Geothermal boreholes with predominately conductive component

In Slovenia, the groundwater is named thermal water according to the Water Act if it springs out with a temperature of at least 20 °C. Large quantities of thermal groundwater are stored in a few hundred metres thick sequence in the western part of the Pannonian basin with higher than normal heat flow. Ground temperature usually rises with depth while the velocity of groundwater flow decreases. This causes a longer residence time of groundwater; therefore, the amount of total dissolved solids (and sometimes of gas) in thermal water usually rises.

Anomalies

The bedrock of north-eastern Slovenia, which is geotectonically positioned in the western part of the Pannonian basin, subsided for up to six kilometres in the last 20 million years. At first, marine sediments were deposited in the Central Paratethys Sea, followed by brackish sediments of the Pannonian Lake. Eventually, alluvial sediments of the predecessors of today's rivers, the Drava and Mura Rivers, deposited. Largest quantities of thermal groundwater are stored in well-permeable Upper Miocene loose quartz sandstone. Lukewarm water is stored also in the above positioned Pliocene sandy gravel while thermomineral water in the Miocene sediments below.

The Pleistocene rainwater was heated to about 80 °C at a depth of 2 km and contains up to 1,200 mg of total dissolved solids per litre. Groundwater recharges near Ptuj and in the hilly area of Goričko and flows in a regional and transboundary aquifer to Hungary (Tóth et al. 2016). Thermal water outflows from wells at approximately 60 °C and is used for space heating, balneology and bathing in Banovci, Lendava, Moravci, Moravske Toplice, Murska Sobota and Ptuj; for greenhouse heating in Dobrovnik, Moravske Toplice and Renkovci; and for district heating of Lendava (Rman et al. 2012, 2016).

Thermomineral water discovered at oil and gas exploration in the village of Moravci in the 1960s is different. This oily water has been produced from the Middle Miocene turbiditic sandstone for over 50 years and was officially declared medicinal in 1964. The village was renamed exclusively because of the occurrence of this water to Moravske Toplice (toplice translates to spa). It is tapped by four wells at depths below 1,200 m. Two of them are inclined which is extremely rare in Slovenia. Thermomineral water reaches up to 75 °C and is one of Slovenian's hottest thermal waters. It is an old diluted brine of Na-Cl-HCO_3 water type, with as much as 15,000 mg of total dissolved solids per litre and a high content of organic compounds. On the surface, CH_4, CO_2 and H_2S gases are released from water. Carbonate incrustations precipitate in wells and pipes due to degassing of CO_2 if not mitigated properly. Thermomineral water is used for space heating and balneology. Distinctive flocculation particles of iron sulphide are formed in bathing pools after the water is oxidised in the air, giving it a typical black colour.

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Thermal waters are abundant in the Pannonian basin and its outskirts because of elevated heat flow which is directly connected to geodynamic extension of the area which results in thinner Earth's crust and consequently higher heat flow and geothermal gradient. Which type of heat flow prevails in a vertical section drilled by boreholes, convective or conductive, can be investigated by several methods. The convective component of heat-flow density (HFD) we determine by two methods: (a) with a Peclet number analysis and (b) in a visual manner, that is in a way where a deeper geotherm is drawn so that the convective part is not considered, but only the conductive component down to a deeper geological section.

Data

The convection share in the T-z profiles (thermograms; Fig. 1) was determined in a visual manner with a help of calculated deeper temperatures in conductive regime. With our approach of (a) or (b) we may conclude that the HFD values in NE Slovenia are in a rough agreement with the HFD values for the Pannonian Basin in general where at the Mohorovičić (Moho) boundary of the Pannonian Basin (Békési et al. 2018), the heat-flow attains 20-30 mW/m^2 in Hungary as basal heat flow, for example. We have investigated geothermal conditions at 29 boreholes in NE Slovenia where conductive component predominates, where some might have some percentage of convective component.

Based on the measured T-z profiles in the Šom-1/88 borehole (#66 in Table 1) the formation temperature at 1200 m depth could be predicted for this borehole to be cca 72 °C, also assuming predictive lithology. It could be assumed that below 1200 m there is perhaps a convection zone down to a depth of 1500 m. Then the conductive HFD is derived from conductive temperature gradient and is 107 mW/m^2. The measured HFD is 131 mW/m^2, therefore the convective HFD component is 24 mW/m^2.

