

**Heat as an artificial tracer for forced-gradient flow in the  
subsurface**

**Qualitative comparison between the sensitivity of fluid  
temperature signals to hydraulic aperture and to thermal  
width values of major vertical fractures in a geothermal  
reservoir operated by a well doublet**

**By**

**Swathi Mohandas Surekha**

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The thesis of Swathi Mohandas Surekha is approved by the thesis examination committee:

1. First Supervisor

-----  
Dr. Iulia Ghergut

2. Second Supervisor

-----  
Professor Dr. Martin Sauter

GEORG AUGUST UNIVERSITÄT GÖTTINGEN

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## **ABSTRACT**

Prediction of temperature decline (thermal breakthrough) during long-term reinjection is one of the main goals of inter-well tracer tests conducted in geothermal reservoirs. However, a clear-cut, unambiguous relationship between the fluid residence time distribution (as measured by tracer tests) and the outflow temperature evolution (as a prediction target) has been established only for a small number of idealized reservoir models; these models assume utmost simplicity of flow-field and (where applicable) matrix-fracture geometry, e.g. parallel flow in a homogeneous single-continuum porous medium (for the hydrothermal reservoir type), or in a single-fracture or parallel multiple-fracture discrete and continuum hybrid (for the petrothermal reservoir type). In real-world reservoirs comprising a finite number of faults or major fractures of finite extension and of possibly irregular orientation, the correlation between solute (tracer) transport and heat transport may become ‘blurred’ (i.e., non-monotonous) or weakened (i.e., of reduced sensitivity) by a rather intricate superposition of ‘accelerating’ and ‘decelerating’ effects of fracture presence on both advective and non-advective transport processes in fractures as well as in their surrounding rock matrix blocks, especially when fracture orientation is ‘oblique’ relative to the inter-well axis. Under the same fluid turnover rate (as prescribed by reservoir economics), fractures may accelerate the flow component along the inter-well axis, or they may accelerate drainage across this axis and ‘away’ from the production well, depending on their hydraulic transmissivity ratios (relative to the surrounding matrix blocks), moreover they may slow down the transport in spite of flow acceleration (and vice-versa), depending on their effective aperture and porosity values. Such fault and fracture settings can be encountered across a great variety of geological conditions, comprising both hydrothermal and petrothermal reservoir types. With the advent of so-called EGS (‘enhanced geothermal systems’), one often has to deal with a combination of pre-existing natural faults or fracture systems, and artificially-induced fractures (e. g., EGS sites Soultz-sous-Forêts in the Upper Rhine Rift Valley, or Horstberg and Groß Schönebeck in the Northern-German Sedimentary Basin). Hydrothermal reservoirs can display a similar degree of complexity at their ‘secondary porosity’ level along with faults and fractures, stemming from their consecutive ontogenetic stages (e. g., in the Malm-Molasse basin). A persisting issue with naturally pre-existing faults and/or fractures as indicated by geophysical (mainly seismic) exploration is that their relevance to reservoir hydraulics and fluid transport cannot be told in advance (i. e., not before drilling and onset of reservoir operation); and, conversely, fractures that become relevant to flow and transport under certain reservoir operation conditions may have remained undetected by prior geophysical exploration.

Past scoping simulations conducted for a geothermal well doublet within a ‘pastiche’ reservoir model comprising five oblique fractures (relative to the inter-well axis) have demonstrated the uncoupling (Ghergut [2013]) between heat and solute (tracer) transport while varying the heat and solute transport parameters uniformly for the whole set of fractures – of which two intersected the injection and production well-screens, respectively, and the further three, non-

intersected fractures were placed ‘inside’ and ‘outside’ the reservoir, respectively (one between the injection and production well, one ‘outwards’ the production side, and one ‘outwards’ the injection side). This same ‘pastiche’ model was later used to look into the effects of the three non-intersected fractures on inter-well tracer test signals, by switching these fractures ‘on’/‘off’ individually (Ghergut [2017]), however without addressing heat transport. It was found that the sensitivity of early tracer signals to the presence or absence of non-intersected fractures ‘inside’ or ‘outside’ the reservoir is insufficient to enable the detection of such fractures by relying on artificial tracers only; however, these findings were limited to the case of smooth and relatively thin fractures (reckoning that larger fractures should have been reliably detected by geophysical exploration and/or standard hydraulic tests at early stages of/after reservoir development).

Unlike in past studies, the main purpose of the present study is to look into the effects of non-intersected oblique fractures (defined in the above-described manner) on heat transport in the geothermal reservoir operated by forced-gradient inter-well circulation within a well doublet, using the already-mentioned ‘pastiche’ model but making more realistic assumptions on fracture properties (rough fractures: hydraulic aperture may differ from transport-effective aperture), and also comparing between the effects of rather thin fractures (which might remain undetected by prior geophysical exploration) and those of larger fractures (which may become ‘visible’ to hydraulic tests but whose transport-effective aperture may differ from their aperture measured by pressure signals).

Using FEFLOW, fluid flow and heat transport are simulated for the entire reservoir volume, but the analysis of simulation results is focused on temperature decline at the production well (thermal breakthrough), because in practice this is usually the only ‘location’ accessible to temperature measurement.

However a series of 3-D temperature field visualizations inside the reservoir body is also presented, as a graphical aid to compare the spreading of the cooled-fluid ‘plume’ longitudinally and laterally (relative to the inter-well axis), since this relative spreading or ‘drainage’ effect was found to provide a clue for explaining how individual fractures ‘inside’ or ‘outside’ the inter-well domain may slow down or accelerate the thermal breakthrough at the production well. Not much effects on temperature decline are found as long as hydraulic apertures of fractures, now treated as rough, stay below a threshold value in the range of 1 mm, consistently with past findings (Ghergut[2017]) for smooth fractures. However, if hydraulic apertures are increased significantly (several mm ... up to 1 cm), even without changing the transport-effective aperture, production temperature signals respond increasingly sensitive to the presence of fractures. This, alongside with findings from Khaleefah [2017, M. Sc. Thesis in prep.], confirms the generic expectation (Ghergut [2007]) that temperature signals tend to respond more sensitively to certain (continuum or discrete) hydraulic features, than to their associated thermal parameter values, thus making heat a suitable ‘tracer’ for the hydraulic characterization of fractured-porous systems. This is the broader message that the numerical simulations conducted within the framework of this study convey beyond the geothermal realm – regarding heat as a suitable ‘tracer’ also for groundwater

studies. For this reason, as well, the main work body – the numerical study of heat transport in the ‘pastiche’ model of a fractured geothermal reservoir operated by a well doublet – is preceded by a brief review (literature study) of past applications of ‘heat as a groundwater tracer’.

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## **ABBREVIATION**

wh	Hydraulic Aperture
wt	Thermal Aperture
FEFLOW	Finite Element Subsurface Flow and Transport Simulation System
EGS	Enhanced Geothermal System
TOUGH2	Transport of Unsaturated Groundwater and Heat
SUTRA	Saturated-Unsaturated Transport
SHEMAT	Simulator for Heat and Mass Transport
CCS	Carbon capture and storage
cm	centimeters
mm	Millimeters
°C	Celsius
°F	Fahrenheit

# **1. INTRODUCTION**

Understanding of flow and transport in porous fractured media is of importance for water supply, mining, tunneling, subsurface storage and the development of geothermal reservoirs in hard rock regions and is possibly one of the main challenges in hydrogeological research. A variety of techniques are available for characterization of the hydrogeology of fractured bedrock aquifer with low matrix permeability such as surface surveys, well logging, hydrologic tests, and tracer tests. In that tracer, testing has become a highly important tool in geothermal research, development and resource management. Its purpose is mainly threefold: (1) For general hydrological studies of subsurface flow, (2) for reinjection research and management and (3) for flow rate measurements in pipelines carrying two-phase water mixtures.

The main goal of geothermal tracer testing is to predict thermal breakthrough and temperature decline during long-term reinjection, or the efficiency of thermal energy extraction in enhanced geothermal system operations. This is dependent on the properties of the flow-channel involved, but not uniquely determined by the flow-path volume. The heat transfer (cooling/heating) mainly depends on the surface area and porosity of the flow channel. Therefore, some additional information on the flow-path properties/geometry is needed, i.e. geological or geophysical in nature.

Temperature has been widely used as a tracer for fluid flow in hydrogeologic investigations. Anderson [2005] provides a thorough review of research applications based on using heat as a groundwater tracer. Heat tracers have been used in the past to characterize from groundwater-surface water interactions to groundwater flow through unconsolidated and fractured rock aquifers. Recent advances in temperature sensing technology applied to hydrogeologic measurement (Selker [2006]; Tyler [2009]) have increased interest in using temperature as a means of measuring and monitoring various hydrologic flow mechanisms; yet, the application of temperature for studies in fractured rock hydrogeologic environments remains limited. Anderson [2005] and Saar [2011] focused on the often-unexplored potential of using natural temperature variations as a cheap, expressive, and complementary means to support the hydraulic characterization of groundwater flow conditions, water balancing, and modeling on local and basin scale. So far, less interest has been on the application of artificial thermal signals, which are actively induced in field measurement campaigns. Thereby, standard applications and interpretation procedures do not exist, that established alternative hydrogeological investigation methods coexist, and that generation of substantial and far-reaching thermal signals is challenging, time-consuming, and potentially costly. In most studies with artificial heat perturbation, understanding coupled hydraulic-thermal processes is of particular interest such as the evolution of thermal anomalies from injection of hot or cold water is mainly studied in the context of geothermal energy use of shallow aquifers (Parr [1983]; Palmer [1992]). The movement of heat in the fractured subsurface can be described mathematically in a manner similar to contaminant migration in discrete fractured systems in which heat is transported by

advection through the matrix and convection by flowing water in the fractures, can be lost or gained by a source or sink and can be slowed in migration by thermal retardation.

Temperature has been shown to be an effective tracer for georeservoir characterization and therefore, the proposed approach aims to illustrate heat as an artificial tracer for forced-gradient flow in the subsurface i.e. by qualitative comparison between the sensitivity of fluid temperature signals to hydraulic aperture and to thermal width values of major vertical fractures in a geothermal reservoir operated by a well doublet.

For this purpose, we will demonstrate a series of scoping simulations using the five-fracture model system, representing a deep geothermal reservoir, with well-doublet placement inducing fluid flow both across and through the fractures. The setup of the “five-fracture” model for demonstrating and analyzing the issue of (partial) uncoupling between hydraulic and thermal or solute tracer transport behavior was conducted using FEFLOW Software. This generic five fracture model where it combines the features at different geothermal reservoir such as at North German basin etc. But currently, this model is essentially a loosely resembles or mimics certain features from geothermal reservoir settings in the Malm aquifer in the Munich area of southern Germany at which tracer tests are currently under consideration (cf. Dewi [2016]). From a review of past studies, we are simply not illustrating other studies on heat as tracer but we are selecting certain aspect of flow and transport behavior, then we are illustrating this aspect in this five-fracture model (Figure 1), this is the reason for introducing this model. Unlike in the past study by Ghergut [2013], where fracture parameters were varied uniformly for the whole set of fractures, but now we ‘switch’ fractures on and off individually if we change the aperture or permeability the effect will be same. Now we should switch on and off fractures individually and look especially on the effects of what will happen if we change the properties of fractures outside and in the middle (between the two boreholes) but not intersect by any of the boreholes.

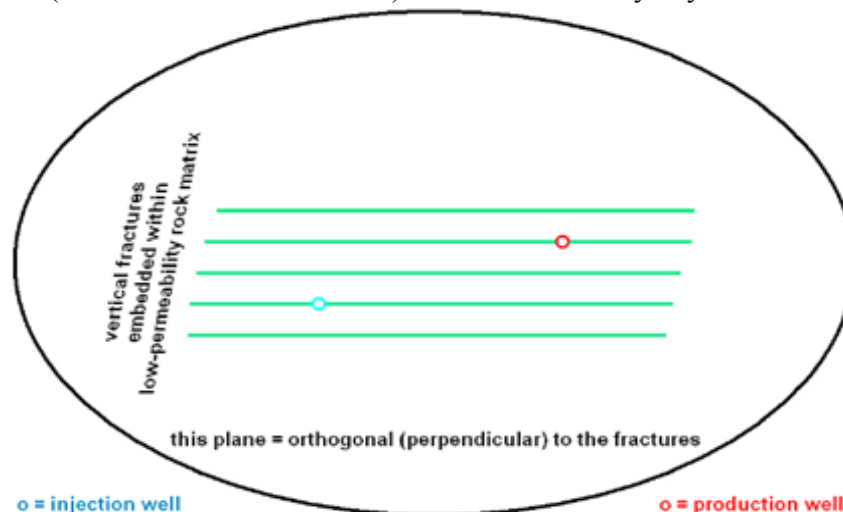


Figure 1: Top view of five fracture model  
(Source: Ghergut [2017])

## **1.1 Objective of this study**

Unlike in the past scope simulation by Ghergut [2013], we make use of a setup of the “five-fracture” model, a generic extremely-simplified “fractured reservoir” model, the main purpose of demonstrating parameter uncoupling between heat and solute (tracer) transport, i.e. parameters were varied uniformly for the whole set of fractures and whereas Ghergut [2017] demonstrated the parameter only for solute transport by ‘switch’ fractures on and off individually and also looked into the effects of non-intersected fractures ‘inside’ or ‘outside’ the reservoir on inter-well tracer test signals. Despite the seemingly extreme simplicity of this model geometry (Figure 1), flow and transport patterns within this geometry do not follow a universal scheme and are also difficult to categorize into a finite number of a distinct type. In the past study Ghergut [2013] some scoping simulations were presented the issue of (partial) uncoupling between hydraulic and thermal or solute tracer transport behavior: heat transport was seen to be more sensitive to fracture apertures, and rather insensitive to matrix porosity, whereas solute transport was seen to be highly sensitive to matrix porosity (as expected) but rather insensitive to fracture parameters, and thus the inability, or limited ability of (especially solute) tracers to capture all relevant features and parameters of a deep georeservoir.

Unlike the past study which dealt with parameterization of this system determining the parameters in practical situation, we're dealing with individual fractures (major fracture) that have been identified by geophysical exploration (seismic exploration), which tells the location of fault zone but this always with a lot of uncertainty (we don't know if the fault zone explored by seismic is hydraulically effective). We use the temperature signals to make this detection or negation of fracture to add additional evidence.

In our study, scoping simulations were conducted by using FEFLOW software, switch on and off of the fractures individually from five fracture model to check the effects of fractures outside and in the middle (between the two boreholes) but not intersect by any of the boreholes and also observed that this has consistence effect on the temperature signals but not at the intersected fractures because these are better known during the drilling process.

The main purpose of the present study is to look into the effects of non-intersected oblique fractures (defined in the above-described manner) on heat transport in the geothermal reservoir operated by forced-gradient inter-well circulation within a well doublet, using the already-mentioned ‘five fracture’ (pastiche) model but making more realistic assumptions on fracture properties (rough fractures: hydraulic aperture may differ from transport-effective aperture), and also comparing between the effects of rather thin fractures (which might remain undetected by prior geophysical exploration) and those of larger fractures (which may become ‘visible’ to hydraulic tests but whose transport-effective aperture may differ from their aperture measured by pressure signals).

As part of past study, the hydraulically effective aperture of fractures may differ from their transport-effective aperture, and changing the hydraulic aperture will lead to a different distribution of fluid (and tracer) fluxes between matrix and fractures, thereby also influencing tracer signals. Therefore, the effects of individual fractures on heat transport and thermal breakthrough at the production well was seen.

In order to exhibit the goals of this study we find the different value of effective fracture for heat transport (thermal) and for hydraulic especially because of fracture roughness, the effective hydraulic aperture is lower than geometrical aperture. For heat transport, the geometrical aperture is controlling parameter but for hydraulic because of fracture roughness means irregularity of fracture surface. But only small part of whole fracture opening will be hydraulic effective. This means in FEFLOW model we can insert different parameter for hydraulic aperture and thermal aperture. We conduct set of simulation when the hydraulic aperture is lower than the factor of the thermal aperture. The idea is to check if temperature be sensitive to hydraulic aperture

Therefore, we present the following technical tasks:

1. Parameter sensitivity study for rough fractures (with “hydraulic apertures” wh systematically lower than “transport apertures” wt):

1.A: Sensitivity of temperature signals w. r. to the presence or absence of fractures

1.A.a: “inside” the reservoir,

1.A.b: “injection-outwards”,

1.A.c: “outwards-production”,

1.A.d: “across the injection screen”,

1.A.e: “across the production screen”.

2.B: Sensitivity of temperature signals w. r. to the hydraulic aperture (wh) of a major fracture inside the reservoir (like in case 1.A.a.)

## **1.2 Area Of Study**

Such fault and fracture settings can be encountered across a great variety of geological conditions, comprising both hydrothermal and petrothermal reservoir types. With the advent of so-called EGS ('enhanced geothermal systems'), one often has to deal with a combination of pre-existing natural faults or fracture systems, and artificially-induced fractures (e. g., EGS sites Soultz-sous-Forêts in the Upper Rhine Rift Valley, or Horstberg and Groß Schönebeck in the Northern-German Sedimentary Basin).

- GroßSchönebeck (petrothermal and 'deep-aquifer' type, crystalline and sedimentary rock). Artificially-created fractures are not meant to increase the permeability, but the transmissivity. They are orthogonal to the interwell axis. Further fractures are assumed to exist (probably two parallel-fracture 'families', orthogonal and oblique to the inter-well axis, accounting for aquifer permeability transversally to the inter-well axis).
- Horstberg (petrothermal and 'modest-aquifer' type, sedimentary rock). Hydrofractures acts (unfortunately) as a short-cut between injection and production well screens. Transversal shift between production screen and hydrofractures is essential to reservoir lifetime. A further (small) fracure may exist at production screen.
- Upper Rhine Rift (hydrothermal type, mainly sedimentary some crystalline rock). Landau where injection and production wells intersect different faults. Insheim where injection and production wells within same fault zone; maybe with reduced permeability ('core zone') in between. Bruxal where injection and production wells located in two different aquifers, separated by large-scale fault.
- KTB (petrothermal type, crystalline rock). Injection and production wells intersect different faults. There may be further (transport-relevant) faults/fractures between the two, but their connectivity is unclear

But currently, this five-fracture model is essentially a loosely resembles or mimics certain features from geothermal reservoir settings in the Malm aquifer in the Munich area of southern Germany at which tracer tests are currently under consideration (cf. Dewi [2016]).

Since the year 2000, the upper Jurassic carbonates of the Southern German Molasse Basin are the target of numerous geothermal combined heat and power production projects, where Malm aquifer is a hydro geothermal reservoir with a high potential for heat (and electricity) production (Figure 2). These carbonates are characterized by a karst-fractured aquifer system Schulz [2012] located 3500–5500m below the surface in the southern part of the Molasse Basin. According to Meyer and Schmidt- Kaler [1989, 1990], the Swabian facies as the central part of the reef belt

formed a deeper-water area between the shallower Franconian–southern-Bavarian platform in the east and the Swiss platform in the west. In the southwest, the Swabian shelf facies deepens gradually towards the pelagic facies of dense, bituminous limestones with, in places, intercalated oolitic layers. These facies describes the transition of the Germanic facies into the Helvetic facies, which is considered as sediments of a deeper shelf area of bedded limestones with very low permeability. Karstification is not observed either; thus, the northern boundary of the Helvetic facies is considered as the southern boundary of the Malm aquifer of the Molasse Basin (Villinger [1988]). This basin represents typical example of a conduction-dominated geothermal play type where the sedimentary sequences of the foreland basin (Molasse Basin) are influenced by significant crustal subsidence towards the orogenic belt (Alps) due to the weight of the thickened crust of the orogenic belt and loading of erosional products from the mountain belt on the non-thickened crust (Moeck and Beardsmore [2014]).

It is presently one of Germany's most important geothermal reservoirs as a result of the fact that the groundwater temperatures is up to 140 °C and more and has a high-flow regime i.e. it is highly permeable. The research project TRENDS (Tracer-assisted evaluation of reservoir behavior under expansive deployment schemes for Malm geothermal resources in the Munich area) aims at quantifying the hydrogeology of Malm geothermal resources with a focus on fluid transport parameters and quantifying fluid flow identifying possible restrictions to reservoir exploitation resulting from either hydraulic or geothermal heat supply 'competition' effects between 'adjacent' reservoirs and predicting heat transport therein under various scenarios for the future deployment and exploitation of Malm geothermal resources in the SE-German area of the Molasse basin. But these goals cannot be achieved without the use of fluid-based tracking procedure for quantifying fluid transport, i.e. tracer test. The use of artificial tracers is challenged by the very large size of Malm geothermal reservoirs, implying very long residence times (RT) of circulating fluids and strong dilution of tracers therein.

