Fluid Temperature Sensitivity to Hydraulic Aperture and Thermal Width Values of Major Vertical Fractures in Forced-Gradient Flow

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Abstract

Heat transport during forced-gradient inter-well, single-phase brine circulation is investigated numerically for a porous-fractured geothermal reservoir model containing a finite number of 'rough' fractures of finite lateral extension, striking obliquely to the inter-well axis. In this context, fracture 'roughness' primarily implies the non-identity between hydraulic aperture (w_h) and transport-effective thermal width (w_t) values. Scoping simulations of heat transport therein reveal (I) a threshold value for w_h, below which fracture effects on thermal decline become negligible, despite (II) the non-monotonous correlation between w_h or w_t values and outflow temperature signals; furthermore, (III) outflow temperature signals tend to respond more sensitively to w_h than to w_t variations, which interestingly implies that heat may serve as a more suitable 'tracer' for characterizing fractured-reservoir hydraulics, than for measuring its thermal parameters. Conversely, the prediction of temperature decline (thermal breakthrough) during long-term reinjection is one of the main goals of inter-well solute-tracer tests conducted in geothermal reservoirs. However, a clear-cut, unambiguous relationship between the fluid residence time distribution (as measured by solute-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+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, especially when fractures strike obliquely to the inter-well axis. Therefore, the ability to infer fracture properties from early outflow temperature (without necessarily relying on solute tracer) signals can be of great value in georeservoir monitoring.

This paper summarizes a Master's thesis work completed at the University of Göttingen (2017), for which Ms. Swathi Mohandas Surekha received financial support from the Erasmus Mundus NAMASTE Program, Action II. The finite-number finite-extension fracture benchmark model used for numerical simulations had originally been developed within "TRENDS", a project funded by the German Federal Ministry for Economic Affairs and Energy (BMWi grant no. 0325515).

Kurzfassung

In ihren Masterarbeiten (Univ. Göttingen, 2017) sondieren Frau Swathi Mohandas Surekha und Herr Nawfal Ahmed Saleh Khaleefah Möglichkeiten und Grenzen des Einsatzes von Wärme (Temperatursignalen) als konservativem Fluidtracer zur Charakterisierung geklüfteter Georeservoire. Ausgehend vom abstrahierten und vielseitig einsetzbaren Benchmarkmodell einer geothermischen Dublette in einem Georeservoir mit fünf markanten Vertikalklüften

(entweder durch die Produktions- [**p**] bzw. Injektionsbohrung [**i**] durchteuft, oder abseits von **p** bzw. von **i** zum 'Reservoirrand' hin, oder 'innerhalb' des Reservoirs zwischen **p** und **i**, cf. Abb. infra), wird die Sensitivität der während des Thermalwasserumsatzes an **p** messbaren Temperatursignale gegenüber Kluftweiten und überhaupt dem Vorkommen oder Nicht-Vorkommen einer markanten Kluft 'abseits' oder 'innerhalb' des Reservoirs untersucht. Hierzu werden am Benchmarkmodell die Öffnungsweiten der Klüfte variiert, bzw. Klüfte einzeln 'weggeschaltet' (d. h. aus dem Modell entfernt, für das betreffende Szenario). – Dies hat zweifache Bedeutung: einerseits als Prognose der thermischen Lebensdauer des geklüfteten Reservoirs für verschiedene Kluftszenarien (*direct modeling*), andererseits als Beitrag zur Bewertung der Verwertbarkeit gemessener Temperatursignale als künstlicher 'Tracer' (*inverse modeling*) zur Charakterisierung von Multi-Kluft-Systemen und womöglich zur 'Kluftdetektion', methodisch relevant auch über die Geothermiewelt hinaus – insbesondere für die Grundwasserströmungserkundung im Umfeld vermuteter signifikanter Klüfte (die in hydraulischen Tests oder der geophysikalischen Erkundung nicht eindeutig detektiert werden konnten). Ob Geothermie, oder Grundwasser, oder andere Georeservoirnutzungen – der Wärmetransport wird durch die gleichen Prozesse bestimmt: Advektion alias Konvektion durch Klüfte (i. d. R. schneller) und Matrixblöcke (i. d. R. langsamer bis vernachlässigbar), überlagert von Diffusion (Konduktion) durch Matrixblöcke, mit jener speziellen Ausprägung an der Grenzfläche Kluft – Matrix, die in der Fachliteratur als "Matrixdiffusion" bezeichnet wird.

