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GEOPHYSICAL EXPLORATION OF THE LOW ENTHALPY KRSKO GEOTHERMAL FIELD, SLOVENIA

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ABSTRACT

The Krsko field in eastern Slovenia is known for its thermal springs, appearing on its southern and western margins. The structure of the Krsko basin was delineated using several geophysical methods, as for instance gravimetry, deep resistivity sounding, well logging and reflection seismics. Geomagnetic survey revealed the probable existence of potential and highly speculative heat source beneath the Gorjanci and Zumberak mountains south of the Krsko basin. Temperature measurements in many shallow and in some deeper wells were done for geothermal gradient determination. Depths to carbonate reservoir, roughly determined with geophysics and proved by drilling in shallower places, reach about 1800 m in the central elongated part of the basin, and are much smaller along its southern margin. At the northern margin geophysics so far gave no signals of thermal water existence in depth. Thermal water occurrence is due to specific synclinal build up, with the impervious clastics overlying the aquiferous carbonates. Differences in thermal conductivities between Tertiary clastics filling the basin and Mesozoic carbonates are the cause of greater temperature gradients in Tertiary layers. Heat flow density is within average values over most of the field. On top of the carbonate aquifers temperatures attain more than 50 °C in eastern part of the field. Thermal water with temperatures of up to 64 °C and yield per well of up to 40 l/s is used for bathing, space and greenhouse heating.

1. INTRODUCTION

On almost whole Krsko field the possibilities exist for the exploitation of thermal water. This area in eastern Slovenia is known for its numerous thermal springs, appearing on its southern and western margins. Extensive geophysical exploration has been performed, that helped in delineating the structure of the basin and depths of Mesozoic carbonate aquifers. Low mineralized thermal water is exploited for space heating and bathing including balneology at Catez and Smarjeta Spas, for greenhouse heating of 5 ha at Agraria, Catez, and at Dobova for swimming. Water temperatures as high as 64°C have been discovered with yield per well of up to 40 l/s. It is believed that additional quantities of thermal water can be exploited for district heating at Brežice as well as for the greenhouse areas and balneology.

2. GEOLOGICAL SETTING

The Krsko field area represents, according to earlier investigations, a tectonic unit of Krsko syncline.To the south it is confined with the Gorjanci massif and to the north with the Sava folds. The syncline axis lies in a WSW-ENE direction and is filled with Middle and Upper Miocene mostly marly sediments. According to latest geological and geophysical research it is called the Krsko basin (Poljak *et al.*, 1997). A more recent hypothesis considers the Krsko basin as a compressional structure with folding as the predominant style of deformation (Gosar, 1998). Thermal springs at the foot of the Gorjanci mountains are an argument for a major fault at the south margin.

The Krško basin is located in eastern Slovenia (Fig. 1). The basement of Tertiary layers consists of Mesozoic carbonates, mostly Triassic dolomites, Jurassic limestones and dolomites and Cretaceous marly limestones that in the deepest parts of the basin lie at depths of 1600 - 1800 metres according to interpretation of reflection seismics and recent geoelectrical soundings (Rajver *et al.*, 1996). On the edge of the basin, especially on the northern, western and southern sides, Mesozoic carbonates are exposed on the surface.

3. GEOPHYSICAL INVESTIGATIONS

The whole studied area was mostly investigated during the complex research (Lapajne *et al.*, 1979) which was divided in five phases running from 1973 until 1978 with the Geological Survey Ljubljana as the main performer. The geological structure of the area was clarified using geophysical methods and geological-tectonical study. The existed thermal and other springs were registered and the aquifer types were hydrogeologically classified.

To acquire a picture of deep geological structure and basin layout of the area, first gravimetric and magnetometric surveys were performed some 40 years ago. The position of the syncline axis was so delineated as well as gravimetric lows and highs that correspond to Tertiary basin thickness and probable magmatic intrusions under the Gorjanci and Zumberak mountains at the southern margin of the basin, respectively (Fig. 2). Later on mostly geoelectrical deep sounding was used as a main research method for the most part of the Krsko field from Kostanjevica in the west to Dobova in the east enabling us to draw a map of Mesozoic carbonate basement (Fig. 3) as potential thermal reservoir under Tertiary sedimentary sequence (Rajver *et al.*, 1996).

