HyTheC

Multidisciplinary Approach to Conceptual Modelling of Hydrothermal Systems in Croatia (HyTheC)

Staša Borović, Maja Briški, Tihomir Frangen, Ivan Kosović, Bojan Matoš, Morena Mileusnić, Ivica Pavičić, Mirja Pavić, Marco Pola, Kosta Urumović, *Mauro Cacace, Duygu Kiyan, Katarina Mišić*, *Renato Buljan, Hrvoje Burić, Tomislav Novosel, Nedeljko Stanić, Josip Terzić*

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About HyTheC

- funded by the Croatian Science Foundation (Grant Nº UIP-2019-04-1218)
- funded amount **267.000 €**
- Employment of **PhD student** and **PostDoc researcher** (half of the funding are their salaries)
- duration: **2/2020 – 5/2025**
- The goal of all installation research projects funded by CSF = establishing competitive research groups of early career scientists specialised in some research topic

Motivation

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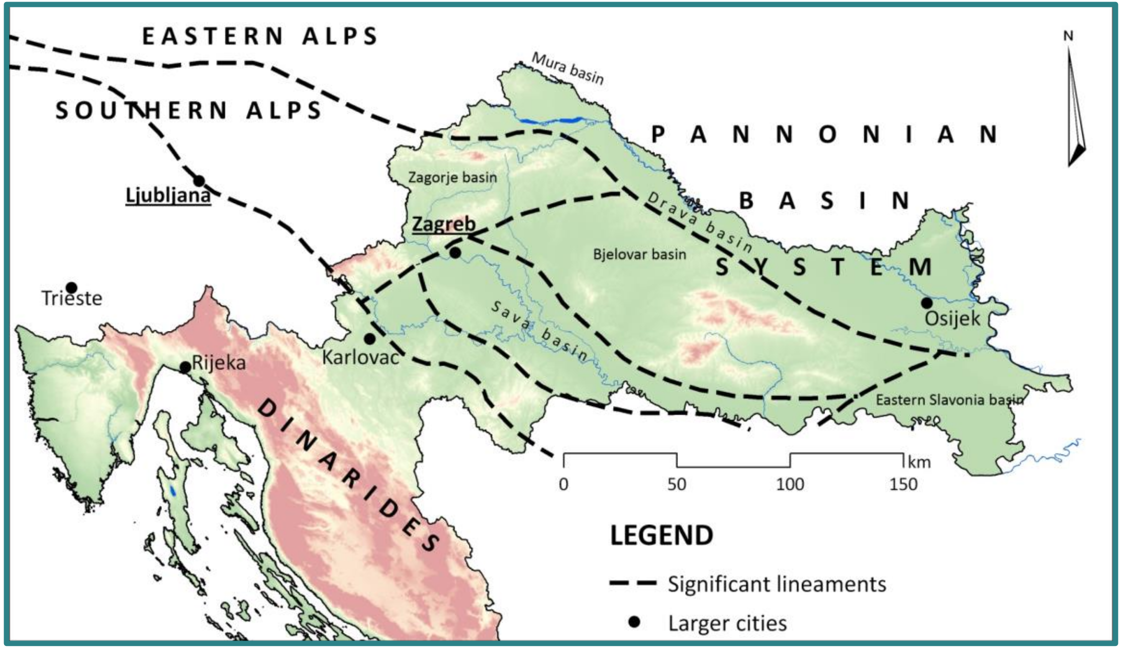
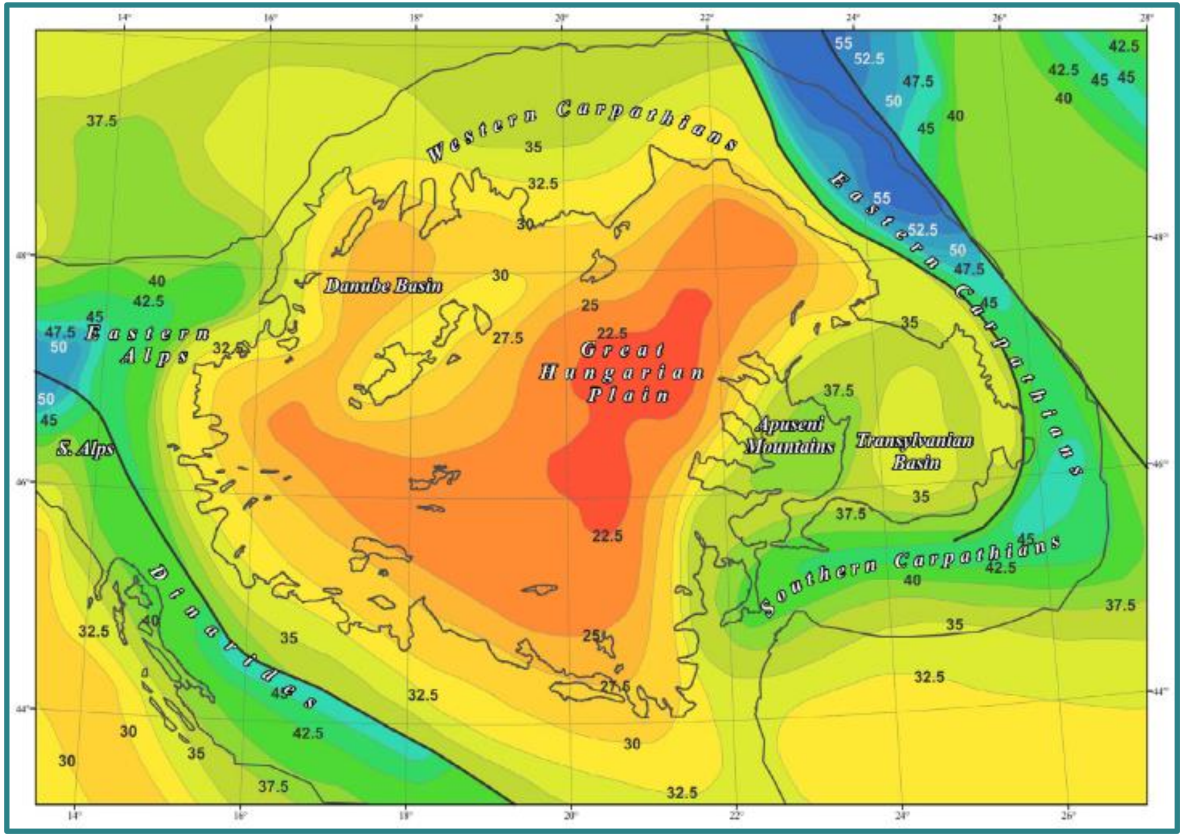


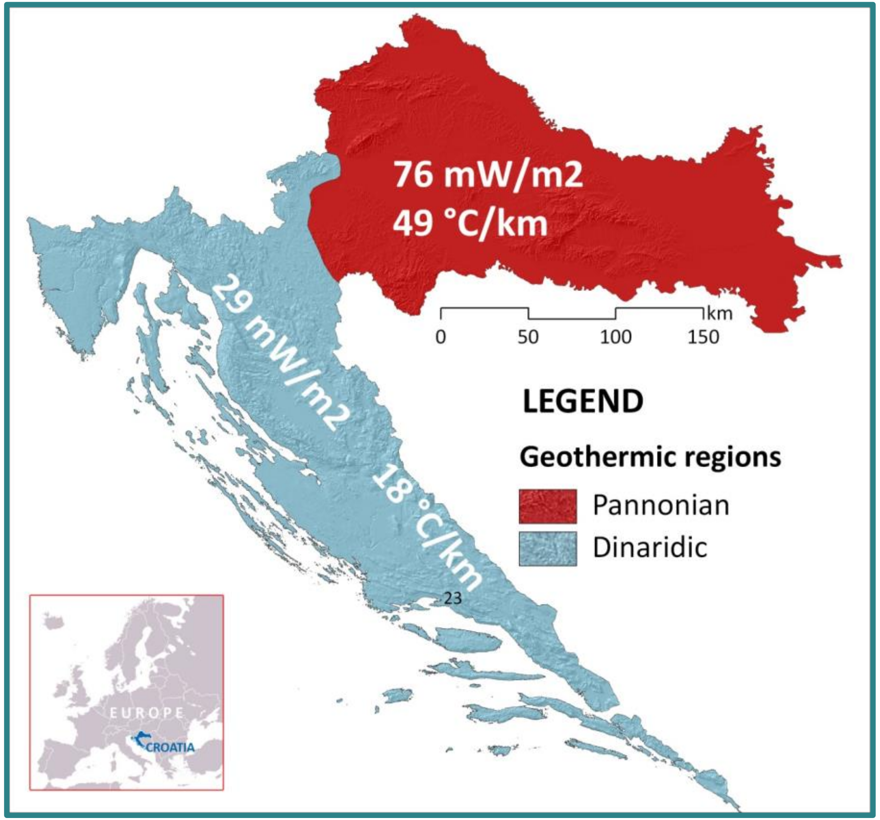
Position of Croatia with regard to large European tectonic units (according to Tari & Pamić, 1998; Lučić et al., 2001; Velić et al., 2012)

