enabled estimation of the heat production of the basement rocks in wells that were not sampled (Sliaupa et al., 2004 – unpublished report). It provides a consistent database for compilation of the heat production map of the crystalline basement of Lithuania, and ZNI in particular (Fig.7). The heat production of cratonic granitois ranges from 4 to 19 μW/m^3 that is much higher than the hosting granulites showing the heat production in the range of 0.8-2.5 μW/m^3.

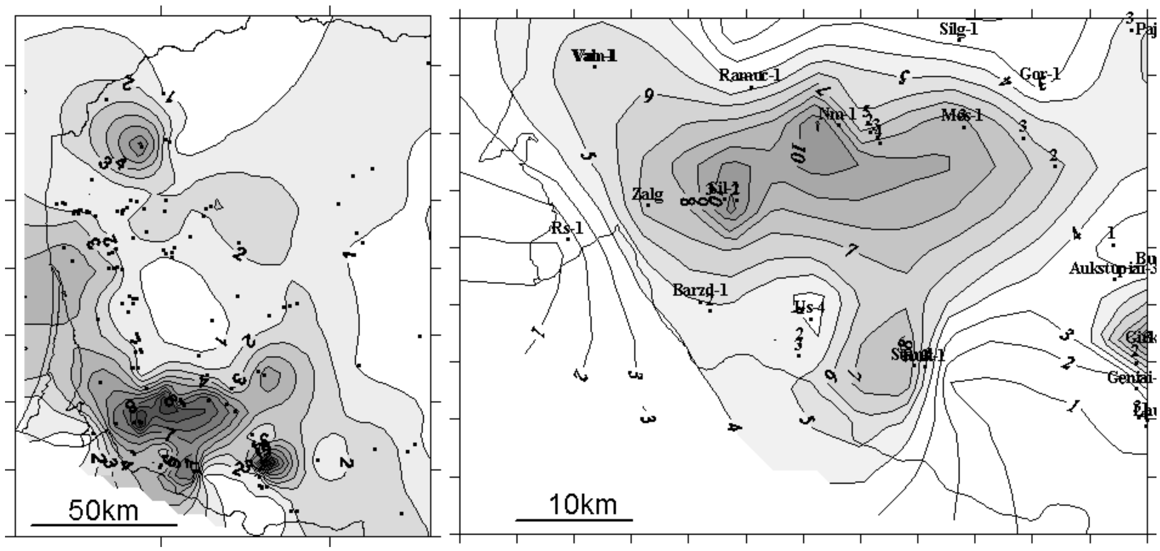

Fig.7. Heat production (μW/m³) of rocks of the crystalline basement of west Lithuania (left) and ZNI (right). ZNI is roughly limited by heat production contour line 4 μW/m³.Dots show studied wells.

There is a direct correlation between heat production and major radiogenic heat producing elements Th, U and K (Fig.8). The concentration of potassium ranges from 3.5 to 7.4%. Thorium is the most abundant in ZNI granitoids, varying from 14 ppm to 254 ppm, while the concentration of uranium is of order 0.9 ppm to 22 ppm. The close correlation between those three elements is defined in the interval of >5.5% potassium, whereas two groups become distinct that show respectively uranium and thorium specialization. The latter group is characterized by the highest heat production. Those two groups associate with different mineralogical specialisation of ZNI granitoids. The apatite dominated granitoids are most common, they are enriched in uranium, while allanite-bearing granitoids of the thorium specialisation are distributed only locally. The latter marks the final stages of formation of ZNI pluton.