"Kluftrauhigkeit" wird bei hiesiger Simulation von Fluidströmung und Wärmetransport dahingehend berücksichtigt, dass die hydraulische Apertur und die transportwirksame Kluftöffnungsweite wie zwei voneinander unabhängige Parameter behandelt werden (cf. Tsang 1992), die den Wärmetransport im Reservoirmaßstab auf unterschiedliche Weise beeinflussen. Auch der Vergleich zwischen den Auswirkungen 'breiterer' und 'dünnerer' (durch die geophysikalische Exploration i. d. R. nicht eindeutig detektierbarer) Klüfte auf den Wärmetransport im Reservoirmaßstab erfolgt unter dem verfeinerten Gesichtspunkt, dass die breiteren Klüfte sehr wohl in hydraulischen Tests (Drucksignalen) 'spürbar' werden, aber ihre transportwirksame Apertur dennoch von der hydraulisch-ermittelten abweichen kann. – Ein interessanter Befund der Masterarbeiten ist hierbei, dass die Temperatursignale eine höhere Sensitivität gegenüber hydraulischen Parametern aufweisen, als gegenüber den thermischen Parametern selbst. Die Drainage-Funktion der Klüfte (zum 'Reservoirrand' hin) wirkt sich stärker auf die effektive Reservoirgröße aus (sozusagen als 'geometrischer' Effekt der Hydraulik), als die Matrixdiffusion (als Transportprozess) auf die Geschwindigkeit der 'Kältefront'. Da diese Drainage-Wirkung primär vom hydraulischen Transmissivitäts-verhältnis zwischen der jeweiligen Kluft und dem anliegenden Matrixblock abhängt, bleiben die Temperatursignale im geförderten Fluid (und damit der 'thermische Durchbruch' bzw. die thermische Lebensdauer des Reservoirs) unbeeinflusst durch das Kluftvorkommen, solange ein Apertur-Schwellenwert (Drainage vernachlässigbar) nicht überschritten wird; wird dieser allerdings überschritten, wirken sich die Klüfte verhältnismäßig stark aus, da ihre Transmissivität nach dem sogenannten *cubic law* mit der Apertur ansteigt. Interessantester Befund der Studie ist, dass in den betrachteten (ggf. skalierbaren) hydrogeologischen Szenarien die Hydrauliksensitivität der Temperatursignale insgesamt höher ist, als die der Drucksignale selbst – was die transportierte Wärme (im Zusammenhang mit anderen Georeservoirnutzungen, als der Geothermie selbst) zu einem besonders attraktiven, konservativen Fluidtracer macht.

Benchmarkmodelle samt ihrer hydrogeologischen Kluft-Matrix-Szenarioparametrisierungen wurden im Rahmen des BMWi-geförderten Forschungsvorhabens "TRENDS" entwickelt ("Tracergestützte Bewertung der Nachhaltigkeit bzw. Lebensdauer einer expansiven Nutzung geothermischer Ressourcen im süddeutschen Malm-Molassebecken", FKZ: 0325515, Univ. Göttingen, 2014 – 2019).

Introduction (motivation for this study, and its technical aims)

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+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 processes 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 (fig. 1) comprising five 'slant' fractures (oblique relative to the inter-well axis) have demonstrated the uncoupling (Ghergut et al. 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 were intersected by the injection and production well-screens, respectively, and the further three, non-intersected fractures were located '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 signals, by switching these fractures 'on' / 'off' individually (Ghergut et al. 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).

