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Possibilities of Production Enhancement of Natural Gas and Geothermal Energy Potential Utilization from Carbonate Reservoir Rocks in the Zavod Structure in the Slovak Part of the Vienna Basin

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ABSTRACT

The reservoir rocks of gas in the Zavod structure in the Slovak part of the Vienna Basin are formed by fractured dolomites at a depth of approx. 4200 m underlying sandy-clayey sediments of Neogene. Under specific conditions of fractured reservoir rock relatively large amount of gas is blocked by active water. Depressurization of an aquifer creates conditions for release of this gas, enhancement of gas field recoverability and simultaneously gives possibilities of geothermal energy utilization.

Gas fields are in their final stage of production and without use of this possibility their abandonment in short time can be expected. The presented paper is treating these problems.

1. INTRODUCTION

In the past no adequate attention was given to possibilities of geothermal energy utilization in the Slovak part of the Vienna Basin (Fig. 1). The lack of interest in geothermal energy utilization had several reasons.

The first reason was the fact, that it is a case of typical oil and gas bearing basin and from the beginning of twentieth century the main attention has been paid traditionally to the reconnaissance, exploration and production of hydrocarbon fields. In the last quarter of the twentieth century besides that the attention was focused on the conversion of hydrocarbon reservoirs into underground gas storage.

The second reason was the fact that not only from a worldwide but also Slovak viewpoint, geothermal activity of the basin is relatively low. For this reason the research of possibilities of geothermal energy utilization was focused on other more active areas, as e.g. the Danube Basin.

Several tens of wells drilled in the of twentieth century within the framework of reconnaissance and exploration of hydrocarbon fields in Zavod structure (Fig. 1) and its close vicinity brought apart from oil-geological information also valuable data on temperature, chemistry and partially also on amount of geothermal waters as in pre- Neogene underlier in deeper Neogene sedimentary fill of the basin. Data shows, that at depths of 4000 to 5000 m it is possible to obtain geothermal waters with temperatures 130 °C to 150 °C from fractured carbonates (largely dolomites) of Mesozoic nappes of the Northern Limestone Alps occurring here in the underlier of Neogene sedimentary fill

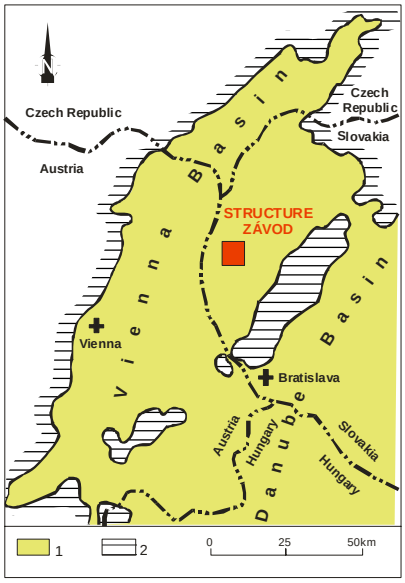


Fig. 1 Position of Structure Závod in the Vienna Basin 1 - Neogene Basins, 2 - Undivided pre-Neogene Alpine-Carpathian units.

At present gas reservoirs in this structure are in their final stage of production and it is necessary to evaluate the further procedure of operations. Newly found knowledge and the gradual decrease of gas production revived an interest in the possibility of geothermal energy potential utilization of this structure.

In this paper there is evaluated the current state and given a proposal of realization of work necessary for the recovery of gas reserves and gradual transition to geothermal energy utilization of the structure. The recovery of remaining gas reserves and simultaneous utilization of geothermal potential can bring in an interesting economical effect in a relatively short time.

2. GEOLOGICAL CHARACTERISTIC OF THE AREA

The underlier of Neogene sediments in the southern part of the Vienna Basin in Slovakia is formed by units of the Northern Limestone Alps. Young-Paleozoic, Mesozoic and Paleogene sequences form a complex system of nappes, slices and post-tectonic elements, which have been formed within Upper Cretaceous and Paleogene period.

Nappe units of Northern Limestone Alps form up to a 6 km thick rock complex, which is subdivided into three basic groups. In the Slovak part of the Vienna Basin lower nappes (bajuvaricum) are represented by Frankenfeld - Lunz slice

system, middle nappes (Tirolicum) by Göller Nappe and higher nappes (Juvavicum) by Schneeberg Nappe.