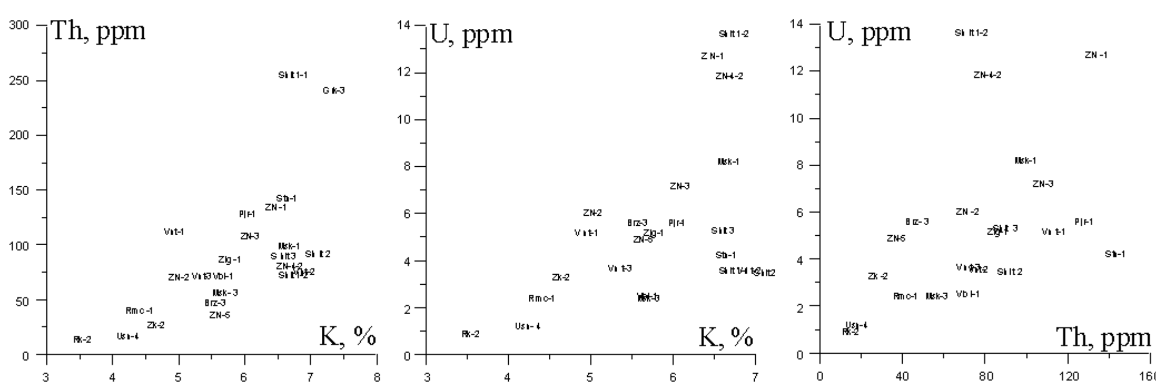

Fig.8. Diagrams showing correlation of U, Th and K concentrations in ZNI. Data points are indicated by short well names.

Temperature measurements are available from a dozen of deep wells of ZNI. The geothermal gradient averages 42-45°C/km in the overlying sedimentary cover. It is somewhat lower in the periphery of the intrusion, varying from 39°C/km in the Zalgiriai and Pajuris areas to 35-40°C in the Usenai area.

DISTRIBUTION OF GEOTHERMS

Distribution of geotherms is modelled using 2D finite element technique (Ciuraite, 2006 – unpublished Bsc. Diploma work). The thermosphysical parameters of the lithosphere were assumed as those presented in the model by (Stephenson et al., 1997). The paramters of ZNI lithologies are presented above.

Table 1. Thermophysical paramters of lithosphere of west Lithuania used in the model.

Layer	**Thickness, km**	**k, W/mK**	**A, $\mu W/m^3$**
Sedimentary cover	2	2.2	0
Hot granite	4	3.1	7.5
Upper crust	25	3.1	1.4
Lower crust	10	2.5	0.4
Mantle	19	4.0	0

According to the well measurement and modelling data the temperature within ZNI ranges from 80-90°C at the top to 190-200°C at the bottom (Fig.9). The prospective temperature 150°C is predicted at the depths of 4.5-5.0 km.

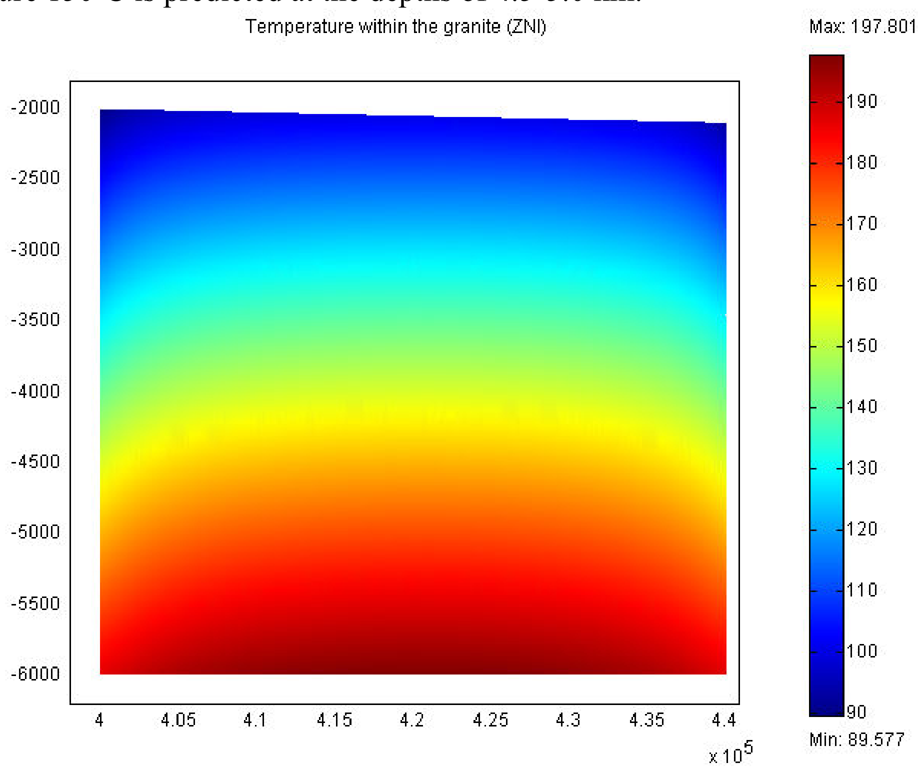

Fig.9. Geotherm distribution within ZNI.