Motivation



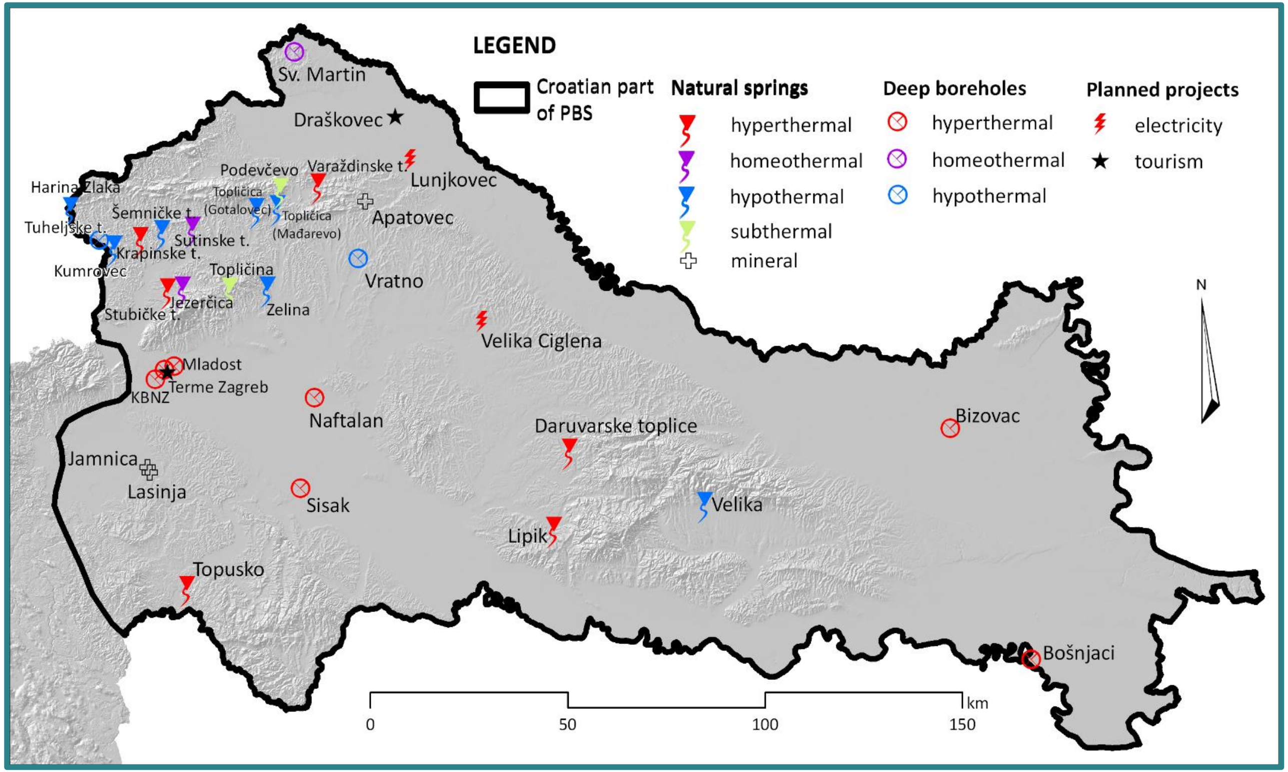
Horvath et al. (2006)

Motivation



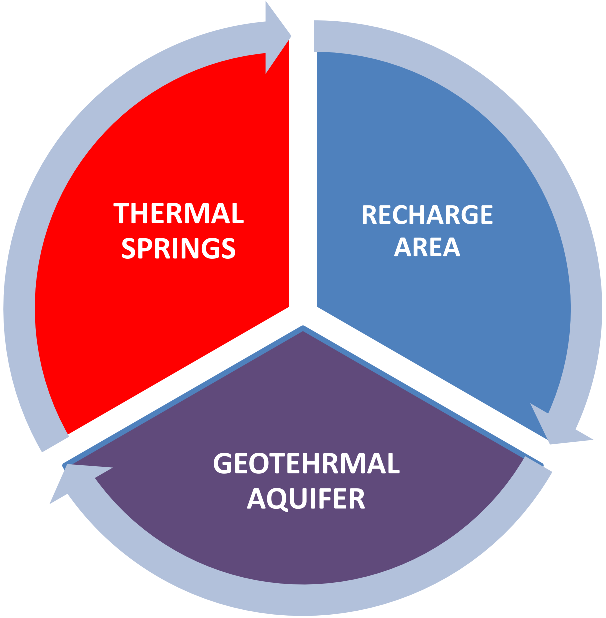
Heat flow densities and geothermal gradients (modified according to Borović et al. 2016)

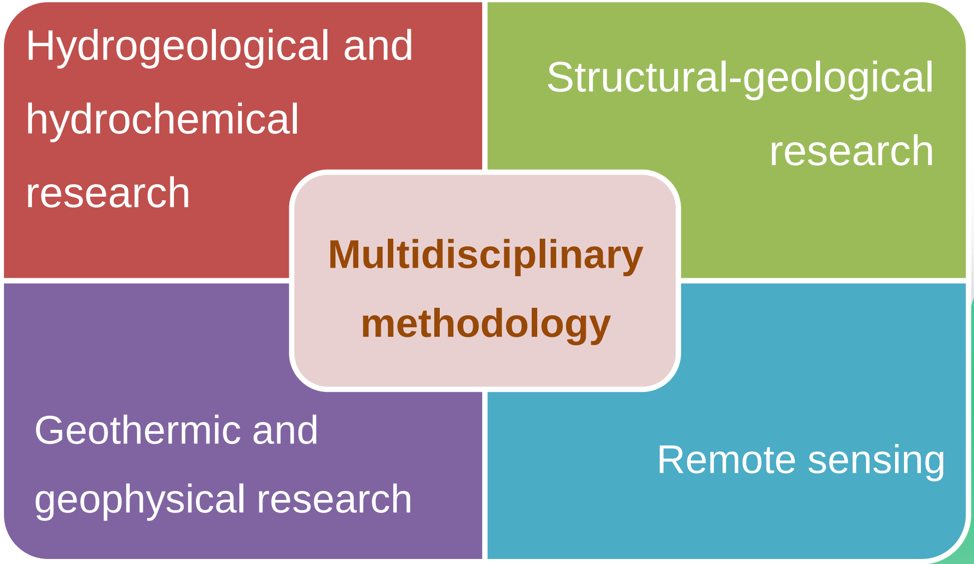
Motivation



Thermal waters in Croatia (according to Borović & Marković, 2015)

HyTheC methodology





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2 YEARS:

Continuous monitoring

- *GW levels*
- *temperatures*

Periodic monitoring

- *in situ parameters*
- *major anions and cations*
- *metals*
- *stable water isotope analyses*
- *radioactive isotope analyses (3H & 14 C*
- *stable 34S and 18O isotope analyses from sulphate anion*

