Update on Composite Geochemical Conceptual Model for the Bešeňová Elevation Geothermal Structure, Liptov Basin, Northern Slovakia

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ABSTRACT

Whether in phase of initial exploration and prospection, drilling, or monitoring on production response, geochemistry and geothermometry gained high reputation in a past worldwide. Amongst basic description and classification of thermal waters, temperature estimation and analysis of technical properties, both methods are frequently applied in conceptual model construction, here presented in conditions of the Bešeňová elevation geothermal structure, northern Slovakia, being recognized as open hydrogeological system of stratified reservoirs in the production part. Paper manifests essential facial analysis and maturity models correlated with mixing and boiling inspection designed plots (chloride – boron, chloride – sodium, chloride – total carbonate) and geothermometers. In conclusions, the Bešeňová elevation appears a complex system of polystageous mixing within infiltration, accumulation and discharge zone, however, with no evidence on boiling. Amongst description of basic reservoir processes, a minor discharge zone in the Sliače area is identified, well conform to a model derived by reservoir base overheating analysis. Immaturity resultant to albite-muscovite-adularia system instability turns Na/K geothermometry inadequate, whilst chalcedony, Mg-corrected Na-K-Ca and K/Mg geothermometry gains the most precise results in temperature estimation. Type curve analysis and mismatch in MCG and TSI geothermometry appears another hint on separate minor convection cells evolution in deep reservoir.

1. INTRODUCTION

Geochemistry of thermal waters is determined by combination of petrochemical (mineralogy, geochemistry), hydrogeochemical (predominant rock dissolution process, water provenance), thermodynamic (temperature, pressure), hydrodynamic (boiling, mixing,) and hydrogeological (effective water-rock interface area, residence time, flow regime, hydraulic conductivity) factors in essence. At the same time, advances in understanding the geochemical background of geothermal systems governed by designing numerous models, approaches and methods, conducted over past decades, aid in interpretation (or modeling) of factors and processes controlling the geochemical composition of sampled fluids based on e.g. relative concentration, molar ratios etc.

Geothermal exploration at the Bešeňová elevation links to opening of shallow reservoir producing well, the BEH-1 (Franko et al., 1979). Later replacements of newer wells screening both, the deep (e.g. ZGL-1; Fendek et al., 1988) and shallow (FBe-1; Vandrová et al., 2009) reservoir governed several periods of geochemical sampling used to monitor and classify geochemistry of thermal waters. In fact, the Bešeňová elevation is recognized the open hydrogeological system since detailed studies of mineral waters associated with the Liptov Basin geothermal field. Following campaigns improved concepts of local hydrogeological regime defining the discharge zone towards centre of the system nearby the Bešeňová town (Franko et al., 1979) or localizing the infiltration zone to the Nízke Tatry Mts. (e.g. Zembjak et al., 1986), meanwhile accepting a deep lateral E – W run-off towards Ivachnová depression (e.g. Remšík et al., 1998). The entire conception was, however, derived by piezometry only. This paper presents geochemistry investigation aimed at reconstruction and interpretation of the Bešeňová elevation structure conceptual model, in terms of hydrogeological regime, structural arrangement and intraformation processes. A principal methodology refers to application of boiling and mixing models (e.g. enthalpy-bicarbonate: Fournier, 1989; enthalpy – chloride: Fournier, 1979; Cl/B or Cl/Na cross plots: Arnorsson, 1985) and geothermometry (silica-, cation-, multicomponent-).

2. THE BEŠEŇOVÁ ELEVATION – BACKGROUND OUTLINE

2.1 Definition

The Bešeňová structure represents a pre-Paleogene basement elevation in a western part of the Liptov Basin geothermal field, northern Slovakia (Fig. 1a). The Late Mesozoic – Quaternary tectonic evolution determined a system's structural limitation to surroundings (Fig. 1b); at Bešeňová fault to Ivachnová depression (W), Choč-Ružbachy fault zone to Choč Mts. (N), Vlachy – Ľubeľa fault system to Liptovská Mara depression (E) and SW – NE heading fault swarms to Nízke Tatry Mts. (S).

2.2 Regional geology

The system corresponds to arrangement of Inner Western Carpathians' Neogene-formed intramountain depressions (Fig. 1c). *Devonian – Mid Carboniferous* magmatites and metamorphites form Tatricum Crystalline (TCR) bedrock beneath *Early Triassic – Mid Cretaceous* para-autochthonous Tatricum Envelope Unit (TEU) and allochtonous Krížna Nappe (KNA) system or *Mid Triassic* Choč Nappe (CAN) tectonic slag respectively (Gross et al., 1980), all carbonates dominated. Above, a *Mid Eocene – Latest Oligocene* transgressive – regressive succession of the Inner Western Carpathian Paleogene (IWCP) and *Quaternary* accumulations form a siliciclastics dominated cover (Remšík et al., 1993), reduced in thickness centrewards the system (Gross et al., 1980).
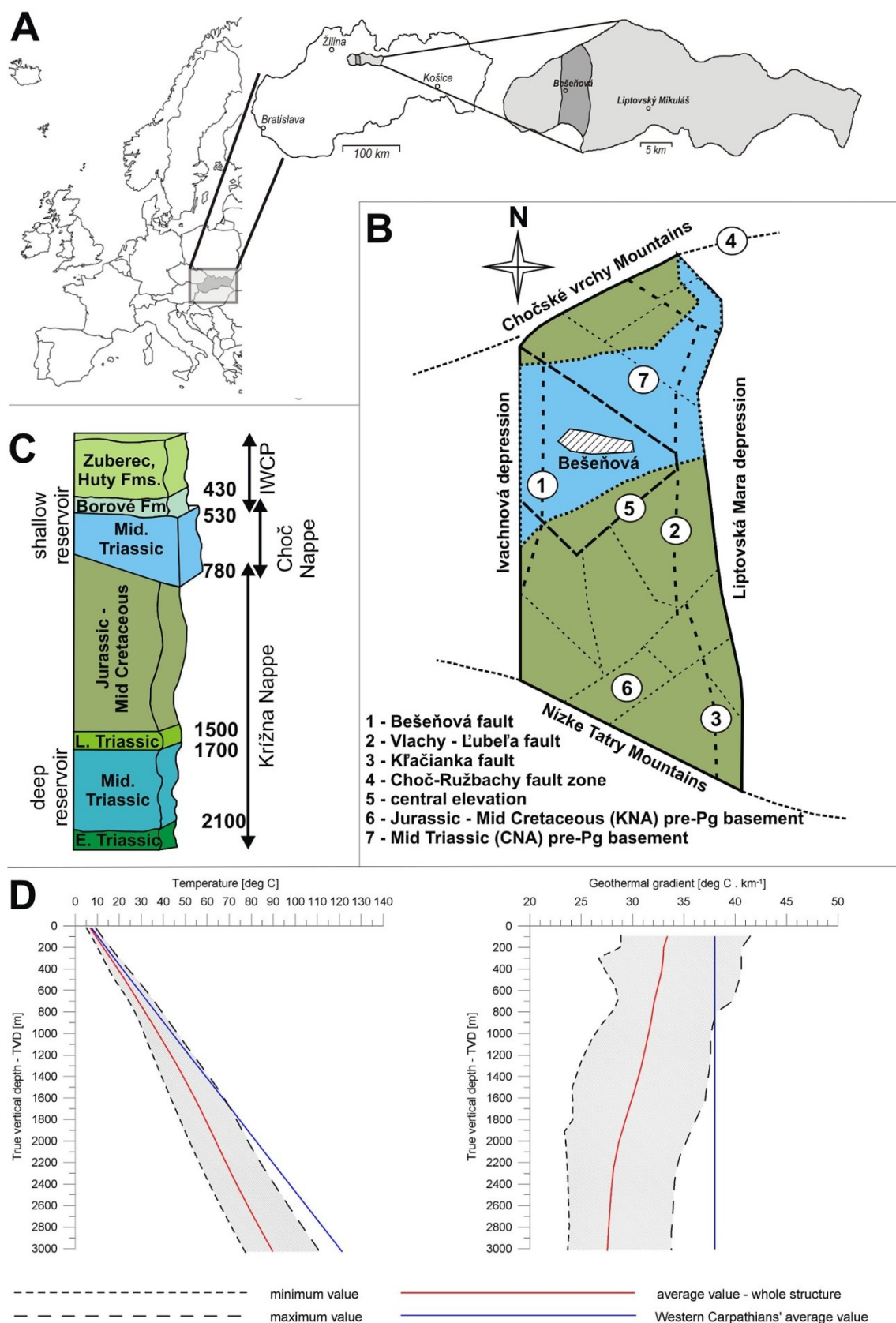
Figure 1: Bešeňová elevation geothermal system description. A) geographical definition, B) regional and structural definition, C) idealized vertical profile with mean TVD of stratigraphic horizons, D) vertical temperature (left) and geothermal gradient (right) distribution

