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# Thermal impacts of magmatic intrusions: a hypothesis of paleo-heating processes in the Tiberias Basin, Jordan-Dead Sea Transform

Nora Koltzer<sup>a,b\*</sup>, Peter Möller<sup>a</sup>, Nimrod Inbar<sup>c,d</sup>, Christian Siebert<sup>e</sup>, Eliyahu Rosenthal<sup>c</sup>  
and Fabien Magri<sup>f,g</sup>

<sup>a</sup>Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Section 6.1 - Basin Modelling, Potsdam, Germany

<sup>b</sup>RWTH Aachen, Faculty of Georesources and Material Engineering, Aachen, Germany

<sup>c</sup>Tel Aviv University, Department of Earth Sciences, Tel Aviv, Israel

<sup>d</sup>Eastern Regional R&D Center, Ariel, Israel

<sup>e</sup>Helmholtz Centre for Environmental Research – UFZ, Halle, Germany

<sup>f</sup>Freie Universität Berlin, Hydrogeology, Berlin, Germany

<sup>g</sup>Helmholtz Centre for Environmental Research – UFZ, Department of Environmental Informatics - ENVINF, Leipzig, Germany

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## Abstract

Extensive evidence of Ca-rich brine at the western side of Lake Tiberias (LT), Israel, refers to dolomitization processes. Dolomitization of Mg-rich brine saturated limestones preferentially occurs at enhanced temperatures. The presence of wide areas of fissured basalt in that area suggests that magma, which erupted through fissures, sufficiently heated initiating dolomitization. In this study we numerically investigate possible paleo-heating processes related to magmatic intrusions.

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**Keywords:** Lake Tiberias; FEFLOW; thermal field; Tiberias Basin; fault; temperature anomaly

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\* Corresponding author. Tel.: +49 331 288-2810; fax: +49 331 288-1349.

E-mail address: [nora.koltzer@gfz-potsdam.de](mailto:nora.koltzer@gfz-potsdam.de)

## 1. Introduction

The Tiberias Basin (TB) is located within the Jordan–Dead Sea Transform and is bordered to the west by the Lower Galilee (Israel), where fractured Pliocene basalts cover an area of about 1,050 km<sup>2</sup> (Fig. 1). Hydrochemical analyses highlight that along the western side of Lake Tiberias (LT), brine is Ca-rich, likely due to dolomitization of limestones [1]. Dolomitization of limestones at laboratory conditions is proved at temperatures above 100 °C [2-3]. Numerical models describing [e.g. 4-6] indicate that local fractures or anisotropy can be responsible of the present thermal field within this area. Here we numerically investigate whether high pale- temperatures could have been induced by heating processes related to magmatic intrusions through faults.