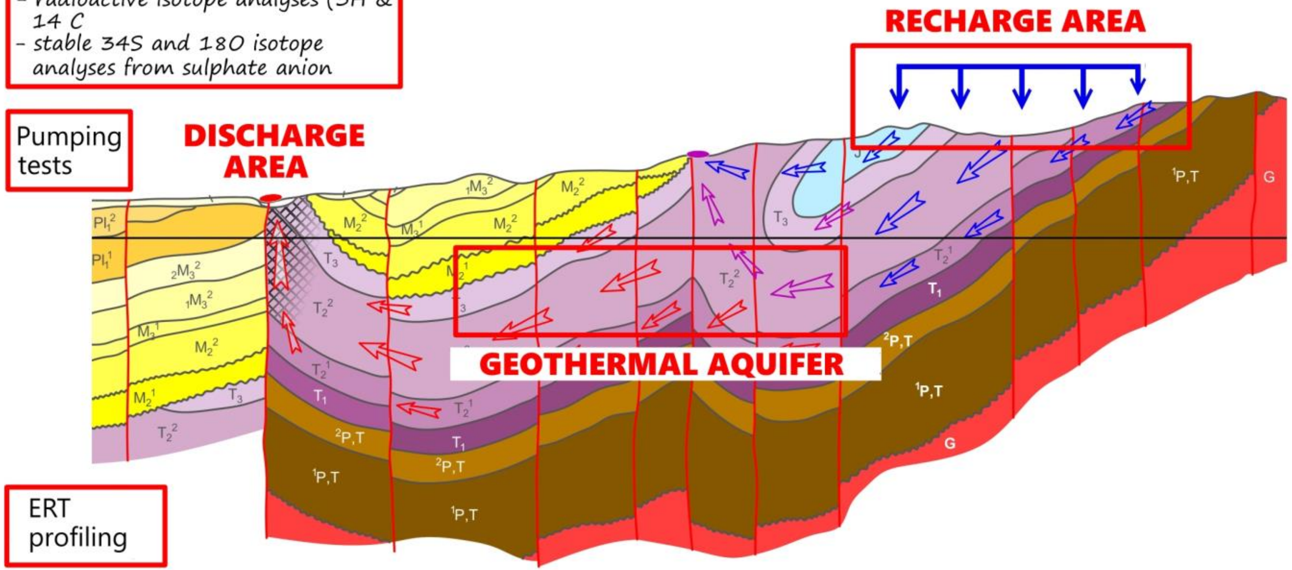
Structural geological mapping

Rock sampling for thermal properties measurements

Magnetotelluric sounding (A)MT

Remote sensing by UAV

Precipitation sampling



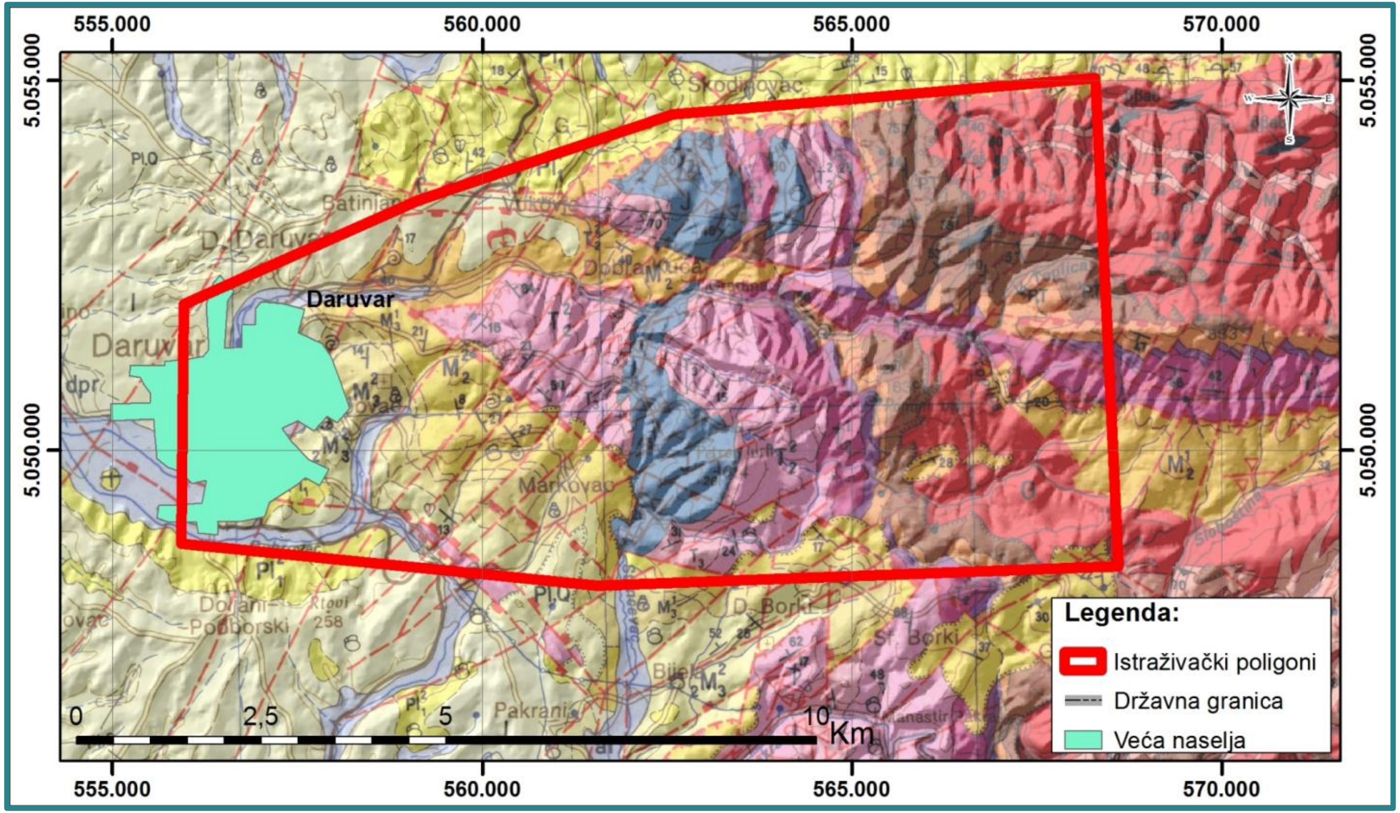
HyTheC pilot areas

Daruvar

Hrvatsko zagorje

Topusko

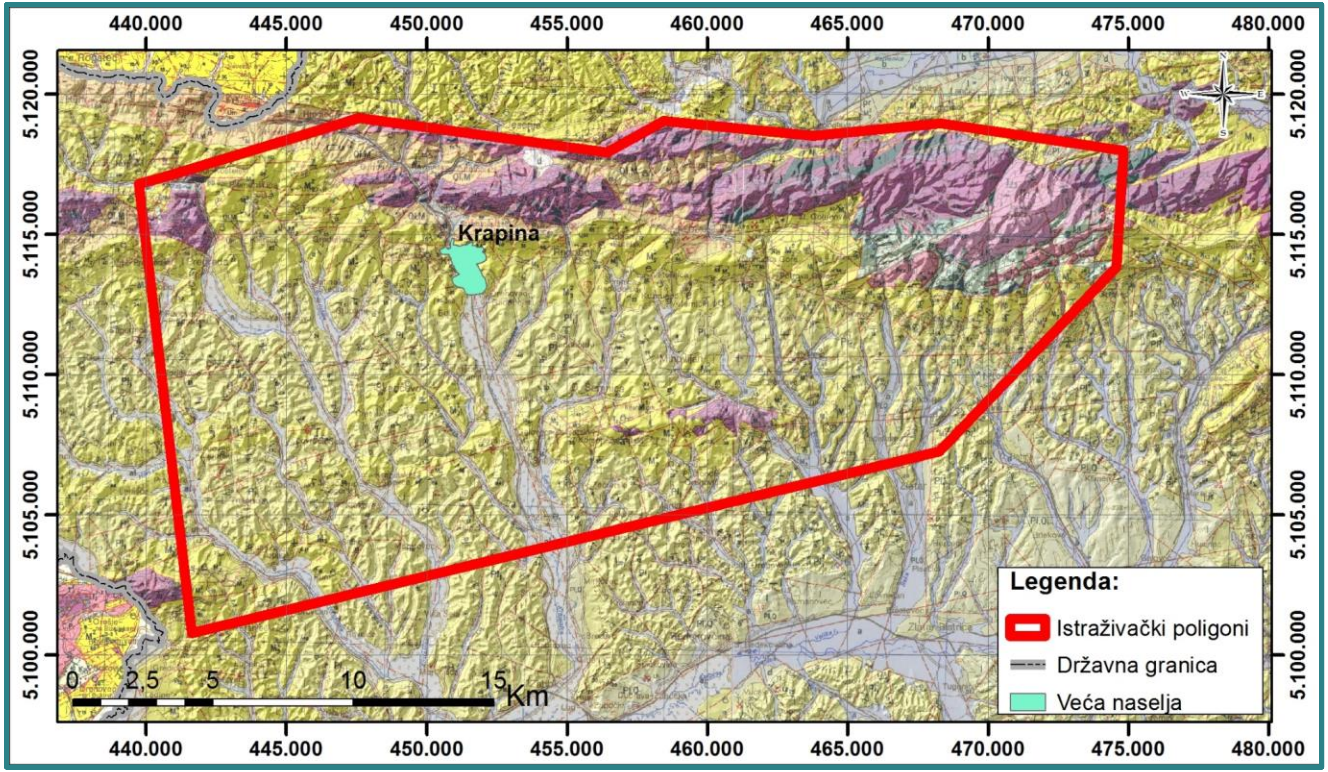
HyTheC pilot areas



Daruvar

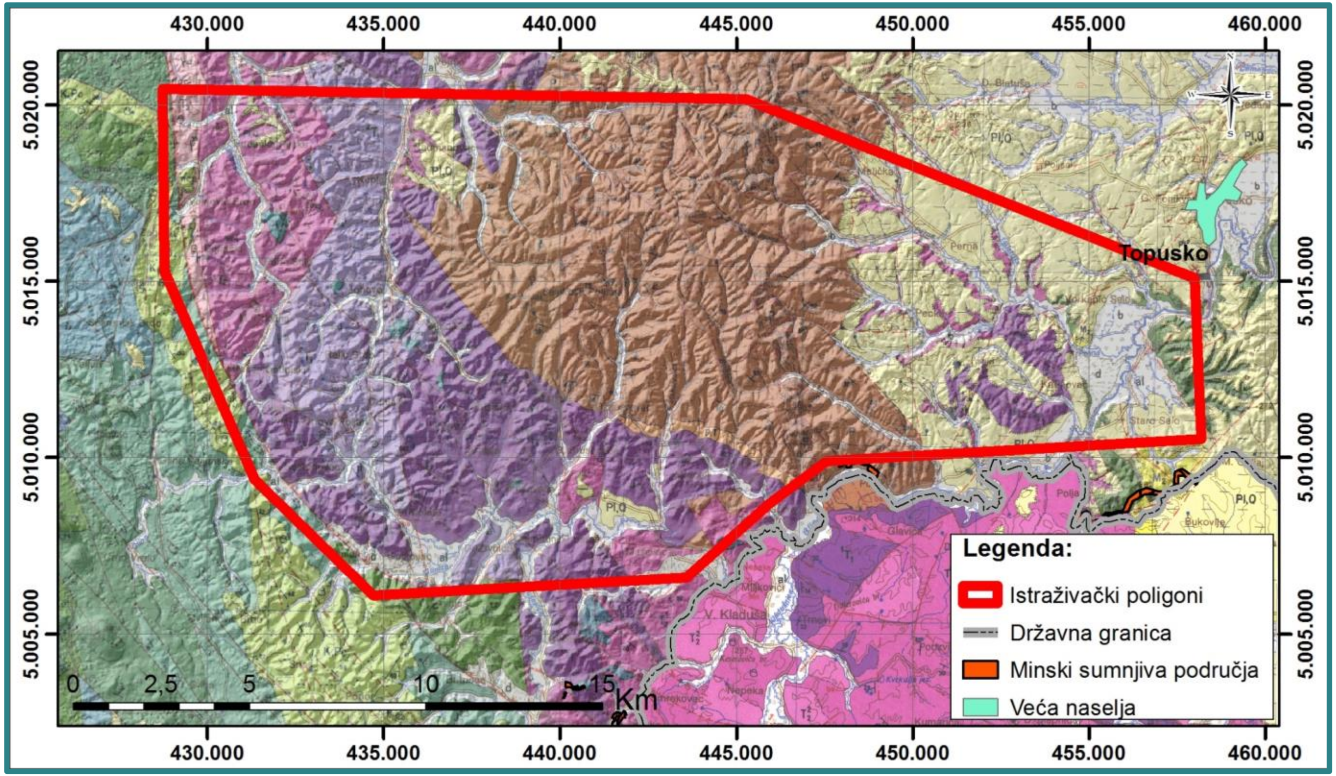
HyTheC pilot areas

HyTheC



Hrvatsko zagorje

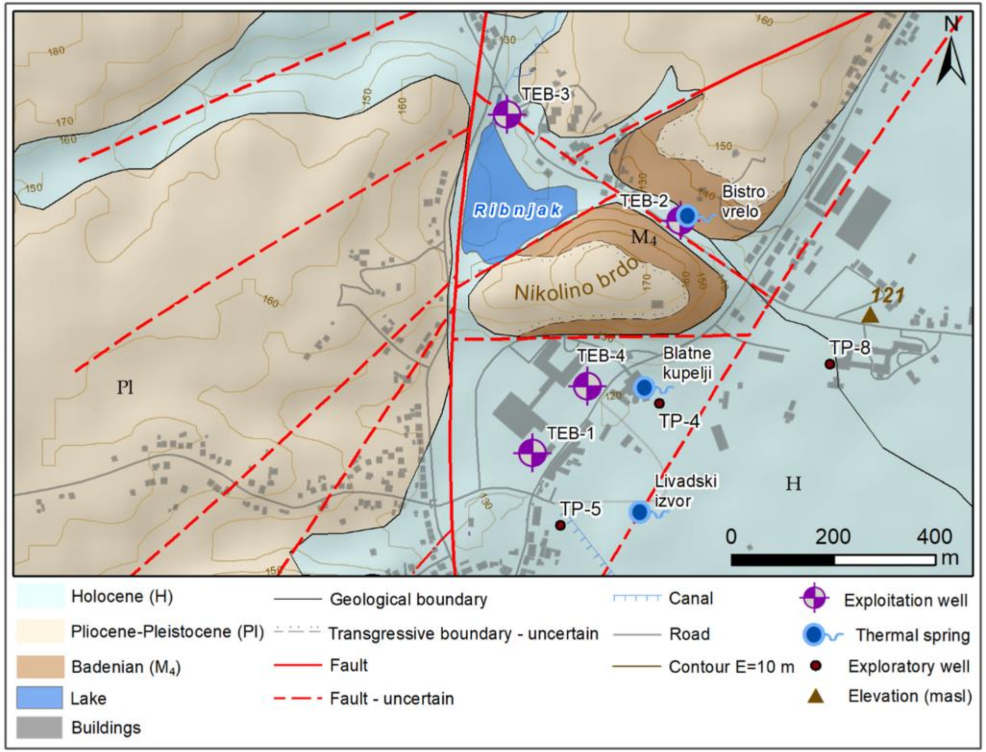
HyTheC pilot areas



Topusko

Thermal water for heating purposes

Topusko

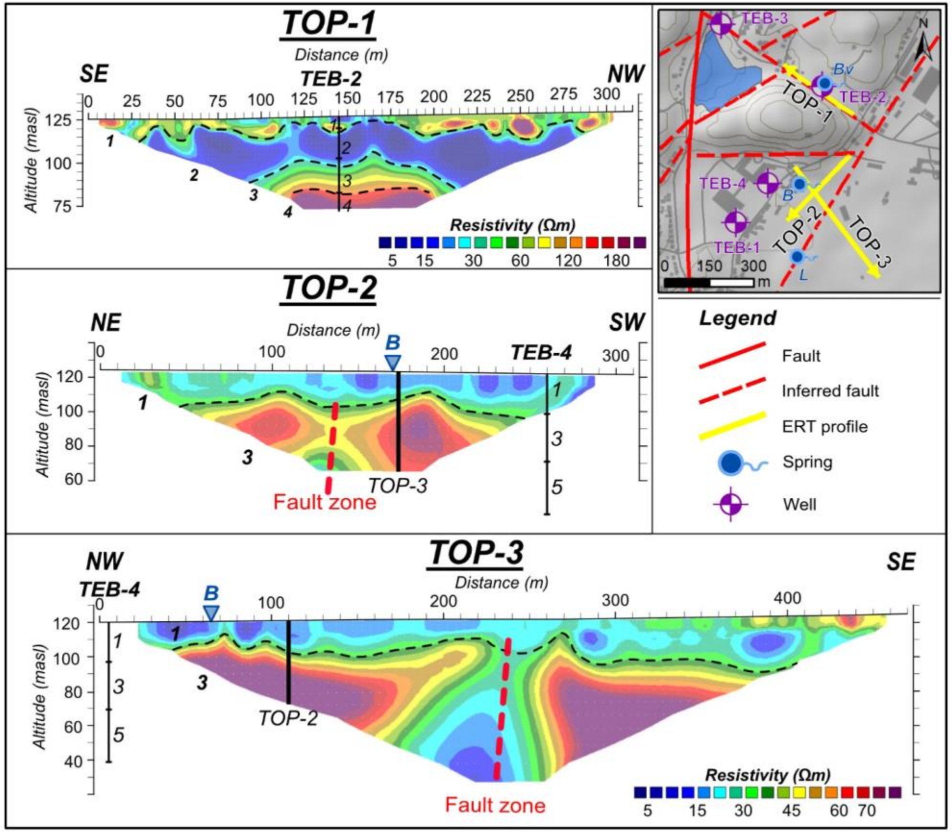


Topusko

DISCHARGE

AREA

Topusko



Previously supposed faults proven by ERT research

Topusko discharge area

- HYDROGEOLOGICAL PARAMETERS
- T = 2 * 10^{-2} m_2/s
- K = 2 * 10^{-4} m/s
- Also done for TEB-3

Pavić et al., 2023

Step-drawdown test

Well: TEB-1 Municipality: Topusko Date: 16-Sep-21

Table S A1

Step	Q (l/s)	Q (m^3/s)	P_{in} (bar)	P_{fin} (bar)	Density (kg/m^3)	Δ (m)	Δ/Q (s/m^2)
0	0.00	0.0000	1.3992	1.3992	981.46	0.00	
1	2.69	0.0027	1.3992	1.3819	981.46	0.18	66.87
2	3.12	0.0031	1.3819	1.3735	981.46	0.27	85.57
3	3.90	0.0039	1.3735	1.3718	981.46	0.29	73.09
4	6.95	0.0070	1.3718	1.3414	981.46	0.60	86.43
5	24.08	0.0241	1.3414	1.0598	981.46	3.52	146.38
6	23.41	0.0234	1.3910	1.0502	981.46	3.62	154.82
REC	0.00	0.0000	1.0598	1.3910	981.46	0.09	

