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# A Cross-Simulator Comparison of Dual-Porosity Approaches for Predicting Temperature Decline

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## ABSTRACT

Many numerical reservoir simulators have been used in the geothermal industry, with their valid performance confirmed using publicly available benchmarks. These simulators will have nearly identical performance for single-porosity models and parameters are easily compared between different simulators. When implementing dual-porosity formulations, the choice between MINC, dual-porosity, and dual-permeability leads a divergence in the comparability of these parameters. Through history matching and analog studies, the modeling community has converged on a range of values for several parameters that improve forecasting with realistic predictions of thermal breakthrough. This paper compares three simulators and their available dual-porosity parameters to identify a conversion approach between the softwares. A field history example from Brady's Hot Springs is presented with the corresponding applicable parameters for several dual-porosity approaches.

## BACKGROUND

In most geothermal reservoir settings, a single-porosity numerical model will underpredict the temperature decline caused by reinjection. In a simple sense, the heat capacity of the hydraulic pathways in a geothermal reservoir is lower than a homogeneous porous media, which is attributed to fluid flow preferentially through fractures rather than matrix permeability. The distribution of fractures and the degree of matrix-fracture connection will determine onset of cooling (thermal breakthrough) and temperature decline for a production/injection configuration. Characterizing this aspect of the reservoir is an important role for numerical simulation and before the startup of production a simulation will heavily rely on analog systems and analog numerical models.

A common method for simulating such systems is to use dual-porosity grids or MINC grids, which account for the preferential flow through the fracture systems with limited thermal recharge from a low permeability matrix. The key parameters for these simulations are fracture spacing, fracture volume fraction, matrix permeability, and (in the case of a MINC simulation), the number of MINC shells.

Literature on analog simulations is limited, but for TOUGH2 simulations utilizing 2 or more MINC layers, a fracture spacings of 100-150 m and a 0.05 to 3% fracture volume are common (Wallis et al 2015). Such a fracture spacing was applied for a reservoir simulation of Ngatamariki (Clearwater et al 2012, Buscarlet et al 2015). A lower fracture spacing of 4.3 m was applied to an iTOUGH2 model of the Mutnosvsky geothermal field (Kiryukhin et al, 2012). A matrix permeability of 1-20 microdarcies is also common for TOUGH2 MINC simulations, one example being the usage of 10 microdarcy matrix permeability in the 2019 simulation of Wayang Windu reservoir (Pasikki et al 2019). The effect of increasing the number of MINC shells above two results in slower temperature decline and less overall decline, as demonstrated for the Ngatamariki simulation (Clearwater et al, 2012) and replicated in this paper. A calibrated model of the Leyte Geothermal Field utilized this approach, with a three-shell distribution (2%-10%-88%) and a fracture spacing of 150 meters (Omagbon et al, 2016).

Values of 100 m fracture spacing, 1% fracture volume fraction, and microdarcy-scale matrix permeability are a useful starting point for simulating a field with limited or no production history using a TOUGH2 MINC based simulator but are not necessarily applicable for other simulators and dual-porosity techniques. This paper aims to establish comparisons between MINC, dual-porosity, and dual-permeability approaches for three simulators: TOUGH2 using the PetraSim interface, CMG-STARS, and TETRAD-G (Pruess 1991, Battistelli et al 2017, Computer Modeling Group 2021, Vinsome and Shook 1993)

## TERMINOLOGY

A **Single-Porosity** model uses a single volume domain for each gridblock, having a single value for porosity and a single permeability tensor (x,y,z-directions). Four methods can be used to simulate separate fracture and matrix domains:

**MINC** (Multiple Interacting Continua, Pruess 1992) uses multiple nested shells representing fracture and matrix domains. In this case the fracture volume fraction refers to the volume of the outermost shells divided by the total gridblock volume. The fracture shell can have a unique porosity and permeability values and the matrix (inner) shells are assigned separate porosity and permeability values. MINC can be used in both TOUGH2 and CMG-STARS but is not an option for TETRAD. Matrix-matrix

connections are optional and are usually turned off for low matrix permeability simulations. The matrix-matrix interaction was set to zero for MINC simulations in this study.

**Dual-Porosity** duplicates each gridblock into two domains which have separate volumes, porosities, and permeabilities. In CMG and TETRAD the fracture and matrix volumes can be modified by either changing the bulk volume of each domain or by changing the net-to-gross ratio of each domain. This choice has important ramifications for converting from single to dual-porosity, as discussed later. Dual-porosity is not an option in TOUGH2 simulations.

**Dual-Permeability** is the same as Dual-Porosity but with matrix-matrix connections activated. If the matrix permeability is small, much less than 1 md, the difference between dual-porosity and dual-permeability is negligible for results, but dual-permeability is important if the matrix permeability is high. Dual-permeability can be used in CMG-STARS and TETRAD but is not an option in TOUGH2.