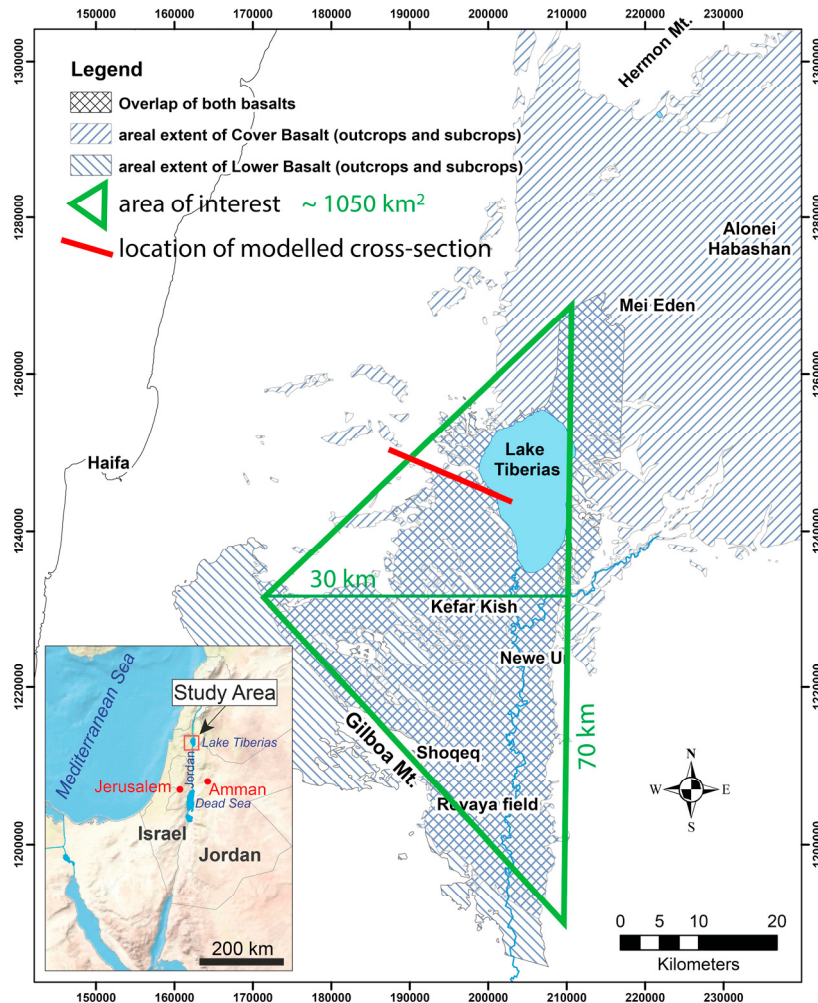


Fig. 1. Map with area of interest, in the green triangle (modified after [7]), location of simulated profile in red. The numerical examples of this article are based on structural features of the Lower Galilee, the profile is W-E oriented.

### 1.1. Geology of the Lower Galilee

Tortonian (Upper Miocene) Mediterranean transgression invaded the Jordan Rift Valley (JRV) through the lower Galilee and the Jezrael Valley forming an inland sea [8]. This transgression deposited massive salt layers at the JRV and the time equivalent marly Bira Formation rift margins and along the transgression path [9]. Migration of

residual brine to Cretaceous and Eocene strata was suggested by Inbar [8]. Uplifting of the lower Galilee started at the Miocene-Eocene boundary [10-11] accompanied by basalts erupting through numerous fissures forming dikes and sills within the Cretaceous and Eocene limestones, building up the Lower Galilee, West of LT. As a result, the Cretaceous limestones, bearing the Mg-rich residual brine, were mostly heated within western Galilee. In contrast, in the Golan Heights, northeast of LT, basalts erupted mainly through cone eruptions [12]. These bounded magmatic extrusions produced high amounts of flood basalts, which mainly cover Eocene formations. These Cover Basalts could only locally heat the surrounding fresh-water aquifers and rocks, preventing dolomitization processes in buried saline aquifers.

In this study, we try estimating to which extent and through which mechanisms fissure eruptions have induced heated brine to flow within the limestone aquifers. The numerical simulations of brine flow are based on the western ending of the 2D cross-section from [4], as located in Fig. 1. The geological setting shown in Fig. 2. is representative for the whole area of the Lower Galilee, where dolomitization likely has occurred within heated Cretaceous limestone aquifers (Turonian and Senonian, light green unit in Fig. 2).

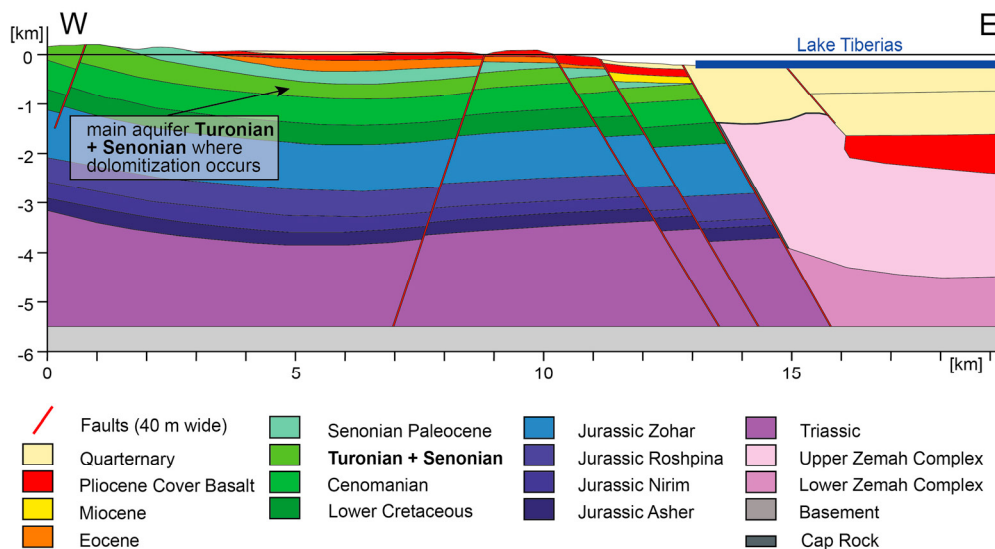


Fig. 2. Geological setting of the exemplary 2D vertical profile (located in Fig.1); the profile is oriented W-E from the Golan Heights to Lake Tiberias and about 20 km long. The geology is adopted from [4].