Variety of large-scale hydrotectonic and mid-scale hydrogeological settings where natural and/or artificially-induced fractures are involved as shown in figure 2. Modified after GFZ Potsdam Bildarchiv Geothermie :

**A:** map of geothermal resources in Germany, Blumenthal [2007],

**B:** conceptual model for the Soultz-sous-Forêts site in the Upper Rhine Rift Valley, Cherubini [2013],

**C:** hydrotectonic model for the Rotliegend reservoir in the N-German Basin, with faults acting as conduits (shown in blue) or as seals (shown in brown), with lower window showing flow velocity field and temperature distribution along major conductive fault, Blöcher [2010],

**D:** stratigraphic and structural model of the reservoir comprising artificially-induced fracs (shown in black) and mid-scale natural fractures (shown in gray) around the Gr. Schönebeck well doublet in the N-German Basin], Przybycin [2015],

**E:** large-scale hydrotectonic and hydrogeologic model of the Malm aquifer below Munich in the S-German Molasse Basin, with simulated temperature distribution to illustrate the influence of three major faults.

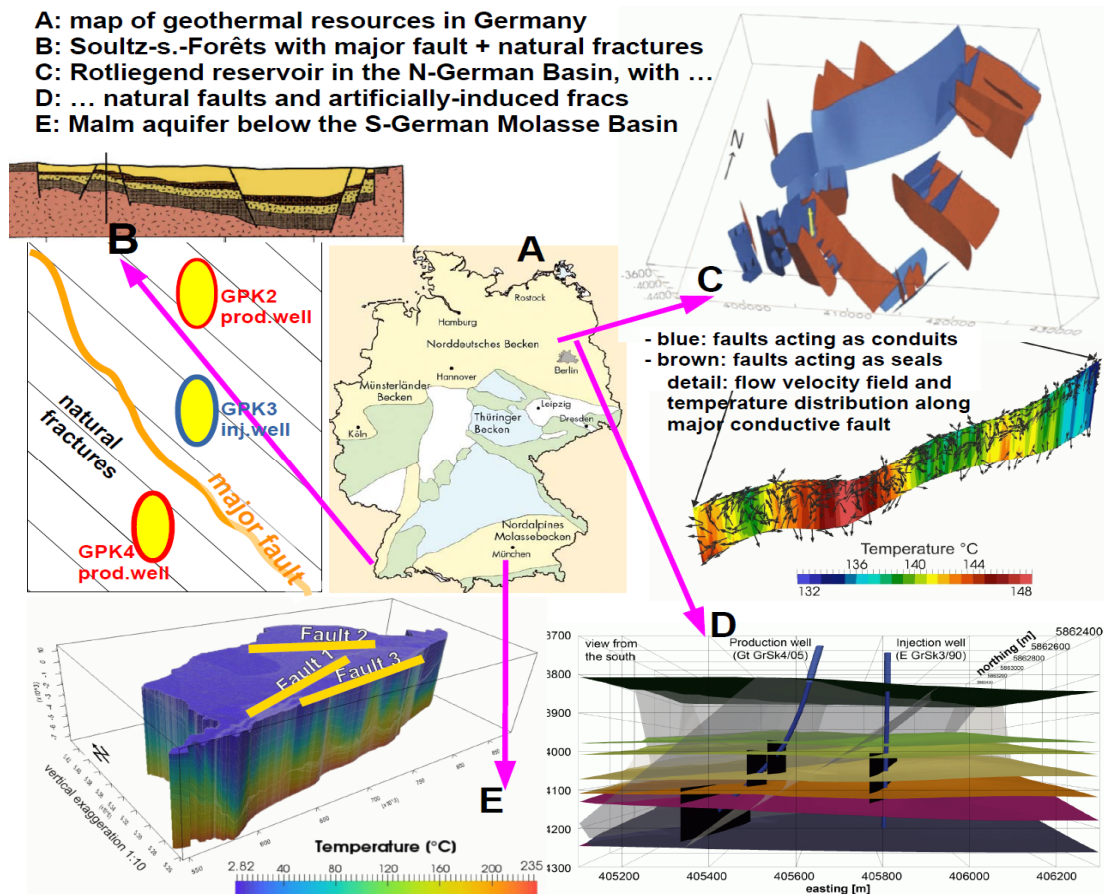


Figure 2: Variety of large-scale hydrotectonic and mid-scale hydrogeological settings where natural and/or artificially-induced fractures.

## **2. THEORETICAL BACKGROUND**

### **2.1 Heat As Groundwater Tracer**

Tracers are commonly used to get insight into the hydraulic properties of the subsurface on the aquifer scale and to identify dominant transport routes. For aquifer characterization, heat is one of the tracers which injected as a thermal tracer in boreholes or wells then temperature changes are measured in the injection well and/or in nearby observation wells, which offers several advantages in comparison to many solute tracers. Good detectability, their lack of influence on the flow regime, conservativeness, and nontoxicity to the environment are the main aspect for the ideal tracer. Heat carried by groundwater serves as a tracer to identify surface water infiltration, flow through fractures and flow patterns in groundwater basins. Groundwater temperatures have been routinely recorded for a long time (e.g. Collins [1925]), mostly as a measure of groundwater quality. Slichter [1905] was the one of the first to point out that heat is a useful tracer of groundwater flow.

Heat-flow theory has influenced the development of groundwater flow theory by using temperature measurements themselves in ground water investigations has been sporadic. The fundamentals of using heat as a ground water tracer were published in the 1960s, but recent work has significantly expanded the application to a variety of hydrogeological settings (Anderson [2005]). Following the publication of three important articles in the 1960s (Suzuki [1960], Stallman [1965], and Bredehoeft and Papadopulos [1965]), researchers became seriously interested in using heat to trace groundwater flow that showed the temperature measurements could be used in analytical solutions of the one-dimensional form of the heat transport equation to solve for groundwater velocity. Early pioneering work by Suzuki [1960] led to a method for analyzing temperature profiles to estimate vertical groundwater flux (recharge and discharge rates). Stallman [1963] used joint head and temperature measurements to numerical model to solve the inverse problem for groundwater velocity and hydraulic conductivity. During the Stallman's paper, Bredehoeft and Papadopulos [1965] introduced a one-dimensional steady-state analytical heat transport model to calculate vertical leakage through a confining bed within the geothermal zone and solve for ground water velocity under constant temperature boundary conditions. Stallman [1965] introduced a model for transient analysis of temperature profiles in the surficial zone. This earlier publication works on ground water temperature profiles, in which investigators modified and extended the models to consider other types of boundary conditions and application to a variety of hydrogeological setting. Trainer [1968] used temperature profiles in water wells as indicators of hydraulically active fracture locations in dolomite bedrock.

Stallman's [1963] suggested that heads and temperatures might be used jointly to estimate groundwater velocity and hydraulic conductivity, by attempting formal inversion of a coupled groundwater flow and heat transport model (Woodbury and Smith [1988]; Wang [1989]; Bravo

[2002]). That means simulated temperatures matches observed temperatures that provide an additional constraint on calibrating a flow model because the velocities required to calibrate the heat-flow model must also calibrate the groundwater flow model. The use of temperature measurements at the Illinois Basin, USA was pioneered by Cartwright [1970] to estimate ground water recharge and discharge rate. Parsons [1970] was among the first to use a numerical model to study thermal patterns in two-dimensional groundwater systems. The Domenico and Palciauskas [1973] solution is used to analyze perturbations in the geothermal zone caused by convection in a regional groundwater flow system. Sakura [1993] pointed the application of the Domenico and Palciauskas [1973] solution to the Yonezawa Basin and showed that the model closely simulated the observed temperatures, confirming the existence of a regional groundwater system in the basin. These studies show that the nature and magnitude of the perturbations caused by groundwater flow are affected by anisotropy and heterogeneity in hydraulic conductivity, recharge rate, and configuration of the water table.

Early papers on this topic, were published during the 1960s and 1970s, called attention to the potential for using heat as a tracer and temperature as a surrogate for head measurements to estimate groundwater fluxes. However, workers understandably continued to focus on measuring and simulating head directly. Heat is an ideal choice because it is easily detectable by means of traditional temperature sensors, distributed temperature sensors (DTSs) or geophysical techniques (Hermans [2014]), and it can be monitored continuously in situ. Capitalizing on the availability of improved temperature sensors and numerical codes, investigators are just starting to explore the full potential for using temperature measurements in a wide variety of hydrogeological settings. The utility of temperature measurements in estimating fluxes in groundwater stream systems is now well established (Stonestrom and Constantz [2003]). Early thermal studies relied ground water temperature can be measured lowering a thermometer down a borehole, although precautions must be taken to ensure that the recorded temperature is representative of water in the aquifer and not been influenced by movement of water in the borehole (Mansure and Reiter [1979]; Keys and MacCary [1971], p. 106). Recent thermal studies benefit from the use of thermocouples and thermistors i.e. obtain a time series of measurements remotely. Waterproof temperature loggers, subsurface temperatures (Stonestrom and Blasch [2003]) and airborne thermal sensors i.e. detect areas of groundwater discharge (Becker [2006]).

In the late 1980s, interest in using heat flow analyses in hydrogeological investigations was further motivated by the publication of two key works-Lapham (1989), who focused on application to streams, and Beck [1989], who focused on application to regional groundwater systems. The work applied to sedimentary basins was pursued using analytical solution in Japan (Sakura [1993]; Inagaki and Taniguchi [1994]; Taniguchi [1993, 1994]; Dapaah- Siakwan and Kayane [1995]). Taniguchi [1993] developed type curves and applied the method to calculate recharge and discharge at two sites in Japan: Nagaoka Plain (Taniguchi [1993]) and Nara Basin (Taniguchi [1994]). These profiles illustrate elongation in the recharge area caused by downward

movement of ground water and compression in the discharge area caused by upward movement of ground water. Ge [1998] presented a one-dimensional, steady-state analytical solution to simulate the temperature signal caused by an isolated fracture or fractured zone. The work on the groundwater basin by Domenico and Palciauskas [1973] demonstrated theoretically that ground water flow causes perturbations in the thermal regime in two dimensions (Parsons [1970]; Smith and Chapman 1983; Garven and Freeze [1984]; Woodbury and Smith [1988]; Forster and Smith [1989]) and three dimensions (Woodbury and Smith [1985]) are affected by anisotropy and heterogeneity in hydraulic conductivity, recharge rate and configuration of the water table. But thermal regime will be unaffected by convection (Jessop [1989]) in some basin. In most studies with artificial heat perturbation, understanding coupled hydraulic-thermal processes are of particular interest. Evolution of thermal anomalies from injection of hot or cold water is mainly studied in the context of geothermal energy use of shallow aquifers [Parr [1983]; Palmer 1992]). With the advent of numerical models, many investigators turned to numerical solutions of coupled groundwater and heat-flow models in two and three dimensions. Yusa [1987] used a two-dimensional coupled model of groundwater flow and heat transport to illustrate the effects of convection on the discharge of hot springs. Uchida [1998] and Uchida [2003] used a three-dimensional, coupled groundwater flow and heat transport model to simulate the groundwater system in the Nobi Plain.

Corbet and Bethke [1992] also showed that current rates of groundwater flow appear to be too slow to transport significant heat. Their two-dimensional coupled groundwater and heat-flow model reproduced observed temperature gradients by using spatially variable values of thermal conductivity of a shale layer.

Building on ideas of Stallman [1963], Bravo [2002] successfully used measurements of surficial temperature in parameter estimation with a coupled groundwater and heat-flow model of a wetland system in Wisconsin where the basal heat influx is relatively low. Anderson [2005] and Saar [2011] emphasized the often-unexplored potential of using natural temperature variations as a cheap, expressive, and complementary means to support the hydraulic characterization of groundwater flow conditions, water balancing, and modeling on local and basin scale. So far, less interest has been on the application of artificial thermal signals, which are actively induced in field measurement campaigns. Reasons for this are that standard applications and interpretation procedures do not exist, that established alternative hydrogeological investigation methods coexist, and that generation of substantial and far-reaching thermal signals is challenging, time-consuming, and potentially costly. Silliman and Robinson [1989] monitored via wireline probe the thermal response induced by pumping and injection in boreholes for assessing fracture interconnectivity. Williams and Conger [1990] employed temperature logs in a borehole to identify flow zones under ambient and pumped conditions. Temperature profiles using probes were used in combination with chemical tracers by Bidaux and Drogue [1993] to characterize flow in fractured carbonate rocks. The chemical profiles were used to supplement

poor resolution temperature data for detecting low-velocity flow. In above literature explained, temperature measurement was particularly used in surface-subsurface interaction but they are not used deep ground water system. Therefore, more research has to be done in the deeper system.

## **2.2 Example**

As per publication Anderson [2005], temperature measurement can be used intensively in surface-subsurface water interaction but not intensively used in the deeper ground. There is a need to do more research on the deeper system. The use of temperature measurement for example distributed in several points in aquifer or temperature in one borehole but measured in the different borehole, and in different depth. The use of these temperature not only use to see how cold or warm it is but also use to characterize the aquifer that means to estimate permeability, transmissivity, permeability contrast and also characterize the groundwater fluxes(how much water comes to aquifer).

The past two studies demonstrate the application of temperature measurement used for hydrogeological characterization.

### **2.2.1 First Example:**

Trainer [1968] recognized that temperature profiles for the wells can be used to determine the vertical distribution of water-bearing fractures because the profiles show inflections which mark the levels of the fracture zones receiving the water. The study area was in the Lockport Dolomite in western New York. There is a downward flow of water from fractures in the upper part of the rock to deeper fracture zones. This downward movement is more effective transfer of heat where the rock is not penetrated by wells. There are strong seasonal differences in surface temperature and of horizontally stratified rocks with layered permeability, temperature profiles in wells serve to identify water-bearing zones in the rock.

The Lockport Dolomite, of Silurian age, crops out in a belt that extends across western New York and into Ontario. Near Sanborn, New York the dolomite is about 120 feet thick and dips very gently to the south. The fracture of two types was well developed in the rock i.e. bedding joints and vertical joints. The bedding joints are present most surface exposures and observed in periscope in numerous wells. whereas Vertical joints are most abundant near the bedrock surface; they commonly extend to depths of less than 10 to 15 feet (Figure 3).

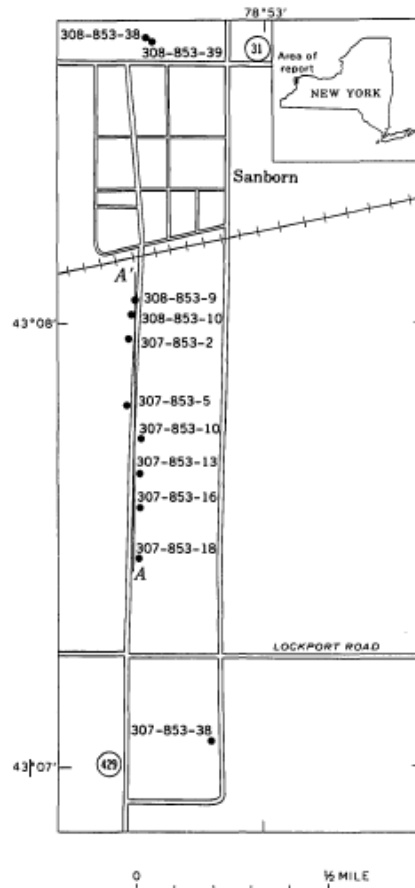


Figure 3: Study area at Sanborn, New York where black dot are well in which temperature data and number beside well symbol are well number. (Source: Trainer [1968] )

An earlier study conducted at Sanborn (Trainer and Eddy [1964], p. D205) showed that the form of measured temperature profiles are marked differently from that of ideal profiles based on the assumption that heat flow is entirely by conduction through the dolomite. The measured profiles are marked clearly in slope, or inflections whereas smooth curves as are the ideal profiles. Fractures found at or near the positions of the inflections are at which water moving down the wellbore flows out into the rock. During winter and early spring, the rock wall of the well loses heat to the downward-moving water when near-surface ground water is relatively cold. The inflections in the temperature profile are seen when the flow of water and the loss of heat are less below the level of each fracture or group of fractures. For summer, the temperature-reversed process occurs when the downward-moving water is warmer than the rock penetrated by the well.

Five temperature profiles of four different well have been measured in the Sanborn area (Figure 4). Using a periscope, fractures or groups of fractures were observed at certain depth: 8, 12, 13, 18, 19, 22-24, 29-30, 32, 38, and 40. The inflections in the temperature profiles are at about 12, 16-19, 21-24, 29-30, 32-34, and 39 feet as seen in the figure. Temperature measurements are

recorded at intervals (commonly 1 or 2 feet) down the well because of inflection of temperature profile.

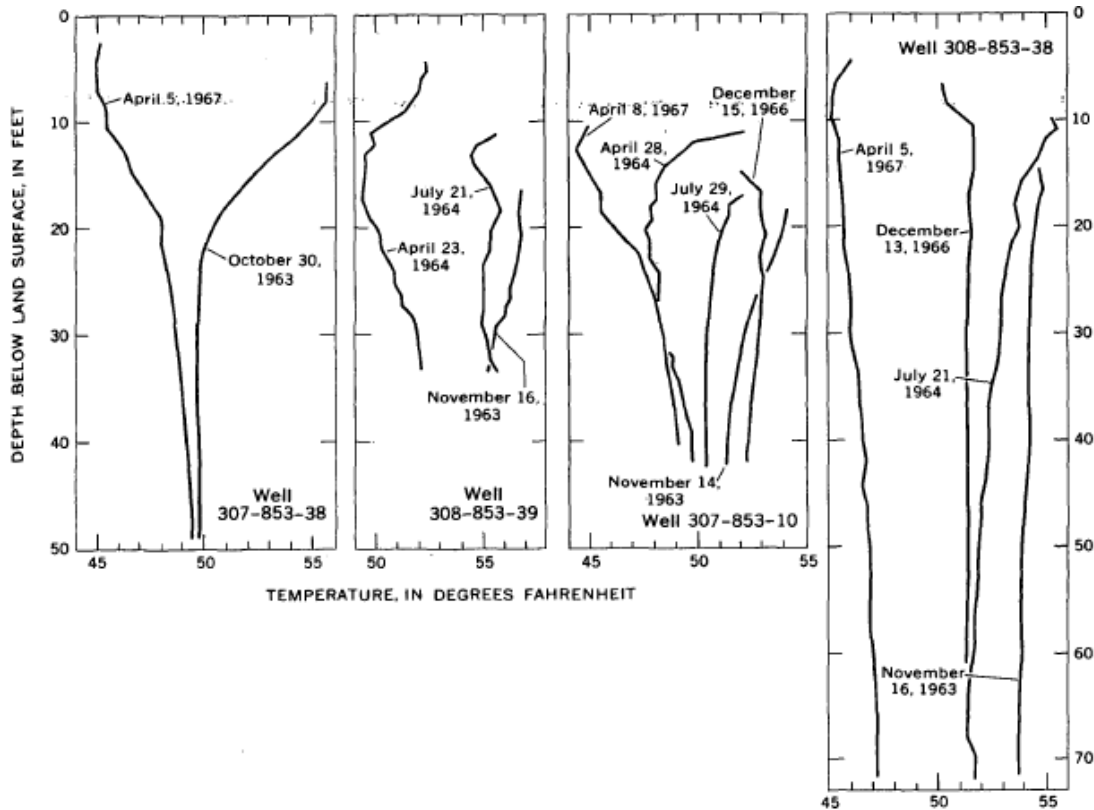


Figure 4: Temperature profiles for four wells in and near Sanborn, N.Y.  
(Source: Trainer [1968] )

Most of these profiles are characterized by inflections similar to those in the profiles for well 307-853- 10, and in most wells, the positions of fractures zones can be determined from the profiles. Well 307-853- 10 together with other data from this well, provide a key to the interpretation of these seasonal changes. Thus, in this area of strong seasonal differences in surface temperature and of horizontally stratified rocks with layered permeability, temperature profiles in wells serve to identify water-bearing zones in the rock.

A periscope survey of well 308-853-39 has 25 fractures. From 8.8 to 11.3 feet and from 28.4 feet to 31.4 feet no fracture was seen. However, inflections in temperature profiles for show hydraulically significant fractures at about 11-17 feet, at about 20-22 feet, and at several places between 23 and 29 feet. Because the profiles are based on measurements made 1 foot apart down the well bore.

On May 23 (1967), showed a downward flow of about 2.3 feet per minute (about 3.3 gallons per minute) between 11 and 16 feet using the current meter. However above 11 feet and below 16

feet, there was no flow measurement detected due which a flow guide could be used to channel all the flow through the meter, is about 1 foot per minute. More water flows seen the fracture zone at about 11-17 feet according to the interpretation of the temperature is a water-bearing zone.

On April 1964, between 11 and 17 feet, suggested that the fracture zone consists of two parts: a thin part at about 11 feet and thick part is between 13 and 17 feet, which is the near-vertical slope of the temperature profile, have been receiving water through several fractures distributed over its entire thickness. Thin fractures under higher head are the source of the water which moves down the well. Two fractures were seen at 8.6 and 8.8 feet. The current-meter data did not provide all the downward-moving water. But thin fracture was seen at 11.3 feet.