2.3 Vertical structure

Two geothermal reservoirs are encompassed (Řemšík et al., 2005). The *deep reservoir* associates with Mid Triassic carbonates (limestones, dolomites, transient varieties) of the Krížna Nappe, forming a solid body through an entire system, tectonically

segmented into several block in depths between 660 – 3200 m, sealed by Early Triassic (base) and Late Triassic (top) rich-in-evaporites siliciclastics (quartzites, pelite shales) dominated aquicludes. The *shallow reservoir* is distinguished in the CNA Mid Triassic dolomites, hydraulically connected to conglomerates, breccias and detritic carbonates of the Borové Formation (IWCP), however, limited in extension (Fig. 1b).Atop, typical claystones-dominated (Huty Formation) and flysch-dominated (Zuberec Formation) horizons, both IWCP group, form regional insulator, while Jurassic – Mid Cretaceous KNA pelitic and organogene carbonates represent a basal aquitard (Fendek & Remšík, 2005). Even occurrence of thermal waters associated with Mid Triassic TEU carbonates can not be excluded, it has neither been proven yet.

2.4 Geothermics and overheating

The Bešeňová elevation is distinguished of increased geothermic activity (varying $q = 55 – 80$ mw.m^{-2}, increasing centrewards) compared to a mean for the Liptov Basin of $q = 58$ mW.m^{-2} (Remšík et al., 1998). However, the geothermal gradient (Fig. 1D) is fairly below a mean value of the Western Carpathians ($G_{tr} = 38$ °C.km^{-1}), defining the deep reservoir temperature interval varying the $T = 25,4 – 81,2$ °C for the top and $T = 34,7 – 97,1$ °C for the base, whereas a limited tectonic slag of the shallow reservoir in the central (production) zone covers the interval of $T = 9 – 50,4$ °C at a top and $T = 13,8 – 60,2$ °C at a base respectively. Overheating ratio analysis (O'Sullivan, 2010) for the deep ($\tau = 0,13 – 0,38$) and shallow ($\tau = 0,07 – 0,32$) reservoir implies variably distributed base heat increment for both zones, whilst differences in calculated-to-critical Rayleigh (deep: $\delta Ra = 1,5 – 9,8$; shallow: $\delta Ra = 2,3 – 12,5$) and Nusselt (deep: $\delta Nu = 0,03 – 0,23$; shallow: $\delta Nu = 0,3 – 0,33$) number point to possibility of separate minor convection cells in both zones only (Fričovský et al., 2014a), far away from end-member influence (Fig. 2A).

2.5 Lateral arrangement

The system of the Bešeňová elevation is recognized hydrogeologically open (Franko et al., 1979). There is agreement in lateral W-trending inflow from the Liptovská Mara depression, and consensus exists on major discharge zone in the centre of the structure in the town of Bešeňová (Remšík et al., 1993) as well as on hidden lateral runoff to the Ivachnová depression (Remšík et al., 1998), whereas infiltration zone is located to northern slopes of the Nízke Tatry Mts. (Fendek et al., 1988). This paper, however, discusses existence of second, minor discharge zone (Fig. 2B) in the Sliače area – SW (e.g. Fričovský et al., 2012).