## 2. Methods

The physical equations of coupled fluid flow and heat transport are solved with the finite element software FEFLOW®. The mathematical formulation is given in [13]. The truncated 2D profile [4], is discretized into 213,727 elements. Due to limitations of the software FEFLOW® the simulations of all scenarios are based on a single liquid-flow as described in [14].

### 2.1. Boundary (BC) and initial conditions (IC)

A Neumann heat flow BC of  $0.06 \text{ W/m}^2$  and a no fluid flow BC are applied at the bottom of the model. At the top of the model, a Cauchy heat flux of  $20 \text{ }^\circ\text{C}$  is set, representing the annual mean temperature. The hydraulic head is assigned as Dirichlet BC along the landside while a Neumann fluid transfer of  $-210 \text{ m}$  (mean sea level: m.s.l.) is assigned along the floor of LT. At the western and eastern sides, the model is closed for fluid flow and heat transport. Pressure and thermal IC are derived through steady state simulations of groundwater flow and purely conductive heat transport, reproducing hydrostatic conditions and a geothermal gradient of about  $30 \text{ }^\circ\text{C/km}$ .

In all scenarios, the initial geothermal gradient is locally disturbed by basaltic intrusions occurring through the three faults, highlighted in Fig. 3. This is done by setting a BC of 1,300 °C along the fault nodes. The basalt heats up the system for 10 years under a purely conductive regime (i.e. impervious rocks). The BC is then deactivated to let the system cool down to a temperature regime allowing the brines to remain in the liquid phase (Fig. 3), i.e. multiphase-fluid flow is neglected during the short magmatic eruptions and cooling. The temperature profile along the faults (Fig. 3) is then used as transient BC to simulate repeated magmatic intrusions that for simplicity are supposed occurring each 50 or 100 years.

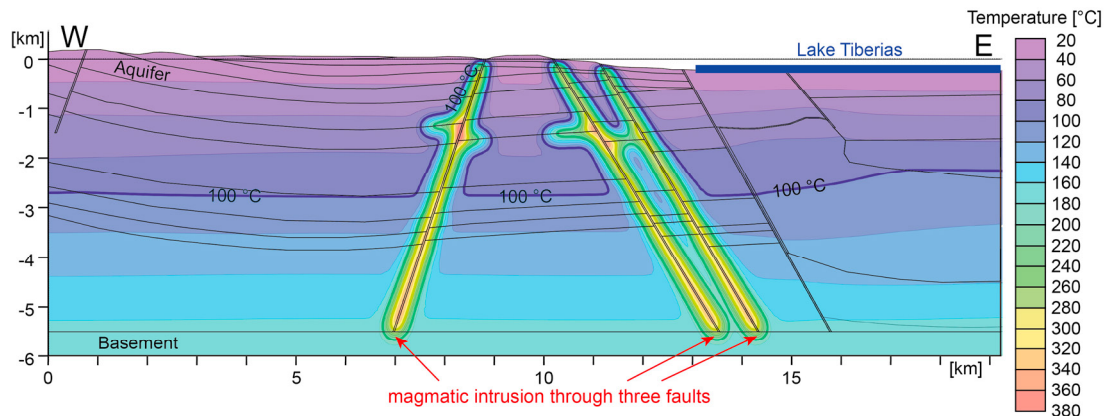


Fig. 3. Temperature field after heating the faults to 1,300 °C for 10 years and conductive cooling at conductive conditions. The thermal plumes around the three faults are used as transient thermal BC to simulate a series of magmatic intrusions.

## 2.2. Scenarios

In the first scenario, heat conduction is assessed by letting the system equilibrate for 1,000 years following the magmatic intrusion. To do so, the magmatic intrusion through three faults is simulated with a constant Dirichlet boundary condition of 1,300 °C over 1,000 years. To show the effect of purely conductive heat transport from the faults to the rocks, the surrounding units are assumed impermeable ( $K = 1\text{E-}30$  m/d). In the second scenario, advective and convective heat transport with and without topography-induced flow (i.e. no regional flow) is simulated. In the third scenario, the porosity and hydraulic conductivity values of the aquifer are twice the values of the previous scenarios, in order to reproduce karstified conditions. Scenarios and outcomes are summarized in Table 1.