Table S A2

LINEAR REGRESSION Δ/Q = b + mQ			
m	b	3686.34	62.78
se_m	se_b	340.06	4.83
r^2	se_y	0.97	7.77
F	d_f	117.51	4.00
ss_{reg}	ss_{res}	7100.12	241.68

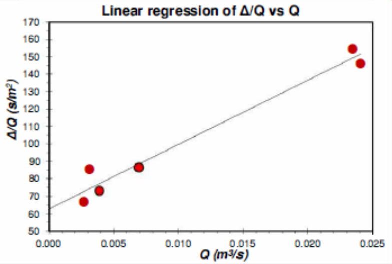


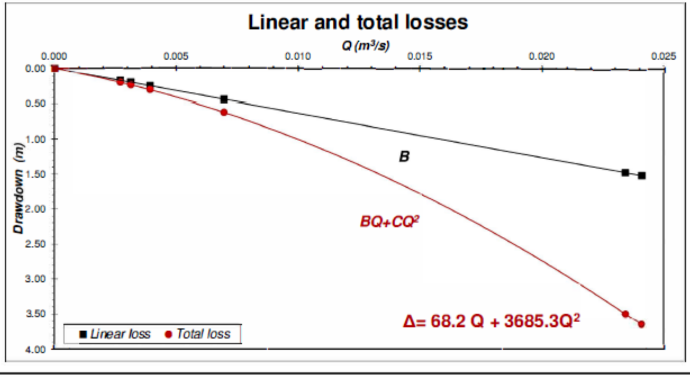
Table S A3

$Δ = (B+B')Q + CQ^2$

B= aquifer loss; B' = linear well loss; C = well loss

$Δ = 62.8\ Q + 3686.3\ Q^2$

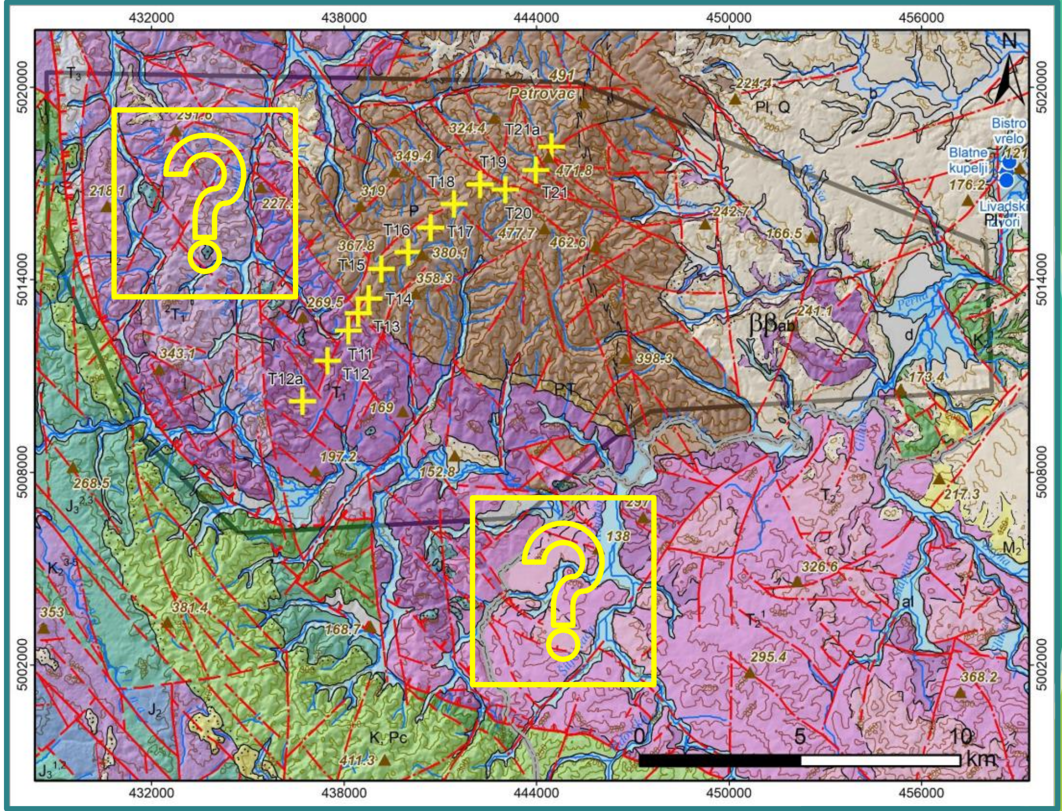
Field data		Linear regression			Well efficiency
Q (m^3/s)	Δ (m)	(B+B')Q (m)	CQ^2 (m)	Δ (m)	(%)
0.000	0.000	0.000	0.000	0.000	
0.003	0.180	0.169	0.027	0.196	86.36
0.003	0.267	0.196	0.036	0.232	84.52
0.004	0.285	0.245	0.056	0.301	81.37
0.007	0.601	0.436	0.178	0.614	71.02
0.024	3.525	1.512	2.138	3.649	41.43
0.023	3.624	1.470	2.020	3.490	42.11
0.000	0.085	0.000	0.000	0.000	



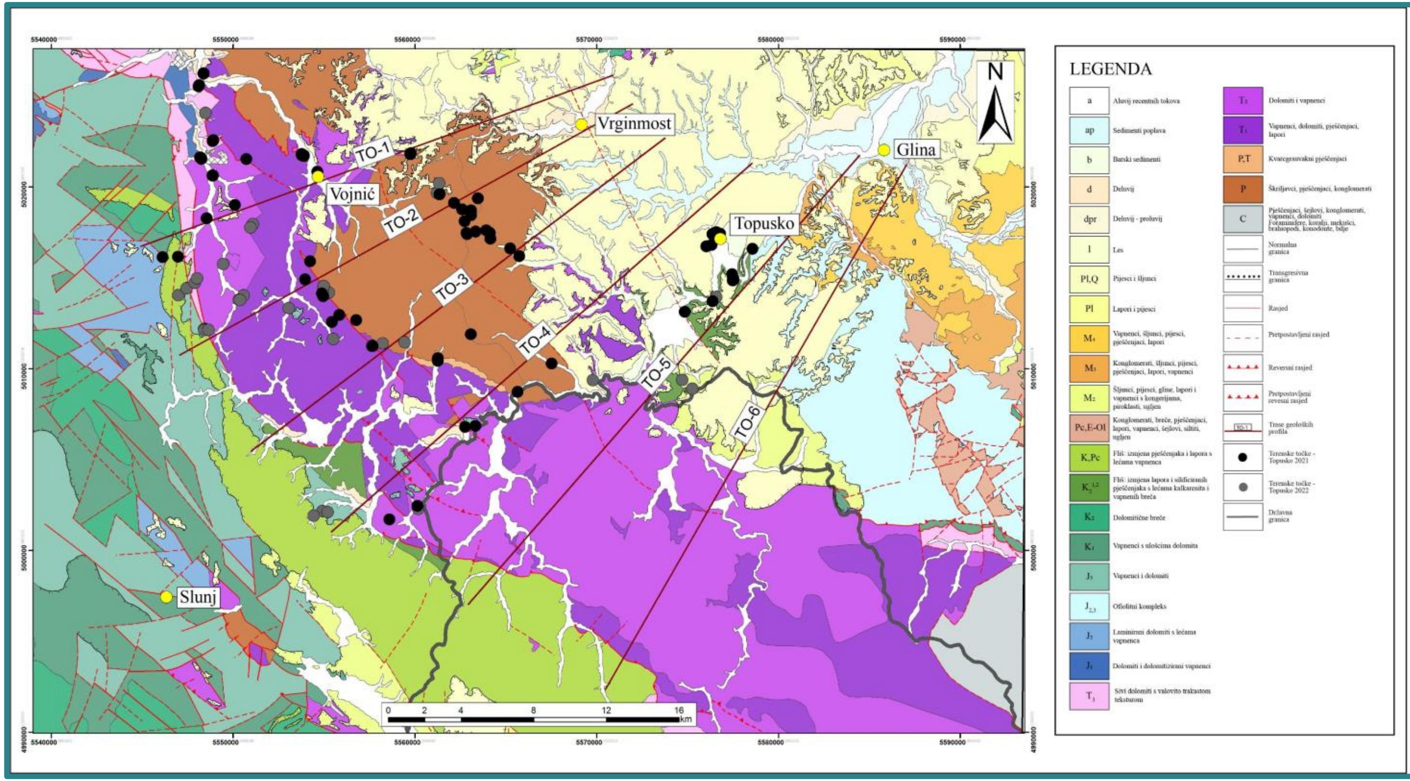
Topusko recharge area

- **Šimunić (2008)** recharge west from the Petrova gora Mt. thrust

- **INA Projekt (1986)** proposed research between Petrova and Zrinska gora Mts. (900 km^2) to determine the geothermal potential