3. HYDROGEOCHEMISTRY – METHODS AND ANALYZES

3.1 Samples adjustment

Conceptual geochemical model reconstruction uses samples taken during several campaigns related to in-situ geothermal exploration or monitoring, with following references for the deep reservoir – boreholes ZGL-1 (Fendek et al., 1988; Remšík et al., 1993; Remšík et al., 1998; Vandrová et al., 2009; Vandrová et al., 2011) and FGTB-1 (Vandrová et al., 2011); the shallow reservoir – boreholes BEH-1 (Franko et al., 1979) and FBe-1 (Vandrová et al., 2009); the infiltration zone – wells B-2 and Rudolf and; central discharge zone – springs (Franko et al., 1979); the Sliače discharge zone – well VŠH-1 (Franko et al., 1979) and springs (Zbořil et al., 1972). Mean values of key geochemical parameters are listed below (Tab. 1).
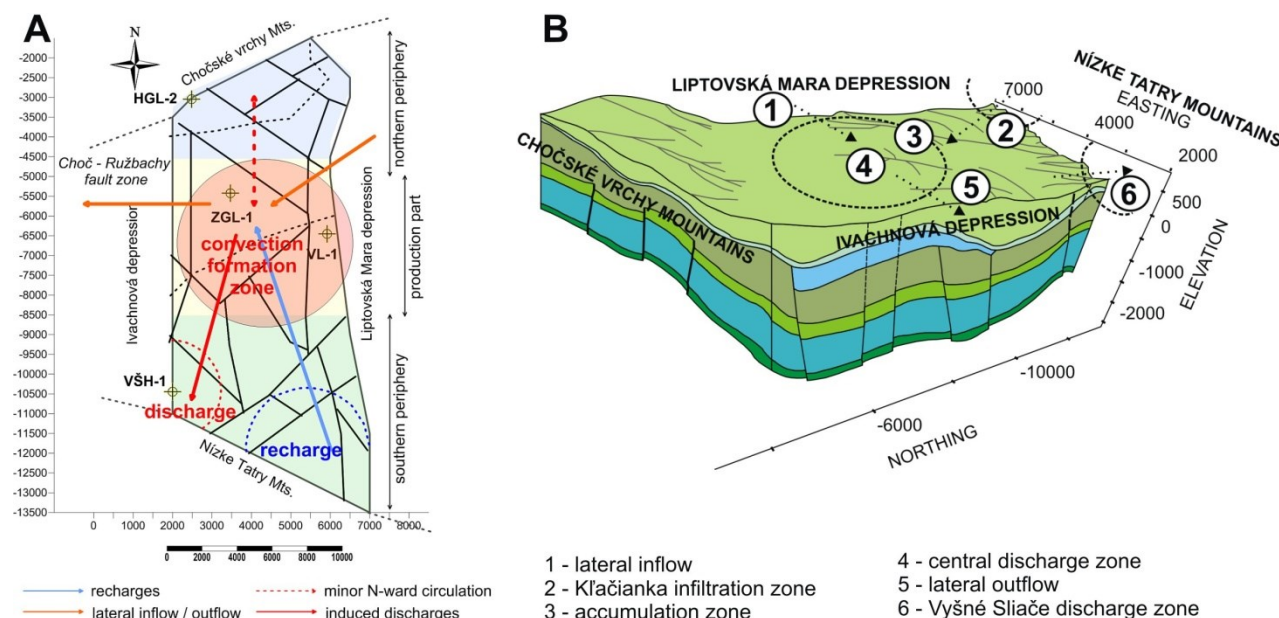

1 - lateral inflow
2 - Kľačianka infiltration zone
3 - accumulation zone
4 - central discharge zone
5 - lateral outflow
6 - Vyšné Sliače discharge zone

Figure 2: Geothermal model derived conceptual scheme (A) and lateral arrangement (B) of the Bešeňová elevation hydrogeothermal structure.

3.2 Facial hydrogeochemistry

Thermal waters are petrogene in origin (Fendek et al., 1988). Detailed analysis (Fig. 3A) expresses, however, complexity in facial arrangement. Analogy to other systems of the Liptov Basin adjusts shallow (Ca-Mg-HCO$_3$) and deep (Ca-Mg-HCO$_3$-SO$_4$) transition channels to the infiltration zone, with the earlier (documented in barrier springs) freshly infiltrating along open faults whereas the latter one is of the massif provenance. The deep reservoir samples record minor transient character in Ca-SO$_4$, Ca-SO$_4$-HCO$_3$ and Ca-Mg-SO$_4$-HCO$_3$ to Ca-Mg-HCO$_3$-SO$_4$ shifting towards the top, relatively decreasing SO$_4$ proportion. In the shallow reservoir, primary (Fričovský et al., 2013a) Ca-SO$_4$-HCO$_3$ (BEH-1) fluids are clearly of deep reservoir origin due to a simple SO$_4$

Fričovský et al.

source lack in CNA dolomites. Samples of Ca-Mg-HCO$_3$-SO$_4$ transient character (FBe-1) must be, thus, secondary in origin (Fričovský & Tometz, 2013a). Variations are recorded in discharge zone too, where the VŠH-1 well records transient Ca-Mg-HCO$_3$-SO$_4$ facies, while springs document mixed Ca-Na-HCO$_3$-(SO$_4$) waters, similar to those found in central accumulation zone.

Table 1: Review on basic geochemistry of thermal fluids – median values in mg.l-1.

sample point	Ca	Mg	Na	K	HCO$_3$	SO$_4$	Cl	B	pH	T.D.S.
FGTB-1	551	152	25	24	710	1490	18,3	0,6	6,5	2900
ZGL-1	473	296	33	26	730	1348	12,4	1,4	6,2	3600
FBe-1	605	153	84	31	1463	1029	28,7	8,3	6,7	2400
Rudolf	290	85	19	6	2030	812	23,2	2,1	7,4	1700
LM-45	254	79	17	6	2117	801	24,3	5,6	7,2	1400
VŠH-1	403	153	159	33	1845	480	68,8	0,6	6	3080
Štiavnička	177	44	17	6	390	130	35,8	0,7	7,2	1100

3.3 Maturity and recharge sensitivity

All samples plot away from maturity region on *Tclsh plot* (Fig. 3B), scattering between peripheral (infiltration and discharge zone) and immature (deep reservoir, shallow reservoir) field. Because the sulphate source is found in Early and Late Triassic formations, the SO$_4$ is used to track longitude and depth of migration. Maturity increases towards deep reservoir, where thermal waters come into contact with both horizons in the production part. Shallow reservoir waters position along the immature – peripheral fluids line is expected due to mixing of deep reservoir evaded and laterally recharged fluids. Recharge zone samples suffer the less SO$_4$ proportion due to dilution, implied by high relative HCO$_3$ level. Combination of accumulation zone samples in the "evaporation-dominated" region on the *Gibb's plot* and transition of recharge and discharge zone representatives between "evaporation" and "water-rock interaction dominated" field (Fig. 3C) hints on decreasing filtration velocity towards production part. Moreover, both reservoirs appear stable in recharge continuity out of seasonal variations, with inflow chemistry corresponding to reservoir environment. Populations of waters adjusted to peripheral parts in combined region point on dynamic environment involving mixing and dilution of various rate.

3.4 Mixing and boiling models

Schoeller's plot (Fournier, 1991) proves two distinct facies for the infiltration zone (Fig. 3D), different in Na/Cl ratio and equivalent concentration in general. Based SO$_4$/HCO$_3$ and SO$_4$/Cl proportions, the superpositioned population represents the deep infiltration channel and vice-versa, whilst combination of gap and relatively uniform lines shape hints mixing between. Two populations for the discharge zone, affine to shallow reservoir; and similar in shape to infiltration zone point to dilution of thermal waters probably by fresh infiltrations and (at least) contribution of the top aquifer on lateral leaks into the area. By a contrast, shallow reservoir samples organize rather into one group varying equivalent anion concentration compared to deep reservoir of almost homogeneous shape. Thereafter, mixing in the shallow reservoir is of a major effect on SO$_4$/HCO$_3$ ratio whilst deep reservoir is discharged in the production zone by fluids of almost similar composition.