RESERVOIR POTENTIAL

The hot dry rock concept of geothermal exploitation involves the drilling of two or more wells to a suitable depth to hit fractured reservoir, pumping cold water into the fractures through an injection borehole (Duchene, 1996). This water extracts heat from the rock as it flows through the fractures, and is pumped to the earth's surface through a production borehole. A confined reservoir (Brown et al., 1999) is considered in ZNI scenario. The reservoir can be either natural (HDR) or engineered (EGS). Both are targeted at the availability of fractured "corridors" of limited extension. In either case the rock structure and texture features are of primary importance (e.g. Genter, Traineau, 1996).

Based on inspection of drill cores several fracturing populations (low- and high-angle) are identified. The fractures are healed by the low-temperature minerals, such as calcite and chlorite. The open fractures are also common. The density of fractures varies considerably across ZNI. In instant, only 1-3 fractures per 10 m are recorded in Barzdenai, Silute, Pajuris areas (Fig.10), whereas about 200 fractures per 10 m are documented in the well Zemaiciu Naumiestis-4 (Fig.11). The latter are oriented subhorizontaly. Yet, the subhorizontal fracturing of the drill cores may be also related to drilling induced discing.

Fig.10. ZNI lithologies showing massive rock structure.

Fig.11. ZNI lithologies showing intense fracturing. The drilling discing is caused by abundant low-angle fractures. At the depth greater than 2008 m the fracturing decreases.

In most cases the rocks have massive structure. In some places the granitoids were subject to ductile deformations, varying from the modest foliation with preserved magmatic textures, such as subhedral plagioclase phenocrysts, to the shearing showing crenulated feldspars and quartz bends, blastomilonitic and „augen“ textures. In areas subject to lower degree deformation the cataclasis and brecciation are described. Those intervals commonly show chloritization of biotite, sericitization and epidotisation of plagioclase. Cataclastic fabrics are typical for Usenai, Zalgiriai, Meskine, Zemaiciu Naumiestis-1 granitoids, western part of the Vainutas area. Most intensive milonitisation was identified in the well Vabalai-1. The latter show steep inclination, whereas slightly cataclastic fabrics are inclined at the low angles. Still, the massive rock structure is the most common in ZNI (Barzdenai, Silute, Pajuris, Rukai areas, most of the wells of the Zemaiciu Naumiestis area, some wells of the Vainutas area).

FLUID CHEMISTRY

The in situ fluid is an important factor to be considered in EGS systems (e.g. Gerard et al., 1997). Fluid density and pressure are critical, as the resulting change in the density can influence the formation of, and the direction of growth of the reservoir. If fresh water is used for the stimulation of the reservoir containing natural brine there is a risk of an upwards migration of the injected fresh water influencing the direction of growth of the reservoir.

No data on the basement fluid composition are available in ZNI. On the other hand, the overlying Cambrian aquifer is well studied and can provide some base for predicting fluid chemistry in the underlying basement. The salinity of Cambrian pore water varies from 158-166 g/l in the northern and central part of the ZNI to 185-192 g/l in the south. The higher salinity is accordingly expected at the greater depth that implies its high density. The Cambrian water chemistry is dominated by Cl (~100 g/l), Na (~35 g/l) and Ca (~25 g/l) with minor content of SO_4 (~0.3 g/l), Mg (~3.5 g/l), K (~0.8 g/l). pH ranges from 5.5 to 6.0.

POTENTIAL OF WEST LITHUANIA

The heat flow is generally increased in Lithuania. The maximum of the heat flow, as described above, is related to ZNI. The other areas show somewhat lower heat flow, which however is also prospective for HDR/EGS systems. The geothermal modelling has been performed based on 40 deep well data in order to define the depth of prospective temperatures in Lithuania (|Figs.12-14). The most prospective areas is confined to ZNI and its western extension under the granulites in the Vilkyciai area.