Research of the areas of Catez and Kostanjevica was done in more detail than elsewhere. There numerous exploration and production wells were drilled. Especially the Catez area was explored in detail using geology, hydrogeology and geophysics (Ivankovic and Nosan, 1973). At both localities, Catez and Kostanjevica, exploration continued in 1985-1986 using additional geophysical measurements. As a result, two successful exploitation wells were drilled, 800 m deep at Kostanjevica and 704 m deep at Mostec near Catez (Verbovsek, 1989). Earlier reflection seismic investigation was performed in 1959 by Geofizika Company from Zagreb (Croatia) in several analogue profiles in the N-S direction and in one in the WSW-ENE direction for oil prospection. As a result the syncline structure was determined. To improve the geologic model, high resolution seismic reflection was used in a reevaluation study of earthquake hazard assessment at the Krsko nuclear power plant site in the mid nineties (Gosar, 1998). Numerous thermometric measurements, mostly temperature, were carried out in shallow and in some deeper boreholes and wells, using the methods and principles described by Ravnik *et al.* (1995), and their results are explained later in the text.

4. HYDROGEOLOGICAL SITUATION

Tertiary sediments are mostly impermeable for water with an exception of lithotamnion limestones of Miocene age that are found as locally limited aquifers, known especially in the Catez area. Their porosity is of karstic type with larger cavities. Triassic dolomites, Jurassic limestones and dolomites as well as large part of Cretaceous sediments present water abundant aquifers that are of regional importance due to their interconnection and widespread occurrence. However, following investigations by Petauer *et al.* (1993) their interconnection is questionable and only speculative. It is expected that thermal aquifers under Tertiary layers of the Krsko basin are recharged from Mesozoic carbonates on marginal areas of the basin. Along the whole southern and southwestern margin of the basin several thermal springs besides cold ones are situated at the contact of Tertiary and Mesozoic sedimentary complexes (Fig. 4).

5. RESULTS OF DEEP DRILLING

More than 20 wells were drilled in the best investigated Catez area. Figure 3 shows many of them. The deepest borehole there reaches 570 m. The maximum yield from a single well is 50 l/s, while temperature reaches 64 °C. The well L-1/86 was drilled on the left riverside at Mostec with depth of 704 m. Its maximum yield is 40 l/s and temperature 61 °C. It has been revealed that the contact of Tertiary and Late Cretaceous with Triassic dolomites dips quite steeply to the north. The most abundant inflows have been discovered along this contact. Temperature increases from the south (Perisce spring) to the north and reaches maximum of 64 °C. Thermogram of the L-1/86 well shows explicit temperature inversion (Fig. 5), a signal of mixing with colder water flow at greater depths from the south to the north. Following Nosan (1973) it would be possible to exploit up to 120 l/s of thermal water with mixed temperature of 60 °C in the whole Catez area. The L-1/86 well confirms that high water temperatures continue to be present to the north and northeast, while to the east and west their extension is not clear so far. At Dobova, northeast of Catez, the exploitation well AFP-1/95 (Fig. 5) with depth of 700 m can yield 15 l/s with temperature of 62 °C. To the south, i.e. towards the basin´s margin, temperature decreases due to mixing with the colder groundwater inside the carbonate aquifers of the Gorjanci mountains.