Indeed, there is no solid mixing expected for the deep reservoir as samples record massive scattering on Na/Cl (*Xcln*) and B/Cl (*Xclb*) plots (Arnorsson, 1985). Joint analysis for the shallow reservoir reveals no trend in Cl/B ratio (Fig. 4A), however, Na/Cl plot gives evidence of population affine to infiltration zone (Na/Cl ratio ≈ 2:1) and the other with no trend, possibly due to deep residential fluids minor "dilution" by infiltrations in shallow transition. Thermal waters of the recharge zone are clearly of two chloride sources and boron level fairly similar to the population of deep reservoir (Cl/B > 20:1), whilst source of Na is of distinct origin (Fig. 4B). Linear trends provide a solid indice on mixing. Variation in Na over a boron level affinity imply a polystageous water-water interaction, first between laterally leaking fluids from both reservoirs, then, dilution of the secondary waters by short residency infiltrations seeping into Paleogene formations prior upwelling as springs. Even some samples cluster, any massive scattering along a cold-water and geothermal end-member is recorded to be a sign of potential boiling within any zone. Detailed boiling possibility inspection is, meanwhile, conducted rather applying chloride-bicarbonate (Fournier, 1989) and enthalpy – chloride (Truesdell & Fournier, 1975) models.

Complexity of the system is well pictured on *chloride-bicarbonate model* (Fournier, 1989), implying chemistry of shallow reservoir fluids formed by joint effect of deep reservoir waters conductive cooling and subsequent dilution by fluids of shallow filtration (Fig. 4C). Alike, thermal waters of the discharge zone vary considerably as a consequence of undergoing the deep and shallow reservoir waters mixing prior dilution by fresh infiltrations at low elevations of various intensity. Neither here (position of samples above the B – D line, nor the chloride-enthalpy plot indicated any signs of boiling again (Fričovský & Tometz, 2013a).

3.5 Geothermometry

Amongst geochemical models, complex geothermometry was carried. *Silica geothermometry* application identifies chalcedony to control silica solubility in fluids. Amongst, a function of (Fournier, 1991; GS-1) shows closest match (35 – 97 °C), however, most of values vary 52 – 97 °C. Moreover, chalcedony geothermometry appears applicable for temperature assessment for deep reservoir

only. Even within, wide temperature range indices incoherent contact of thermal fluids with silica source. For other zones, mismatch in sampled (expected) to calculated temperatures is resultant to mixing (Fričovský et al., 2013).
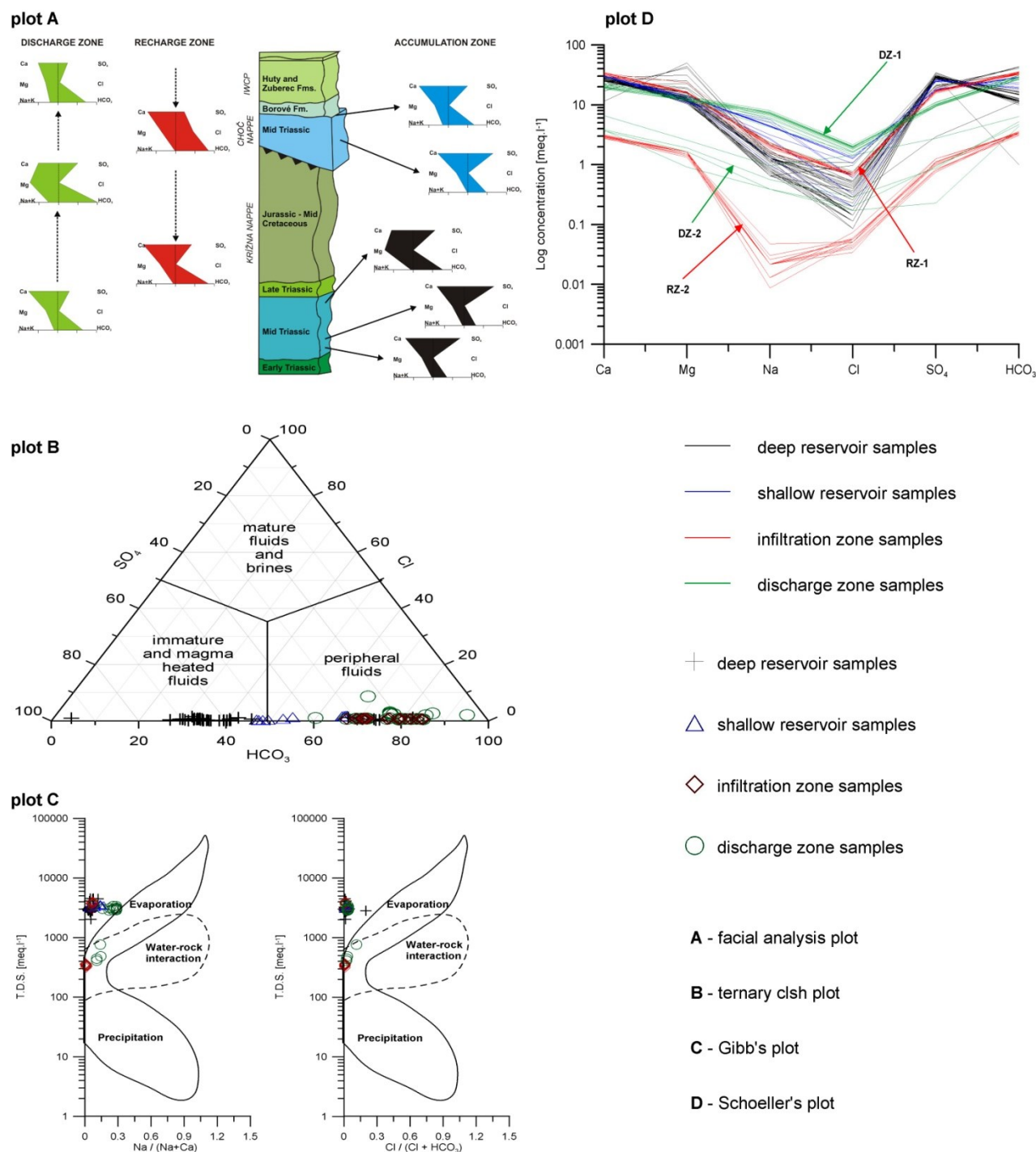

Figure 3: Hydrogeochemistry – examples on facial, maturity and mixing analysis.