By July 1964 the fractures in the uppermost part of the rock had been drained, the prominent bulge in the April temperature profile had largely decayed, and the column of water and walls of the well had been warmed by several degrees. Over 3 month period the temperature change was about 3 1/2 °F at the bottom of the well. After drainage of the unconfined aquifer, the heat was carried down the well by water from the zone at 11-17 feet has highest hydraulic head among water-bearing fractures tapped by the well. Therefore, this zone has lost water rather than gaining it. The downward moving water was now derived from the rock just below the 13-foot level, and it was warming the rock adjacent to the deeper part of the well. But also in November 1963, dewatering of the fracture zone at 11-17 feet, and to warming of the column of water and of the rock adjacent to the well.

Temperature profiles measured in wells 308-853-39 and 308-853-38 which are about 40 feet apart. The downward-moving water seems to be carried more rapidly at greater depth at well 308-853-38 which implied by the near-vertical form of the temperature profiles.

Well 307-853-38 penetrates 40 feet of unconsolidated sediment, and well casing was done at the upper part of the rock to prevent leakage of water around the end of the casing and into the well. The significance of inflections in the upper parts of temperature profiles for the well is not known. But the lower parts of the profiles shows the annual range in temperature at depth of well not characterized by the internal flow of water. Temperature profile at depth of 30 feet for well 307-853-38 is 1°F whereas for well 308-853-38 is about 8°F. This large fluctuation annual temperature fluctuation at depth, caused by the movement of water down wells.

In October and November 1963, temperature measurements were made at the bottoms of 69 wells of 30 feet deep. Of these 69 wells, 7 percent had bottom temperatures lower than 50°F whereas 93 percent had bottom temperatures was higher than 50°F or higher. These data strongly suggest that downward flow of water occurs in most bedrock wells deeper than 30 feet in the

Sanborn area. By extension, they imply the widespread occurrence of zones of bedding fractures such as Johnston [1964] found near Niagara Falls.

### **2.2.2 Second Example:**

Sakura [1993] evaluated groundwater flow on the distributions of subsurface temperature in the Yonezawa Basin, Northeastern Japan. The vertical temperature profiles in the wells were measured four times in 1990, to investigate the influence of groundwater flow on the distributions of subsurface temperature. A shallow system was identified, whose temperature changed seasonally under the influence of the artificial pumping for melting snow in the city area. The other was a regional system, which caused a significant disturbance of convective thermal regimes and produced the high-temperature zone in the central part of the basin.

In a regional ground-water flow system, recharge areas are along groundwater aquifer on the peripheral mountain and discharge to the river basins. Groundwater flow concentrates three-dimensionally in the surface center of the basin. Therefore groundwater flows on the island and mountain to be divergent, whereas that in the basin is convergent.

Yonezawa Basin, situated in the southern part of Yamagata Prefecture, is 27 kilometer long from north-south and 15 kilometer east to west (Figure 5). Many tributaries of the Mogami River generate in the peripheral mountain regions and flow toward the center of the basin. The basin contains alluvial fan deposits along at the base of the mountains and contains a flat lowland in its central part (Nagae [1991]).

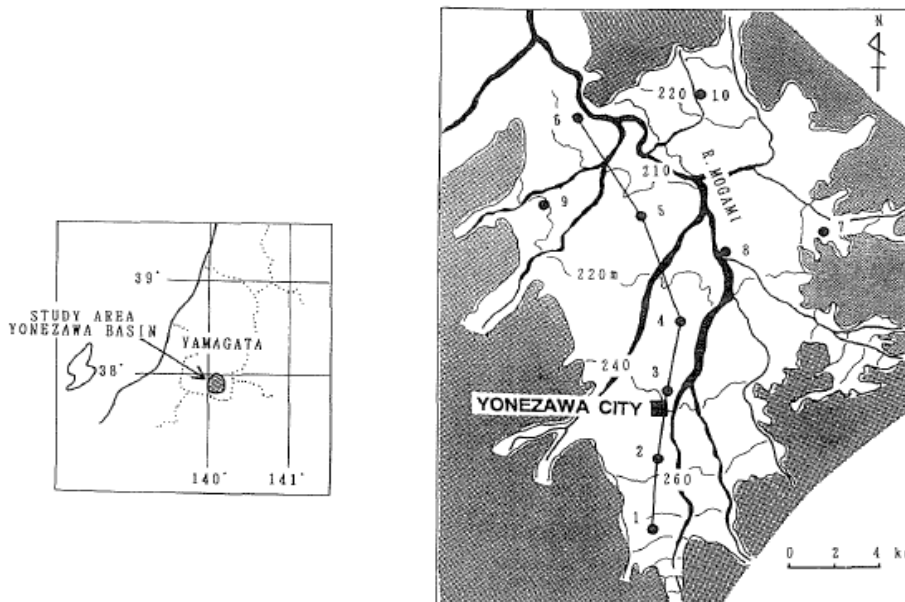


Figure 5: Location of study area and observation wells at Yonezawa City, Northeastern Japan (Source: Sakura [1993])

There were ten observation wells of certain well depths ranging from 50 meters to 200 meters. Temperature profiles were measured in the observation wells four times, once each on 17 March, 11 June, 11 September, and 18 December 1990. The temperature was measured using a thermistor in the well. The temperature was measured at 2 meters intervals and the precision of the temperature measurement was 0.01°C.

Two-dimensional temperature distributions along cross sections indicate that the temperature of the deeper groundwater remain constant throughout the year i.e. lower zone at the isothermal line of 14°C, whereas the temperature of shallow groundwater changes changed seasonally i.e. upper zone at an isothermal line 14°C as shown in Figure 6.

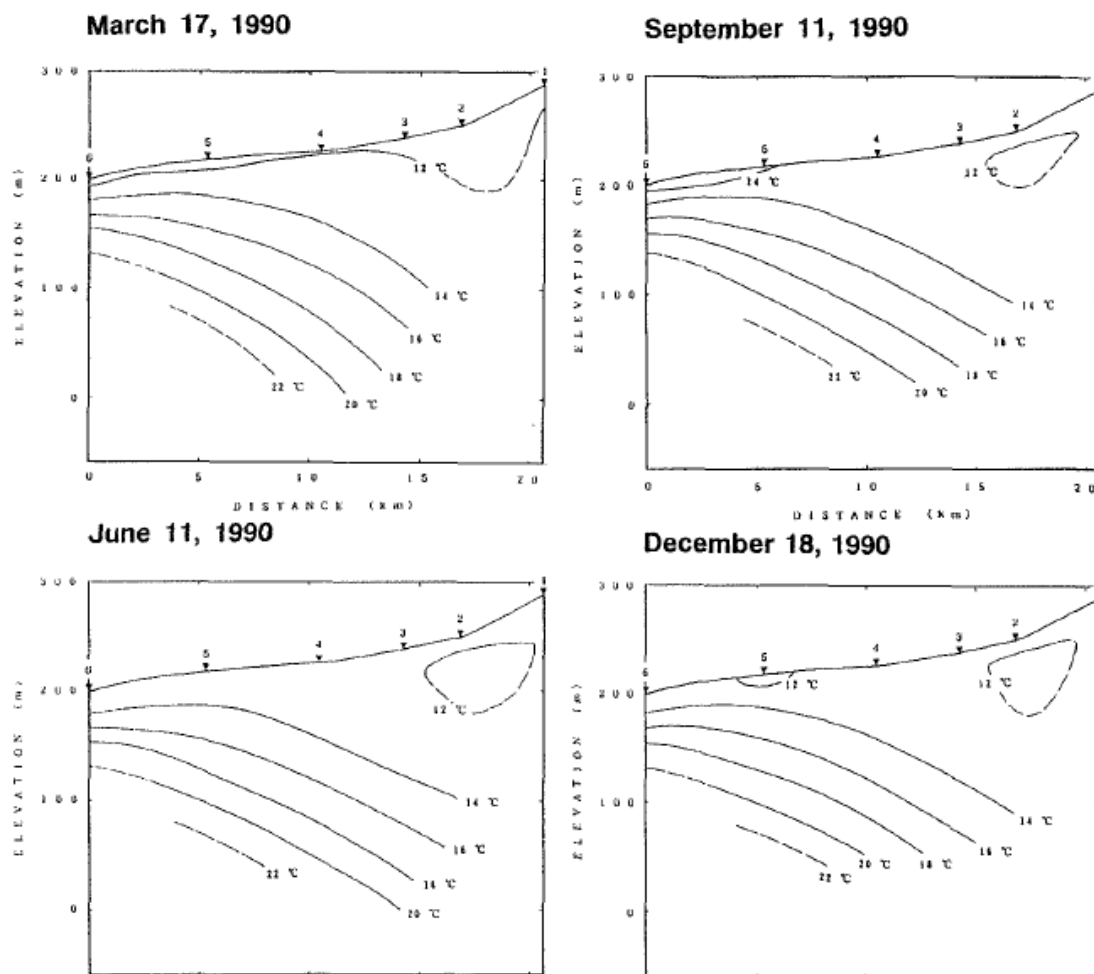


Figure 6: Subsurface temperature in a cross section along the observation well 1-6 of four different months. (Source: Sakura [1993])

In the month of March 1990, the surface layer was cooled from above the water table. In the month June and September, the surface layer was heated from above the water table, but a cold water having temperatures less than 12°C was centered at 50 meters below land surface.

Therefore, it decreases during these two months. In December the groundwater of the entire basin was being cooled having temperatures less than 12°C, formed at the surface area near the well 5 and therefore it is increasing.

A large amount of groundwater was used during the winter to melt snow in the city. Groundwater was pumped from the aquifer at the depth of several 10 seconds of meters below the surface, which caused groundwater heads around the pumping well to decrease. The decrease in groundwater heads induced recharge from the surface water of Mogami River.

For deeper groundwater system, below an isothermal line of 14°C, where temperatures remain constant throughout a year. The isothermal line of 20°C at well 6 was relatively shallow at 70 m below the surface at well 6, where groundwater discharge occurred, and it was relatively deep at 200 meters at well 4, where groundwater recharge occurred. These characteristics of the isothermal line suggest that the regional groundwater flow caused a significant advective disturbance of conductive thermal regimes in the Yonezawa Basin. Although this was a simple application of heat transfer theory presented by Toth [1962], by Parsons [1970]. Domenico & Papadopulos [1973] he observed and calculated distributions of subsurface temperature with calculated one. This fact confirms the existence of regional groundwater flow in the Yonezawa Basin.

From the temperature data of obtained on 17 March, a shows a high-temperature zone with temperatures greater than 18°C was located near the structural center of the basin and lower temperatures surrounded it. Takahashi [1967], Cartwright [1970] and Sakura [1978], where temperature data were used to understand the groundwater flow in the basin. For the one-dimensional view of the groundwater temperature distribution by profiling the temperature in a well the groundwater temperature in the well is equal to the surrounding subsurface temperature. This is the most important point for temperature when compared to other physically-based measurements or tracer techniques, such as chemical components.

Subsurface thermal regimes existing up to several kilometers below the land surface have been reported to be affected by the regional groundwater flow (Beck [1987]) and are consistent with the subsurface temperature increase toward the structural center of the basin as observed in this study. There is an impact on groundwater extends throughout the central part of the basin.

The vertical temperature profiles in the wells were measured four times in 1990, to investigate the influence of groundwater flow on the distributions of subsurface temperature. From the results, it is clear that two types of groundwater flow systems that influence of groundwater flow on the subsurface thermal regime. The first one was shallow groundwater system was identified, whose temperature changed seasonally under the influence of the artificial pumping for melting snow in the city area. The other one was a regional groundwater system, which caused a

significant disturbance of convective thermal regimes and produced the high-temperature zone in the central part of the basin.

### **2.3 Tracer Used For Georeservoir Characterization**

Geothermal reservoirs, waste-disposal, as well as carbon capture and storage contain mobile and immobile fluid regions, and sometimes also contain different fluid and solid phases. The hydraulic, thermal, geomechanical and hydrogeochemical lifetime of a reservoir depends on the volumes and/or interface areas of some of these regions and/or phases. Mostly, their transport-effective values cannot be measured by geophysical and hydraulic methods. Since they essentially relate to fluid-based transport processes, attempting to measure them by tracer tests is a sensible endeavor.

While dealing with deep hydrogeological systems, the assessment of their relevant hydrogeological parameters, such as fracture/matrix permeability, storativity, transport-effective porosity, reservoir size, reservoir shape, is mainly accomplished within the context of georeservoir engineering and management, mostly for energy production (hydrocarbon exploration, radioactive waste disposal, gas storage, geothermal heat extraction, or CCS, (CO<sub>2</sub>) storage). The major limitation in measuring the hydrogeological properties of deep hydrogeological systems is that access is frequently limited to just one or two boreholes, often facing low hydraulic conductivities. Therefore, any experimental characterization effort will have to be tailored to these restrictions. Most of the previous work concentrated on hydraulic parameters, while only few studies dealing with measuring fluid transport parameters. Major work was conducted in the continuum/discrete modeling of fractured porous rock hydrogeology (Kolditz [1997], Neumann [2005], Tsang and Doughty [2003], McDermott [2006]), and of its tracer-assisted characterization (Maloszewski and Zuber [1993], Zemel [1995], Neretnieks [2007], Tsang [2008]). The present result contributes to some aspects of artificial tracer use, which have not been discovered by previous works. From last few decades, tracer-related ideas in the geothermal field served as a guideline. Whereas the issues raised by Gringarten and Sauty [1975], Pruess and Bodvarsson [1984], Horne [1985] for single-fracture georeservoirs seem to have found satisfactory answers by now (e. g., Chrysikopoulos [1993], Kocabas and Horne [2005]). The questions raised by Gringarten and Witherspoon [1973], Brown [1999] on the thermal drawdown in multiple-fracture systems, and by Murphy [1999] for artificially-fractured EGS ('Enhanced Geothermal Systems') still seem to lack satisfactory answers.

Juliusson and Horne [2010] regarding the tracer-based prediction of heat transport in fracture networks. Challenging work was made Murphy [1999], to use sorptive tracers for the quantification of 'surface areas' in geothermal reservoirs (Rose [2011, 2012]; Dean [2012], Leecaster [2012], Reimus [2012]). Even work on heat exchange area density in geothermal reservoirs has already been identified by Pruess and Bodvarsson [1984], Kocabas and Horne

[1987], Kocabas [2005], Carrera [1998], Pruess and Doughty [2010]. The focus of Pruess and Bodvarsson [1984] was on thermal breakthrough prediction for a reservoir dominated by one vertical fracture. However, ‘surface areas’ addressed by those methods seem to differ systematically from the reservoir-scale heat exchange areas that actually determine the thermal lifetime of a geothermal reservoir said that it depends on two parameters i.e. fracture aperture and fracture spacing both of which can theoretically be determined from inter-well tracer tests (Ghergut [2007, 2011]). Kocabas and Horne [1987], Kocabas [2005] conducted similar calculations on thermal breakthrough, but their main focus was on the design of a novel, single-well injection-backflow method for determining the “thermal parameter”; they also derived exact closed-form solutions for temperature signals from a particular type of single well intrawell (SWIW) test, and compared these with numerically-evaluated solutions. Similar to many of new tracer methods now emerging within the geothermal field may ironically prove more useful to principle aims of deep-hydrogeological characterization, than to their originally intended purposes in geothermal reservoir assessment.

Reinjection of spent geothermal fluids has become a standard reservoir management strategy over the past decade. Reinjection serves not only to maintain reservoir pressure but also increases energy extraction efficiency over the life of the resource. Of course, since the spent fluid is frequently much cooler than the fluid in situ, these benefits depend strongly on locating injection in such a fashion that “short-circuiting” within the reservoir does not occur. While optimizing an injection strategy to avoid premature thermal breakthrough is sometimes iterative, a properly designed tracer test can be used to trace flow paths within the reservoir, and to predict the timing of thermal breakthrough.

## **2.4 Why do need Tracer Test?**

For an efficient and sustainable use of georeservoirs, optimal reservoir management procedures are required. Such procedures often rely on tracer tests. Due to in-situ interactions between the tracer and the reservoir, recorded tracer signals contain an integral signal of the reservoir properties. For this reason, tracer test application offers a powerful technique for the characterization and observation of georeservoirs. To restrict the various respective definitions from engineering, medical and natural sciences for tracer, indicator or marker methods, this work is strictly limited to georeservoir tracers. Here, a georeservoir tracer is defined as matter, or energy, with a temporally and spatially known input function of a measurable quantity (e.g. the temperature of the injected fluid, or the concentration of a specific chemical compound) intentionally introduced into a reservoir. The tracer tests are supposed to yield two kinds of information essential for predicting thermal breakthrough in fluid-based geothermal systems: the distribution of fluid residence times in the reservoir under given hydraulic regimes, and the density of heat exchange (fluid-rock contact surface) areas.

The first tracer test for geological application, using chaff, was reported almost 2000 years ago in Trachonitis (today southern Syria; Davis [1980]). The modern scientific history of tracers is nearly 150 years old. One of the first successfully reported tracer tests was conducted in 1877 in which dye was used to reveal a hydraulic connection (Knop [1878]). Quantitative geothermal reservoir characterization using tracers has its roots techniques originally developed for chemical engineering (Levenspiel [1972]). Robinson and Tester [1984] analyzed tracer tests conducted at the Fenton Hill Hot Dry Rock (HDR) reservoir. They defined a modal volume as the reservoir volume corresponding to low impedance fracture connections. This volume can be determined from flow rates and the time at which the tracer effluent concentration is at a maximum. Robinson and Tester [1984] also determine total reservoir pore volume, which is calculated from the mean residence time of the tracer and flow rates.

Traditional reservoir-engineering geologic studies can establish the existence of fractures but cannot provide means of detection and evaluation of preferential path networks. Tracer tests, however, can accomplish this purpose successfully the minimum detectable level obtained by available detection techniques. Furthermore, for economic justification, the tracer capital cost should be attractive, for environmental reasons the tracer should be nontoxic, and for practical purposes, the tracer should be widely available. Moreover, a major consideration should be the tracer solubility limit; insoluble compounds are definitely undesirable. Selecting a suitable tracer that satisfies most of these criteria is not a trivial task. The tailing of tracer breakthrough curves observed in geothermal studies to a certain extent implies a multidimensional flow field, but most importantly indicates that the transport of tracers through fractured reservoirs is governed by dispersion along with mass transfer into zones of immobile liquid, as well as by equilibrium and non-equilibrium processes associated with tracer interactions with the solid formation and other soluble species present in geothermal fluids. Diffusion of tracers from fractures into the porous matrix is virtually always an important transport mechanism unless matrix porosities are very low, fracture spacing is extremely small, and/or fracture apertures are large (Grisak and Pickens [1980]). For relatively short (tens of hours) tracer experiments, the fracture spacing and matrix diffusion are of minor importance (Matoszewski and Zuber [1985]); thus, matrix diffusion cannot explain the observed skewness of tracer breakthrough curves. Mathematical modeling of these transport mechanisms, in conjunction with assumptions based on geological and geochemical information, is used to estimate fracture aperture and to predict thermal breakthrough of reinjected fluids (see e.g., Walkup and Home [1985]). Although for certain geothermal reservoirs there is evidence of a direct correlation between the rate of tracer return and thermal breakthrough (Horne [1982a]), this correlation is site specific, dependent on unknown reservoir composition and geometry and in certain situations may not be a useful relationship (Pruess [1990]). Furthermore, rapid tracer returns do not necessarily indicate premature thermal breakthrough because the velocity of the thermal front is related to the formation solid surface area available for heat transfer (Pruess and Bodvarsson [1984]). Additional characterization of reservoir properties and assessment of the success of stimulation

treatments may be achieved through testing with conservative or reactive tracers. The most common tracer test involves the injection of aqueous solutes into one or more injection wells and monitoring of tracer returns in fluids produced from offset production wells (Shook [2001]; Sanjuan [2006]). Interdiffusion of solute tracers between fractures and rock matrix produces characteristic tails in tracer breakthrough curves (BTC), that may permit determination of fracture-matrix interface areas (Pruess [2002]; Pruess [2005]; Shan and Pruess [2005]).

Tracer testing has multiple applications in geothermal research and management. The main purpose in conventional geothermal development is to study connections between injection and production boreholes as part of reinjection research and management. The results are consequently used to predict the possible cooling of production boreholes due to long-term reinjection of colder fluid. In EGS-system development tracer testing has a comparable purpose even though it's rather aimed at evaluating the energy extraction efficiency and longevity of such operations through studying the nature of connections between reinjection and production boreholes. For general hydrological studies of subsurface flow, such as flow under undisturbed conditions and regional flow. For flow rate measurements in pipelines carrying two-phase water mixtures. The power of tracer tests in reinjection studies lies in the fact that the thermal breakthrough time (onset of cooling) is usually several orders of magnitude (2–4) greater than the tracer breakthrough time, bestowing tracer tests with a predictive power. This is actually what distinguishes tracer tests in geothermal applications from tracer tests in groundwater hydrology and related disciplines. Geothermal tracer tests are mostly conducted through boreholes and can involve (i) a single borehole injection backflow test, (ii) a test involving one borehole-pair (injection and production) as well as (iii) several injection and production boreholes.

Geothermal reservoirs and other technology-relevant georeservoirs in the realm of energy production (like CCS, gas storage or spent-radionuclide repositories) contain mobile and immobile fluid regions, and often also different fluid and solid phases.