The Neogene underlier in the Zavod structure is formed by the Göller Nappe (Fig. 2). The underlier relief of the concerned area was within the late Paleogene period early Lower Miocene intensively abraded and peneplanationed.

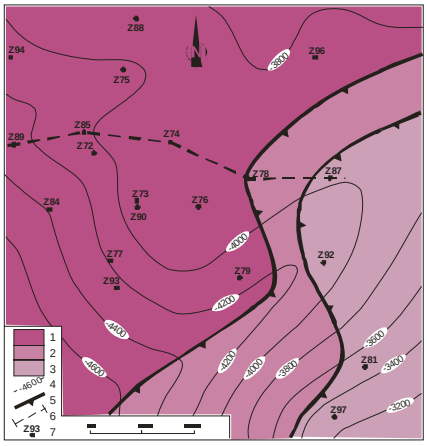


Fig. 2 Structure Závod - Map of pre-Neogene top.
1 - Lower Göller Nappe,
2 - Lower slice of the Upper Göller Nappe,
3 - Upper slice of the Upper Göller Nappe,
4 - Isobaths,
5 - Thrust boundary,
6 - Cross section,
7 – Well.

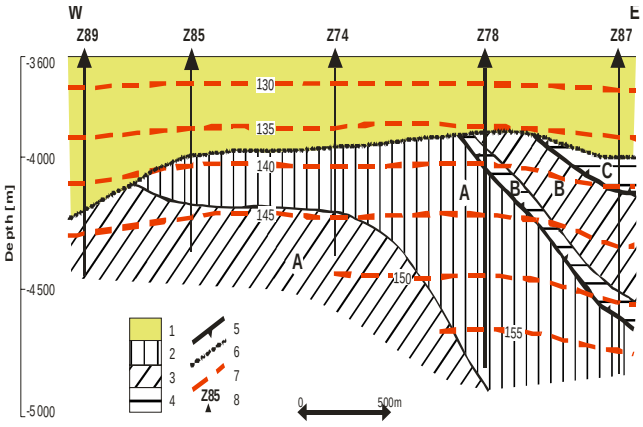
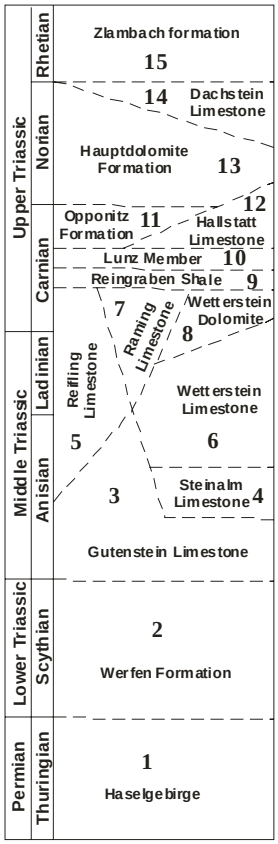


Fig. 3 Structure Závod - Cross section with steadysate temperatures.
A - The Lower Göller, Nappe
B - Lower slice of the Upper Göller, Nappe
C - Upper slice of the Upper Göller, Nappe
1 - Neogene
2 - Upper Triassic
3 - Upper Triassic (Main Dolomite)
4 - Lower, Triassic - Permian
5 - Thrust plane
6 - Un-conformity
7 - Isotherm
8 - Well

Well results show, that the Göller Nappe forms several slices with a complex internal structure and relatively steep dip of beds (Fig. 3).

Characteristic lithological profile of the Göller Nappe is shown in Fig. 4. The sequence begins in Permian by evaporites and claystones, continuing in Lower Triassic by quartzites, sandstones and variegated claystones. In the Middle Triassic prevailed sedimentation of various types of shallow water limestones. At the beginning of the Upper Triassic sedimentation of carbonates was interrupted and for a short period was replaced by deep water sedimentation, mainly of pelites. Later on in Upper Triassic sedimentation of carbonates was renewed. In the Uppermost Triassic sedimentation with limestones and anhydrites took place. Younger Jurassic-Cretaceous sequences of the Göller Nappe were not found in the studied area.