Table 1. Overview of the three different scenarios.

Scenario	Technical settings	Main results
1 conductive heat transport	No fluid flow	Heat plume localized at the fault / sill intersection (Fig. 4)
2 influence of topography	With regional flow and without regional flow (i.e. flat head; equal to LT lake level (-210 m m.s.l.)	Wide areas of merging thermal plumes, peak Darcy velocity 1.5 m /yr (Fig. 5)
3 karstified aquifer	Increased hydraulic conductivity (1.1 m/d) and porosity (0.3) values of the main aquifer	Darcy velocity of 3 m/yr is higher than in scenario 2 (Fig. 6)

### 3. Results and Discussion

In the following three scenarios, the transport mechanisms controlling the thermal field after magmatic intrusions through faults are investigated. The first Scenario shows a purely conductive regime for heat transport from faults and sills into the surrounding rocks. In the second scenario the impact of topography driven flow on advective and convective heat transport mechanisms is investigated. The influence of karst and thereby an increase of hydraulic conductivity is tested in scenario 3.

#### 3.1 Scenario 1

During the magmatic intrusion (10 years), heat is conducted 30 m laterally in the rocks. At the end of the simulation run (1,000 years), the 100 °C isotherm is approximately 600 m away from the heat source of 1,300 °C (Fig. 4). This scenario suggests that conductive heat transport alone is likely not sufficient to heat up wide areas up to temperature favoring dolomitization processes. Similar results are obtained by numerical simulations of the Skaergaard intrusion [15] where the cooling of a pluton is simulated and the surrounding of the plume is heated up just in proximity of the plume.

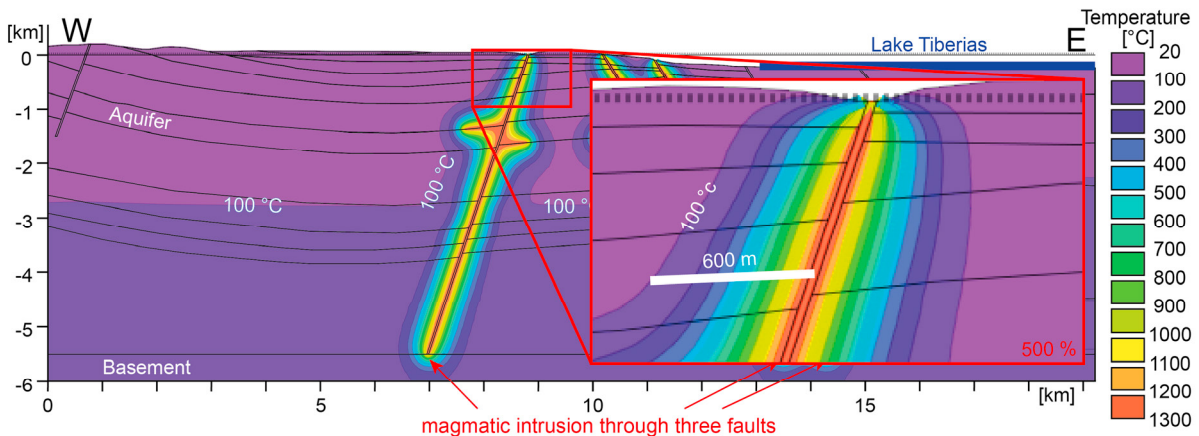


Fig. 4. Zoom into the western fault; heat transport laterally 600 m into the rocks after 1,000 years of ongoing intrusion.

#### 3.2 Scenario 2

As explained in the section 1.1, the studied profile is based on the geological setting from [4]. Thermal plumes rise along the fault driven by buoyancy and merge within the Turonian and Senonian aquifer, forming wide areas of heated brines (Fig. 5). Due to the regional flow directed toward LT (blue arrows in Fig. 5c) the protrusion of the plume is limited to the west (Fig. 5b). Brine at 100°C stretches over 1.5 km in western direction. By setting the hydraulic head equal to the sea level of LT at -210 m m.s.l. over the landside (i.e. no regional flow), it turned out that the aquifer is heated up to 100 °C up to a distance of 3.1 km after 50,000 years (Fig. 5a). For longer periods, the plume propagates further to the west as it is not limited through topography-driven recharge flow in the opposite direction.