In the deep-geothermal realm, it does not suffice to drill and find rock layers of good permeability and high temperature. One must also ensure that the reservoir can be operated sustainably for a long period (at least 30years). Sustainability of a geothermal reservoir cannot be evaluated from a permeability measurement (Figure 7). Fluid residence times and heat exchange areas are two main parameters determining the thermal lifetime of a geothermal reservoir. The lifetime of a particular georeservoir (from a hydraulic, thermal, geomechanical and/or hydrogeochemical point of view) depends on the volumes and/or interface areas of some of these regions and/or phases (Ghergut [2013a]).

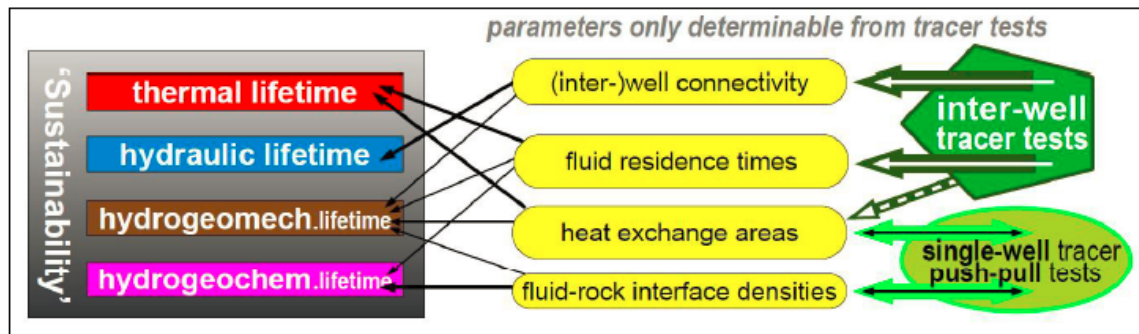


Figure 7: Tracer methods contribution to assess sustainability of geothermal reservoir.  
(Sources Ghergut [2013a] )

'Sustainability' involves at least four aspects as:

- (a) thermal lifetime (associated with production temperature drop, or 'thermal breakthrough'),
- (b) hydraulic lifetime (associated with permeability reduction, typically by chemical processes),
- (c) hydrogeochemical lifetime (associated with pore pressure changes, etc. inducing the seismic activity of 'undesired' kind),
- (d) hydrogeochemical lifetime (associated with fluid-rock interactions, dissolution/precipitation etc., also impacting upon (b)).

Parameter heat exchange areas are directly involved in (a), and indirectly, yet significantly involved in (b) – (d) by thermo-hydraulic-mechanical-chemical (THMC) coupled processes. Thus, this parameter is worthwhile developing field methods to measure it reliably. Since hydraulic and geophysical methods cannot measure it, tracer methods appear to be the first (or unique) option. They can be measured, at least in principle by means of inter-well (IW) or single-well (SW) tracer test (Kocabas and Horne [1987], Kocabas [2005]). And, since inter-well tracer tests notoriously suffer from ambiguity between advective and non advective effects on tracer BTCs (an issue thoroughly investigated in many papers by Zuber and Maloszewski), a single-well method with a flow-field reversal, reducing advective effects and enhancing non-advective effects, indeed appears as very promising. Im-/mobile fluid or interphase interface areas can be determined from single-well tracer push-pull tests relying on kinetic exchange processes between compartments or phases. Single-well tests are more sensitive with respect to such processes than advective-dispersive processes and than in inter-well tests. Inter-well tests are not physically insensitive with respect to kinetic exchange processes, but they are strongly affected by ambiguity between dispersion and non-advective non-equilibrium processes.

In general, tracer tests can be categorized into two major types. The first involves Inter- or Multi-well scenarios, where the tracer is injected at a given point (e.g. injection well) and measured elsewhere (e.g. observation or pumping well). In recent decades, several successful Inter-well Tests have been reported: e.g., Dash [1983], Adams and Davis [1991], Rose [2001] and Sanjuan [2006]. However, it is also possible to measure again at the injection point, as reported by (Haggerty [2000], Altman [2002], Behrens [2009] and Maier [2011]). These tests, known as

Single-Well Injection-Withdrawal (SWIW), Push-pull or Huff-puff, complement Inter-well Tests with additional information. In single-well or injection-backflow tracer tests, a physicochemically characterized fluid is spiked with an artificial tracer, if natural tracers are not applicable, and is injected into the formation (Davis [1980]). The injected fluid is allowed to remain in the reservoir for the desired time period before the injection well is produced. The physicochemical changes observed between the injected and recovered fluids provide information on the chemical interactions of the tracer or the dissolved constituents of the injected fluid with the formation matrix, on the natural fluid flow, on the reservoir structure, and on the heat-transfer mechanism among the formation solids and the injected fluid (Wright [1984]; Adams [1985]).

Although injection-backflow tracer tests provide information about the reservoir in the immediate vicinity of the well, which can be used for preliminary field evaluation and for subsequent multiwell tracer test design (Kocabas [1986, 1989]; Kocabas and Home [1987]), they have not been used extensively in geothermal systems. In multiwell tracer tests, at least one production well is used to monitor continuously or periodically the physicochemical properties and tracer concentrations of the produced geothermal fluid. While the primary advantage of Inter-well Tests is that they are able to investigate flow-path properties over long distances, encompassing large reservoir volumes, SWIW enables flow reversibility observations which are advantageous for the evaluation of time-dependent processes (e.g. Nordqvist and Gustafsson, [2002]; Ghergut [2012b]). When fracture are thin, there will be more spreading across the fracture due to matrix diffusion, matrix diffusion is dominating. For porous matrix, the transport of matrix is slower therefore it takes longer time to reach the production well whereas for tight matrix it move faster since their porosity is lower so it flows faster. Single well test, they are more symmetrical and more centered from one borehole whereas for intra well test, they are more squeeze if the system is heterogeneous and it is heterogeneous in fracture as shown in Appendix 1.

Single-well ‘push-then-pull’ (SW) tracer methods appear as attractive for a several reasons: less uncertainty of design and dimensioning, and lower tracer quantities required, than for inter-well (IW) tests; stronger tracer signals, enabling easier and cheaper metering, and shorter metering duration required, reaching higher tracer mass recovery, than in IW tests; last not least: no need for a second well. However, SW tracer signal inversion faces a major issue: the ‘push-then-pull’ design weakens the correlation between tracer residence time distribution (RTD) and fluid transport parameters, inducing insensitivity or ambiguity of tracer signal inversion against some of those georeservoir parameters that are supposed to be the target of tracer tests par excellence: pore velocity, transport-effective porosity, fracture aperture and spacing or density (where applicable), fluid/solid or fluid/fluid phase interface density. Hydraulic and geophysical methods cannot measure the transport-effective values of such parameters because the signals they detect correlate neither with fluid motion nor with material fluxes through (fluid-rock,) phase interfaces.

Typically, pressure signals obtained in hydraulic tests do not enable to distinguish between geological formations with equal permeability, but different transport-effective porosity, nor between formations with equal permeability, equal transport-effective porosity, but different fluid-rock interface area. The ability to measure this latter parameter is crucial to lifetime predictability for geothermal, gas storage, waste disposal, or hydrocarbon reservoirs (especially in advanced depletion stages). In inter-well tracer tests are used to determine fluid residence time distributions (RTD) and flow storage distribution (RTD, FSD) that means the amount of time a fluid element could spend inside a chemical reactor.

Statistical moments of RTDs provide important information about the reservoir:

- The zeroth-order RTD moment can tell something about reservoir boundaries.
- The first-order RTD moment, or mean residence time (MRT) represents a measure of reservoir size (the reservoir volume that can be used for fluid storage, under a certain injection regime).
- Higher-order RTD moments provide information about reservoir heterogeneity; traditionally, the 2nd-order moment is associated with flow-path dispersion (from hydrodynamic up to reservoir scale); from RTD analysis also a flow-storage repartition (FSR) can be derived, which is sometimes interpreted as representing reservoir shape (cf. Shook [6]), with certain limitations when matrix diffusion or kinetic exchange processes become important.

The single-well tracer push-pull tests are used to quantify processes other than advection-dispersion: typically, tracings can be used to quantify non-advective processes which are the exchange of some extensive quantity (mass, energy) between fluid and solid/fluid phases by processes like matrix diffusion or sorption/partitioning, whose rate or amount depends on the density (area per volume) of involved fluid/rock interfaces. Flow field reversal during the 'pull' phase is supposed to largely compensate the effects of flow-path heterogeneity (excepting the hydrodynamic level), and to enhance the effects of tracer exchange processes at fluid/rock interfaces, thus enabling to quantify interface densities from measured tracer return signals; yet this depends on whether the fluid volumes and flow/shut-in durations used in the push-pull test match the system's homogeneity scale and the (a priori unknown) bulk exchange rates.

In most geothermal reservoirs large-scale permeability is dominated by fractures, while most of the heat and fluid reserves are stored in the rock matrix. Early-time fluid production comes mostly from the readily accessible fracture volume, while reservoir behavior at a later time depends upon the ease with which fluid and heat can be transferred from the rock matrix to the fractures.

In the case of geothermal reservoirs operated by well doublets, McDermott [2005] managed to identify a single dimensionless parameter ( $Cr$ , ‘critical number’) that quantifies the interference between the cooling of a geothermal reservoir (‘thermal lifetime’) and the favorable effects of coupled Thermal Hydraulic Mechanical processes, which delay the cooling of the reservoir, thus prolonging its thermal lifetime. For CCS reservoirs, it is as yet unclear whether such a ‘critical number’ can be defined. At first sight a unique definition of ‘thermal lifetime’, ‘hydraulic lifetime’ etc. cannot be formulated in general, as those are strongly dependent on reservoir structure and applied model concept (deep tight rock, fracture-dominated, fractured-porous, multiple-continuum, etc.). Additionally to structural and large-scale hydrogeological features, the interplay between different ‘lifetime’ outcomes is inherited from the lifetime-controlling parameters associated with fluid transport, of which ‘heat exchange areas’ and ‘fluid-rock interface densities’ represent most striking examples of parameters whose meaning cannot be defined in a scale, boundary and process-independent way (Ghergut [2011a, 2013] for single-fracture, and multiple fracture systems of finite or infinite lateral extension). Even for the simplest, single-fracture system of infinite longitudinal and transversal extensions, a well-defined parameter like the transport-effective fracture aperture will effect upon thermal lifetime by two opposite mechanisms, as an:

--advective parameter: the fluid residence time (within a fracture) is directly proportional to the fracture aperture (for a given flow rate). The fluid travel time increases with increasing aperture from this perspective, inter-well tracer tests (in which fluid residence times are the most sensitive and most directly measurable parameter) should be expected to be very sensitive with respect to fracture apertures. Whereas single well tracer push-pull tests (known to be generally insensitive with respect to advective parameters) could be expected to be rather insensitive with respect to fracture apertures.

--non-advective parameter: the intensity of matrix diffusion (between a fracture and its surrounding rock, in both directions) is inversely proportional to the fracture aperture. The rate of heat exchange between fracture and matrix increases with decreasing aperture, which accelerates transport across the fracture, but retards transport along the fracture-matrix diffusion is amongst the most important of various non-advective transport processes. Single-well tracer push-pull tests are supposed to provide increased sensitivity with respect to non-advective parameters, compared to inter-well tests. From this perspective, single-well tracer push-pull tests could be expected to be highly sensitive when compared to fracture aperture.

Thus, apart from having different values depending upon the process it is involved in, as has first been explained by Tsang [1992] (distinguishing between “hydraulic aperture”, “geomechanical aperture”, and “tracer transport aperture”), the very transport-effective aperture can simultaneously act as a lifetime-increasing, and as a lifetime-reducing parameter.

These two above-described expectations contradict each other. In any particular tracer test, either inter-well or single-well, there will be the interplay between the advective and the non-advective "function" of fracture apertures. From this interplay, the actual sensitivity of a particular tracer test with respect to fracture aperture. This is difficult to predict in a general manner, to overcome this problem by conducting numerical simulations of heat and solute tracer transport in inter-well and single-well tests, for a number of fracture system geometries, considered to be representative of real geothermal reservoirs.

The heat exchange area as a target parameter (lifetime-increasing, and as a lifetime-reducing parameter) can be defined by (Ghergut [2011])

-in geothermal reservoirs dominated by a single fracture or fault, the heat exchange area density (area per mobile-fluid volume) is given by the reciprocal of transport-effective aperture (after Tsang [1992])

-in geothermal reservoirs consisting of a large number of approximately parallel fractures, the heat exchange area density (area per bulk reservoir volume) is given by the reciprocal of fracture spacing.

For groundwater water modeling, solute transport has advection-dispersion equation i.e. concentration vs time (tracer signal) whereas heat transport it has same advection-dispersion equation i.e. temperature versus time(thermal signal).For solute transport code MT3D is linked flow code MODFLOW whereas FEFLOW includes an option for both heat and solute transport. Advection is used for transport of solutes, while convection is used for transport of heat transport.

Quantitative geothermal reservoir characterization using tracers is based on different approaches to predicting thermal breakthrough curves in fractured reservoirs (Shook [2001]; Kocabas [2005]; Read [2013]). The characterization and modeling of heat transfer in fractured media are particularly challenging as open and well-connected fractures can induce highly localized pathways which are orders of magnitude more permeable than the rock matrix (Klepikova [2016]; Cherubini and Pastore [2011]).

The study of solute transport in fractured media has recently become a widespread research topic in hydrogeology (Cherubini [2008, 2009, and 2013]; Masciopinto [2010]), whereas the literature about heat transfer in fractured media is somewhat limited. Hao [2013] developed a dual continuum model for the representation of discrete fractures and the interaction with the surrounding rock matrix in order to give a reliable prediction of the impacts of fracture–matrix interaction on heat transfer in fractured geothermal formations. Geiger and Emmanuel [2010] found that matrix permeability plays an important role in thermal retardations and attenuation of thermal signals. At high matrix permeability, poorly connected fractures can contribute to the heat transport, resulting in heterogeneous heat distributions in the whole matrix block. For lower matrix permeability heat transport occurs mainly through fractures that form a fully connected pathway between the inflow and outflow boundaries, which results in highly non-Fourier

behavior characterized by early breakthrough and long tailing. Tracer tests of both solute and heat were carried out at Bonnaud, Jura, France (de Marsily [1986]), and the thermal dispersivity and solute dispersivity were found to be of the same order of magnitude.

Numerous field observations (Tsang and Neretnieks [1998]) show that flow in fractures is being organized in channels due to the small-scale variations in the fracture aperture. Flow channeling causes dispersion in fractures. Such channels will have a strong influence on the transport characteristics of a fracture, such as, for instance, its thermal exchange area, crucial for geothermal applications (Auradou [2006]). Highly channelized flow in fractured geologic systems has been credited with early thermal breakthrough and poor performance of geothermal circulation systems (Hawkins [2012]). Lu [2012] conducted experiments of saturated water flow and heat transfer in a regularly fractured granite at meter scale. The experiments indicated that the heat advection due to water flow in vertical fractures nearest to the heat sources played a major role in influencing the spatial distributions and temporal variations of the temperature, impeding heat conduction in the transverse direction; such an effect increased with larger water fluxes in the fractures and decreased with a higher heat source and/or a larger distance of the fracture from the heat source. Neuville [2010] showed that fracture–matrix thermal exchange is highly affected by the fracture wall roughness. On the same year, Natarajan [2010] conducted a numerical simulation of thermal transport in a sinusoidal fracture–matrix coupled system. They affirmed that this model presents a different behavior with respect to the classical parallel plate fracture–matrix coupled system. The sinusoidal curvature of the fracture provides high thermal diffusion into the rock matrix.

Analytical and semi-analytical approaches have been developed to describe the dynamics of heat transfer in fractured rocks. Such approaches are amenable to the same mathematical treatment as their counterparts developed for mass transport (Martinez [2014]). One of these is the analytical solution derived by Tang [1981]. While the equations of solute and thermal transport have the same basic form, the fundamental difference between mass and heat transport is that (1) solutes are transported through the fractures only, whereas heat is transported through both fractures and matrix, and (2) the fracture–matrix exchange is large compared with molecular diffusion. This means that the fracture–matrix exchange is more relevant for heat transport than for mass transport. Thus, matrix thermal diffusivity strongly influences the thermal breakthrough curves (BTCs) (Becker and Shapiro [2003]). Contrarily, since the heat capacity of the solids will retard the advance of the thermal front, the advective transport of heat is slower than for solute transport (Rau [2012]). The quantification of thermal dispersivity in terms of heat transport and its relationship with velocity has not been properly addressed experimentally and has conflicting descriptions in the literature (Ma [2012]).

Probably,  $y$  [thermal] and  $y$  [solute] are not completely uncorrelated (as they always have something in common: a given geological setting), but a general correlation formula making  $y$

[thermal] predictable from  $y$  [solute] is unlikely to exist. As can be seen from the Table 1, not many methods are available for determining the transport-effective values (for heat or solute transport) of fluid-rock interface density values.

<i>Parameter . . . .</i>	heat ...	solute ...
	transport-effective fluid-rock interface density ( $1 / y$ )	
	$1 / y[\text{thermal}]$	$1 / y[\text{solute}]$
essential for predicting:	thermal lifetime of reservoir	hydro-geochemical processes, and thereby induced porosity / permeability changes
<b>Potentially determinable by:</b>		
<b>geophysical exploration</b>	problematical	no
<b>borehole geophysics</b>	no	problematical
<b>hydraulic testing</b>	no	no
<b>tracer tests</b>	yes (using heat as a tracer); restricted to single-well testing scale	yes (using soluble tracers); restricted by ambiguity of effects from non- / AD processes
<b>micro-seismic experiments</b>	still to be verified	no

Table 1: Methods for determination of heat and solute transport-effective values.

## **2.5. Difference Between Conservative Tracer And Thermosensitive Tracer.**

The reservoir temperature distribution and prediction of the thermal breakthrough are essential components for a sustainable reservoir management and efficiency improvements in the geothermal power generation. Early tracer test signals (detectable within the first few years of operation) are expected to correlate with late-time production temperature drop (so-called ‘thermal breakthrough’, supposed to not occur before some decades of operation) of a geothermal reservoir Ghergut [2013].

Whenever a geothermal reservoir exhibit ‘single-fracture’ system, its thermal lifetime will, ideally, be determined by two parameters i.e. aperture and porosity (Pruess and Bodvarsson [1984], Kocabas [2005]), whose inversion from conservative-tracer test signals is straightforward and non-ambiguous (provided that the tracer tests, and their interpretation, are performed in accordance with the rules of the art). The single-fracture exhibit behavior in terms of heat transport, whereas for multiple fractures, this clear-cut correlation is broken (Gringarten and Witherspoon [1973], Kolditz [1995], Kolditz and Clauser [1998], Juliusson and Horne [2010a/b]). The multiple-fracture exhibit behavior, in terms of solute tracer transport (or vice-versa), whose effective values of fracture aperture, spacing, and porosity are essentially uncorrelated between heat and solute tracers (Figure 8).

Solute transport parameters derived from conservative-tracer tests will no longer characterize the heat transport processes (and thus temperature evolutions) taking place in the same reservoir. Parameters determining its thermal lifetime will remain ‘invisible’ to conservative tracers in inter-well tests.

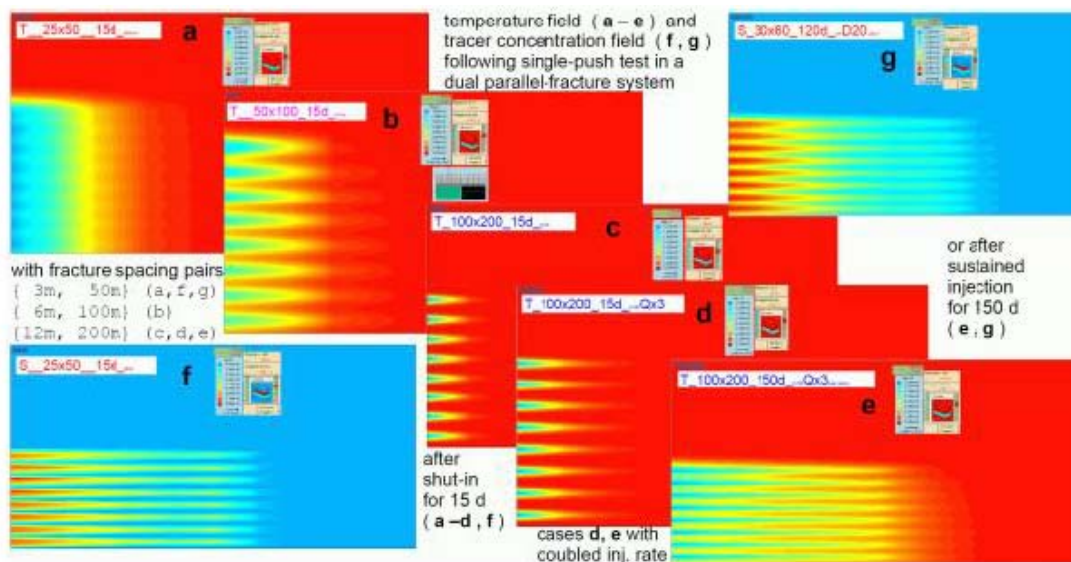


Figure 8: Single- and multiple-fracture behavior for heat and solute transport within one and the same reservoir (Sources: Ghergut [2013])

This study demonstrates this problem on the example of a five-fracture system, representing a deep geothermal reservoir, with well-doublet placement inducing fluid flow and heat transport ‘obliquely’ to the fractures. A more detailed analysis of this ‘oblique-fracture’ paradigm, alongside with further examples can be found in Ghergut [2011a/b, 2012a/b]. Temperature and Solute concentration field snapshots (Figure 9) are shown in a 2-D section, but numerical simulations were conducted using a 3-D model since a 2-D model reduction would not yield correct results (fractures being of finite extension in all directions).