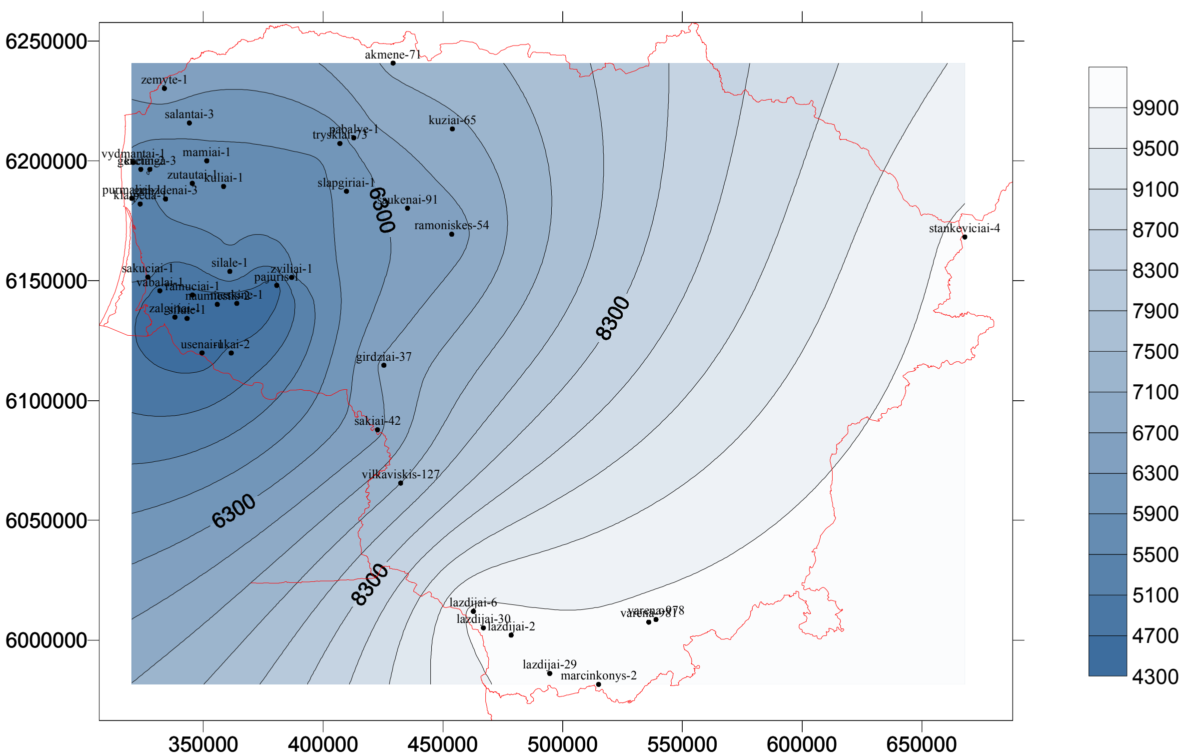

Fig.12. Depth of 150°C isotherm in Lithuania, km (Ciuraite, 2008).