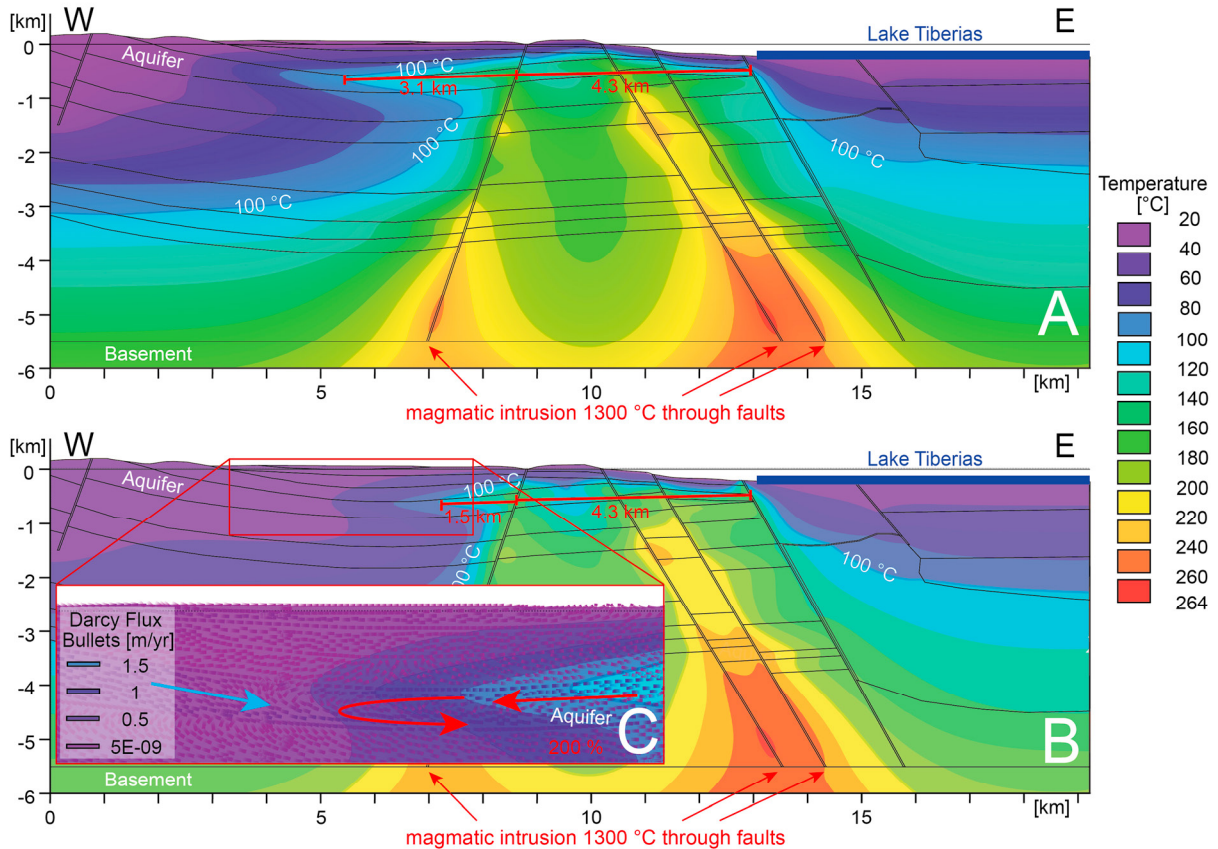


Fig. 5. Simulations of Scenario 2 with and without topography driven flow after a simulation time of 50,000 years and magmatic events each 50 years lasting for 3 days show different wide propagation of the thermal plume from the western fault westwards into the aquifer. A: without topography driven flow 3.1 km of the aquifer is heated up higher than 100 °C. B: with topography driven flow propagation of the plume is restricted through recharge from the opposite direction and therefore the heat plume is reduced to half (1.5 km). C: Darcy flux vectors show flow direction and velocity (up to 1.5 m/yr) in the aquifer. Blue: recharge flow; Red: convective flow.

### 3.3 Scenario 3

The limestone aquifer is karstified [16]. To test the influence of karst on heat transport, the parameter values for porosity and hydraulic conductivity are twice those of scenario 2. The increased hydraulic conductivity and porosity lead to a faster flow of heated brine (3 m/yr). After a simulation time of 10,000 years the thermal plume propagates 1.8 km laterally in the aquifer westward (Fig. 6), bounded by the topography driven recharge flow toward the lake.