Hydrogeological structure around the Toplicnik thermal spring at Kostanjevica has been investigated in detail. Six structural-exploitation wells have been drilled nearby with depths from 45 to 192 m, and two thermometric gradient boreholes northerly, both 100 m deep. The well V-6 (45 m deep) has proved the yield of 40 l/s with 27 °C from Jurassic limestone, which is the highest temperature at Toplicnik. Wells are located along the left and the right bank of Krka river. The contact of Tertiary clastic sediments with Mesozoic carbonates dips steeply to the north. This was proved with deep geoelectrical soundings in 1985-1986 north and northeast of the Toplicnik spring. Thermometric borehole V-7/85, located in the prolongation of the zone of increased temperatures to the north, exhibits prominent elevated temperature gradient (Fig. 5) in Miocene marls. In 1986 the 800 m deep well SI-1/86 was drilled northeast of Toplicnik (Fig. 5). It is artesian well with free flow of about 10 l/s, however, some 45 l/s of thermal water with 35.5 °C can be pumped from the Jurassic limestone aquifer reached by well at a depth of 633 m. Low permeable Miocene marls and carbonatic sandstones lay above Mesozoic carbonates.

Detailed investigations of wider Smarjeta Spa area have been followed by drilling of eleven wells with maximum depth of 495 m. Thermal water of maximum temperature of 34.5 °C flows from Mesozoic, mostly Triassic carbonate aquifers.

6. ANTICIPATED GEOTHERMAL MODEL OF THE KRSKO BASIN

Geological and hydrogeological structure of the Krsko basin exhibits favourable conditions for the formation of elevated temperatures. Thick Miocene layers, predominantly composed of marls, sandstones and claystones, show great contrast in thermal conductivity in comparison with Mesozoic carbonates. While values on samples of Tertiary sediments show about 1.6 to 1.8 $Wm^{-1}K^{-1}$, the carbonates exhibit much higher values, about 4 to 4.5 $Wm^{-1}K^{-1}$. Thermal conductivity has been measured on numerous cores from boreholes in Toplicnik and in Catez area using the generalized transient hot wire method similar to the Japanese QTM method (Ravnik *et al.*, 1995). If more or less the same heat flow density is assumed over the wider Krsko field (about 50 mWm^{-2}), temperature gradient in Miocene layers is elevated due to their lower thermal conductivity. This is the well-known blanketing effect, presented as the temperature anomaly over the wider Krsko basin in Fig. 6.

However, due to higher water permeability of Mesozoic carbonates, the heat transfer is effective also in convective way. Cold meteoric water penetrates to deeper parts towards the north where it is warmed, and then most of water turns along the Tertiary-Mesozoic contact to the south, rising up along the inclined carbonate basement. There the basement is fractured and permeable enough as a consequence of deep fracture and fault zones. Certainly some water circulates further to the north and northeast, especially from the Catez area. Along the margin of the basin thermal water mix with cooler groundwater in carbonates of the Gorjanci mountains. There thermal spas occur representing natural draining as the fulfilled condition for the restoration of before mentioned water flow (Verbovsek, 1989). The width of the mixing area ranges from several hundred metres to 1 km at Catez. Greater part of thermal water very probably flows from the north to the south in wider, more fractured zones. They appear at Catez, Buseca vas, Toplicnik, and probably elsewhere. If wells are drilled inside these zones to the north, temperature increases as long as they are in the mixing zone, and the reached steady value remains more or less the same down to the deepest levels of the basin.

The highest temperatures that can be reached in the whole Krsko field are around 70 °C, and due to given geological structure the possibility for such high values is greater to the east from Kostanjevica. Outside of zones of thermal water outflows temperature gradients are still elevated but less than they are inside such zones. An example is well SI-1/86 near Kostanjevica in comparison with, for example, borehole V-7/85 inside the zone (Fig. 5).

The geothermal cross-section D-E-F (Fig. 7), stretching from the Orlica hill in the north across the Krsko field to Gorjanci mountains in the south, exhibits the role of probable fault zones of dinaric (NW-SE) and balaton (SW-NE) direction. This system of faults very likely enables the thermal water circulation from deeper parts to surficial layers. Thermal anomaly near Catez is well expressed.