Conventional *cation geothermometry* application suffers excess CO_2 typical for carbonatogene waters and high Mg^{2+} concentration whether it is due to prevailing dolomite environment or mixing (Fournier, 1989). Thus, *Na/K geothermometry* gives overestimated temperatures (Tab. 2), resultant to instability in albite – adularia or albite – microcline alteration system (Fig. 5A). Use of *K/Mg geothermometry* appears valid in temperature estimation for deep (Fournier, 1991; GM-1; T_{med} = 69 °C) and shallow (Giggenbach, 1988; GM-2; T_{med} = 32 °C) reservoir only as in other zones, deviation in results is controlled by high Mg^{2+}, dilution provenanced level and instability in Na/K and K/Mg system (Fig. 5B). Even the *Na-K-Ca geothermometer* (Fournier & Truesdell, 1973; GNKC) is developed for temperature estimation in acid waters, it is apparent (Tab. 2) the function overestimates formation temperature conditions within the entire system. Moreover, the *Mg-correction* (Fournier & Potter, 1979; GNKCM) is capable to correct the dolomite environment determined high Mg^{2+} for deep reservoir only (T_{med} = 64,3 °C), turning temperature overestimation in other zones being solid indices of polystageous mixing and dilution again. Immaturity of the system, reflected in rapid variations of

Na/K, K/Mg and Na/Mg (Fig. 5C) ratios through the system is well seen on Na-K-Mg geoindicator (Giggenbach, 1988), approving most of cation geothermometers invalid, overestimating temperatures by a fold of 2 – 4 (Fričovský & Tometz, 2013b).
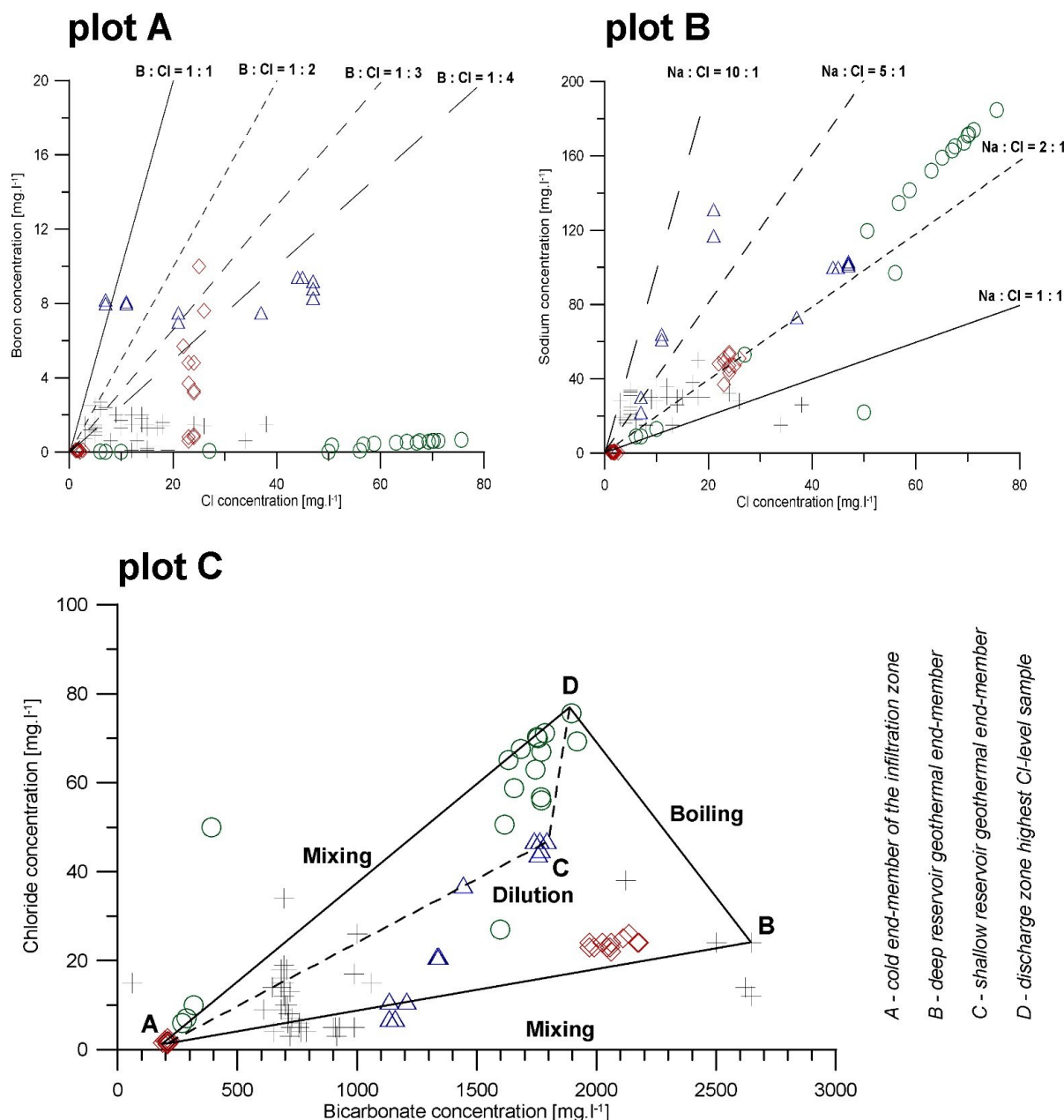
plot A

plot B

plot C

Figure 4: Mixing analysis – chloride – boron (A); chloride – sodium (B) and chloride – total carbonate models application.