1 - Evaporites and shale
2 - Quartzites, sandstones and variegated shale
3 - Gray to black bedded limestone intercalated with dolomite and in places by breccias or cherty dolomite
4 - Light-coloured to white organodetrital limestone
5 - Gray and light-gray cherty limestone in places intercalated with marlstone
6 - Light-coloured to white organodetrital limestone and in places reef limestone
7 - Dark to light limestone
8 - Dark-gray bedded dolomite overlain by light-gray to white locally massive dolomite
9 - Dark shale
10 - Black or greenish sandy shale variably alterating with beds of dark-gray to greenish sandstone
11 - Yellowish clayey limestone
12 - Variegated limestone
13 - Main Dolomite - thick masses of gray massive or reef dolomite and bedded lagoonal dolomite
14 - Light-gray to white bedded organodetrical limestone with variegated shale
15 - Gray thick-bedded clayey limestone, shale and anhydrite

Fig. 4 Lithostratigraphic units of the Göller Nappe.

The Main Dolomite of Upper Triassic is reservoir rock, in which the reservoirs of gas and petroleum were found. It is simultaneously also a potential reservoir of geothermal waters. Stratigraphic span of Neogene sediments is from Lower Karpatian to Dacian. These sediments are characteristized by alternating sandy and clay layers in a variable ratio. Smaller amounts of geothermal waters with a lower temperature can be gained from Neogene sandstones.

3. PRESENT SITUATION

After seismic surveys in 1975 there was a proposal to verify the uplift of pre-Neogene underlier in the Zavod structure by exploration drilling. The Zavod-72 well (Fig. 2) at a depth of 4200 m drilled Upper Triassic carbonates saturated by hydrocarbons. This result was followed by waste drilling exploration. Successively in the 80's 20 wells were drilled, which encountered pre-Neogene rocks in different depths in interval of 3450 to 6450 m.

Reservoir rock from which until now economically utilizable inflows of natural gas and petroleum have been gained is the Upper Triassic Main Dolomite. Porosity is of two types: primary (matrix porosity) which originated

during sedimentation and consequent lithification of rocks, and secondary – substantially more important, characteristic by a system of all directional fractures, which originated due to tectonic stress during the processes of folding and thrusting of nappes. Total porosity fluctuates to 4.5 % (mean 2.95 %) and permeability to 250 mD (mean 80 mD) while showing large spatial variability. Laboratory measurements of the well core samples showed that the primary porosity values range varies from tenths of per cent to 1., 5 % (mean value 1.2 %). From the viewpoint of the primary permeability was found out that the absolute majority of analyzed samples was impermeable as evaluation of the rock matrix was concerned. Quantitative interpretation of logs also provided comparable results.

The average effective value of secondary porosity used in calculation of thermal energy potential is 1.75 % and average value of permeability is 80 mD.

Natural gas has a high methane content (in average 94 – 95 %) and hydrocarbons are also present. Presence of hydrogen sulphide (mean content of 120 and 150 $mg.l^{-1}$) is a negative phenomenon, due to which it was necessary to construct a desulphurization plant because of the production of acid gas.

Natural gas in places calculated by volumetric method to 5.4 Bm^3 and petroleum 182 MT. Recoverable natural gas reserves are under determined recoverability coefficient 0.78 are 4.2 Bm^3 and 142 MT, respectively.

Large space variability of petrophysical properties of reservoir rocks caused considerable problems in the production of the field. The majority of wells shortly after starting up the production were relatively quickly flooded by water and the clarification of gas field hydrodynamic conditions was unsuccessful.

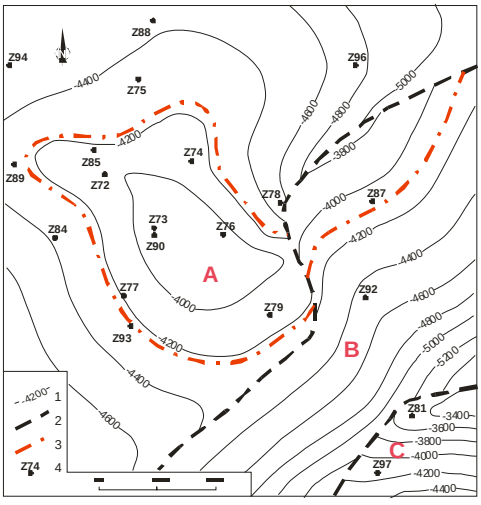


Fig. 5 Structure Závod - Map of the Main Dolomit top.
A - Lower Göller Nappe
B - Lower slice of the Upper Göller Nappe
C - Upper slice of the Upper Göller Nappe
1 - Isobaths
2 – Erosion edge
3 - Gas-water contact
4 – Well.