Some other boreholes in NE Slovenia with the characteristic T-z profiles, which represent apparent convective component or just hidden and implied convective component (possible also beneath the bottom of the certain borehole), are the following ones: Sob-1/87 in Murska Sobota (#33 in Table 1), T-4/87 at Radenci (#39), Pg-7/88 at Petišovci (#51), Dan-3/90 at Dankovci (#113), Mt-7/93 at Moravske Toplice (#128). However, there are some other boreholes where the convective share is at least roughly determined in visual manner: Mt-6/83 at Moravske Toplice (#8), Pg-9/89 at Petišovci (#444).

Examples of boreholes in NE Slovenia with (normal) T-z profiles, which do not show or imply any convective component (but which is calculated with Peclet analysis in a small value), are for example these two: Ljut-1/88 borehole at Ljutomer (# 41 in Table 1) and Peč-1/91 borehole at Pečarovci (# 98).

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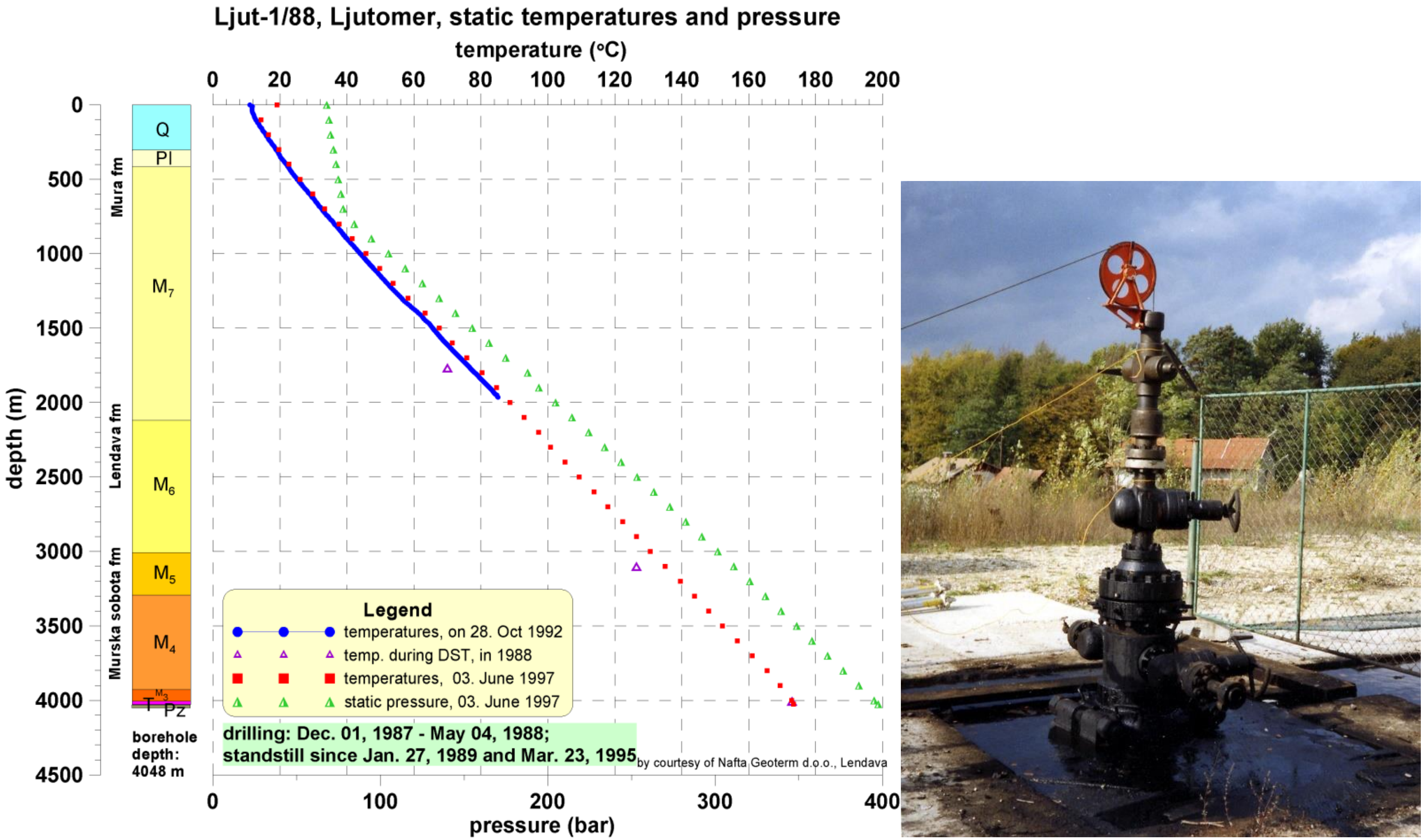