Multicomponent geothermometry reflects to complex equilibrium temperature (e.g. Chiodini et al., 1996) and total saturation index (Cooper et al., 2013) derived temperature calculation. The latter one, presented in (Fričovský et al., 2014b) uses simple rather than quadratic TSI function as there is no need to correct the loss in CO_2. Carried for the deep reservoir only, TSI derived temperatures vary T = 72 – 94 °C with T_{med} = 79 °C, indicating TSI=0 attainment in bottom parts of the horizon. Type-curve analysis (Fig. 5D) reveals similarity in shape approves non-boiling environment, whilst dispersion in covered temperature range points on incoherent accessibility of thermal waters to major equilibrium controlling components (dolomite, calcite, Na/K silicates), thus may be indicative of minor convection formation in the deep reservoir – conform to expectations of geothermal model (Fričovský et al., 2014a). Because of instability in Na/K system, complex equilibrium temperature is analyzed plotting together the TSI temperature, K/Mg (Fournier, 1991) and chalcedony (Fournier, 1991) geothermometer, to find a convergence / interception derived end-members. There is a discrepancy between temperature of two interception points (Fig. 5E) and the TSI derived. Due to chloride concentration, waters equilibrated at T_{TSI} = 79 °C can not be considered the geothermal end-member. Instead, waters involved in vertical filtration come into contact with 'residential' fluids not involved in a mass flow (T = 65 – 70 °C) and mix, giving arise of end-member component (T = 71 °C, cCl = 16 mg.l^{-1}). Forth, convection apparently does not relate to the entire effective profile but realizes in minor and separate convection cells.
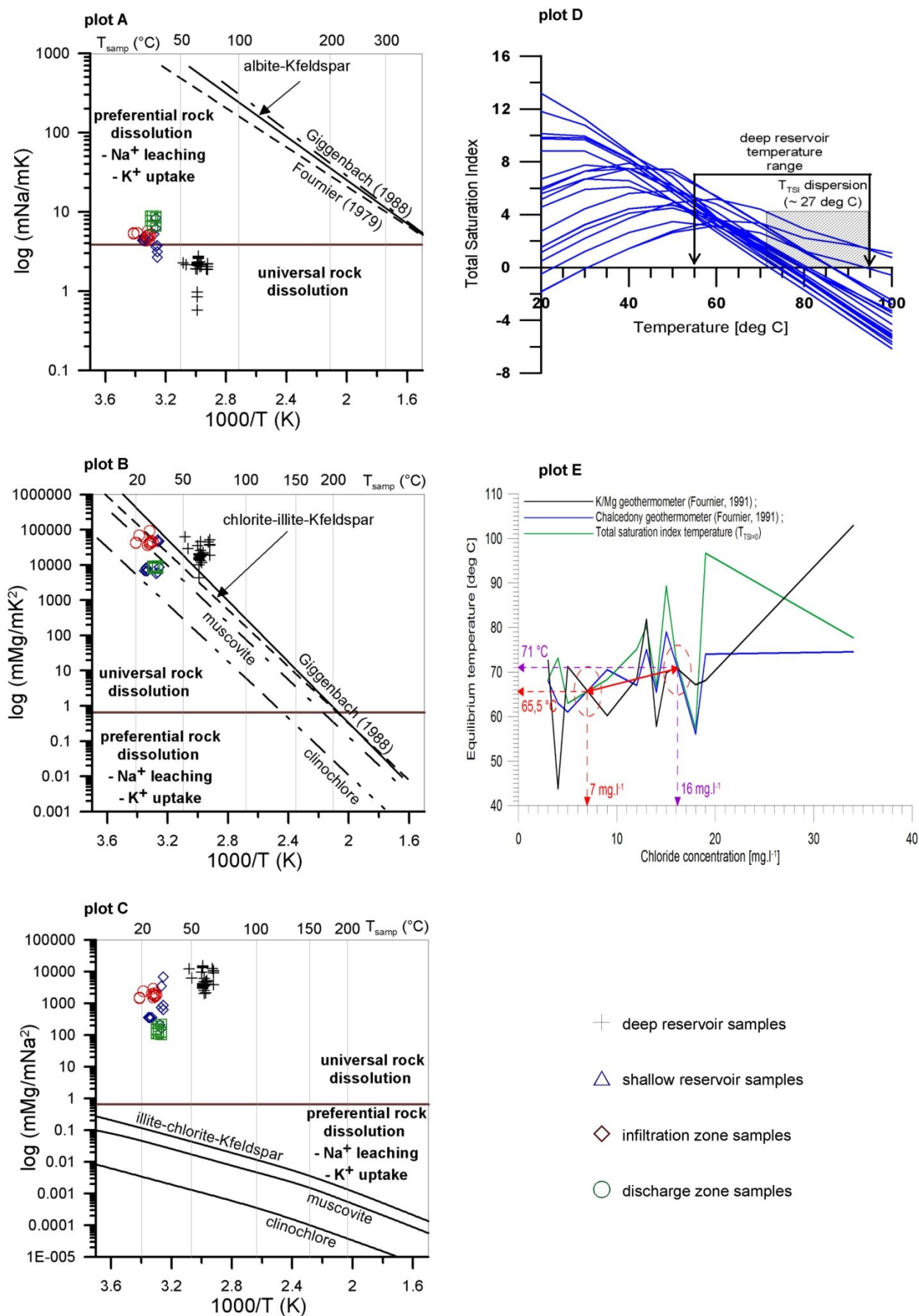
Figure 5: Hydrogeochemistry : molar ratios – Na/K (A), Mg/K (B), Mg/Na (C); total saturation index type-curves (D); multicomponent equilibrium temperature (E).

Table 2: Quantitative geothermometry application overview.

zone	GS-1	GM-1	GM-2	GN-1	GNKC	GNKCM
deep reservoir	71	69	36	354	283	64
shallow reservoir	28	88	32	112	201	66
recharge zone	39	51	40	83	205	48
discharge zone	51	85	33	10	191	47

4. RESULTS – CONCEPTUAL MODEL

Amongst presented techniques, refinement of conceptual model of the Bešeňová elevation hydrogeothermal structure is based on the enthalpy – total silica and silica – total carbonates models application (Fričovský & Tometz, 2013a), use of graphical geoindicators (Fričovský & Tometz, 2013b) all in combination with regional piezometry (e.g. Fendek et al., 1988). Hydrogeochemistry approves previous ideas of open hydrogeological character (e.g. Franko et al., 1979) and emplacement of major architectonic zones of hydrogeothermal system (e.g. Remšík et al., 1998), however, subsequently gives an idea of the production zone provenanced thermal waters in the Sliače area, possible only in case it is the discharge zone (Fig. 6).

4.1 Kľačianka infiltration zone

Macrofacial analysis, with most of an aim put to SO_4/HCO_3 and SO_4/Cl ratio, correlates to analogies observed in neighboring systems, as waters are expected to use two filtration channels different in geological environment, filtration patterns and seeping regime. Waters in deep regime (Ca-Mg-HCO_3-SO_4) infiltrate in a massif of the Nízke Tatry Mts. into loosened and weathered Mid Triassic – Late Triassic carbonates soon coming into contact with SO_4 source (Early / Late Triassic formations) and start to migrate northwards due to declination in relief, or using open faults and fissures, with velocity controlled by detrite and pelite impurities in limestone varieties. The shallow channel (Ca-Mg-HCO_3) is expected referring to fluids seeping along faults at the periphery of the basin, filtrating fast. Overestimated Na-K-Ca (Fournier & Truesdell, 1973) and low effect of Mg-correction (Fournier & Potter, 1979) on temperature estimation give a hint on excess Mg^{2+} source possibly related to dilutive and thermal – cold (TCM) character of mixing between both channels only. Meanwhile, the contact of two channels may be read from SiO_2 scattering that is in a contrast to relatively uniform lithology, understood as a record of incoherent water-rock contact duration and silica-hydrolysis intensity. This turns the Mg/Ca and Mg/K ratio high at the periphery. Forth, the dilution rate determines the final geochemical character of thermal fluids (Ca-Mg-HCO_3 to Ca-Mg-HCO_3-SO_4) prior submersion into transition towards reservoirs.