7. EXPECTATIONS AND POSSIBILITIES FOR GEOTHERMAL DIRECT USE

For determining locations and the zone widths of thermal water outflows thermometric boreholes (at least 100 metres in depth) are to be drilled and geophysical measurements performed to acquire depth to the carbonate basement. In first phase such investigations should be oriented towards the north from the known thermal springs. There the highest temperatures (up to 65 °C) can be expected in depths of 500 to 800 metres. The yield per well is expected to reach 50 l/s, and total yield in single areas can reach at least 300 l/s. At the inlet temperature of 60 °C, outlet temperature of 30 °C and water flow of 300 l/s, the thermal power can be roughly 38 MWt for such single area. Water is low mineralized and suitable for district heating of Brezice town, agriculture (greenhouses), aquaculture, bathing and balneology. These temperatures can probably be reached also outside these outflow “zones” of thermal water, however, the borehole depths in this case would be much higher, around 1200 to 1600 metres.

8. CONCLUSIONS

The occurrence of thermal water is due to specific geological structure of this area, filled with clastic low permeable and low thermal conductive sediments, and with water bearing carbonate aquifers in the basement. Great difference in thermal conductivity of the Tertiary and Mesozoic sediments gives rise to higher temperature gradients inside the Tertiary sediment sequence. The heat is supplied by conductive heat flow and is dispersed by convective groundwater flow along the fault zones in the carbonate bedrock. Along the southern and western margin of the field, where several thermal springs occur, such thermal convection is also responsible for the elevated gradients in the Tertiary sequence. Thermal water from springs is already somehow cooled due to mixing with cold groundwater seeping from the Gorjanci carbonate massif. Temperature of about 60 to 70 °C can be expected along the whole syncline axis down to depths of about 1600 - 1800 metres. Same temperature can be attained also at shallower depths in zones of expressed convective groundwater flow. The aim of future research is to locate such zones in the hinterland of known thermal springs towards the syncline axis using mostly geophysical methods.

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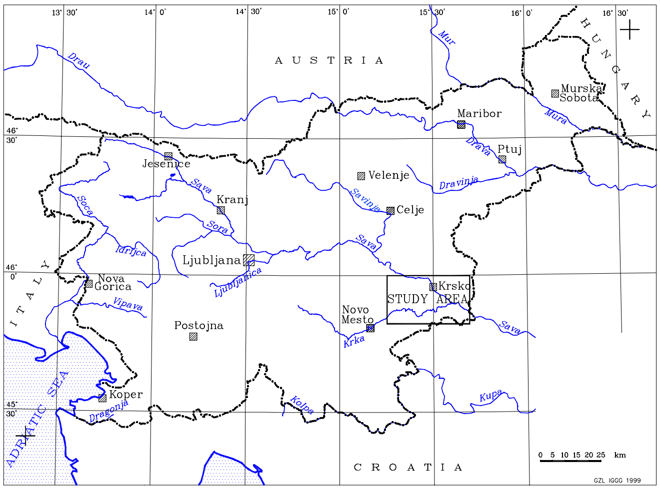