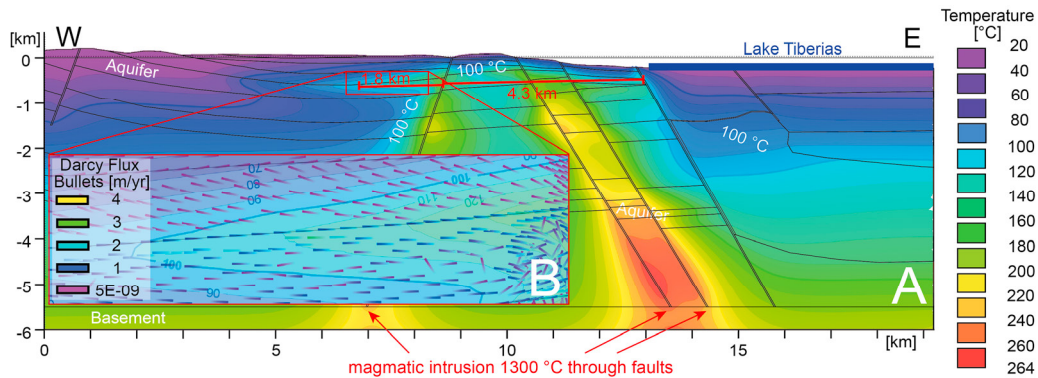


Fig. 6. Simulations of scenario 3 show in A: Darcy velocities of 3 m/yr and in B: The thermal plume propagating 1.8 km westwards from the fault.

### 3.4 Conceptual model

Five key heat transport mechanisms (Fig. 7) were identified and can be highlighted affecting the thermal field in consequence of magmatic intrusions:

- 1) Conductive heat transport plays a minor role, as the propagation of the thermal front is restricted to the near surrounding of the magmatic intrusion. The aquifer cannot be heated up with only conductive heat transport.
- 2) In the liquid phase, heat is transported via buoyant/convective flow. Heated fluids rise along the faults and flow laterally into the aquifer. The higher the hydraulic conductivity and the porosity are, the wider is the heated brine extension in the aquifer.
- 3) The aquifer is flushed with cool water from recharge areas. Topography driven flow limits the propagation of the thermal plume.
- 4) Karst processes would have a strong impact on plume propagation. With a higher hydraulic conductivity and porosity the thermal plume propagates faster into the aquifer.
- 5) Briefly after magmatic intrusion steam is built at the contact zone of magma and limestones. The vapor phase will probably be degassing along the magmatic intrusion and other pathways and the thermal energy escapes very quickly. Since the vapor phase was not implemented in the simulations, this hypothesis has to be further investigated numerically.

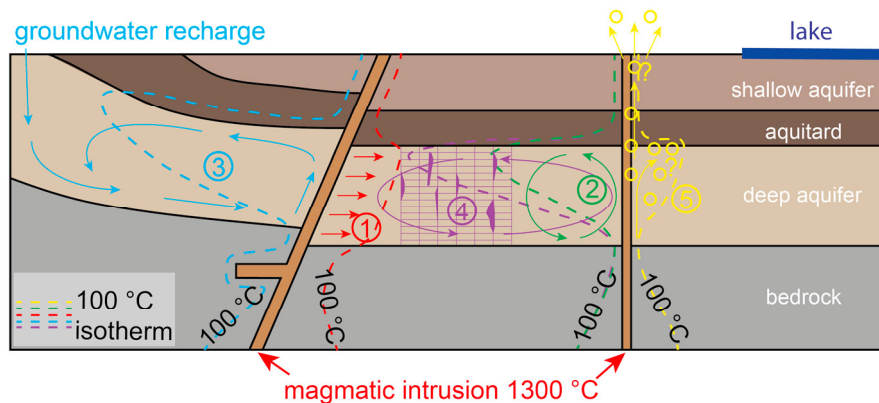


Fig. 7. Conceptual schematic scheme of five mechanisms heating up the deep aquifer. Thermal energy is transported from basalt intrusions through faults and sills laterally into the aquifer and by geothermal heat from below.



## 4 Conclusions and Outlook

The simulations indicate that magmatic-induced advective-convective heating may have generated temperature conditions favorable for dolomitization, which in turn may explain the existence of two different brines that are found around the LT. The simulations show that conductive heat transport plays a minor role. The interaction between advective-convective heat transport and topography-driven flow is the major control of the heat plume propagation, while the permeability of the aquifer determines flow velocity. Further investigations are needed to quantify energy dissipation due to multi-phase fluid-flow.

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