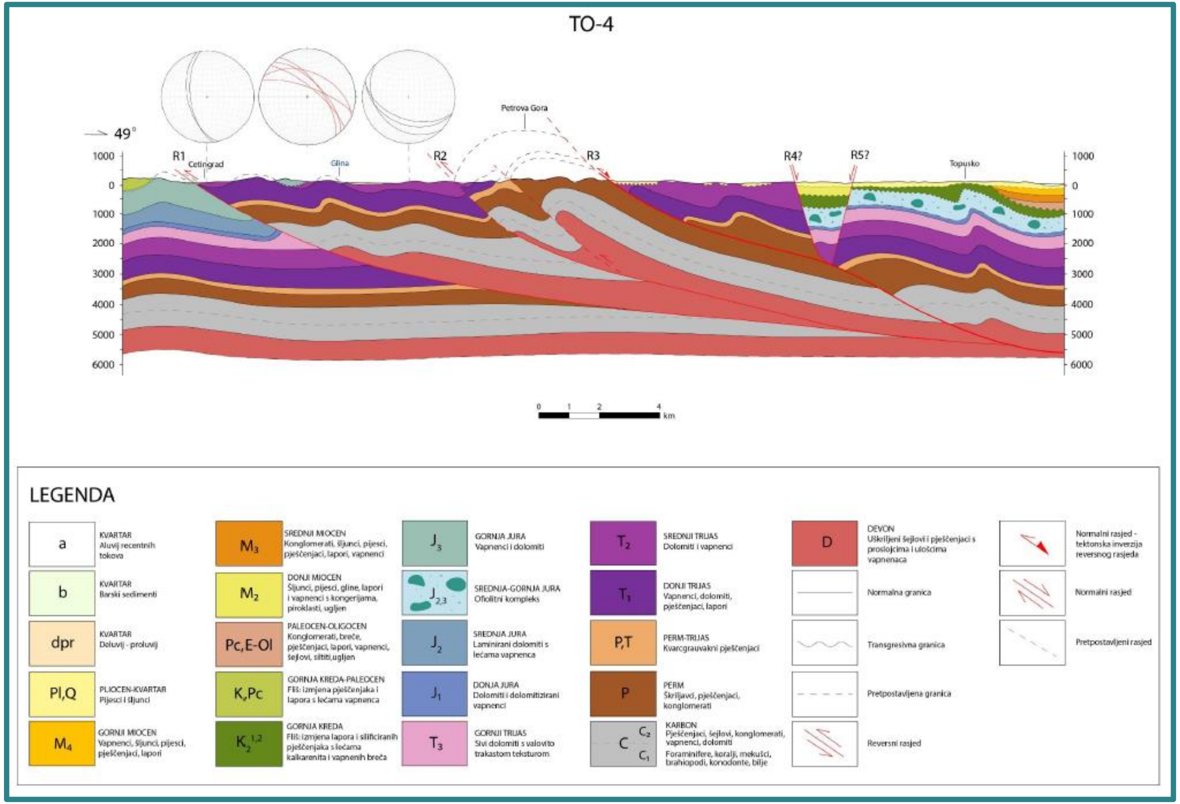


Topusko recharge area



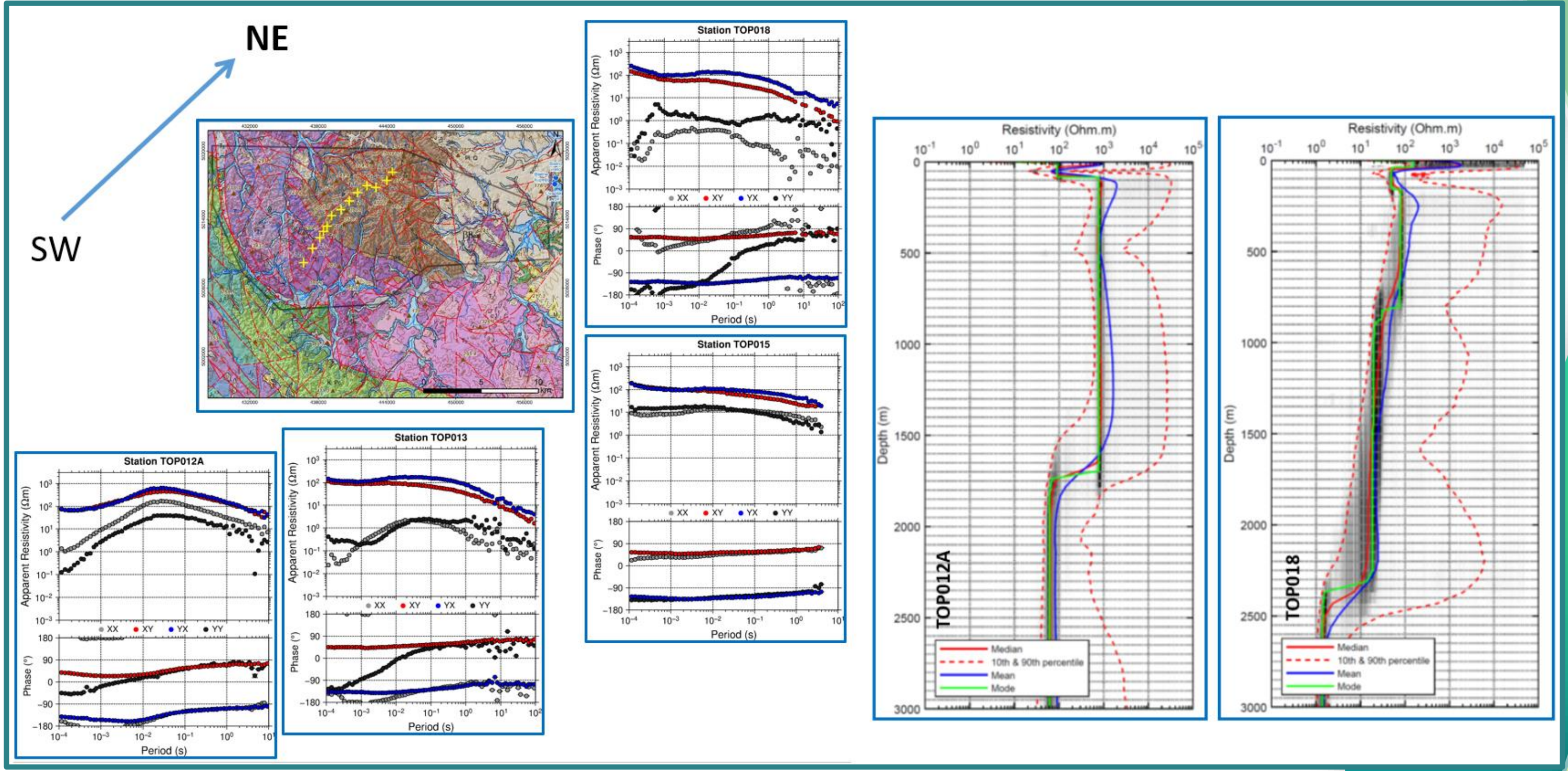
Mišić (2022): Synthetic geological map based on OGK SFRJ in 1:100.000 scale, sheets Črnomelj (Bukovac i dr., 1984), Karlovac (Benček i dr., 2014), Sisak (Pikija, 1987), Ogulin (Velić & Sokač, 1982), Slunj (Korolija i dr., 1980), Bosanski Novi (Šikić, 1988) te Geološka karta SFR Jugoslavije mjerila 1:500 000 (Savezni geološki zavod, 1970)

Topusko recharge area



Mišić (2022)

Topusko recharge area



Topusko hydrochemistry

Sampling site	Statistics	T	pH	EC	TDS*	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	NO_3^{2-}	SiO_2
		°C	-	µS/cm						mg/L				
Livadski izvor spring	Mean	52.4	6.5	620.4	545.6	80.78	16.30	17.66	11.0	244.7	98.31	17.5	0.6	38.1
	Min	51.4	6.38	582	497	78.21	14.58	17.32	10.7	231.8	78.62	14.47	0.3	35.3
	Max	53.2	6.755	635	562	82.42	16.92	17.92	11.3	257.42	106.81	19.38	2.9	40.5
	St. dev.	0.5	0.1	10.1	14.1	0.8	0.5	0.2	0.2	6.8	7.3	1.3	0.8	1.4
Blatne kupelji spring	Mean	48.0	6.8	636.2	556.3	83.41	16.73	17.87	11.1	249.57	100.74	17.87	0.5	37.8
	Min	44.1	6.51	593	503	78.70	14.79	17.60	10.9	233.02	81.60	14.64	0.3	28.6
	Max	51.9	7.395	650	574	86.02	17.28	18.17	11.5	258.64	108.66	19.68	0.6	41
	St. dev.	2.3	0.3	13.0	15.2	1.8	0.5	0.2	0.2	6.0	7.4	1.3	0.1	2.3
Well TEB-4	Mean	62.2	6.6	625.8	554.8	81.96	16.72	17.87	11.2	248.88	100.02	17.63	-	39.1
	Min	46.8**	6.35	607	502	79.64	14.97	17.54	10.9	234.24	75.40	12.81	-	36.3
	Max	65.2	6.71	670	577	82.76	17.21	18.17	11.5	268.40	109.24	19.60	-	41.4
	St. dev.	3.9**	0.1	13.9	16.8	0.7	0.4	0.2	0.2	7.7	8.7	1.7	-	1.5