Figure 1. Location of the Krsko basin in Slovenia. Study area is indicated

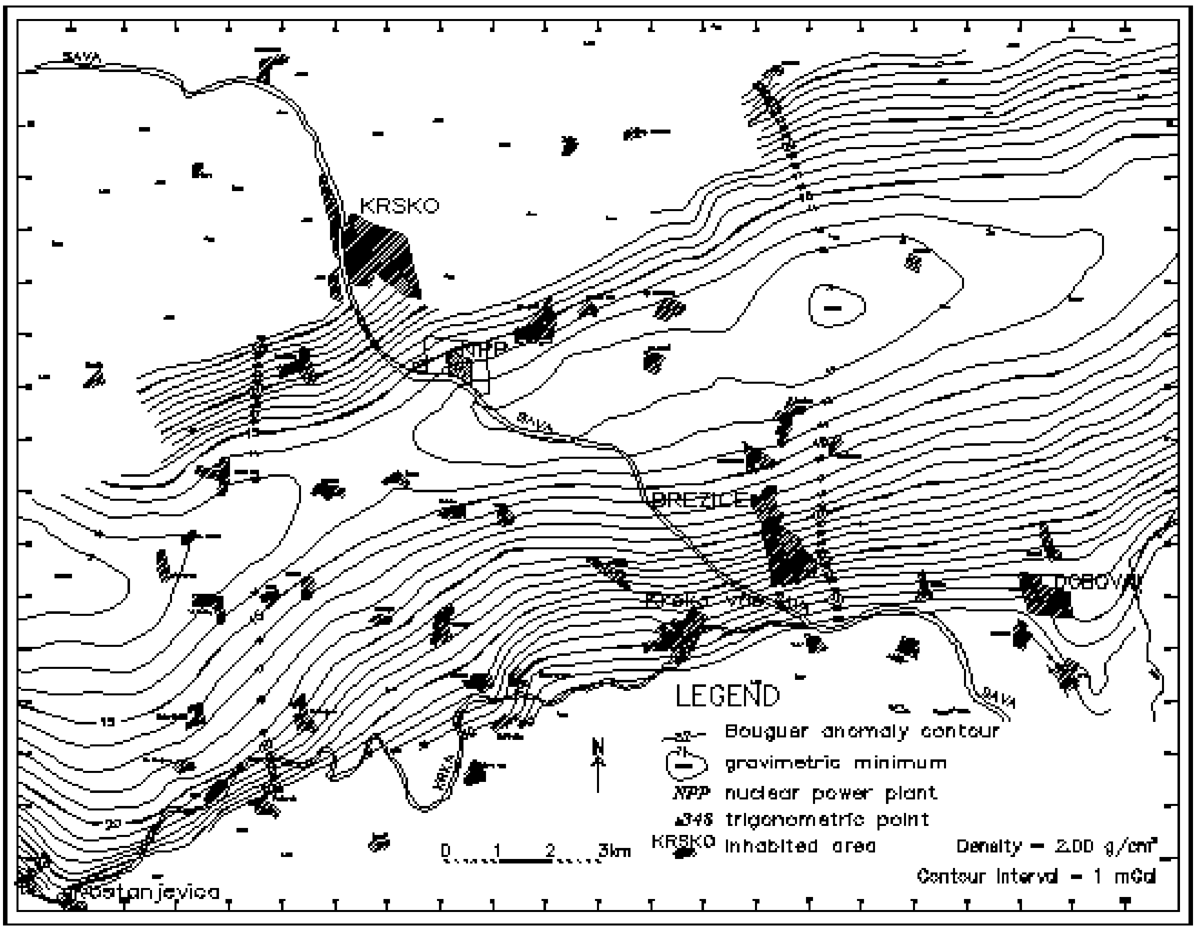

Figure 2. Bouguer anomaly map of the Krsko basin (Urh, 1955).