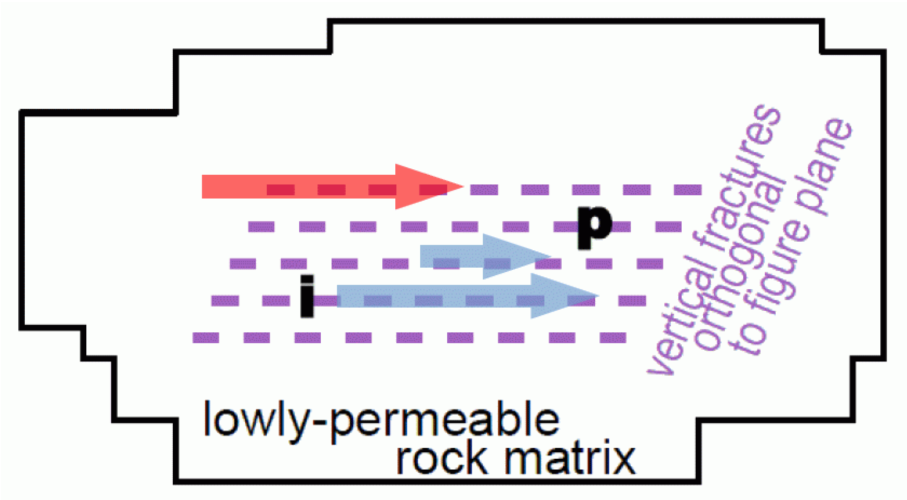

Fig. 1: The ‘pastiche’ model of a reservoir containing a finite number of finite-extension major vertical fractures, operated by a ‘slant’ well doublet.

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: their hydraulic aperture may differ from their 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 (Diersch et al., 2014), fluid flow and heat transport are simulated for the entire benchmark model 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 reservoir location accessible to temperature measurement. However a series of 3-D temperature field visualizations inside the reservoir body is also presented (fig. 2), 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 et al. 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), confirms the generic expectation (Ghergut et al. 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 promising ‘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 or hydrocarbon reservoir investigations and monitoring.

Model parametrization, and hydrogeological scenarios

For the rock matrix of fig. 1 we assume anisotropic permeability (typical hydraulic conductivities $K_{xx} = K_{yy} = 10^{-7}$ m/s, $K_{zz} = 5{\cdot}10^{-8}$ m/s, also depending on temperature). Hydraulic-effective aperture (w_h) and transport-effective width (w_t) values for the fractures were varied between 0.2 mm and 2 cm. Each combination of K_{ij} and $w_{h,t}$ values (including their 'switch-off' case, $w_{h,t} \rightarrow 0$) represents a 'hydrogeological scenario'.

Other relevant parameters of the rock matrix were kept unchanged (transport-effective porosity: 5 %, heat capacity: $2.5{\cdot}10^6$ J/m³/°, heat conductivity: 3 J/m/s/°, transport dispersivity: in the order of few metres). The initial, undisturbed reservoir fluid temperature is assumed 150 °C in well-screen depth; the re-injected fluid is assumed to have been cooled to 60 °C. Free outflow and undisturbed temperature profiles are assumed at the outer reservoir boundaries. The well doublet is operated at 2,000 m³ fluid turnover per day.

The 3-D model domain (sized 2 km longitudinally, 500 m laterally, 200 m transversely), halved by virtue of approximate symmetry relative to a fracture-orthogonal plane containing both well-screens, is discretized by ~30,000 quadrilateral prism elements (~60,000 nodes) whose size varies in space but is not adaptive in time. Time step sizing is adaptive (AB/TR), with shortest time step 10^{-8} day and largest 6 days.

Qualitative findings

The various effects of individual fractures on fluid flow and heat transport patterns can be recognized and compared to each other at least qualitatively in the snapshot sequence of figure 2. Each snapshot set shows 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:

- cut along the injection-outwards fracture, i. e., in 60 m lateral distance from the model domain mid-plane, on the injection side (first snapshot set, labeled "–60"),
- cut along the fracture intersected by the injection well, i. e., in 30 m lateral distance from the model domain mid-plane, on the injection side (second snapshot set, labeled "–30"),
- cut along the "inside-reservoir" fracture, i. e., at the model domain mid-plane (third snapshot set, labeled "-0"),
- cut along the fracture intersected by the production well, i. e., in 30 m lateral distance from the model domain mid-plane, on the production side (fourth snapshot set, labeled "+30"),
- cut along the outward-production fracture, i. e., in 60 m lateral distance from the model domain mid-plane, on the production side (last snapshot set, labeled "+60").

In particular, we focus on the effects of 'inactivating' one of these three fractures, respectively, while keeping w_t and w_h for the other four fractures unchanged:

- turning off the outward-production fracture (first snapshot of each set),
- turning off the "inside-reservoir" fracture (second snapshot of each set),
- turning off the injection-outwards fracture (third snapshot of each set).

The reference case (shown at the bottom of each snapshot set) is the one with all fractures present, with w_t = 2 cm, w_h = 6 mm.