4.2 Transition zone

Due to vertical reservoir stratification in the production part, transition realizes within shallow and deep environment at different velocities, depth, duration and geological environment. Deep transition expresses soon increase in K/Mg, K/Na and Mg/Na ratios due to uptake of K-silicates. Subsequent submersion into Mid Triassic carbonates decreases the pH resultant to dissolution of carbonates and CO_2 accretion in the solution with karstification amplitude high enough to turn the calcite and dolomite oversaturated prior entering the production (accumulation) zone. Because of high pH, albite hydrolized from the Jurassic – Mid Cretaceous zone converts into muscovite, increasing the K/Na ratio in combination with preferential illite leaching from detritic impurities in Mid Triassic carbonates. While illite hydrolysis continues fluently towards the deep reservoir, thermal waters become oversaturated to muscovite just ahead the production part. Because of contact with Early / Late Triassic formations towards production part of the accumulation zone, thermal waters obtain Ca-Mg-HCO_3-SO_4 to Ca-Mg-SO_4-HCO_3 character.

For the shallow transition, low temperatures and relatively fast filtration in the Borové Fm., later submerging into CNA Mid Triassic dolomites preserves ionic ratios apparently the same, compared to those in the infiltration zone. Na/K silicates are leached preferentially turning fluids oversaturated to muscovite, with a source for the hydrolysis in IWCP cover formations. However, sank into dolomites, thermal waters attack Jurassic – Mid Cretaceous bedrock formations, increasing Na/K ratio, meanwhile geochemical character (whether Ca-Mg-HCO_3-SO_4 or Ca-Mg-SO_4-HCO_3) depends on the initial, dilution controlled.

4.3 Deep reservoir

Towards the base, the deep reservoir fluids decrease the Na/K ratio continuously due to albite alteration into muscovite, turning oversaturated basewards, however, with a K^+ loss balanced by adularia and illite uptake. The SO_4 compound increases with prolonging a contact with Early Triassic formations. Subsequently, anhydrite becomes oversaturated and alternates to gypsum, the latter dissolved from the formation in a meantime. As implied by discrepancy in a geothermal end-member temperature (T = 71 °C) and total-saturation index derived temperature (T_{med} = 79 °C), portion of thermal waters is expected to be involved in minor, separate convection cells. During upflow, excess free CO_2 boosts Na-silicates hydrolysis from impurities in carbonates, increasing Na/K ratio, whilst illite, adularia and muscovite set on to deposit due to oversaturation, determining waters immature in the Na/K system. At the same time, thermal waters in upflow mix with residential waters to give an arise to geothermal end-member composition at (T = 71 °C, cCl = 16 mg.l^{-1}). The more evidence on convection is recorded on SiO2 variation implying incoherent ability of thermal fluids to dissolve silica from impurities. The chalcedony, being an aqueous SiO2 concentration control, equilibrates towards base of the zone (T_{med} = 86 °C). Due to interception principle and TSI curves analysis, the contact realizes in quasi-isochemical regime. Moreover, TSI curves give a hint on isochemical reservoir inflow regime as well due to high lateral dispersion, preserving, however, a similarity in shape. This indices convection-involved thermal waters sensitive to inflow character and recharge realization through the entire effective profile. Still, there is no evidence on reservoir boiling recorded.

4.4 Shallow reservoir

The shallow reservoir represents aquiferous zone of polystageous mixing at different elevation, with at least two distinct facies recorded on key plots. Origination of the first relates to deep reservoir evaded thermal waters along open fault systems. Increase in Na/K ratio during upflow is resultant to oversaturation triggered muscovite and illite deposition the illite leaching (source in Late Triassic) is not able to balance, decreasing aqueous K^+ concentration. Simultaneously, albite leaching from Jurassic – Mid Cretaceous horizon, however, with a part of the Na^+ dissolved being soon consumed into muscovite due to low pH. Decrease in Mg/K and Mg/Na ratio hints on conductive cooling dolomite precipitation (Mg^{2+} loss) at a rate much higher compared to loss in K^+.

The second facies is recognized of residential mixed thermal waters, originated due to mixing of evaded thermal fluids with recharges from shallow transition. The hint is found in Mg/K increase of the facies resultant to Mg^{2+} additional source from shallow transition invading fluids. This is in a good match to inadequacy of Mg-correction application and dolomite oversaturation, as Mg^{2+}, if no mixing, would be uptaken in solid phases formed.

Simultaneously, mixing is well evidenced on macroscale. As there is no SO_4 source in the zone, Ca-Mg-HCO_3-SO_4 waters must be of deep reservoir origin. A shift into Ca-Mg-HCO_3-(SO_4) may be explained due to dilution with Ca-Mg-HCO_3-(SO_4) waters from shallow transition channel.

4.5 Sliače discharge zone

There are indices on relation of the Sliače thermal waters (VŠH-1 well, springs) to both reservoirs, even it is in a mismatch to piezometry. Still, explanation may be found in base overheating induced convection.

Calcite and dolomite are expected to precipitate, uptaking the Ca^{2+} and Mg^{2+} due to conductive cooling or oversaturation. Meanwhile, compared to deep reservoir, a decrease in Mg/Na over increase in Na/K and Mg/K preservation give a sign on dolomite precipitation due to cooling (Mg^{2+} loss) instead of Na-leaching (lack of the Na-silicates source), whereas K-silicates begin to deposit after lateral leak from the reservoir at amplitude lower than deposition of dolomite. Exactly the same may be derived for the Na/K ratio, as its increase responds to K^+ precipitation in a form of adularia and muscovite, whereas illite approaches equilibrium slowly. Highest Na/K, however, must be a sign of Na^+ source, found in dissolution of Na-silicates as shallow reservoir fluids leave the reservoir (increase in Na/K) and joint effect of intense K-silicates precipitation.