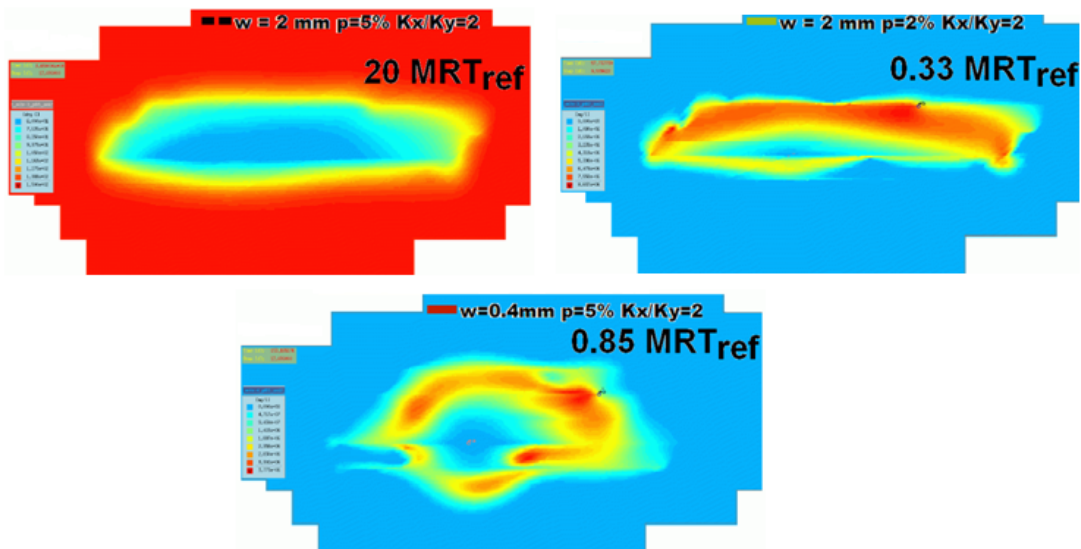


Figure 9: Heat and tracer transport in the fracture system (Sources: Ghergut [2013])

In this study, scoping stimulation was done using FEFLOW where fracture parameters were varied uniformly for the whole set of fractures. As shown in figure 10, thermal drawdown in this system is found to strongly depend on fractures. For heat tracer, we have almost same curves because we have the same aperture even with different matrix porosity and isotropy factor. If the aperture is different, then signal will differ. For heat transport, there will be little influence on porosity but more influence on aperture. Therefore all the signal are identical with varying porosity and matrix anisotropy there will be a stronger influence on aperture from the set of simulation. When aperture becomes large, the effect decreases because of matrix diffusion influence gets lowered. At the heat, transport is insensitive to matrix porosity and poor sensitivity to matrix permeability anisotropy and most sensitive to fracture aperture. Thermal lifetime results from the opposite effects of fracture aperture as an advective and a non-advective parameter; in the fracture-matrix-flow system, the latter is found to prevail.

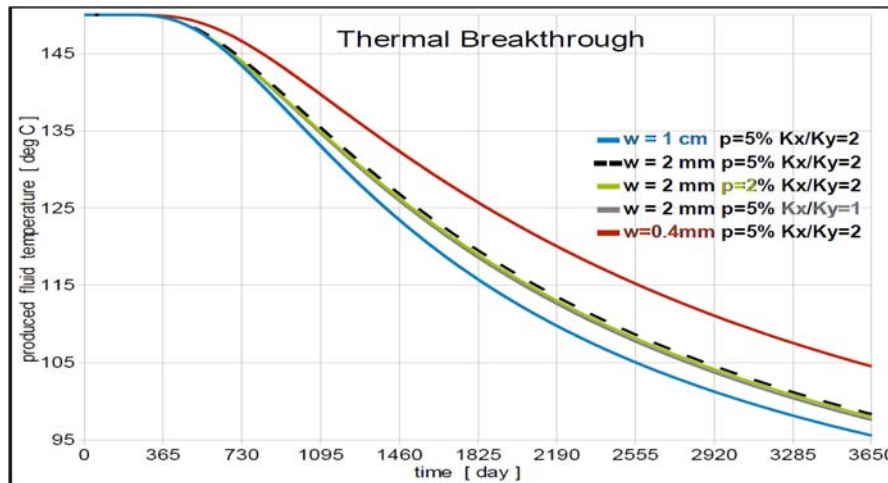


Figure 10: Thermal drawdown for the fracture system. (Sources: Ghergut [2013])

The conservative-solute tracer signals from inter-well tests in the same system do not show a clear-cut correlation with fractures' aperture (Figure 11). In conservative-solute tracer signals, fracture aperture effects on tracer transport are masked by the very long residence time associated with the matrix flow component. That means solute tracer signal does not depend on aperture but only depend on matrix porosity for solute tracer: the fastest trace signal is for the lowest matrix porosity and not necessarily for the longest aperture of the fracture. Although this is the highest aperture so we expect it will slow down the transport but it is not because matrix porosity is the strongest influence it does not depend upon fracture aperture because of parameter interplay. Matrix permeability ratio ( $K_{xx}/K_{yy}$ ) we assume preexisting orientation of fracture has the highest permeability (factor 2). Therefore conservative tracer signal is most sensitive to matrix porosity, poor sensitivity to matrix permeability anisotropy and ambiguity with respect to fracture aperture.

But for thermosensitive tracers are able to 'magnify' the visibility of fracture aperture effects against matrix flow effects. Thermosensitive tracers prove able to re-establish a well-defined correlation with (and early warning before) thermal breakthrough (Figure 11).

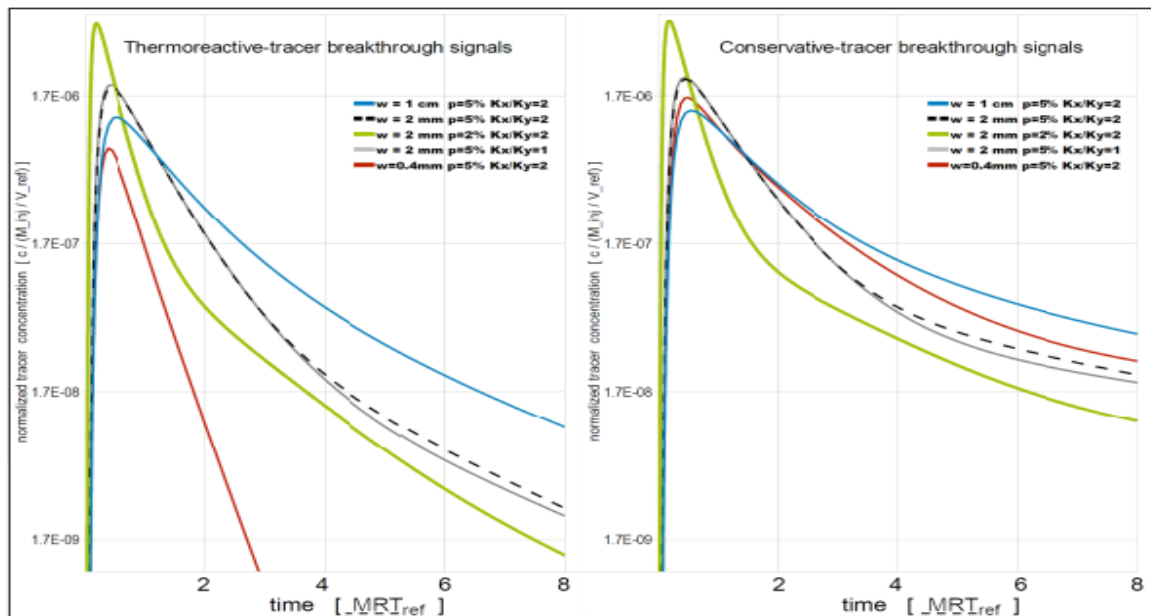


Figure 11: Thermosensitive- versus conservative-tracer signals for the fracture system where MRT is the mean residence time (of the fluid in a reservoir) (Sources: Ghergut [2013])

Thermosensitive tracers are chemicals which are thermally sensitive. A number of hydrolyzable compounds with different kinetic properties i.e., esters and amides (Robinson [1984]; Robinson and Tester [1990]; Nottebohm [2012]; Maier [2015a; 2015b]; Schaffer [2016]), were recently proposed as thermo-sensitive tracers (TSTs) for characterizing the thermal state of geothermal reservoirs.

Practical application of Thermosensitive tracers, a flexible reservoir transport modeling tool was developed. The tool can capture the reaction of several simultaneously applied tracer compounds and their evolution in the reservoir for different temperature settings (e.g., sharp/smooth thermal fronts) and flow conditions (e.g., different aquifer heterogeneities, hydraulic operation modes). Only by using ‘thermosensitive’ substances as tracers (assuming their thermal degradation to be governed by Arrhenius’ law), a reliable correlation between (early) tracer signals and (later) thermal breakthrough can be re-established as shown in figure 11. Even though the Arrhenius parameters, which characterize the temperature-dependent tracer reaction, there is no universal simulation tool available, which is able to model and analyze the tracer behavior for complex geometries and temperature distributions as encountered in potential and exploited geothermal reservoirs.

A more general analysis of thermoreactive tracer’s ability to predict and monitor thermal drawdown was conducted by Plummer and Palmer [2010, 2011]. Thus, thermosensitive tracers seem to essential for predicting the thermal breakthrough, in such geothermal reservoirs whose ‘hydrogeological personality’ is defined by a finite set of fractures (of in-/finite extension), with flow occurring both across and along the fractures (Ghergut et al. [2011a/b]).

In terms of the ‘gebo benchmark-model’ typology investigated by Hördt [2011], Hahne and Thomas [2011, 2012]; pursuing earlier work by Thomas and Schulz [2007], Thomas [2006, 2010]), such systems combine flow and transport patterns of the ‘petrothermal’ type and of the so-called ‘deep-aquifer’ type:

- across the fractures, heat is traveling faster than conservative-solute tracers.
- along the fractures, conservative-solute tracers experience much less retardation by transverse exchange (matrix diffusion), than heat;.
- fluid (and tracer) flow is not limited to the fractures; flow within the matrix yields an essential contribution to prolonging the fluid (and tracer) residence time and thereby increasing the reservoir’s thermal lifetime.

Thermal lifetime thus results from flow ‘splitting’ between fractures and matrix (depending on their relative hydraulic transmissivity), alongside with the opposite effects of fracture aperture as:

- an advection parameter (fluid travel time increases with increasing fracture aperture),
- an advective unrelated parameter (the fracture-matrix exchange rate increases with decreasing fracture aperture, the latter accelerating transport both across and along the fracture).

Non-conservative tracers, sorptive or thermosensitive compounds can be used to overcome the certain disparity between heat and tracer transport. However, major differences exist, regarding tracer functionality within them, between the distinct types of geothermal systems (Figure 12):

- ‘hydrothermal’ systems, or ‘hot natural aquifers’, with predominant, or equivalent, ‘porous-medium’ character
- ‘aquifer’-based EGS
- ‘petrothermal’-type EGS
- natural porous-fractured systems.

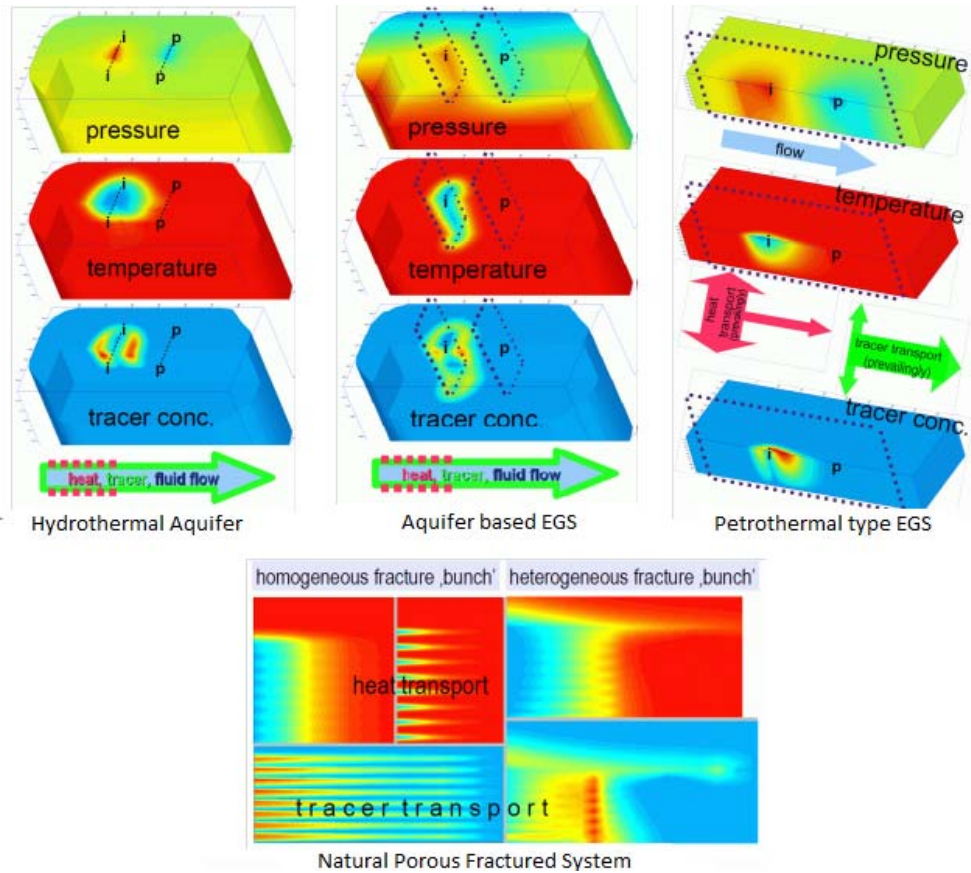


Figure 12: Pressure field, thermal front, and tracer spreading Different types of Geothermal system (Sources: Ghergut [2013])

Heat transport occurs prevalingly along the flow direction, in hydrothermal systems and ‘aquifer’-based EGS; it is dominated by the transverse exchange between matrix and fracture, in ‘petrothermal’-type EGS. For natural porous- fractured systems, the prevailing direction(s) of heat transport cannot be told a prior (Table 2).

	HYDROTHERMAL	DEEP-AQUIFER	PETROTHERMAL
<b>flow direction</b> <b>tracer transport</b> <b>heat transport</b>			
naturally given thickness	good	more or less	n.a.
naturally given permeability	good	moderate – – fairly good	no
role of artificial fracs	n. a.	increase the cross section for flow	enable flow (create permeability)
frac aperture $w$	n.a.	unimportant	crucial to hydraulic feasibility, but thermal lifetime is indep. of $w$
frac surface area $A$	n.a.	crucial to thermal lifetime (proportionality!)	thermal lifetime usu. indep. of total $A$

Table 2: Contrasting roles of artificial fractures in different EGS reservoir types. (Sources: Ghergut [2013])

Conservative tracers remain indispensable to characterizing any of these reservoir types, but their residence time distribution correlates differently with thermal lifetime, the more pronounced the petrothermal character (the effective aperture) will prevail within a lifetime. Thermosensitive are more useful for an aquifer based EGS than in petrothermal, sorptive tracer is more useful in petrothermal than in aquifer in an aquifer is recommended. For characterizing Natural fractured system (conservative, sorptive, thermoreactive) is recommended.

### **3. OUTLINE OF APPLIED METHODOLOGY**

#### **3.1 Heat Transport In Groundwater Flow**

Within the Earth's upper crust, heat flow occurs via two primary mechanisms, conduction, and advection (commonly by groundwater). Flow measured in a borehole and typically are intended to represent the conductive component of heat flow from the Earth's upper crust. The hydrogeologic relation between heat flow and fluid flow has been the topic of considerable research, summarized in review articles by Anderson [2005] and Saar [2011]. Cross-sectional numerical models have been used to demonstrate thermal anomalies associated with active groundwater flow (e.g., Smith & Chapman [1983], Forster & Smith [1988a, b], Forster & Smith [1989], Nunn & Deming [1991], and Deming [1993]).

Heat can be transported from point to point in a porous medium by way of three processes: conduction, convection, and radiation. Conductive transport may be described by a linear law relating the heat flux to the temperature gradient. Convective heat transport is the movement of heat by a moving ground water. Radiation, better known as thermal electromagnetic radiation, is the radiation emitted because of the temperature of a body. Compared to pure heat conduction through an aquifer system, advective transport of heat results in the reduction of temperatures and near-surface heat flow in upland recharge areas and an increase of temperatures and near-surface heat flow in lowland discharge areas. Using reasonable hydrogeologic parameters, temperature and heat flow distributions have been shown to be sensitive to variations in recharge and discharge magnitude and location, depth and length of the aquifer system, and permeability.

Flowing groundwater transports heat through the subsurface; thus, temperature based methods can be used for identifying active groundwater flow. The concept that temperature can be used to characterize groundwater flow is the basis for this study. Inflections in temperature profiles and accelerated heat transport are indicators of groundwater flow. Fiber-optic distributed temperature sensing was chosen as a powerful tool that could be used for monitoring temperature in the subsurface with high spatial, temperature, and temporal resolutions. Groundwater flow and heat transport can be described by a set of coupled equation expressing the mass and energy conversation. One dimension form of flow and transport equation was first discovered by substituting Darcy law and Fourier law into energy and mass balance equation. The coupled groundwater flow and heat transport used to estimate the hydraulic conductivity groundwater flow and heat transfer occur under steady state conditions. The groundwater flux vector is defined by Darcy's law. Heat is transferred not only by conduction due to a temperature gradient but also by advection due to groundwater flow. The flow medium is isotropic and homogeneous. The groundwater is incompressible and its density is constant. If the above assumptions as presented by Parsons [1970] are correct, we can use the mathematical approximate solution of heat transfer in the groundwater flow medium introduced by Domenico & Papadopulos (1973)

Following Domenico and Schwartz (1998), the three-dimensional heat transport equation

$$\frac{\kappa_e}{\rho c} \nabla^2 T - \frac{\rho_w c_w}{\rho c} \nabla \cdot (Tq) = \frac{\partial T}{\partial t} \dots \dots \text{Equation 1}$$

where T is temperature; t is time;  $\rho_w$  and  $c_w$  are density and specific heat of the fluid and  $\rho$  and  $c$  are density and specific heat of the rock fluid matrix; q is the seepage velocity or specific discharge vector; and  $\kappa_e$  is a term that includes the effective thermal conductivity of the rock-fluid matrix.  $\rho_w$  and  $c_w$ , q, c, and  $\kappa_e$  are constants where ad temperature is a dependent variable. The analogy between Equation 1 and the advection-dispersion equation, which describes the transport of solutes in water. The first term in Equation 1 is analogous to the diffusion/dispersion term in the advection-dispersion equation, while the second term, which represents transport of heat by moving groundwater, is analogous to the advection term.

The first term in Equation 1 represents transport of heat by conduction (analogous to the transport of solutes by molecular diffusion) as well as transport by thermal dispersion (analogous to hydrodynamic dispersion in solute transport theory). The term,  $\kappa_e/qc$ , in Equation 2 is analogous to the molecular diffusion coefficient in the advection-dispersion equation for solute transport.

The second term in Equation 1 represents the transport of heat by flowing groundwater, a process known as advection or convection. The terms advection and convection are used interchangeably and may refer to the transport of heat and/or solutes. Advection is used for transport of solutes, while convection is used for transport of heat. Free convection refers to heat transfer in response to flow driven by temperature induced density differences, while forced convection refers to heat transfer by flow driven by any other mechanism. Most commonly, forced convection occurs in response to topographically driven ground water flow.

Early workers focused on analytical solutions of the one-dimensional form of Equation 1. Later, numerical solutions were used to consider more complicated boundary conditions in one-dimensional problems and to study basin-scale transport in two and three dimensions. Generic codes with user's manuals and graphical user interfaces (GUIs) are available to solve coupled groundwater flow and heat transport problems. Some of these codes were designed to solve complex problems involving geothermal systems (e.g., TOUGH2) or geologic processes (e.g., SHEMAT), while others (e.g., VS2DH, SUTRA, and FEFLOW) were introduced for simulation of shallow aquifers.

The ground water flow equation is coupled to the heat transport equation through the velocity term ( $q = vn$  in Equation 1 where v is velocity). Velocity is dependent on hydraulic conductivity,

which is partly governed by fluid density and viscosity, both of which vary with temperature. To incorporate the nonlinearity caused by the dependence of hydraulic conductivity on temperature, the groundwater flow, and heat transport equations are solved iteratively to allow feedback between the solutions within a time step.