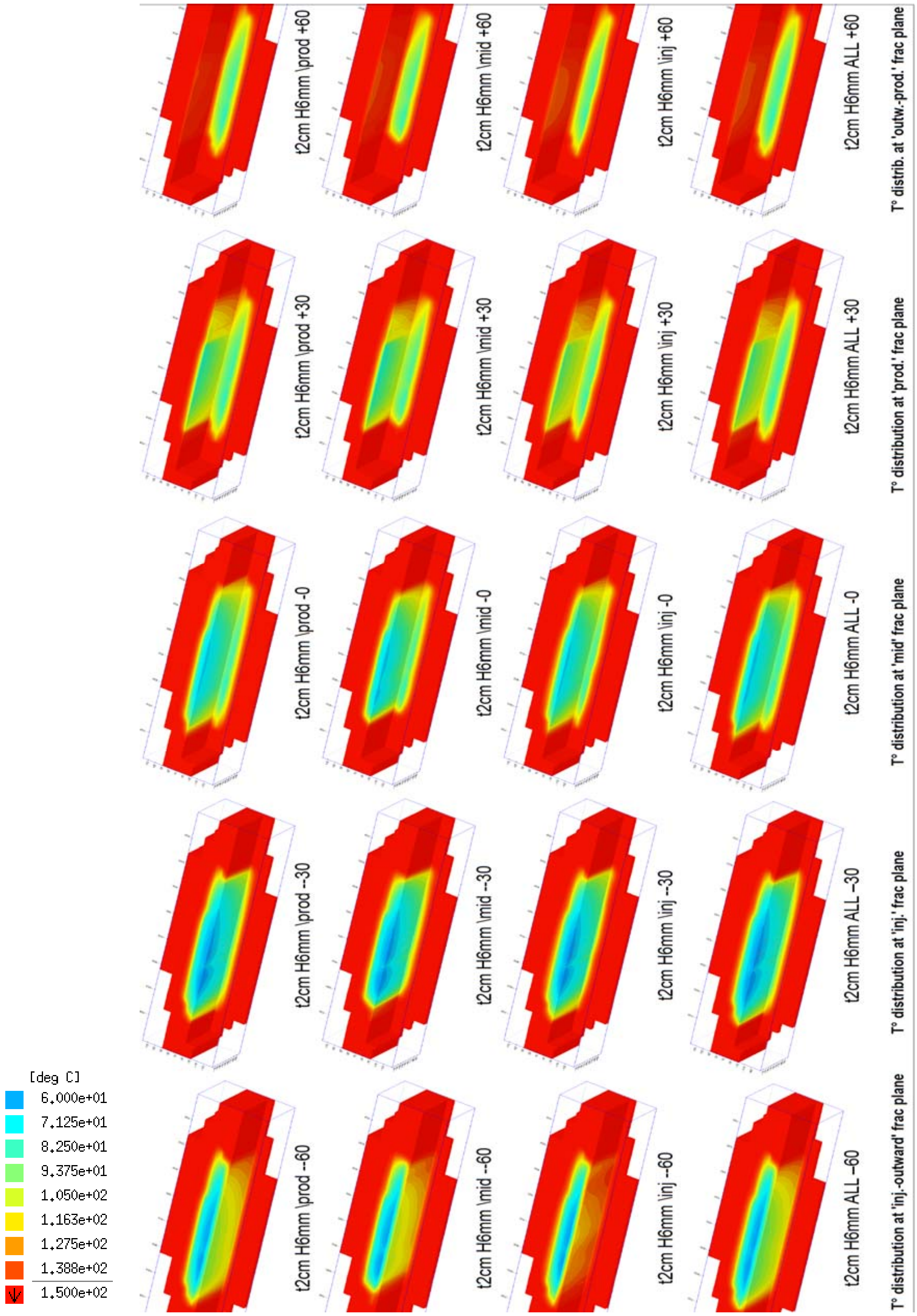

Fig. 2: Late temperature field shown at each major frac plane for each 'missing-frac' scenario (color scale from deep-blue, 60 °C, to far-field red, 150 °C), model domain remote edges (where temperatures stay unchanged) being omitted for the first and last snapshot set. Grey shading indicates a view-cutting plane orthogonal to all fracs.

Quantitative findings

When all fractures are assumed as 'very rough', with hydraulic aperture ten times lower than their transport-effective aperture (w_h = 2 mm and w_t = 2 cm), thermal breakthrough is found to be almost insensitive to the 'switching off' of individual fractures (figure 3, upper section).