At present it seems that the reservoir is subdivided into at least two independent hydrodynamic units (Fig.5). The first is a complex hydrodynamic unit comprising Z-72, 73, 74, 76, 77, 79, 89 etc. wells, in the frame of which cyclically produce only Z-73 well to 0.7 MM m^3 monthly and Z-83 well to 0.2 MM $mil.m^3$ monthly. Both wells produce gas with relatively high amount of water. The second is an independent hydrodynamic unit of Z-78 well. Z-78 well produced in 2003 about 2 MM m^3 of natural gas monthly.

Till the end of 2003 in the Zavod structure 1.35 B m^3 of natural gas and 43 Mt of petroleum, i.e. 32 % or 30 % of calculable recoverable reserves were produced in total.

4. DEPRESSURIZATION OF AQUIFER

On the basis of complex spatial variability of petrophysical properties of reservoir rocks, relatively fast flooding of a majority of wells and in course of production we can judge that gas fields of the Zavod structure belong among non-traditional types. In such reservoirs of natural gas with pressurized water regime (active aquifer), primary production terminates practically without a drop of pressure. Economical factors of production termination are given by the decrease of gas production and an enormous increase of water production under still high reservoir pressure. As a result of spatial variability of petrophysical properties, underlying water infiltrates very quickly through zones with good porosity and permeability into high structural levels of gas part of the reservoir. However simultaneously in reservoir rocks with low porosity and permeability and in marginal zones of reservoir there are remaining considerable reserves of isolated gas (60 % to 80 % of initial reserves).

The increase of natural gas recoverability under these conditions according to worldwide experience is possible using secondary production by depressurization of the aquifer. Huge and forced water withdrawal from flooded wells results in a pressure drop of aquifer and the release of natural gas from isolated parts of the reservoir.

Depressurization, under similar conditions was performed in a series of reservoirs in the USA (Alazan, Dubble Bio) and Russia (Orenburg) resulted in the increase of recoverability by 10 to 20 %.

The method of intense water withdrawal in the later stage of production is almost always an effective way to increase recoverability of natural gas. As indicated by the research of application of depressurization of gas fields aquifer, return of cost incurred on this method takes up to three years.

Successful and economically profitable implementation of this process requires following conditions:

- real gas price
- water production by overflow or gaslift
- possibilities of geothermal water utilization
- presence of water-bearing strata suitable for water disposal.

The best technical-economical results are reached in case of active influence on water pressure regime already at the beginning of producers flooding, but also in gas fields

According to the production results at gas fields of the Zavod structure residual recoverable gas reserves are approximately 2.85 B m^3, i.e. present recoverability ratio is 0,25. If the recoverability ratio would be increased by aquifer depressurization on the value of 0.35 or 0.45 some 0.54 B m^3 or1.08B m^3 of natural gas can be gained.

5. GEOTHERMAL SETTING

Thermal setting in the Zavod structure were evaluated on the basis of reservoir temperatures established by testing in 20 wells, which drilled into the pre-Neogene underlier. For verification of the reliability of temperatures gained this way, the temperature at 4 000 m subsurface datum was determined in each of these wells. Temperatures at this depth level vary from 131 °C to 138 °C with a mean value of 133.6 °C ± 2.0 °C, while the standard deviation 2 °C corresponds approximately to the accuracy of individual temperature data. Temperature settings in the Zavod structure are documented by the map of geoisotherms on top of the Main Dolomite as a principal potential reservoir rock of geothermal water (Fig. 6) and by geoisotherms in geologic cross-section (Fig. 3). The dominant element determining the nature of the temperature fields on top of the Main Dolomite bodies in individual geological–tectonic units is their morpho-structural relief (Fig. 5). Temperatures vary from 130 °C to 170 °C depending on the burial depth (Fig. 6).