Transport of heat through a fractured rock aquifer system is a complex phenomenon that is dependent on the properties of both the fracture network and porous rock matrix. On a bulk scale heat transport in fractured rock is similar to heat transport in unconsolidated porous media as described in equation (1). However, on a fine scale, flow and heat transport is unevenly distributed between fractures and the porous matrix. These domains often have sharply contrasting flow properties causing thermal transport in advecting groundwater to occur in both the fracture and porous matrix domains in a manner inconsistent with transport in unfractured porous media. For a detailed analysis of heat transport in fractured rock hydrogeologic settings, thermal transport must be represented in a more rigorous manner such as by applying fully coupled discrete fracture network codes where flow and transport processes are simulated in both the fracture network and matrix domains. Thermal transport with groundwater flow in discretely fractured media is presented by Molson and Frind [1994 and 2012] and Yang [1996a, b].

### **3.2 Five Fracture Model Description**

This study demonstrates the problem on an example of a five-fracture system, representing a deep geothermal reservoir, with geothermal well-doublet placement inducing fluid flow both across and along the fractures. Assume a geothermal well doublet, here we have injecting well and production well (Figure 13) producing the hot fluid and reinjection the colder water. There is something called as tracer plume in which cold water plume which is spreading into the system, we can use as a tracer. There is two reason for reinjection, one is to get rid somehow and another reason is to maintain reservoir pressure or otherwise you would be depleting later you have ever stronger pressure drawdown. We are interested in how temperature evolution will at the production borehole. Assume a steady dipole flow field. Some solute tracer is added at the injection well. At the production well, tracer breakthrough can, sooner or later, be measured. The tracer breakthrough curves (BTCs) that would be measured at the production well, for various values of the fluid rock interface density (to which the dimensionless parameter shown on the plot relates like a logarithm).

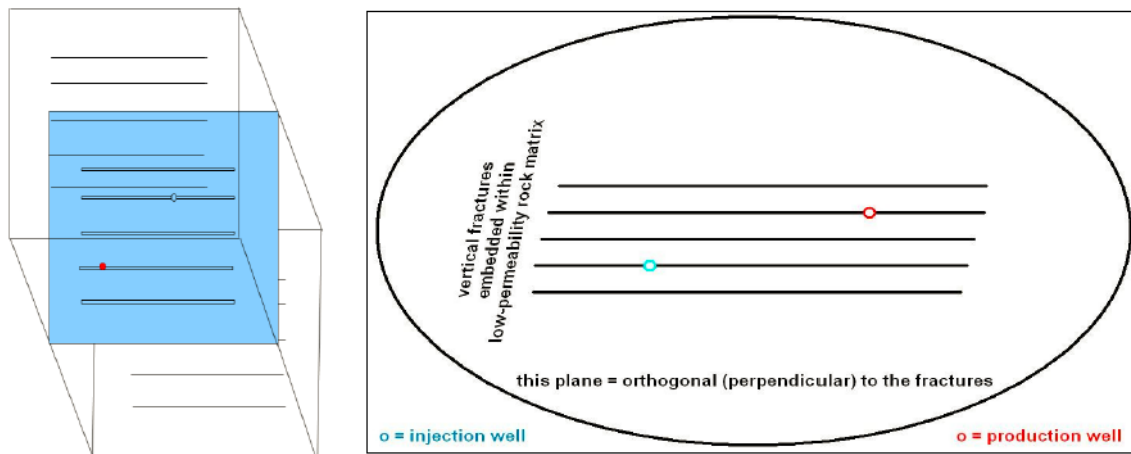


Figure 13: Conceptual model and symmetries of the five -fracture system, as used in the numerical simulations. (Source: Ghergut [2017] )

We assume, having caricature model that means combination detailed deterministic model (site specific model) and simplified deterministic model (based on assumption). Here combination means we take a homogeneous matrix and but we assume the certain placement of fracture. Essentially the fracture they can intersect the well or it can be in between or they can be outside not far outside (still have an influence on reservoir behavior). Although the system looks extremely simple, five fracture in homogenous fracture of given porosity and permeability but the behavior can be different because of their relevant parameter. Each of these parameters can produce contradicting effect on temperature because of its influence on transport both through advection.

When we place the borehole in a way that they are not in one fracture (injection & production wells) and also not everything transversal but also perpendicular, inter-well lines are perpendicular to the fractures. Therefore, it very complicated because of the distribution of flow between fracture and matrix. This means we have flow distribution both across the fracture and along the fracture, so it's oblique. On the other hand, if we considering of advection as a process so the fractures the accelerating elements. Then we have advection in both directions through matrix more in permeable medium and direction along the fracture. If we assume of lateral heat transfer so the fractures will be more retarding elements because retardation (this later heat transfer) will make the heat advance slower along the fracture. This is what makes the behavior of this system so complicated and we cannot predict by looking at the geometry if the fracture width is increased or decreased what will happen to temperature. The fracture can be accelerating or retarding element due to its depends on the aperture of fracture. When we have flow along the fracture then aperture is smaller, therefore, the faster the flow through advection. For advection, the effect is linear; flow velocity in the fracture is proportional to  $1/w$  (aperture). It has accelerating effect on flow velocity. Therefore there will be advective along the fracture. But for transport, thinner aperture: higher the gradient will be more intensive matrix diffusion.

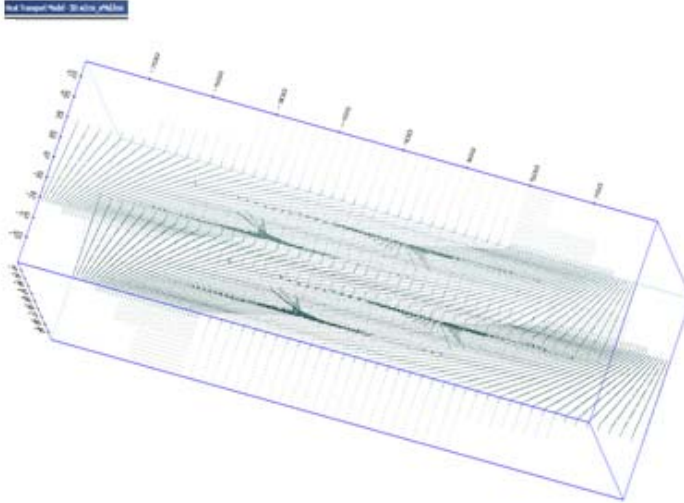
This will be on retarded on transport process. Thinner fracture the stronger matrix diffusion that means stronger retardation through lateral diffusion. For thin fracture, higher gradient therefore concentration difference i.e. [Concentration in fracture (CF) –concentration of matrix (CM)]/aperture (w). The volume balance, we have an aperture at denominator from volume balance: this means quadratic aperture=  $1/w^2$  (aperture). The effect will even stronger it will have a retarding effect due to matrix diffusion across the fracture. But it even can retard along the fracture but accelerate across the fracture. It goes faster in this direction and retards in other direction, it can be either side. Therefore, accelerating effect on flow but retarding effect on transport (sum of advection and conduction or later diffusion). The essential features of this generic “five-fracture” model are used for inter-well forced-gradient circulation of fluid (like in a geothermal well doublet), with placement of major vertical fractures “between” the wells, “across” the well screen(s), and/or “adjacent” (“outwards”) to the inter-well dipole; a “model scenario” means a certain combination (presence or absence) of up to five fractures, with a certain combination of fracture and matrix transmissivity and porosity values. The fracture model loosely resembles, or mimics certain features from geothermal reservoir settings in Southern Germany at which tracer tests are currently under consideration ( Dewi [2016]), or from geo-settings in Northern, Central and Southern Germany at which tracer tests were conducted since 2003 (Ghergut [2013, 2016]), comprising both natural and artificially induced fractures, orthogonal and/or oblique to the inter-well ‘axis’, some intersected, some not intersected by the wells, some ‘feared’ to act as a hydraulic or and/or transport short-cut, some ‘hoped’ to act as lifetime-prolonging for the geothermal system under consideration.

### **3.3 Software Applied**

FEFLOW (Finite Element Subsurface Flow and Transport Simulation System) is a computer program for simulating groundwater flow, mass transfer and heat transfer in porous media and fractured media. FEFLOW is developed by DHI-WASY GmbH, a German company. DHI-WASY’s areas of expertise encompass groundwater hydrology, surface water hydrology and geographic information systems. In these fields, DHI-WASY provides software, training and consulting services FEFLOW software is suitable for numerous different applications in flow and transport processes simulation in porous media, ranging from lab scale to continental scale. The program uses finite element analysis to solve the groundwater flow equation of both saturated and unsaturated conditions as well as mass and heat transport, including fluid density effects and chemical kinetics for multi-component reaction systems. Using FEFLOW we are able to model the transport of heat within the aquifer as this account for potential temperature effects on groundwater flow and the influence of the unsaturated zone on heat conduction. Our numerical groundwater modeling skills allow us to examine the aquifer’s thermal properties and the transportation of thermal energy by water flow and heat conduction through rock. FEFLOW 6 provides extensive Geographic Information System (GIS) support, now integrated with powerful visualization capabilities including custom 2D and 3D animation. FEFLOW is used in different application such as study of pollutant dispersion, evaluate

remediation and decontamination strategies, study of groundwater drawdown and rise in mining areas, mine dewatering studies, survey of saltwater intrusion, isotope calculation for detection of groundwater age, design of geothermal power plants (hot dry rock , heat pump systems),coupled groundwater/surface water simulation with mike11 and hydro as-2d,geotechnical applications (tunnel construction, construction site dewatering),calculation of dam seepage, soil-column calculations, infiltration calculation, assessment of availability of groundwater resources, estimation and control of strategies for groundwater management, design of well-head protection zones, studies for environmental impact assessments, design of groundwater monitoring program and also in applications in research.

### **3.4 .FEFLOW Model Description**

<p><b>Model Type</b></p>	<p><b>Processes subject to simulation:</b></p> <ul style="list-style-type: none"> <li>– fluid flow (Darcy flow in rock matrix, ‘cubic-law’ flow in fractures)</li> <li>– heat transport (by advection-dispersion and by diffusion, also deemed as ‘convection’ and ‘conduction’, respectively)</li> <li>– thermohydraulic coupling (temperature dependence of hydraulic conductivity): ignored</li> </ul>	<p><b>Time dependency of simulated processes:</b></p> <ul style="list-style-type: none"> <li>– steady-state fluid flow</li> <li>– transient heat transport (up to 10 years simulation time)</li> </ul>	<p><b>Comment:</b> assuming steady-state hydraulics is not quite correct, was however proven by accompanying simulations (Ghergut [2016], pers. comm.) to be a reasonable approximation</p>
<p><b>Model Geometry And Size</b></p>	 <p>(For larger view refer Appendix 2 )</p>	<p><b>Model Geometry:</b> Refer to the five-fracture scheme (top view); the appendix 2 illustrates the steady-state flow velocity field in one of the simulated scenarios (wt = wh = 2 cm, with the ‘inside’ fracture turned off)</p> <p><b>Model Size:</b></p> <ul style="list-style-type: none"> <li>– longitudinally: 1.8 km</li> <li>– laterally: 400 m</li> <li>– depth (half of physical depth): 100 m</li> </ul>	<p><b>Comment:</b> assuming vertical symmetry w. r. to the horizontal plane connecting the injection and production well-screen sections was proven by accompanying simulations (Ghergut [2016], pers. comm.) to be a reasonable approximation</p>
<p><b>Spatial Discretization</b></p>	<ul style="list-style-type: none"> <li>-fixed in time (not adaptive)</li> <li>-varied in space (refinement around wells and fractures)</li> </ul>	<ul style="list-style-type: none"> <li>– nodes: 57826</li> <li>– elements: 28480</li> </ul>	

<p><b>Temporal Discretization</b></p>	<p>adaptive (AB/TR, forward Adams-Bashforth, backward trapezoid time-integration scheme)</p>	<p>– shortest time step: <math>10^{-8}</math> day  – largest time step: 6 day  – number of time steps per simulation: in the order of several hundred</p>	<p><b>Comment:</b> in smooth case: it turns up results needed more time steps, shorter time steps, compared to rough case in preparations which needed longer time steps, smaller total number of time steps is sufficient to insure comparable accuracy.</p>
<p><b>Main Hydrogeologic Parameters</b></p>	<p><b>Rock Matrix:</b>  – hydraulic conductivity:  <math>K_{xx} = K_{yy} = 10^{-7}</math> m/s  <math>K_{zz} = 5 \times 10^{-8}</math> m/s  – transport-effective porosity: 5 %  – heat capacity: <math>2.5 \times 10^6</math> J/m<sup>3</sup>/°C  – heat conductivity: 3 J/m/s/°C  – dispersivity: in the order of few metres, adapted to the element size</p>	<p><b>Fractures:</b>  – aperture and width values: varied between scenarios where same thermal aperture (<math>t</math>) = 2 cm, whereas hydraulic aperture(H) is varied from 2 mm to 6 mm , as indicated in the results chapter  – dispersivity: in the order of few metres, adapted to the fracture element size</p>	
<p><b>Initial Conditions</b></p>	<p>-flow velocity = 0 (no head gradients) within whole model domain  -temperature = 150°C within whole model domain</p>		
<p><b>Boundary Conditions</b></p>	<p>– injection well: 2000 m<sup>3</sup>/day, with prescribed fluid temperature 60°C  – production well: 2000 m<sup>3</sup>/day, with free-outflow b.c. for heat  – outer boundaries: free outflow and prescribed temperature value (equal to the initial value, cf. supra)</p>		

Table 3: Model description using FEFLOW

## **4. RESULTS FROM SCOPING SIMULATION**

The past scope simulation by Ghergut [2013], we make use of a setup of the “five-fracture” model, a generic extremely-simplified “fractured reservoir” model, mainly the purpose of demonstrating the parameter uncoupling between heat and solute (tracer) transport, parameters were varied uniformly for the whole set of fractures and also looked into the effects of non-intersected fractures ‘inside’ or ‘outside’ the reservoir on inter-well tracer test signals. Despite the seemingly extreme simplicity of this model geometry (figure 1), flow and transport patterns within this geometry do not follow a universal scheme and are also difficult to categorize into a finite number of a distinct type. In the past study Ghergut [2013] some scoping simulations were presented the issue of (partial) uncoupling between hydraulic and thermal or solute tracer transport behavior: heat transport was seen to be more sensitive to fracture apertures, and rather insensitive to matrix porosity, whereas solute transport was seen to be highly sensitive to matrix porosity (as expected) but rather insensitive to fracture parameters, and hydraulic tests (pressure signals) respond ambiguously to the presence of fractures, and are rather insensitive to matrix porosity, thus the inability, or limited ability of (especially solute) tracers to capture all relevant features and parameters of a deep georeservoir.

Unlike the past study which dealt with parameterization of this system determining the parameters in practical situation, we're dealing with individual fractures ( major fracture ) that have been identified by geophysical exploration (seismic exploration), which tell you the location of fault zone but this always with a lot of uncertainty (we don't know if the fault zone explored by seismic in the reservoir is hydraulically effective). There may be some fracture which is not seen in seismic exploration some situation, we conduct the hydraulic test, there could be fracture some distance from the borehole which could not be seen in seismic exploration or other way around. This is reason we use this temperature signals to make this detection or negation of fracture to add additional evidence, therefore, we will switch on and off some fracture from the “five-fracture” model, we make one disappear ( either in the middle or outside but nearby outside fracture), and see if this has consistence effect on the temperature signals and not the intersected fractures because these are better known during the drilling process, but they have clear effect on hydraulic test. When we conduct the hydraulic test, we see the shape of hydraulic signal whether it is in the fracture or porous matrix. In order to exhibit the goals of this study, we find the different value of effective aperture for heat transport (thermal) and for hydraulic. Typically because of fracture roughness, the effective hydraulic aperture is lower than geometrical aperture. For heat transport, the geometrical aperture is controlling parameter but for hydraulic because fracture roughness means irregularity of fracture surface. But only small parts of whole fracture opening will hydraulic effective. This means in FEFLOW model, we can insert different parameter for hydraulic aperture and thermal aperture. We conduct set of simulation for rough fractures i.e. hydraulic aperture is lower than of factor than thermal aperture. The idea is to check if the temperature is sensitive to the hydraulic aperture. The expectation is YES. Although the hydraulic aperture is supposed to be relevant to hydraulics

and thermal aperture to the heat transport. The hydraulic aperture will change the distribution of the flow between fractures and matrix so it will change the transmissivity ratio because the flow will be distributed according to the transmissivity ratio and if the ratio will change then the heat transport will also be effected and it will be effected by both by hydraulic aperture in the advective heat transport part and this is a tricky issue. Therefore we conduct scope simulation (not full analyses of the system). From the scoping simulation, thermal breakthrough curve and 3 D snapshots were obtained.

#### **4.1. Thermal Breakthrough Curves**

When all fractures are assumed as rough (hydraulic aperture systematically smaller than the transport-effective aperture), with a hydraulic aperture value of 2 mm and a transport-effective aperture of 2 cm, the thermal breakthrough is found to be almost insensitive to the ‘switching off’ of individual fractures as shown in figure 14. It is accelerated by up to less than 1% additional temperature drop after 10 years, the effect of ‘switching off’ one fracture being most pronounced for the mid fracture at all times, and least pronounced for the injection-outward fracture at all times – unlike in the case of smooth fractures, where the most pronounced effects were found for the mid fracture at early times, and for the ‘injection-outward’ fracture at later times, as shown by Khaleefah [2017]. On the other hand, the absolute amount of temperature drop after 10 years is found to be quite similar (from 150° C to ~97° C) to the case of smooth fractures with the same value of hydraulic and transport-effective aperture (2 mm) that was simulated by Khaleefah [2017].

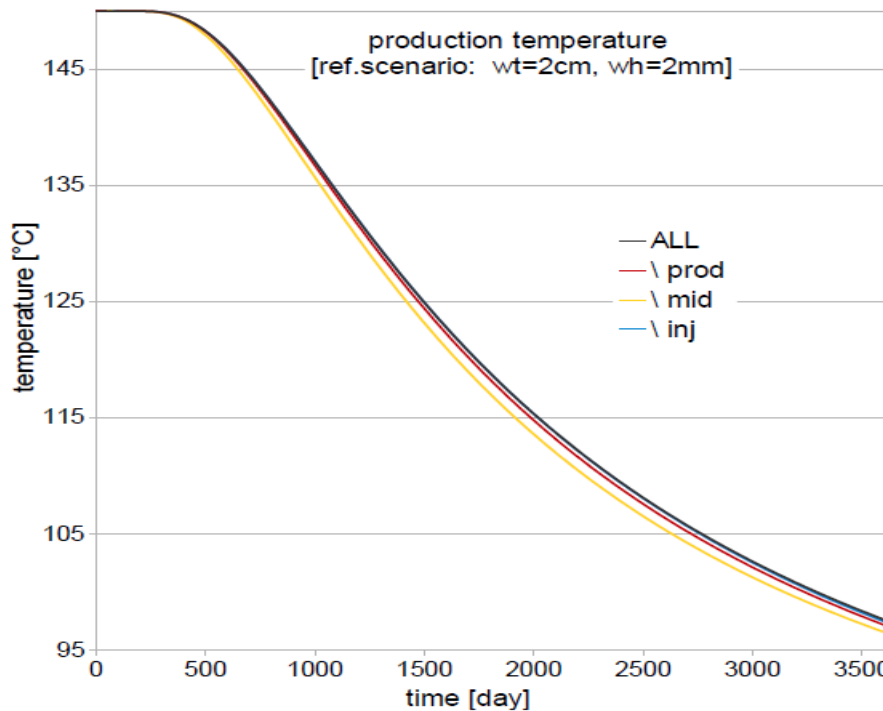


Figure 14: Thermal breakthrough seen when all fractures are assumed as rough (hydraulic aperture value of 2 mm and a transport-effective aperture of 2 cm).

When the hydraulic aperture of all fractures is assumed three times larger ( $wh = 6$  mm instead of 2 mm, with  $wt = 2$  cm unchanged) as shown in figure 15, the thermal breakthrough is seen to be much more sensitive with respect to the presence or absence of individual fractures, but the effect of ‘switching off’ individual fractures is quite different, compared to the case of smooth fractures with  $wt = 2$  cm as addressed by Khaleefah [2017]:

- ‘switching off’ the mid fracture will have the most pronounced accelerating effect on thermal breakthrough, augmenting the ten-year temperature drop by  $\sim 8$  °C (temperature drop by  $\sim 58$ °C instead of by  $\sim 50$ °C);
- ‘switching off’ the injection-outward fracture will have a slowing effect on the thermal breakthrough, reducing the ten-year temperature drop by  $\sim 4$  °C (temperature drop by only  $\sim 46$ °C instead of by  $\sim 50$ °C).

On the other hand, ‘switching off’ the outward-production fracture will have an accelerating effect on thermal breakthrough, augmenting the ten-year temperature drop by  $\sim 5$  °C, which is qualitatively similar to the case simulated by Khaleefah [2017] (and for the same quite plausible reason), but with a larger absolute amount of temperature drop.