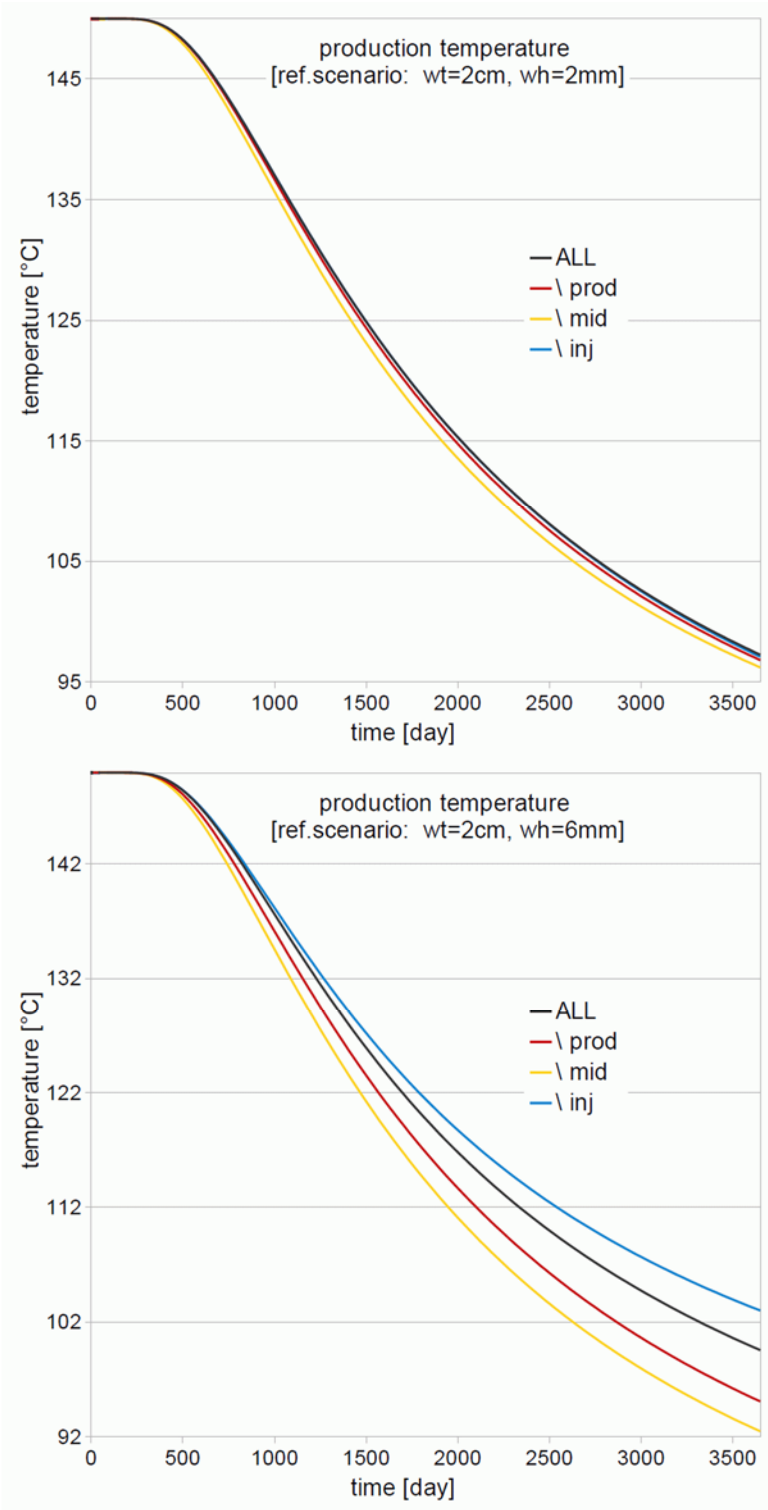

Fig. 3: Thermal breakthrough simulations for each 'missing-fracture' scenario.

It is accelerated by up to only 3 % additional temperature drop (–1.5 °C) 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 reported in 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 presented in 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 w. r. to the presence or absence of individual fractures (figure 3, lower section), but the effect of 'switching off' individual fractures is quite different, compared to the case of smooth fractures with w_t =2 cm as reported in Khaleefah (2017):

- 'Switching off' the inner fracture will have the most pronounced accelerating effect on thermal breakthrough, augmenting the ten-year temperature drop by ~8 °C;
- 'Switching off' the injection-outward fracture will have a slowing effect on thermal breakthrough, reducing the ten-year temperature drop by ~4 °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 ~5 °C, which is qualitatively similar to the case reported in Khaleefah (2017), and for the same plausible reason, but with a larger absolute amount of temperature drop.