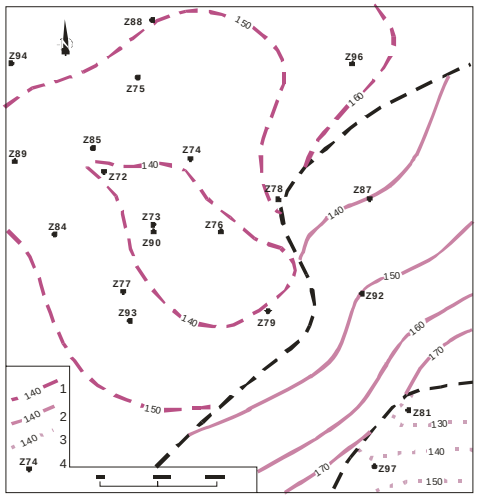


Fig. 6 Structure Závod - Map of the Main Dolomite top steady-state temperature.
1 - The Main Dolomite top isotherm of the Lower Göller Nappe
2 – The Main Dolomite top isotherm of lower slice of the Upper Göller Nappe
3 - The Main Dolomite top isotherm of upper slice of the Upper Göller Nappe
4 – Well.

Temperature gradient in Neogene segments varies in of 30.2 to 32.9 °C/km with mean value 31.2 ± 0.6 °C/km. The mean thermal conductivity of sandy clay Neogene sediments has a value of 1.98 ± 0.36 $W.m^{-1}.K^{-1}$, which in the case of the mean temperature gradient 31.2 °C/km results in the thermal flow density of 61.8 $mW.m^{-2}$.

Characteristic temperature gradient for the sequence formed by the Main Dolomite is 21.3 ± 3.1 °C/km. In the Upper Triassic limestones and shale sequence the mean temperature gradient is higher – 27.7 ± 1.6 °C. Dolomite shave mean thermal conductivity 3.03 ± 0.29 $W.m^{-1}.K^{-1}$, typical thermal conductivity for Upper Triassic limestones and shales is 2.34 ± 0.42 $W.m^{-1}.K^{-1}$.

Employing this data on temperature gradients and thermal conductivity of pre-Neogene underlier resulting heat flow is 64.5 $mW.m^{-2}$ for the Main Dolomite complex and 64.8 $mW.m^{-2}$ for the sequence formed by Upper Triassic limestones and shales. Both these values are in mutual compliance and correspond also very well with the heat flow determined for sequences of Neogene sediments.

The value 63.7 ±1.7 $mW.m^{-2}$ determined as a mean from heat flows calculated for different lithostratigraphic units can be considered being a characteristic heat flow in the area of the Zavod structure.

6. THERMAL ENERGY POTENTIAL

Thermal energetic potential of geothermal energy reserves in the Zavod structure were calculated for the Main Dolomite sequence as the most prospective reservoir rock of geothermal waters. It had been assessed using geothermic volumetric method, which determines the amount of heat accumulated in rocks and geothermal water of the hydrogeothermal reservoir (Muffler and Cataldi, 1978, Haene, 1985).

The quantity of heat E_0 bound to a unit of geothermal water reservoir rock area is determined by relation:

$$E_0 = [(1 - \phi) . \rho_h . c_h + \phi . \rho_v . c_v] . (T_H - T_0) . Z \quad [J.m^{-2}]$$

where:

ϕ - effective porosity;

ρ_h - bulk density $[kg.m^{-3}]$

c_h - rock heat capacity $[J.kg^{-1}.K^{-1}]$,

ρ_v - water density $[kg.m^{-3}]$

c_v - water heat capacity $[J.kg^{-1}.K^{-1}]$,

T_H - reservoir temperature of geothermal water [°C],

T_0 - neutral zone temperature [°C] and

Z - thickness of geothermal water reservoir rocks [m].

A substantial part of geothermal energy reserves is in the majority of hydrogeothermal structures bound to the surrounding rock (approx. 90 %). Only about 10 % of the reserves are bound to water components and it is not possible to recover all energy determined by the geothermic volumetric method. To determine a utilizable amount of thermal energy a recovery coefficient is used depending on the type of hydrogeothermal structure, above all on the effective porosity of reservoir rocks.

Muffler and Cataldi (1978) determined formula for calculation of recovery coefficient as follows:

$$R_0 = 1{,}25 . \phi$$

where:

ϕ represents a mean value of effective porosity of geothermal water reservoir rocks.