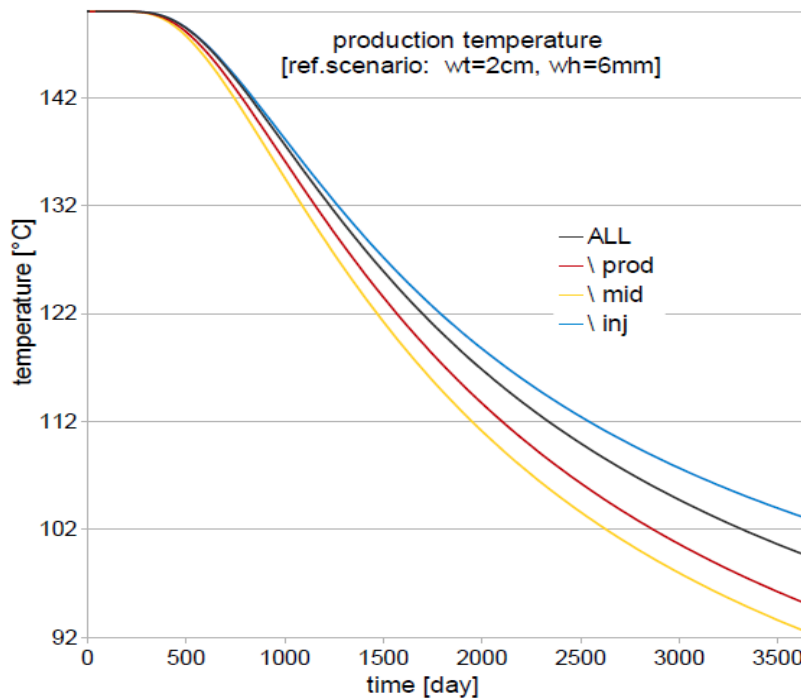


Figure 15: Thermal breakthrough is seen when the hydraulic aperture of all fractures is assumed three times larger (wh = 6 mm instead of 2 mm, with wt = 2 cm unchanged).

Furthermore, the ten-year temperature drop (below 103 °C for all scenarios) is seen to be larger than in all cases with the same transport-effective aperture (2 cm) but a larger hydraulic aperture (2 cm instead of 6 mm) that were simulated by Khaleefah [2017] (staying above 103 °C for all scenarios).

## **4.2 3-D Cut Along Each Of The Five Fracture Planes**

Each of the five 3 D snapshot plot sheets shows a different 3-D cut (cf. figure 16 with cut-lines in magenta), along each of the five fracture planes (for smooth fracture is showing longitudinally cut at the injection well where for the rough fracture is showing the whole fracture) :

- cut along the outwards-production fracture at lateral distance of -60 meters,
- cut along the fracture intersected by the production well at lateral distance of -30 meters,
- cut along the inner fracture at lateral distance of 0 meters,
- cut along the fracture intersected by the injection well at lateral distance of 30 meters
- cut along the injection-outwards fracture at lateral distance of 60 meters.

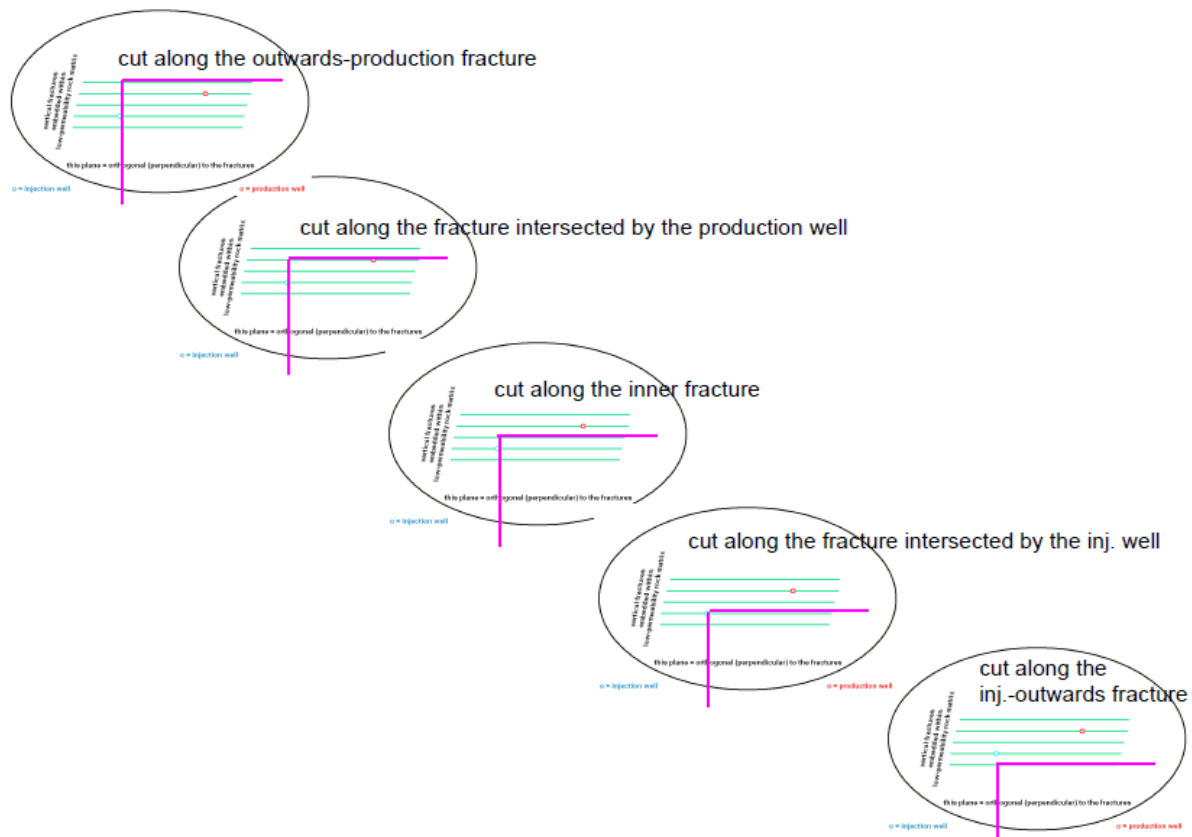


Figure 16: 3-D cut along each of the five fracture planes

### **4.3 3 D Snapshots Plot**

The following five snapshot sequences, each showing the ‘late’ temperature field (after 10 years of continuous fluid circulation, with produced fluid re-injection at 60 °C) in the 3-D reservoir domain, cut along one of the five fractures, respectively (figure 16 with cut-lines in magenta):

- cut along the injection-outwards fracture, i.e., in 60 meters lateral distance from the model domain mid-plane, on the injection side (first snapshot sheet, labeled “-60”) as shown in figure 17,
- cut along the fracture intersected by the injection well, i.e., in 30 meters lateral distance from the model domain mid-plane, on the injection side (second snapshot sheet, labeled “-30”) as shown in figure 18,
- cut along the “inside-reservoir” fracture, i.e., at the model domain mid-plane (third snapshot sheet, labeled “-0”) as shown in figure 19,
- cut along the fracture intersected by the production well, i.e., in 30 meters lateral distance from the model domain mid-plane, on the production side (fourth snapshot sheet, labeled “+30”) as shown in figure 20,

– cut along the outward-production fracture, i.e., in 60 meters lateral distance from the model domain mid-plane, on the production side (last snapshot sheet, labeled “+60”) as shown in figure 21.

enable to compare between the effects of ‘inactivating’ one of three fractures, respectively:

- turning off the outward-production fracture, while keeping thermal aperture (wt) and hydraulic aperture (wh) for the other four fractures unchanged (upper snapshot of each plot sheet),
- turning off the “inside-reservoir” fracture, while keeping thermal aperture (wt) and hydraulic aperture (wh) for the other four fractures unchanged (second snapshot of each plot sheet),
- turning off the injection-outwards fracture, while keeping thermal aperture (wt) and hydraulic aperture (wh) for the other four fractures unchanged (third snapshot of each plot sheet),
- the reference case: all fractures present, with thermal aperture (wt) = 2 cm, hydraulic aperture (wh) = 6 mm (lowest snapshot of each plot sheet).

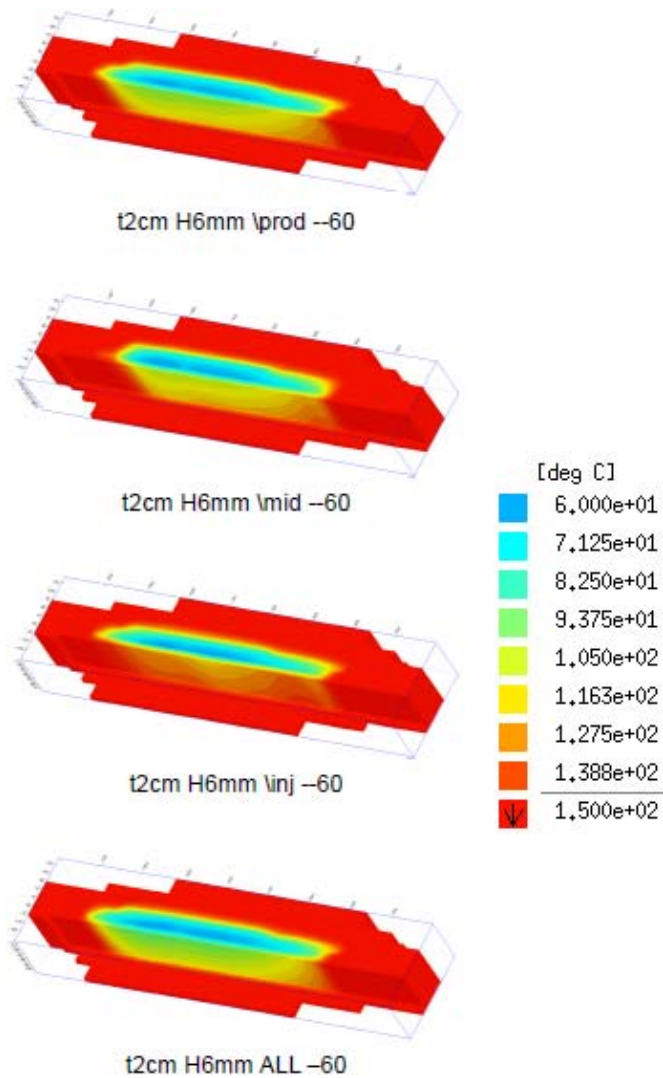


Figure 17: Temperature ( $T^\circ$ ) distribution along the injection- outwards fracture plane for each 'missing - fracture' scenario where t is thermal aperture and H is hydraulic aperture.

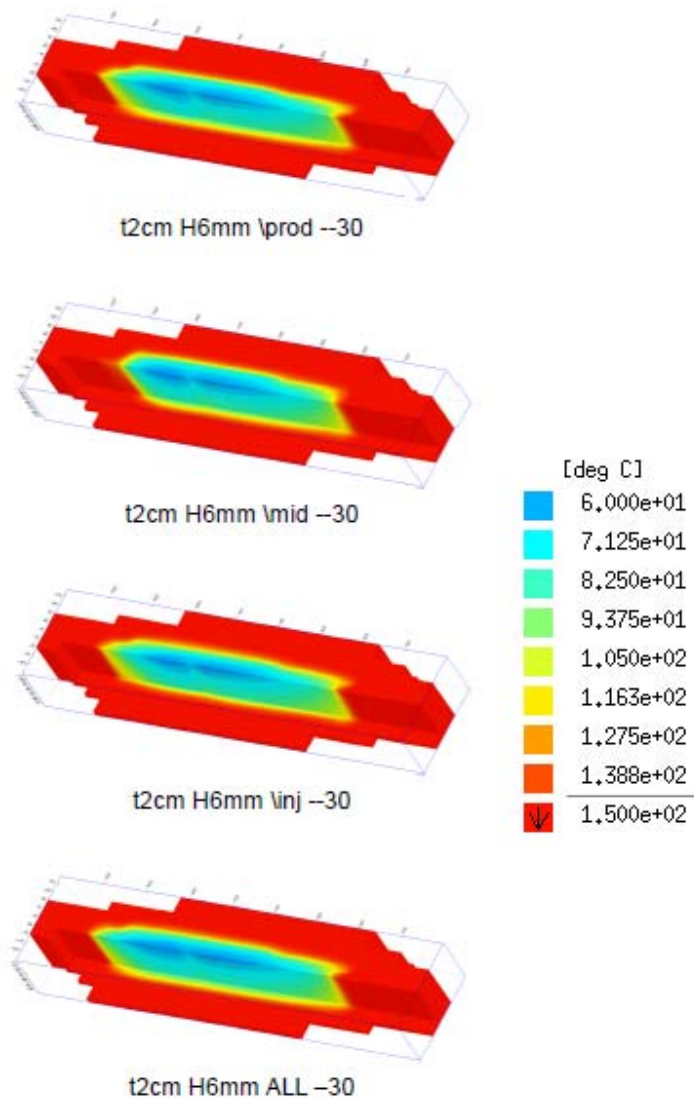


Figure 18: Temperature ( $T^\circ$ ) distribution along the injection fracture plane for each 'missing -fracture' scenario where  $t$  is thermal aperture and  $H$  is hydraulic aperture.

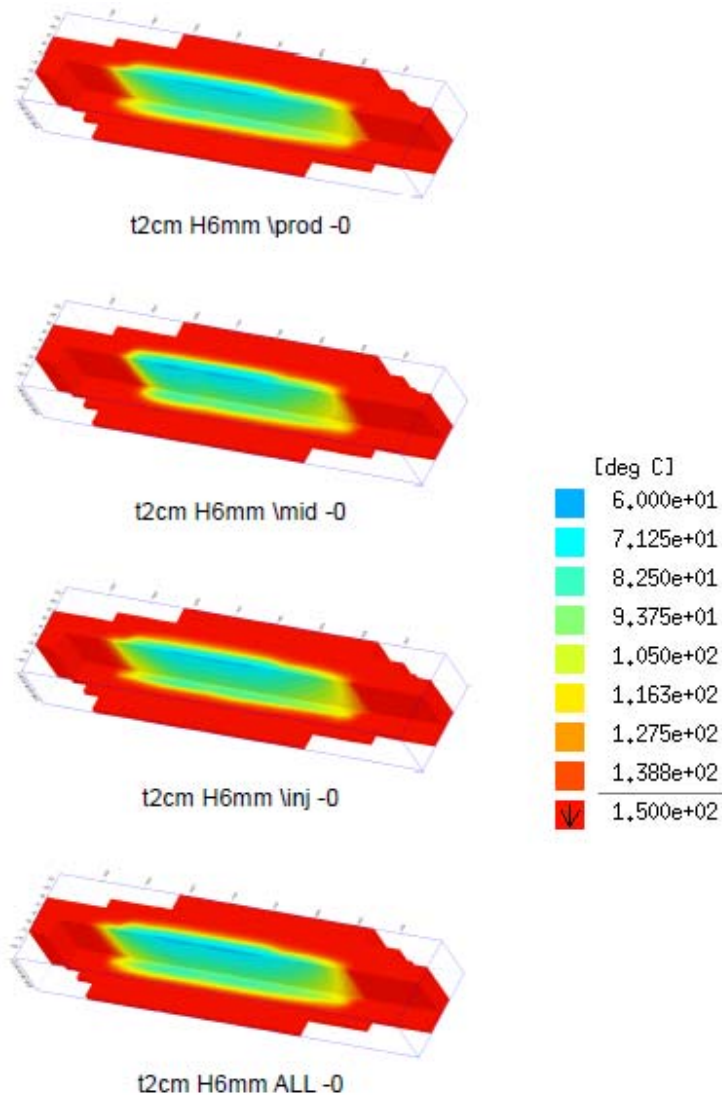


Figure 19: Temperature ( $T^\circ$ ) distribution along the mid fracture plane for each 'missing -fracture' scenario where  $t$  is thermal aperture and  $H$  is hydraulic aperture.

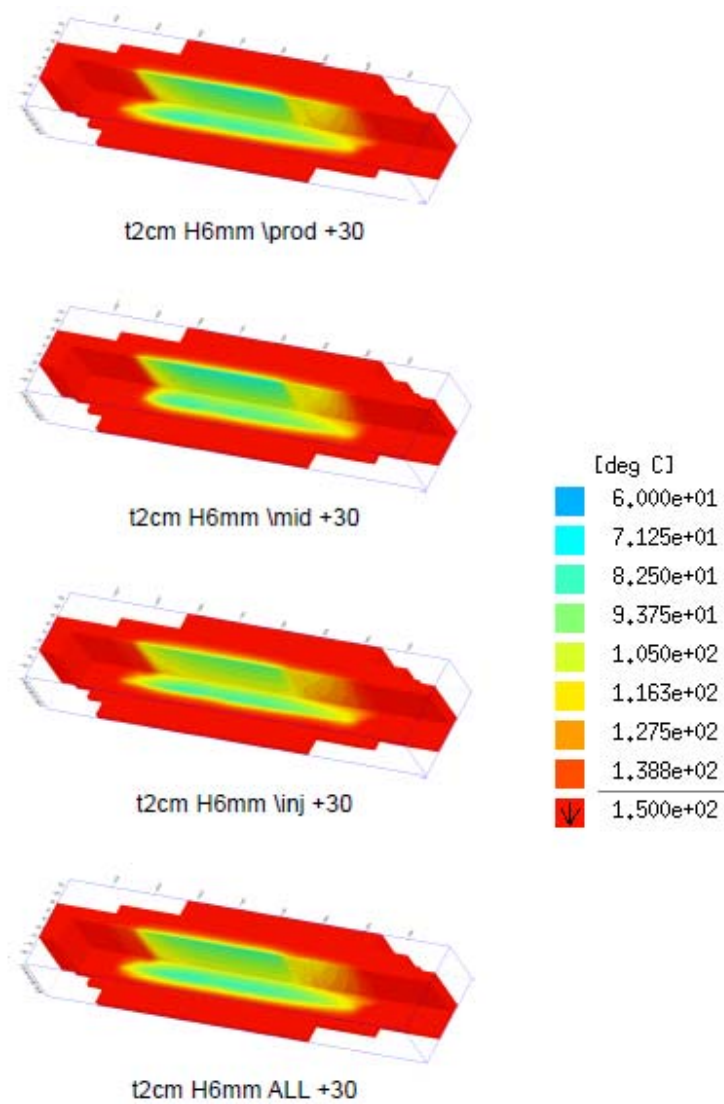


Figure 20: Temperature ( $T^\circ$ ) distribution along the production fracture plane for each 'missing -fracture' scenario where  $t$  is thermal aperture and  $H$  is hydraulic aperture.

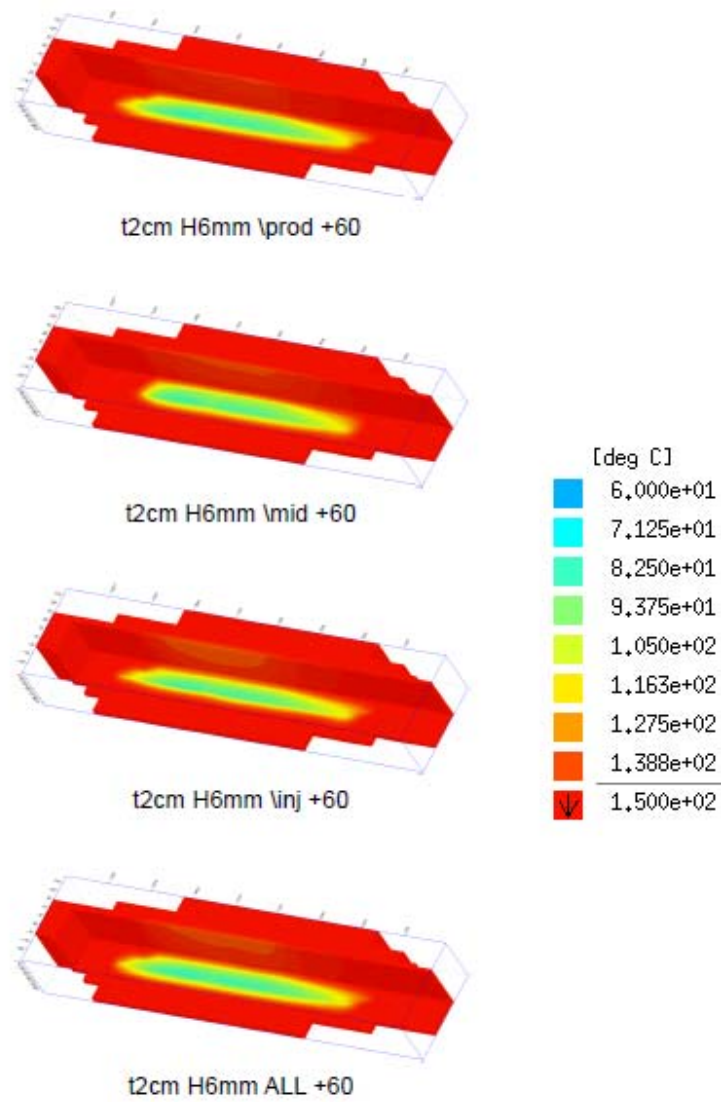


Figure 21: Temperature ( $T^\circ$ ) distribution along the outwards- production fracture plane for each 'missing -fracture' scenario where  $t$  is thermal aperture and  $H$  is hydraulic aperture.