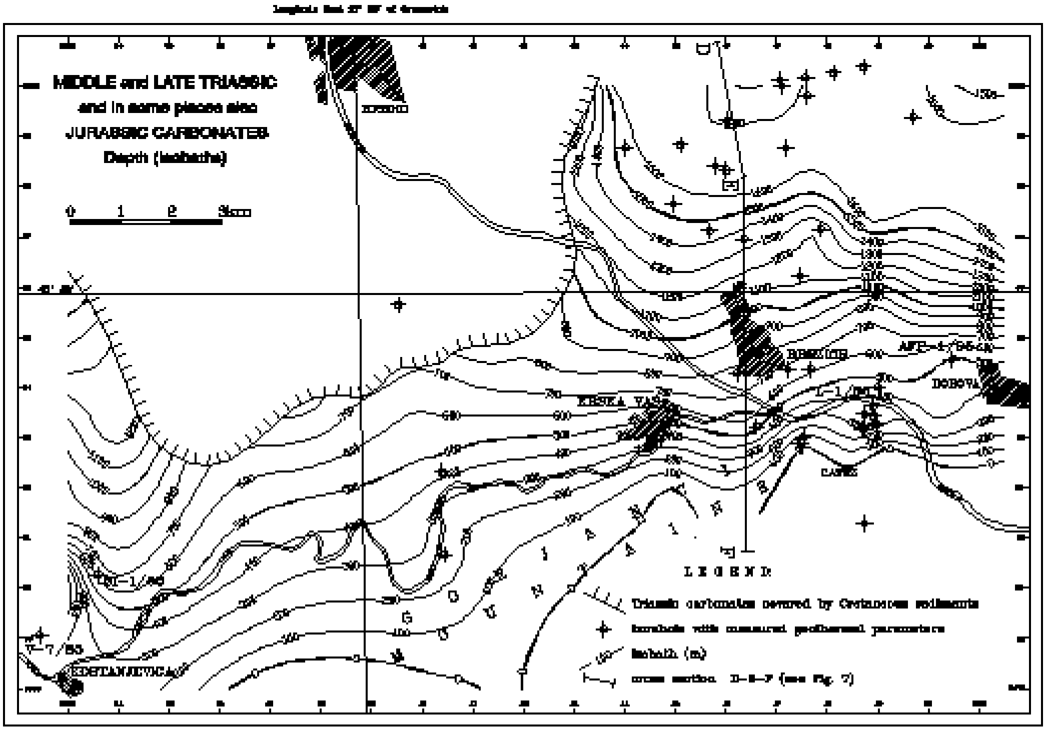

Figure 3. Depth to Mesozoic carbonate basement in the Krsko basin (Rajver et al, 1996).

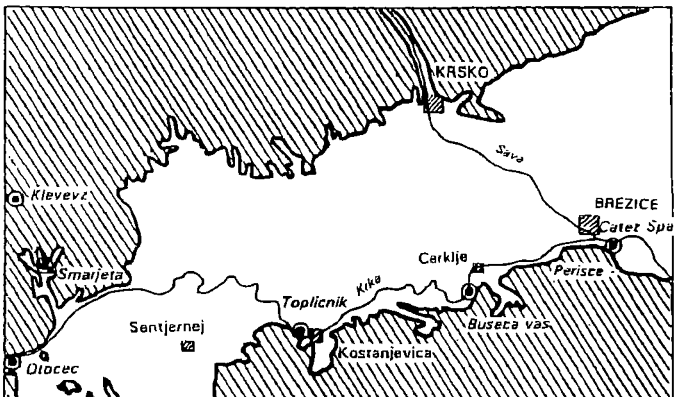

Figure 4. Map of thermal springs in the Krsko basin (Verbovsek, 1989).