The amount of heat E recoverable from hydrogeothermal structure is then defined by formula:

$$E = R_0 . E_0 \qquad [J.m_{-2}]$$

The degree of structure recoverability may be assessed in detail only on the basis of a mathematical modeling of reservoir parameters, taking into account not only the geological structure and geothermal setting, but also the way of withdrawal and injection of geothermal waters.

In the calculation of thermal energy potential for a hydrothermal structure the value 1.75 % of the effective porosity of the Main Dolomite was used. Its bulk density determined by measurements is 2.8 ±0.03 $g.cm^{-1}$. The bulk heat capacity of dolomites of dolomites is 2.270. 10^6 $J.m^{-3}.K^{-1}$, with its bulk density 2.8 $g.cm^{-3}$ gives a heat capacity of 810.7 $J.kg^{-1}.K^{-1}$. After recalculation of reservoir temperatures of dolomites their heat capacity varies in intervals of 926.5 - 970.6 $J.kg^{-1}.K^{-1}$.

The density of geothermal water depends on temperature, pressure and mineralization varies in span of 939.2 – 990.5 $kg.m^{-3}$. Calculated values of heat capacity also depend on temperature, pressure and mineralization. These values vary in intervals of 4 001 - 4 028 $J.kg^{-1}.K^{-1}$. The average mineralization of geothermal water in this area is 60 $g.l^{-1}$.

Tops of geothermal water reservoir rocks in the area for which thermal energy potential was calculated varies in intervals of 3300 to 5400 m (Fig. 5). Corresponding temperatures for these depths are from 130 to 170 °C (Fig. 6). The thickness of geothermal water reservoir rocks varies in span from 0 to 1800 m (Fig.7). The temperature of a neutral zone on the basis of meteorological data was determined to be 9 °C. Reduction coefficient values characterizing the recoverability degree of geothermal waters from the structure is 0.022. Its low value is in compliance with low effective porosity of reservoir rocks.

On the basis of given data a prospective thermal-energy potential of geothermal energy reserves was calculated in the Main Dolomite bodies, occurring in the Lower Göller Nappe, in lower slice of the Upper Göller Nappe and in the upper slice of the Upper Göller Nappe (Fig.8, Table 1).

Geothermal waters of the Zavod structure should be utilized with respect to their chemical and technological properties using withdrawal-injection systems. In a suitable space allocation of withdrawal and injection wells and optimum way of withdrawal it is possible to ensure the operation for 40 years.

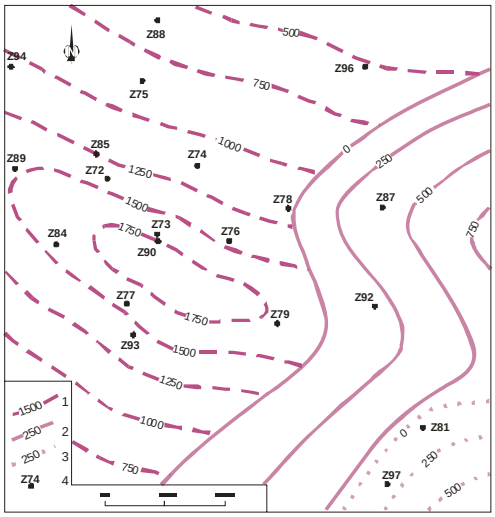


Fig.7 Structure Zavod – Map of the Main Dolomite Thickness.
1 - Isopachous line of the Lower Göller Nappe,
2 - Isopachous line of lower slice of the Upper Göller Nappe,
3 - Isopachous line of upper slice of the Upper Göller Nappe,
4 – Well.

Table 1: Prospective thermal-energy potential of geothermal energy reserves in the Zavod structure.

Unit	area [km^2]	TEP [GJ]	TEP [MW]
Main dolomite of the Lower Göller Nappe	10,22	$87,760.10^6$	69,57
Main dolomite of the lower slice of Upper Göller Nappe	5,24	$13,024.10^6$	10,32
Main dolomite of the upper slice of Upper Göller Nappe	0,84	$1,720.10^6$	1,36
Total	16,30	$102,504.10^6$	81,25

TEP-thermal energy potential
TEP-given in MW was calculated for the withdrawal
Injection systems lifetime of 40 years.