The Mg^{2+} compound is expected to be lost from the solution due to uptake in dolomites in major. A balance in Mg/K from the deep reservoir and shallow reservoir must be explained by Mg^{2+} source, as in quiet conditions, Mg^{2+} deposition would be higher by several folds compared to losing K^+ in K-silicates. Rapid Mg^{2+} drop is expected compared to drop in Ca^{2+}, due to dolomite saturation amplitude. A mismatch between is another hint on additional Mg^{2+} source. Moreover to the mixing theory, the Mg-correction function is apparently capable to balance reservoir dynamics (negative pH vs T_{NKCM}), but, due to higher temperatures, it is not possible to balance apparent excess Mg^{2+}. Definite mixing in TCM regime takes part after deep and shallow reservoir thermal waters at a TTM regime. Contact must suffer with fresh invasive infiltration into the zone, roughly reaching production part prior thermal waters tend to upwell and form springs.
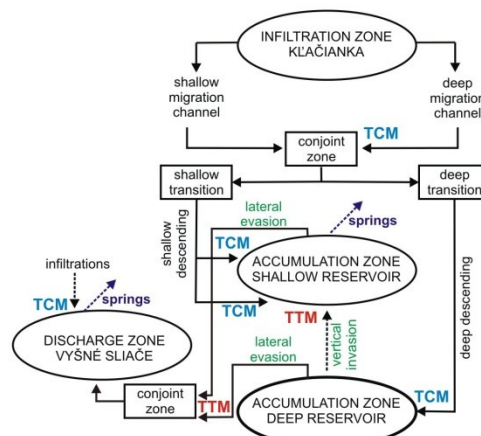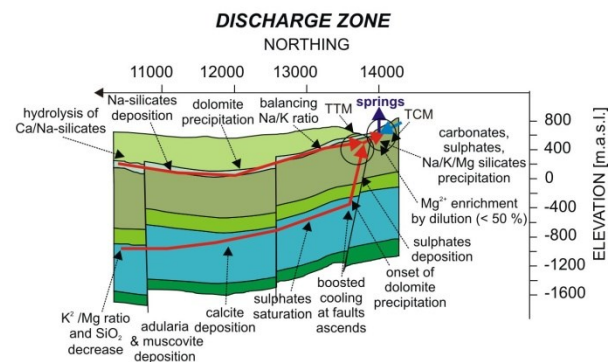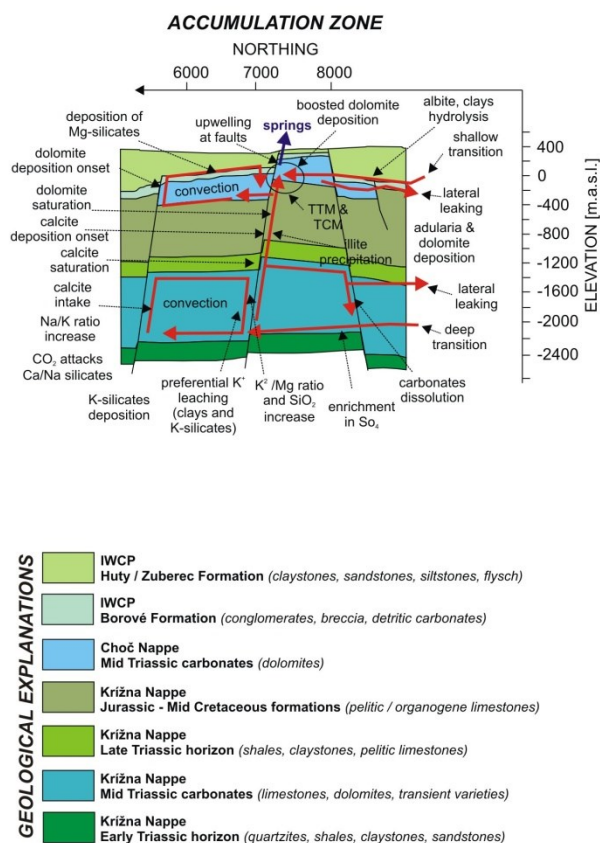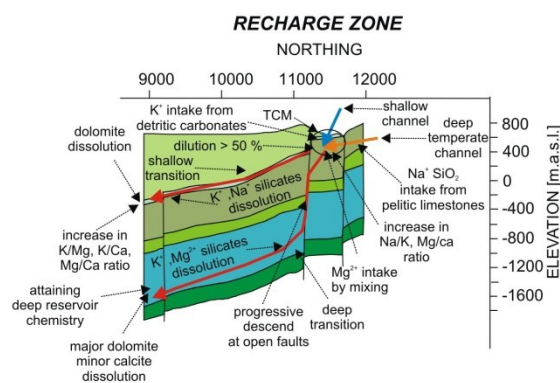
4.6 Notes and remarks

It is important to note the geochemistry derived conceptual model does not exclude existence of the central discharge zone in the Bešeňová town vicinity. Indeed, this outflow zone is well proven by existence of travertine domes (Franko et al., 1974; Franko et al., 1979). Origination of these waters relates to thermal waters of the shallow reservoir as they vertically evade the zone along open fault systems at Ca-Mg-HCO_3-(SO_4) character and mix with Quaternary / weathered Paleogene hosted waters to obtain a final Ca-Na-HCO_3-(SO_4) composition. It is important to note that thermal waters in lateral inflow from the Liptovská Mara depression are of same chemistry as deep reservoir fluids, as no other indices on additional facies were identified. Moreover, existence of thermal waters in the TEU Mid Triassic carbonates must not be excluded, however, there are no signs on vertical invasion into deep reservoir found yet. The possibility is, however, indirectly implied by deep reservoir base unconform overheating.

5. SUMMARY

Since the beginning of geothermal waters aimed exploration of the Bešeňová elevation hydrogeothermal system in 1979 (BEH-1 well), the system is considered of open hydrogeological character, with general agreement in location of infiltration zone at the northern slopes of the Nízke Tatry Mts. and accumulation and discharge zone in its central part nearby the Bešeňová town, as well as on lateral hidden outflow towards the Ivachnová depression on the west (e.g. Remšík et al., 1993). Still, the system was considered of simple infiltration–accummulation–outflow character, with not so many studies focused on intraformation dynamics.

Indeed, use of macrochemistry in combination to qualitative and quantitative geothermometry analyzes reveals complexity of the system (Fig. 6) and proves its vertical stratification. Whilst there is no evidence on boiling, there are several records on mixing, whether it is between the deep and shallow filtration channel within infiltration zone; quasi-isochemical intraformation mixing in the deep reservoir between thermal fluids involved in a minor convection and 'residential'; thermal – thermal mixing in the shallow reservoir between hosted and deep reservoir evaded facies simultaneous to the latter originated waters mixed with infiltrations from the shallow transition; or thermal – thermal mixing of convection-induced laterally leaking thermal waters from both zones towards the Sliače area prior rapid dilution by short-residency infiltrations in a thermal-cold regime and upwell as springs.

Presented contribution gives a brief overview on interpretation of macrochemistry and geothermometry, resultant in redefinition of conceptual model of low enthalpy geothermal system of the Bešeňová elevation. As applying hydrogeochemistry and geothermometry only for interpretation, even in correlation to piezometry, it is a first of its kind in conditions of geothermal fields in Slovakia.

Figure 6: Bešeňová elevation hydrogeothermal structure – conceptual model and scheme.

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