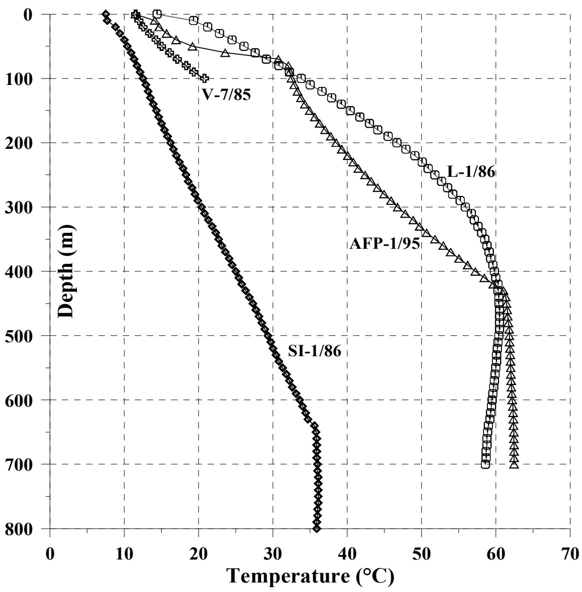

Figure 5. Thermograms of four selected boreholes

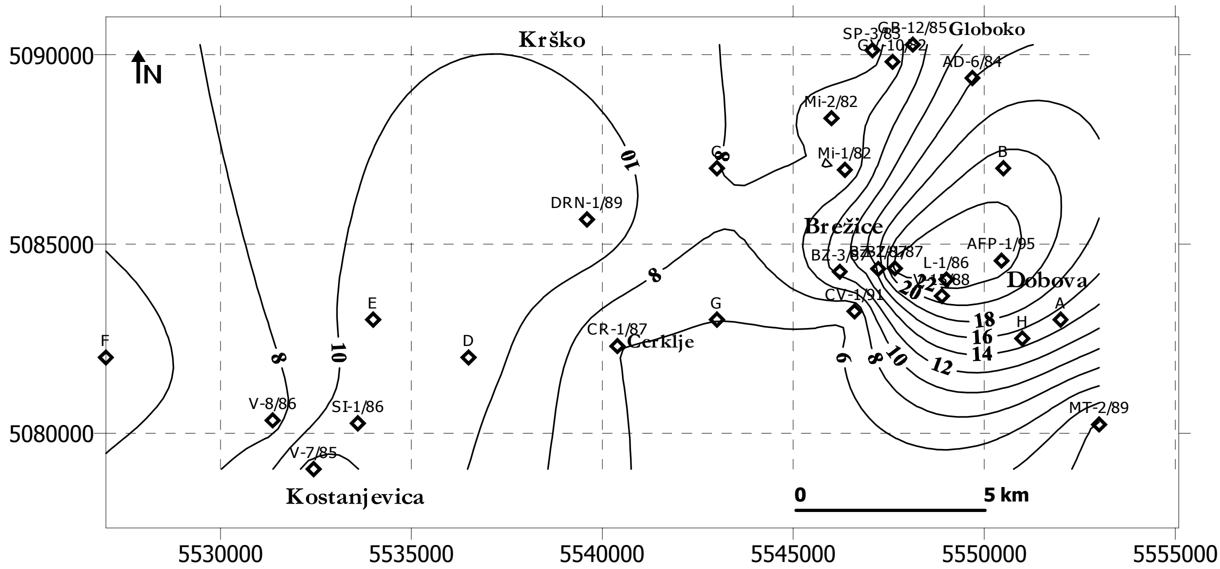

Figure 6. Temperature anomaly (°C) due to blanketing effect of the sedimentary cover.

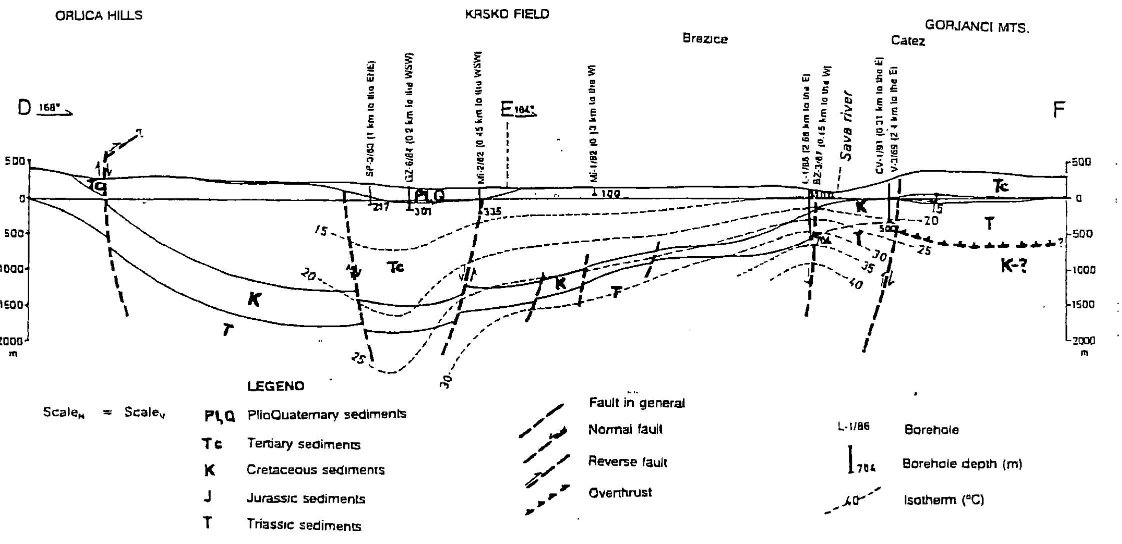

Figure 7. Geothermal cross-section D-E-F across the Krsko basin (Rajver et al, 1996).