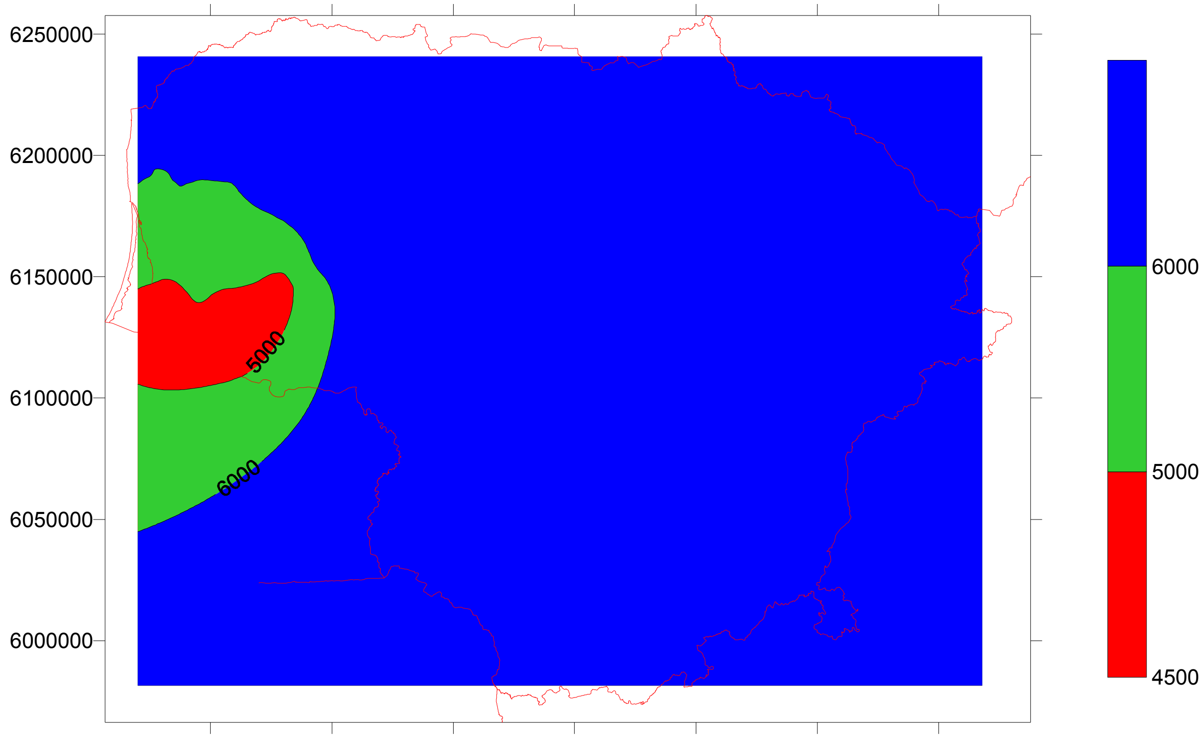

Fig.13. Identification of the most prospective (red), prospective (green) and not prspective (blue) geothermal areas (depth of 150^{o}C isotherm) (Ciuraite, 2008).

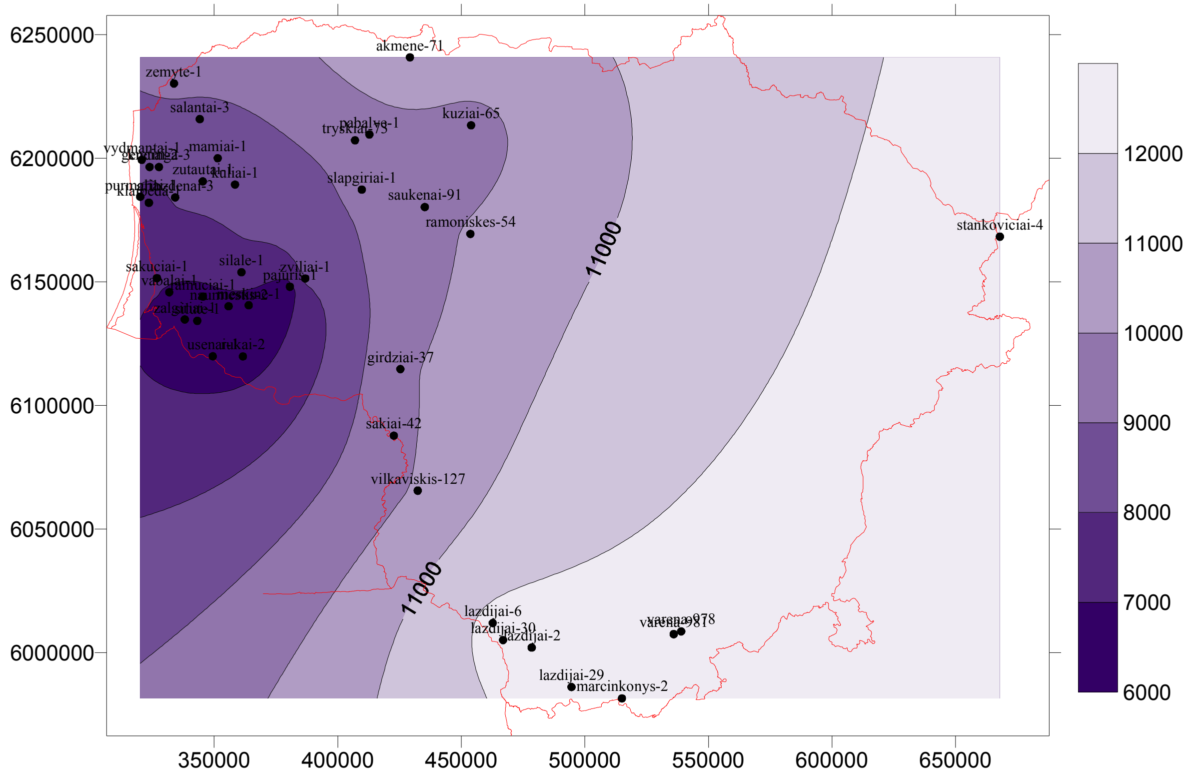

Fig.14. Depth of 200°C isotherm in Lithuania, km (Ciuraite, 2008).