Furthermore, the ten-year temperature drop (below 103 °C for all scenarios) is seen to be larger than in all scenarios with the same transport-effective aperture (2 cm) but a larger hydraulic aperture (2 cm instead of 6 mm) that were presented in Khaleefah (2017), for which it stayed above 103 °C in all 'missing-fracture' scenarios.

Concluding remarks

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 Khaleefah (2017) for somewhat different scenarios involving smooth fractures in a similar geological setting, enable to re-formulate our results in a more general manner and derive some recommendations for the georeservoir monitoring practice, as well as suggestions for future modeling studies:

1.) A threshold value appears (not much surprisingly) 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 et al. (2013), but the threshold value might be larger for real-world georeservoir settings; therefore we recommend to re-scale the results of future simulations in terms of dimensionless variables and parameters (as was attempted by Ghergut et al. 2013 and 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 ($T_o°$ – $T°$(*time*)) by $T_o°$ (where $T_o°$ denotes the initially undisturbed or far-field temperature at reservoir bottom);

2.) 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 et al. 2013, but a general analysis is still lacking);

3.) Fracture roughness in real-world georeservoirs implies that the values of hydraulic aperture, heat transport-effective aperture, and solute transport-effective aperture may differ from each other (cf. Tsang 1992), 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 physically different for each; it is beyond doubt that all three aperture values will somehow correlate to each other, but this needs to be established from modeling studies addressing fracture roughness in detail;

4.) Under certain circumstances, temperature signals tend to respond more sensitively to hydraulic features, than to their associated thermal parameter values, thus recommending heat as an adequate ‘tracer’ for the hydraulic characterization of fractured-porous systems (not only in the geothermal realm, but also for groundwater studies or hydrocarbon reservoir investigations and monitoring);

5.) Outflow temperature signals need to be recorded for a rather long time before the effects of fractures become detectable unambiguously (in our scenarios, for at least ~2 years; cf. also Ghergut et al. 2016, 2018); 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 or other georeservoir studies (cf. Ghergut et al. 2014), whose duration may be need to be limited by several additional considerations.

References

Mohandas Surekha S.: 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. M. Sc. Thesis, University of Göttingen (2017)

Khaleefah N. A. S.: Heat as an artificial tracer in groundwater studies – Qualitative evaluation of the detectability of major vertical fractures by fluid temperature monitoring at the production well of a geothermal doublet, assuming smooth fractures (identity between hydraulic aperture and thermal width). M. Sc. Thesis, University of Göttingen (2017)

Tsang Y. W.: Usage of ‘Equivalent Apertures’ for Rock Fractures as Derived From Hydraulic and Tracer Tests. *Water Resour. Res.*, **28**(5): 1451-1455 (1992)

Ghergut J., Behrens H., Licha T., Sauter M.: Tracer-based prediction of thermal reservoir lifetime: scope, limitations, and what reactive tracers can tell. Stanford Univ., *SGP-TR*-**198**: 309-315 (2013)

Ghergut J., Behrens H., Sauter M., Schmidt S., Wagner B.: On the visibility of non-intersected ‘nearby’ fractures in inter-well tracer tests: scoping simulations. Stanford Univ., *SGP-TR*-**212**: 6 pp. (2017); cf. atq. *SGP-TR*-**191**: 303-312 (2011); *SGP-TR*-**187**: 57-63, 64-70 (2009); *SGP-TR*-**183**: 184-191 (2007)

Diersch H.-J. G., with various contributions by O. Kolditz and others: FEFLOW − Finite element modeling of flow, mass and heat transport in porous and fractured media. Springer, Berlin Heidelberg, XXXV, 996 pp. (2014)

Ghergut J., Behrens H., Sauter M.: Petrothermal and aquifer-based EGS in the N-German Sedimentary Basin, investigated by conservative tracers during single-well injection-flowback and production tests. *Geothermics*, **63**: 225-241 (2016)

Ghergut J., Behrens H., Bensabat J., Sauter M., Wagner B., Wiegand B.: Sorption, matrix diffusion, … need not make a major difference for frac characterization from short-term tracer signals. Stanford Univ., *SGP-TR*-**213**: 11 pp. (2018)

Ghergut J., Behrens H., Sauter M.: Short-term fluid, heat, and solute transport in deep georeservoirs likely to become EGS: some challenges to ICDP hydrogeologists who might like using artificial tracers. Stanford Univ., *SGP-TR*-**202**: 177-182 (2014)