- **Results of periodic monitoring (3/2021 – 2/2023)**
- **72 water samples)**

- mildly acidic pH
- TDS 497 - 577 mg/l → low mineralisation
- TDS typical for HTSs of the PBS-a (<1 g/l; Milenić et al., 2012)

low mineralisation points to meteoric water recharge

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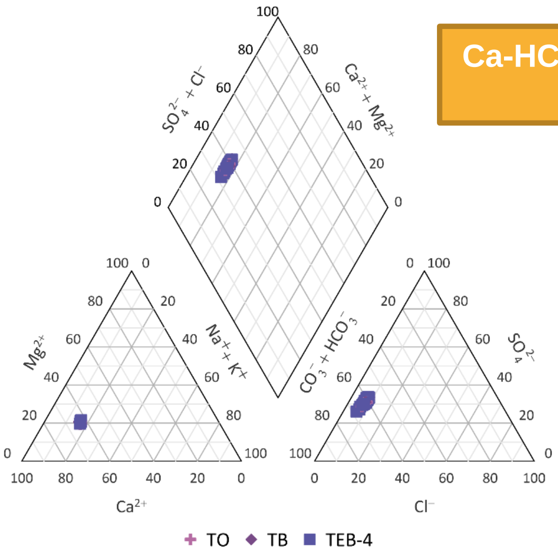
Principal anions and cations

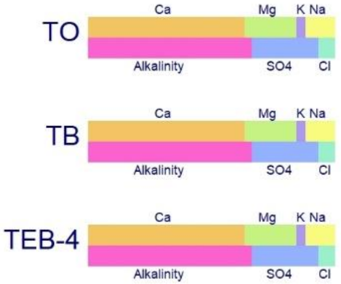
Quality of the analitics checked by calculating *Charge Balance Error*:

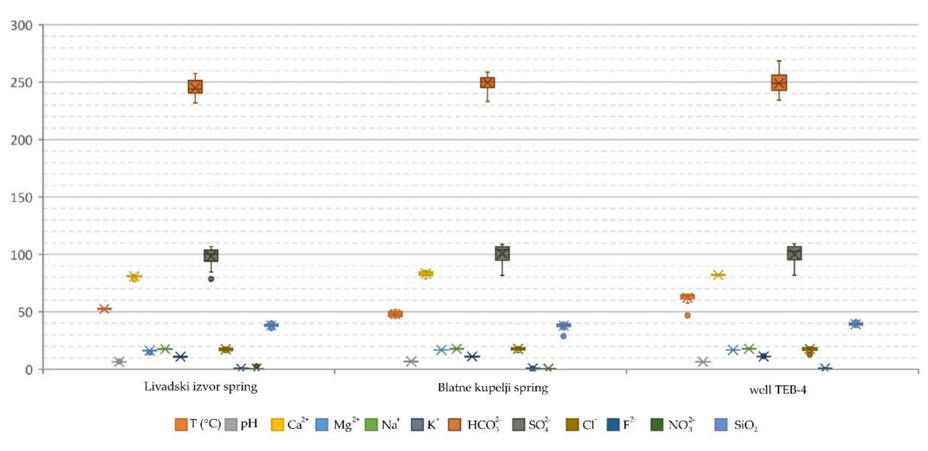
$$C.B.E(\%) = \frac{\sum cations - \sum anions}{\sum ions} \times 100\ (\%)$$

Piper diagram - Topusko (2021-2023)



Ca-HCO$_3$ hydrochemical facies





$Ca^{2+} > Na^+ > Mg^{2+} > K^+$

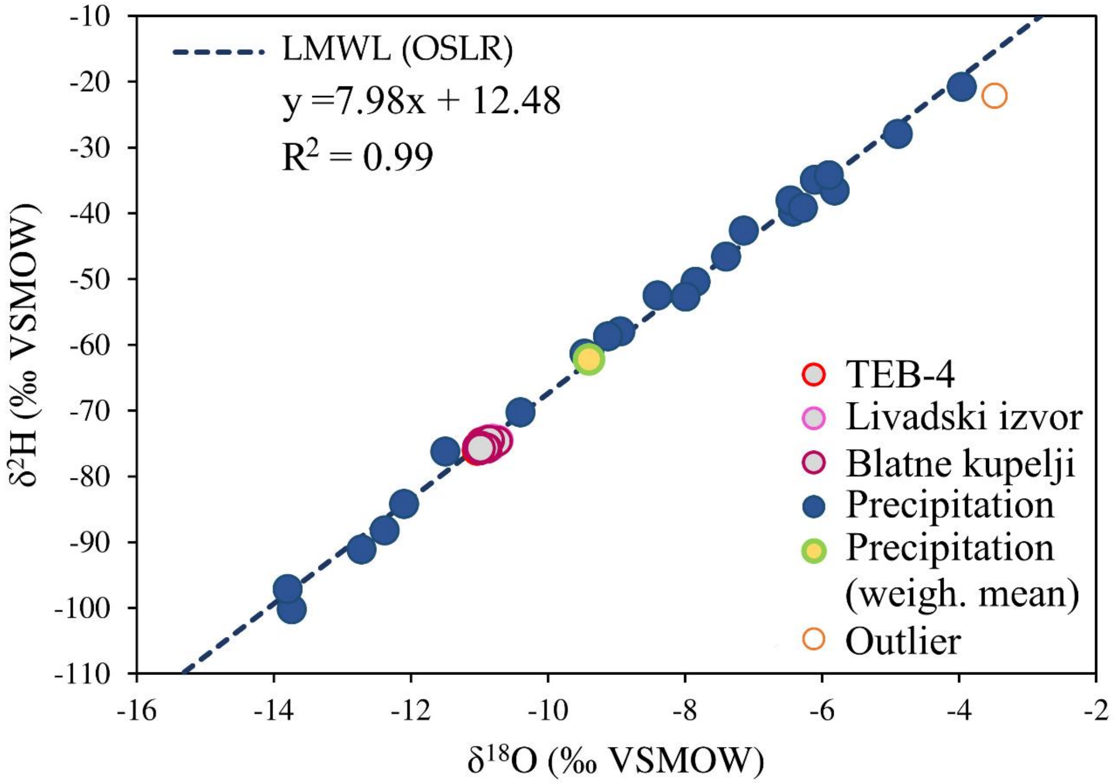
Ca^{2+} dominant

Ion composition very stable

↓

Large and stable HTS

Stable water isotopes



Geothermal aquifer receives meteoric water recharge

Radioactive isotopes - tritium

^{3}H

Well, sampling date	Depth (m)	Conditions	Bq/L	TU (tritium unit)
TEB-4; 12.5.2022.	80.8	Maximal use of thermal water*	0.10 ± 0.10	0.89 ± 0.82
TEB-4; 13.9.2022.	80.8	Minimal use of thermal water	0.02 ± 0.03**	0.14 ± 0.28**

* The end of the district heating season, which lasts around 205 days. ** Below detection limit

- **^{3}H not detected →** recharge before 1950
- **^{3}H > 0.5 TU →** mixing with younger water from shallower aquifers

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Radioactive isotopes - radiocarbon ^{14}C

Well, sampling date	Conditions	^{14}C (pMC)	^{14}C (pmc)	$\delta^{13}C$ (‰ VPDB)	Apparent DIC ^{14}C age (BP)
TEB-4; 12.5.2022.	Maximal use of thermal water*	13.1 ± 0.1	26.8	-4.3	16 330 ± 40
TEB-4; 13.9.2022.	Minimal use of thermal water	12.4 ± 0.1	25.3	-4.3	16 790 ± 40

*The end of the district heating season, which lasts around 205 days.

- **Corrections for A_0 needed →** water dissolves Triassic carbonates which have ^{14}C activity of zero (decayed long ago!)