## **5. DISCUSSION**

In the reference scenario, when all fractures are assumed as rough (hydraulic aperture ( $w_h$ ) systematically smaller than the transport-effective aperture( $w_t$ )), with a hydraulic aperture value of 2 mm and a transport-effective aperture of 2 cm, thermal breakthrough is found to be almost insensitive to the ‘switching off’ of individual fractures. When mid fracture is missing, it shows the accelerating effect at all times, whereas missing outwards injection shows the slowing effect at all times. Here the fracture is hydraulically very smaller, they do not influence the flow so much. Therefore, they have same signals in all case, this means that heat transport to the matrix is dominating. When fluid meets the fracture, the fluid flows through the fracture and this will not change very much. Hence signal looks similar, the fracture themselves in this case where there is a small hydraulic aperture, they don't make much difference. Unlike in the case of smooth fractures, where the most pronounced effects were found for the mid fracture at early times and for the ‘injection-outward’ fracture at later times and least pronounced for the mid fracture at late times, as shown by Khaleefah [2017].

When the hydraulic aperture of all fractures is assumed three times larger ( $w_h = 6$  mm instead of 2 mm, with  $w_t = 2$  cm unchanged), the thermal breakthrough is seen to be much more sensitive with respect to the presence or absence of individual fractures, but the effect of ‘switching off’ individual fractures is quite different, compared to the case of smooth fractures with  $w_t = 2$  cm as addressed by Khaleefah [2017].

When injection outward missing, it will have a slowing effect because it will attract some more fluid then reservoir becomes larger. Larger volume will take a longer time to get into production borehole. There will be less drainage effect but to compensate the missing volume then it will spread more laterally due to which there will be increasing effective reservoir size through the lateral direction. Therefore, thermal lifetime increases.

When all the fracture is present, this cold plume spread more at laterally. It could be the reason for increase in effective reservoir size as we increase lateral extension. Drainage effect is maximum when all fracture present. When one fracture is removed, another fracture will compensate absent of removed fracture. There will be more drainage effect when the fluid is injected into the system. The fluid goes to two fractures or it has one fracture, it has gone through that fracture where it goes laterally. Therefore, we cannot say in advance that is reason for simulation

Effective reservoir size is roughly the product of this lateral distance and this longitudinal distance as shown in figure 22. Presence and absence of fracture may influence both lateral and or longitudinal extension. Because we don't change the injection/production rate, the fluid has to “go” somewhere. Therefore, there can be some degree of reciprocal compensation between lateral/ longitudinal extension variations. Therefore, cannot tell in advance which one will finally prevail. Therefore, we need more scoping study".

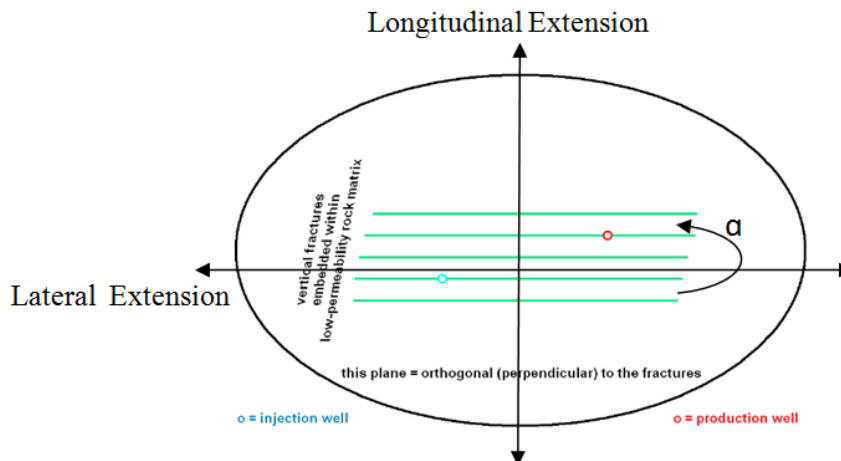


Figure 22: Top View of five fracture model showing lateral and longitudinal extension

When mid fracture missing, there will be less diversion of the whole plume in a lateral direction, and then reservoir size decreases. Therefore, it reaches the production borehole earlier. When we don't have the fracture in the middle, it will drain more fluid laterally so the drainage effect is missing. Therefore, it has accelerated effect and thermal lifetime decreases.

When the hydraulic aperture is increased, it has two contradicting effects. Higher transmissivity according to the cubic law (aperture is increased by a factor of 3 (2mm to 6mm), transmissivity is increased ( $3^3 = 27$ ) i.e. 30 times higher transmissivity. It may have stronger drainage effect. But when there is a higher aperture, there will also porosity which means it will accelerate the drainage in terms of transmissibility but it decelerates the drainage because of increase in cross section.

The most striking or visual evidence effect is seen in along outward production (Figure 21):

- When production fracture is missing shows least cooling at the upper part (little bit yellow at fracture plane) and lateral extension of cold plume little bit stronger at the bottom part of the reservoir. Therefore, thermal breakthrough is little bit accelerated and thermal lifetime little bit decreases.
- When injection fracture missing shows strongest cooling at the upper part and more elongated lateral extension colder plume compensate to missing volume. Hence it spreads more laterally at bottom of the reservoir. It takes a longer time to reach the production well. Therefore, thermal breakthrough is decelerated and thermal lifetime increases.
- When mid fracture missing, shows intermediate cooling at upper part whereas it also has least lateral extensive colder plume at the bottom. It has no drainage effect less fluid

move to a part of the reservoir and the plume reaches the production well earlier. Therefore, thermal breakthrough is accelerated and thermal lifetime decreases.

Drainage effect is seen when all fracture are present. This is broader expectation because it also happen when one fracture is absent, but still you have pressure of fluid and the fluid has to go somewhere and this will force another fracture to have more drainage so to compensate missing fracture it can also happen that if one fracture is missing there will more drainage at another fracture to compensate because we don't change the injection rate/production rate.

Along with production fracture plane (Figure 20):

- more cold fluid contribution is seen when mid fracture is missing. The less deviation through the reservoir. More cold fluid contribution it explains missing mid fracture less lateral drainage along " a "part through reservoir (Figure 22).
- least fluid contribution is seen when fracture are present. The most of spreading smallest quantity of fluid arriving the production, this is consistence. The more drainage effect is seen here.

The past scoping simulation Ghergut [2017] shows drainage and lateral spreading as shown in figure 23. All tracer signals are same, where a slight difference was seen. More drainage lateral spreading is seen when one fracture missing (upper case) and whereas least drainage lateral spreading is seen when all fracture present (lower case). Comparison between when one fracture is missing (last second case) was rather at end of simulation late time, tracer as has been disappear it concentrated what left a margin of reservoir mostly through matrix diffusion through the fracture or matrix. Therefore, we can say simulated tracer signal from reference thus also support explanation about lateral drainage effect.

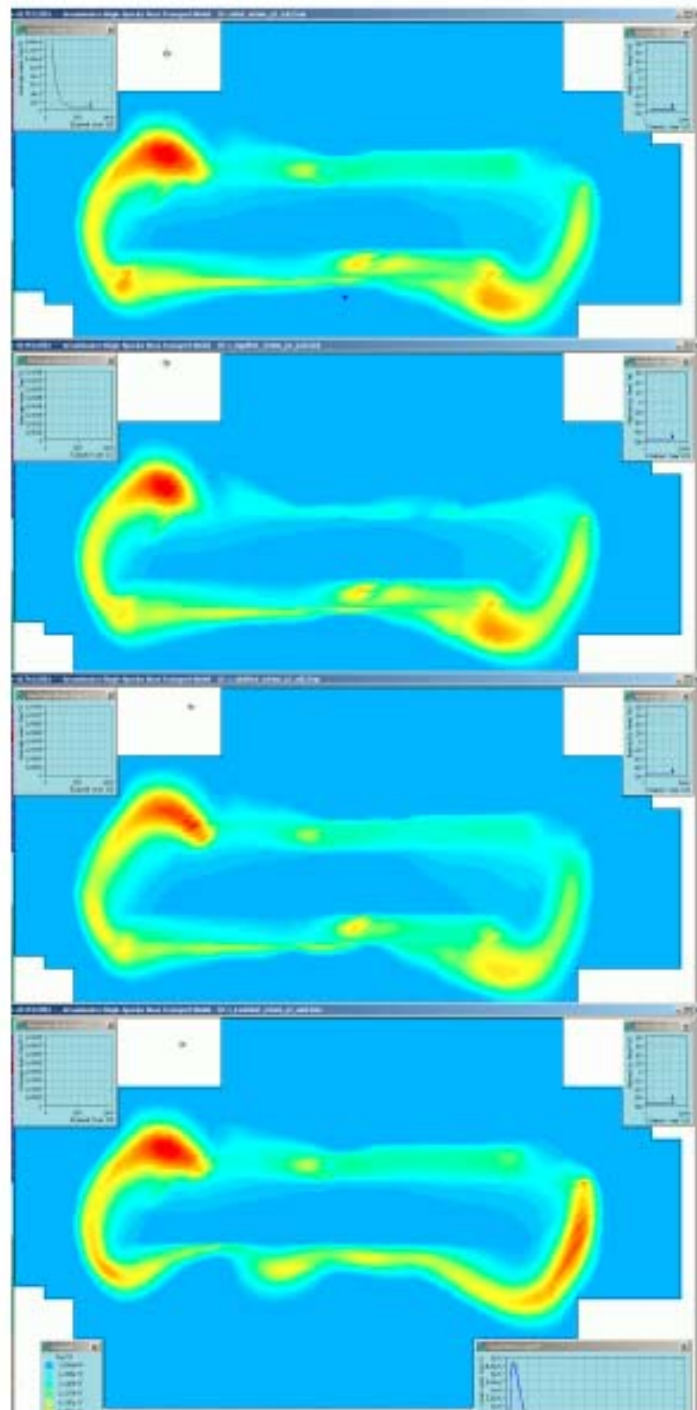


Figure 23: Past scoping simulation conducted in the all-fractures-present case, compared to the one-fracture-missing cases (Ghergut[2017] )

## **6. CONCLUSION**

In past scoping simulations, Ghergut [2013] illustrated the parameter uncoupling between heat (thermal) and solute (tracer) transport, where fracture parameters were varied uniformly for the whole set of fractures whereas Ghergut [2017] conducted simulation only by solute transport (tracer signal) by switching fractures on and off individually in a geothermal well doublet within a ‘five-fracture reservoir’ model. But now temperature signal was observed switching fractures on and off individually either on middle, outside injection or outward production. When all fractures are assumed as rough (hydraulic aperture systematically smaller than the transport-effective aperture), the thermal breakthrough is found to be almost insensitive to the ‘switching off’ of individual fracture and similar effect also observed for smooth fracture (hydraulic aperture systematically equal to transport-effective aperture). The implicit message is that temperature signal is sensitive to hydraulic parameters. The difference in the signal was observed when the hydraulic aperture was changed and keeping thermal aperture unchanged.

When the hydraulic aperture of all fractures is assumed three times larger, the thermal breakthrough is seen to be much more sensitive with respect to the presence or absence of individual fractures. But the effect of ‘switching off’ individual fractures is quite different compared to the case of smooth fractures. When injection outward is missing, it has less drainage effect but to compensate the missing volume then it will spread more laterally due to which there will be increase in effective reservoir size through the lateral direction. Therefore, thermal lifetime decreases. When mid fracture missing, there will be less diversion of the whole plume in the lateral direction which makes reservoir smaller. Therefore, thermal lifetime decreases. Drainage effect is maximum when all fracture present. When one fracture is absent, but still you have the pressure of a fluid and the fluid has to go somewhere and this will force another fracture to have more drainage so to compensate missing fracture. It can also happen that if one fracture is missing there will more drainage at another fracture to compensate because we don't change the injection rate/production rate.

However a series of 3-D temperature field visualizations inside the reservoir body used to compare the spreading of the cooled-fluid ‘plume’ longitudinally and laterally (relative to the inter-well axis), since this relative spreading or ‘drainage’ effect was found to provide a clue for explaining how individual fractures ‘inside’ or ‘outside’ the inter-well domain may slow down or accelerate the thermal breakthrough at the production well.

Presence and absence of fracture may influence both lateral and or longitudinal extension because we don't change the injection/production rate; the fluid has to “go” somewhere. Therefore, there can be some degree of reciprocal compensation between lateral/ longitudinal extension variations. Therefore, cannot tell in advance which one will finally prevail. Henceforth, we need more scoping study.

## **7. RECOMMENDATION**

A comparative evaluation of our findings from scoping simulations on heat transport during forced-gradient inter-well circulation in a geothermal reservoir containing a finite number of rough fractures of finite extension, jointly with findings from N. Khaleefah's study for somewhat different scenarios involving smooth fractures in a similar geological setting [2017, M. Sc. Thesis in prep.], enable to re-formulate our results in a more general manner and derive some recommendations for the georeservoir monitoring practice, as well as for future modeling studies:

- A threshold value appears to exist for the hydraulic aperture of fractures, below which their effects on thermal decline at the production well become negligible; this value is in the order of 1 mm for the particular geological setting and reservoir dimensions of the 'pastiche' model introduced by Ghergut [2013], but the value might be larger for real-world geothermal reservoir settings; therefore we recommend to re-scale the results of future simulations in terms of dimensionless variables and parameters (as was attempted by Ghergut [2013, 2017] for solute tracer signals, introducing a "reservoir turnover time unit"  $T_1$  and a "reservoir turnover volume unit"  $V_1$  however with the caveat that this was only a pseudo-scaling, not enjoying invariance w.r. to matrix porosity values); for temperature, a dimensionless variable is easily defined, dividing the current temperature decline ( $T_0^\circ - T^\circ(\text{time})$ ) by  $T_0^\circ$  (where  $T_0^\circ$  denotes the initially undisturbed or far-field temperature at reservoir bottom);
- The correlation between fracture aperture values and production temperature decline is non-monotonous, especially for fractures 'inside' the inter-well domain; to overcome this limitation to fracture parameter inversion from measured temperature signals, we recommend the joint use of conservative and thermosensitive tracers; the latter may disambiguate the aperture inversion from conservative tracer signals under certain circumstances (a particular example was provided by Ghergut [2013], but a general analysis is still lacking);
- Fractures roughness in real-world georeservoirs implies that the values of their hydraulic aperture, their heat transport-effective aperture, and their solute transport-effective aperture may differ from each other, which severely limits the applicability of the much-praised "joint inversion" or "concomitant inversion" of pressure, temperature and solute tracer signals, because the very parameter subject to inversion from each of these signals will be a different one; maybe their values will somehow be correlated to each other, but this needs to be established from modeling studies addressing fracture roughness in detail;
- Under certain circumstances, temperature signals tend to respond more sensitively to hydraulic features, than to their associated thermal parameter values, thus recommending heat as a suitable 'tracer' for the hydraulic characterization of fractured-porous systems (not only in the geothermal realm, but also for groundwater studies);

- Outflow temperature signals need to be recorded for a rather long time before the effects of fractures become detectable (in our scenarios, for at least ~2 years); for geothermal reservoirs, production temperature monitoring belongs to standard practice, but things may look different when heat is used as an artificial tracer in groundwater studies, whose duration may be need to be limited by different other considerations.

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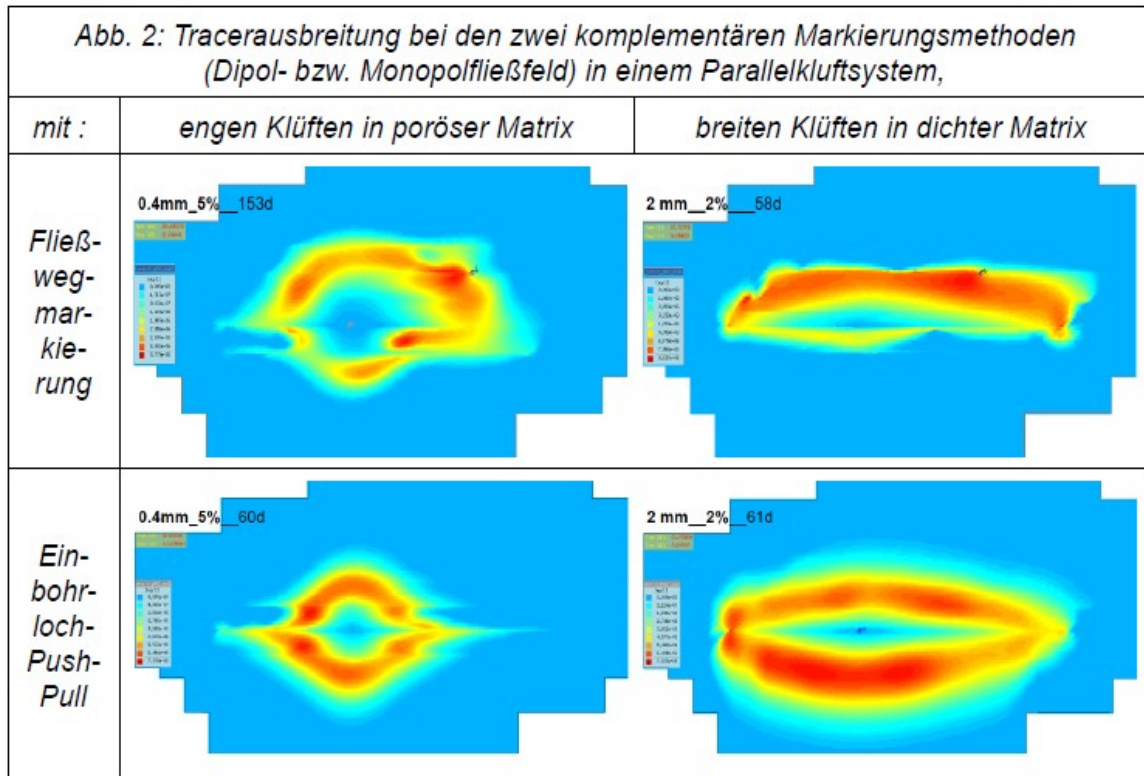
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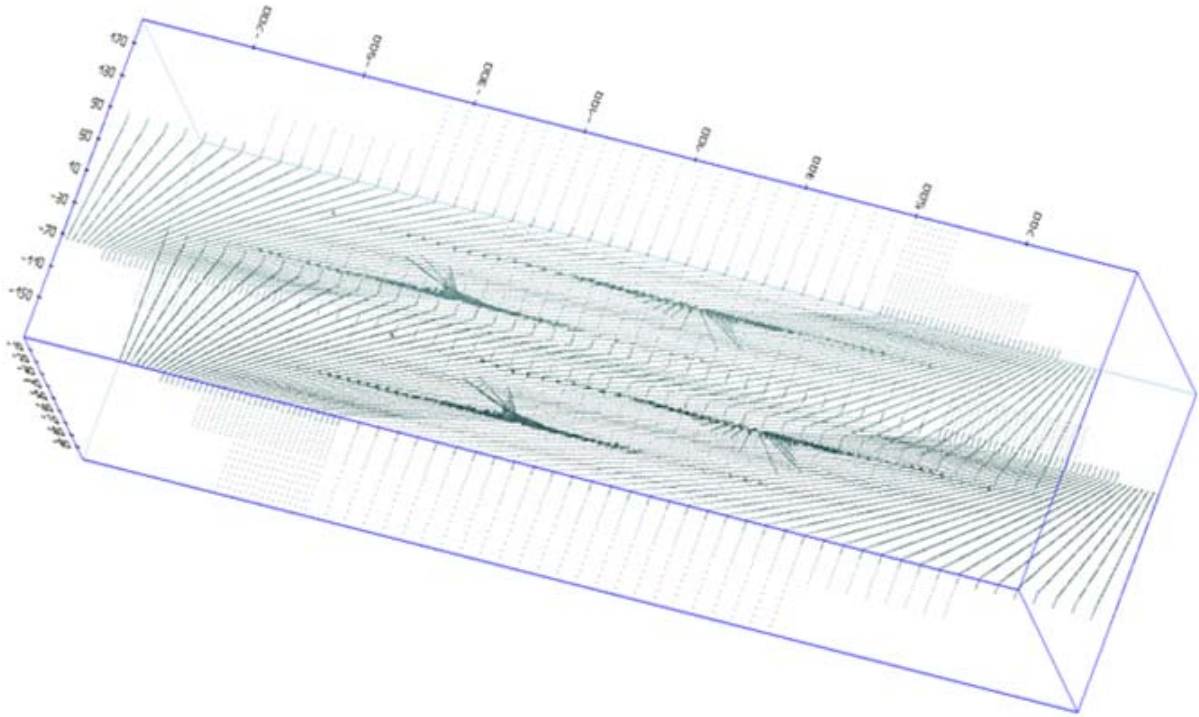
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## 9. APPENDIX



Appendix 1: Single well and Intrawell test  
(Source: Ghergut [2011])



## Appendix 2: 3D Model Description