Fig. 1. Thermogram and photo of the deepest borehole in Slovenia, LJUT-1/88 in Ljutomer, from which also many cored rock specimens have been measured on thermal conductivity and HFD determined. The well is now liquidated.

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borehole database №	borehole name	location name	borehole depth, m	X	Y	q_total, mW/m^2	q_conductive share only	smaller uncertainty in calculation	extra convective share of q, mW/m^2	Legend for QGIS
1	SG-1/54	Hrastje Mota	435,4	5162575	5582610	106	106			0
2	Mt-2/61	Rimska čarda, Sebeborci	1462	5173245	5590305	120	120			1
4	BS-2/76	Benedikt	788	5163250	5567850	145	103		42	3
5	Pg-6/81	Petišovci	3200	5155212	5612170	112	112			1
8	Mt-6/83	Moravske Toplice	987	5171710	5593854	132	107		25	2
15	L-1/86	Mostec - Čatež	704	5084060	5549010	182	70		112	3
30	BŽ-3/87	Brežice-Grad	100	5084265	5546216	68	68	?		1
33	SOB-1/87	Murska Sobota	870	5169066	5589233	127	107		20	1
34	GB-1/87	Gabrnik	2196	5148860	5573128	88	88	?		0
39	T-4/87	Radenci	818	5166824	5580820	154	109	?	45	3
40	PDG-1/87	Podgorje	350	5173781	5564061	89	89			0
41	LJUT-1/88	Ljutomer	4048	5152934	5591661	128	116		12	1
42	SOB-2/88	Murska Sobota	887	5169010	5589560	108	108			0
51	Pg-7/88	Petišovci	2990	5155910	5614262	137	115	?	22	2
52	DOK-1/88	Dokležovje	1934	5162281	5590973	108	108	?		0
53	Mg-6/85	Murski gozd	3858	5151620	5617160	124	124			1
66	ŠOM-1/88	Plodršnica	1100	5166855	5558465	131	107		24	1
82	MB-1/90	Maribor	152	5154860	5552805	103	103			0
87	MB-1/91	Maribor - Stražun	1331	5154851	5552948	112	112			1
98	Peč-1/91	Pečarovci	2098	5177995	5587186	129	110		12	1
106	MB-2/91	Maribor - Stražun	1600	5155450	5551775	112	112			1
113	Dan-3/90	Dankovci	1400	5179609	5590378	150	110	?	40	2
128	Mt-7/93	Moravske Toplice	991	5171443	5593917	122	102		20	1
148	Mrt-1/93	Sv. Martin - Kobilji breg	3299	5169450	5606240	102	102	?		0
155	Sre-1/91	Središče	2708	5181242	5601493	107	107	?		0
205	Mot-1/76	Motvarjevci	3835	5173231	5604542	111	111			0
211	AFP-1/95	Dobova - Gabrje	700	5084560	5550455	187	72	?	115	3
212	Pan-1/76	Panovci	2744	5180731	5592969	98	98	?		0
409	Be-2/04	Benedikt	1857	5162972	5568622	216	103	?	112,6	3
444	Pg-9/89	Petišovci - Dolina	3011	5156442	5615063	154	114		40	3
515	Re-1g/11	Renkovci	1484,7	5166014	5599545	104	104			0
516	SOB-3g/12	Murska Sobota - Černelavci	1520,3	5169855	5588015	112	112			1
517	SOB-4g/13	Murska Sobota	1201,1	5169740	5589160	111	111			1
530	Niko-1/08	Nuskova	64	5186007	5578785	100	100			0
Legend:	*boreholes in the Čatež geothermal field*									

Table 1. Boreholes in north-eastern and eastern Slovenia where the HFD has been calculated (34 boreholes in total, of them 3 in the Čatež field) and visible convective share determined at 12 boreholes (2 of them in the Čatež geothermal field).

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