The total prospective thermal energy potential of geothermal energy reserves in the Zavod structure represents 81.25 MWt ore. Present effectivity of utilization of operated geothermal resources in Slovakia, determined above all, by technical and economical possibilities, represents 48.5 % (Fendek et al., 1999). In case of the keeping this effectivity the prospective thermal-energy potential of geothermal energy reserves in the Zavod structure is 39.41 MWt ore.

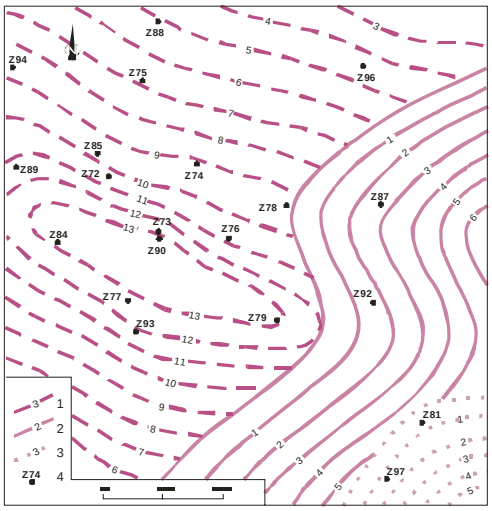


Fig. 8 Structure Zavod - Map of the Main Dolomite heat energy potential.
1 – The Main Dolomite heat energy potential contour of the Lower Göller Nappe,
2 – The Main Dolomite heat energy potential contour of lower slice of the Upper Göller Nappe,
3 – The Main Dolomite heat energy potential contour of upper slice of the Upper Göller Nappe,
4 – Well.

7. CONCLUSIONS

As outlined in previous chapters, gas reservoirs of the Zavod structure are practically in their final stage of production. That's why it is necessary to consider the utilization of secondary production method, so called depressurization of the aquifer, i.e., an intense withdrawal of water from flooded wells, which may result in the drop of aquifer pressure exerted upon gas reservoirs and consequent release of natural gas entrapped in isolated parts of the reservoir. During implementation of this method it is possible to simultaneously carryout a good practical geothermal and hydrodynamic research in the locality.

In the first phase it is necessary to analyze in detail the production of gas fields, to elaborate projects of well work overs and to carry out long-term well testing and injection testing. There are seven wells at disposal now, three of which are finishing their gas production and four are suspended. A part from that monitoring of gas and water production development, also monitoring of crucial parameters of geothermal potential evaluation (temperature, pressure, interferences, amount of dissolved gas, etc.) should be the aim of this phase. The outcome of operations in the first phase will be the determination of water production volume which is necessary for depressurization of aquifer and the proposal of utilization of geothermal water.

In the second phase it is necessary to make mathematical modeling of optimum regime of utilization of the structure of the geothermal potential after the gas recovery termination and the proposal of geothermal energy utilization possibilities depending upon the economy of individual project types. The use of geothermal water is supposed primarily for heating of industrial buildings, flats, houses and for preparation of hot water for industrial purposes. It can be used also for agricultural and recreation purposes. Considering relatively high temperatures, electricity production is not excluded.

Parties interested in geothermal energy utilization are minor towns in the vicinity, and industrial parks under construction in the neighborhood can be potential consumers.

The utilization of geothermal energy is possible, or necessary already in the case of successful depressurization of the aquifer. If the depressurization would not provide the desired effect, it is possible to proceed to use geothermal energy alone.

During the production of geothermal water it is necessary to take into account the presence of hydrocarbon gasses and hydrogen sulphide. The separation of a gaseous media should not cause major problems in the Zavod structure (if it would be necessary, because it would be a case of injection in the primary circuit and the heat transmission to the secondary circuit through a heat exchanger system). Wells are completed for such a surroundings and the majority of requisited technological equipment is at the disposal at the locality.

We can conclude, that by simultaneous realization of efforts to meet both objectives, i.e. the enhancement of gas recoverability and the utilization of geothermal energy potential, cost can be substantially reduced in comparison to carrying out those operations separately. Under the above circumstances the implementation of proposed works in the Zavod structure appears to be very effective and the fact that it is a case of ecological energy is also important.

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