CONCLUSIONS

The largest Middle Proterozioc cratonic Zemaiciu Naumiestis intrusion represents highly prospective HDR geothermal object. It is characterized by maximum heat flow due to anomalous heat production that results in elevated temperatures. According to sensitivity and modelling results temperature within ZNI ranges from 90 to 250°C. The predicted depth of the isotherm 150°C is in the range of 4.5-5.0 km (2 km drilling through the sedimentary cover and 2 km drilling of the crystalline basement). The isotherm 200°C is predicted at the depth of 6.0-6.5 km.

A small commercial geothermal power plant producing for example of 5 MW of electricity capacity using the water of 150°C would require flow rates on the order of 150 L/s (Fig.12). Therefore, the large enough confined reservoir is required. The fracturing and textural conditions vary considerably across the massif. Some parts of the intrusion are intensely tectonized, whereas solid homogeneous blocks are defined in between.

ZNI has some important advantages in comparison to sedimentary geothermal aquifers. The exploration does not depend on the location and parameters of the potential customer, which are the main factors for sedimentary geothermal systems to be accounted.

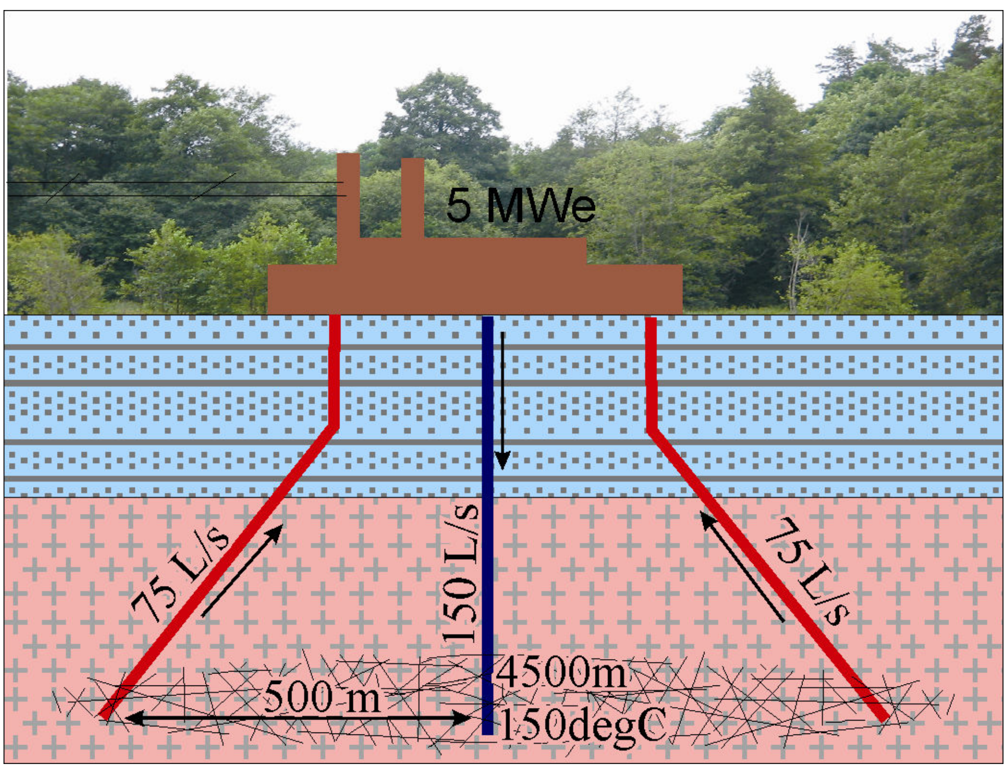

Fig.12. principle working scheme of the ZNI geothermal power station.

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