- With corrections, age probably **8.473 – 9.536 years BP**

Effects of the research

- GT resources are investigated globally for projects of GT water and energy utilisation
- There is usually a significant gap between the specific locations of utilisation in comparison to regional scale researches of entire HTSs
- Long-term sustainable utilisation of natural thermal springs cannot be planned or secured without system-level understanding

Effects of the research

- Multidisciplinary research group has been formed which can answer this challenge using the appropriate skill set, equipment, and methodology
- Final bilingual publication with a critical review of applying the methodology to three HTSs with diffrent initial knowledge will be a useful guide for future investigations

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Effects of the research

- **PROBLEM:**
  - Thermal springs and thier recharge areas are not protected by sanitary protection zones like springs used for water supply
  - If they are not used as a heat source the aquifers also don’t need to be tested according to Hydrocarbons and geothermal water exploitation act
- That way the utilisation and protection of HTSs remain poorly regulated since thermal springs are mostly not used either for water supply, or as a heat source
- **GOAL:**
  - To share the knowledge about the neccessity of sustainable utilisation and management with the users, while also trying to influence the decision-makers and regulatory bodies to implement the contemporary knowledge and concepts into the regulatory framework

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Publications

Article

Reconstruction of Fault Architecture in the Natural Thermal Spring Area of Daruvar Hydrothermal System Using Surface Geophysical Investigations (Croatia)

Ivan Kosović [1], Maja Briški [1], Mirja Pavić [1,*], Božo Padovan [2], Ivica Pavičić [3], Bojan Matoš [3], Marco Pola [1] and Staša Borović [1]

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[2] Terra Compacta Ltd., Ulica Psunjska 3, 10000 Zagreb, Croatia; tc@terra-compacta.hr
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Abstract: The sustainable utilization of geothermal energy mostly depends on the characteristics of the geothermal resource from which it is extracted. Among others, detailed geological modeling is a key factor for estimating the potential of a geothermal resource. This research focuses on the modeling and reconstruction of the geological setting of the Daruvar thermal spring area using geophysical techniques. An integrated geophysical approach based on electrical resistivity tomography (ERT) and both active and passive seismic (MASW and HVSR) methods was used. Based on ERT results and the stratigraphic logs of the wells in Daruvar, three resistivity layers/geological units were identified. The deepest layer with resistivity < 150 Ωm is the Triassic carbonate that constitutes the thermal aquifer. Sharp lateral variations in the resistivity distributions within the bedrock were interpreted as fault damage zones saturated with thermal waters. Integrating the results of the seismic methods, the thickness of the first seismic layer that corresponds to the Quaternary cover was estimated from 5 to 20 m. Here, results of the geophysical investigations were combined into a 3D geological model highlighting the occurrence of subvertical N-S and E-W trending faults in the Daruvar spring area. The N-S-trending fault was interpreted as a fault plane parallel to the regionally mapped Daruvar fault. This fault juxtaposes the Triassic carbonate complex of the thermal aquifer with a Neogene sedimentary sequence of significantly lower permeability. Neogene–Quaternary

Article

Multidisciplinary Research of Thermal Springs Area in Topusko (Croatia)

Mirja Pavić, Ivan Kosović *, Marco Pola, Kosta Urumović, Maja Briški and Staša Borović

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Abstract: Topusko is the second warmest natural thermal water spring area in Croatia, located at the southwest edge of the Pannonian Basin System. Due to favourable geothermal properties, these waters have been used for heating and health and recreational tourism since the 1980s. Thermal springs with temperatures up to 50 °C are the final part of an intermediate-scale hydrothermal system. However, systematic research on the Topusko spring area has not been conducted to lay the foundation for sustainable resource utilisation. Multidisciplinary research including the hydrogeochemical characterisation of naturally emerging thermal water, an electrical resistivity tomography (ERT) investigation conducted to reconstruct the subsurface geology, and hydrogeological parametrisation of the geothermal aquifer was carried out to refine the existing local conceptual model. The results show Ca-HCO_3 facies of Topusko thermal waters, which get heated in a Mesozoic carbonate aquifer. The water equilibrium temperature in the geothermal aquifer is estimated to be 78 °C based on the *SiO_2-quartz* geothermometer. The fault damage zone, which enables the upwelling of thermal water, was identified by ERT investigations. The transmissivity values of the aquifer derived from the results of step-drawdown tests range from 1.8×10^{-2} to 2.3×10^{-2} m^2/s. Further multidisciplinary research is necessary to improve the existing conceptual model of the Topusko hydrothermal system.

Keywords: thermal spring; hydrogeochemical characteristics; electrical resistivity tomography; hydrogeological parameters; hydrothermal system; Croatia

Article

Identification of Aquifer and Pumped Well Parameters Using the Data Hidden in Non-Linear Losses

Kosta Urumović [1], Josip Terzić [1], Jasna Kopić [2,*] and Ivan Kosović [1]

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[2] Vinkovci Water and Wastewater Association Ltd., Ul. Dragutina Žanića Karle 47a, 32100 Vinkovci, Croatia
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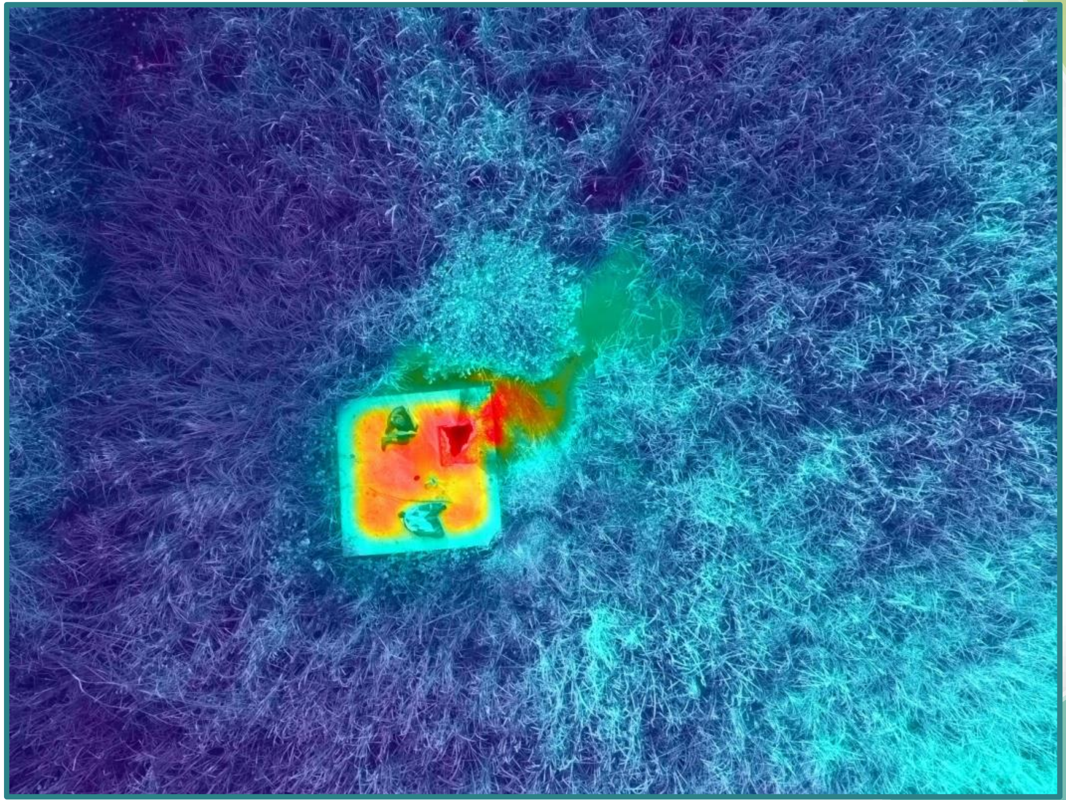
Abstract: During the pumping of wells, the groundwater level drawdown, as measured in the pumped well, is increased by non-linear losses caused by the water flow velocity through the well screens. This undermines the adequacy of the direct use of the measured drawdown data in the well for the purpose of the realistic identification of the effective well radius and aquifer parameters. This anomaly is avoided by reshaping the drawdown function into a function of the specific drawdown s_w/Q of the pumped well. This reshaping simplifies the exclusion of non-linear losses from the sequence of measured data of the water level in the well at the position of the effective radius of the pumped well. Combining the data of linear losses and the respective pumping rate of the pumped well, a function of the specific drawdown of the radial flow s_w/Q was formed. This function describes the aquifer parameter relations during the respective test pumping. A consistent sequence of the function of the specific drawdown s_w/Q of the pumped well reveals the actual value of the coefficient of nonlinear losses. Moreover, the specific drawdown function enables the reliable estimation of aquifer transmissivity using only the pumped well drawdown data.

Keywords: well-loss parameters; specific drawdown; effective well radius; well-loss constant; transmissivity

- All publications available on the project web site
- https://hythec.wordpress.com/publications/



Thank you for your attention!