A **Discrete Fracture Network** (DFN) creates separate fractures that are connected to the main porous media simulation grid which can be single- or dual-porosity. These fractures will be given unique values for aperture and permeability. DFNs are an option in CMG-Stars, but not in TETRAD or TOUGH2.

In CMG-STARS the dual-porosity shape factor is adjustable; this study uses the Gilman and Kazemi shape factor (*GK), but the simulations were minimally sensitive to this choice. In TETRAD simulations, in place of a shape factor, a transmissibility multiplier of 6 was used for fracture-matrix connections, representing perpendicular sets of parallel fractures in three dimensions. In TOUGH2, a 3-D fracture orientation was used.

Throughout this study, an effort was made to use as many identical properties as possible, and to use defaults for properties that were not adjustable across simulations, such as some fluid properties.

**PROCESS MODEL COMPARISON – 2 SHELLS**

A single-layer model was used to compare the dual-porosity behavior of the three simulators. The model is 2000x2000x100 meters with 40x40 meter uniform gridblocks. An injector/producer pair was tested spaced at 707 meters, a production rate of 55.6 kg/s, and 75% reinjection at a temperature of 80 °C. The single-porosity simulation has a uniform porosity of 5% and uniform permeability of 50 md in the X, Y, and Z-directions. The compressibility of the pore space is set to 2x10^-6 1/kPa and the rock has a heat capacity of 1 kJ/kg-C, density of 2600 kg/m3, and thermal conductivity of 181.44 kJ/m-C-day. At initial conditions, the grid is set to a uniform temperature of 180 °C and pressure of 100 bar. The boundaries are closed and the 25 blocks in the upper left corner have a volume multiplier of 10^5 to simulate boundary recharge. Figure 2 shows a comparison of the single-porosity behavior of this model for the three simulators, showing excellent agreement for both pressure and temperature behavior over 30 years.

Two TOUGH2 MINC models were used as the basis for comparing dual-porosity behavior across simulators. The first TOUGH2 model uses two MINC shells, a fracture spacing of 100 meters, a fracture volume fraction of 1%, and a matrix permeability of 0.001 md. Matrix porosity was kept at 5% and fracture porosity was set at 90%. In addition to these changes, the volume multiplier on the corner was reduced to 5x10^4 to maintain the pressure behavior in the TOUGH2 simulation, although not in the CMG-STARS MINC model. This model was also tested with coarse gridding (100x100 meter blocks) which showed an overall similar behavior but slightly more temperature decline (23 °C decline over 30 years compared to 19 °C over 30 years in the finer gridded model).

To replicate this model in CMG-STARS MINC, two changes are necessary. First, fracture spacing must be reduced to 40 meters – a model with 100 m fracture spacing will over predict temperature decline compared to TOUGH2. Secondly, fracture volume fractions must be input both in the MINC block and also using the parameter *FRFRAC, assigning a fracture volume fraction of 1%. If *FRFRAC is not used, alternatively a fracture porosity of 0.9% will replicate the TOUGH2 model behavior. As noted above, the volume modifier on the recharge blocks is kept at 5x10^5 for the CMG-STARS MINC model. A comparison of MINC models using TOUGH2 and CMG is shown in Figure 3.

Dual-porosity can also be used in both CMG-STARS and TETRAD to replicate this behavior. To implement a 1% fracture volume fraction, *FRFRAC is set to 1% in CMG-STARS, whereas for TETRAD bulk volume multipliers ('BVMUL') are set at 1% on the fracture blocks and 99% on the matrix blocks. For the CMG-STARS model a fracture spacing of 45 m results in the best match, whereas 40 m has the best match for TETRAD. TETRAD has two additional dual-porosity parameters: the fracture width ('FRACWID') is set at 0.001 meters and the fraction of rock in the fractures ('FROCK') is set at 0. The results are minimally sensitive to fracture width but will change if 'FROCK' is set above 0. Because these volume modifiers do not change the inter-block cross-sectional area for darcy flow, the fracture domain permeability is unchanged from 50 md, and the matrix domain permeability is set to 0.001 md.

An alternative to volume modifiers is a net-to-gross modifier of 0.01 on the fracture domain and 0.99 on the matrix domain. Net-to-gross modifies the cross-sectional area of connecting blocks, so the permeability of the fracture domain should be increased to

5000 md to maintain the pressure match. Fracture porosity is set to 90% and the best match is achieved with 40 m fracture spacing for both CMG-STARS and TETRAD. A comparison of the MINC and Dual-Porosity models is shown in Figure 4.

**PROCESS MODEL COMPARISON – 4 SHELLS**

A second TOUGH2 process model was tested using four MINC shells set to volume fractions of 1%, 5%, 25%, and 69%. This model shows less temperature decline compared to the two-shell model.

The CMG-STARS implementation of a four-shell MINC model moderately replicates the TOUGH2 model using the same volume distribution with a reduced fracture spacing of 40 m, but shows less overall cooling. A higher fracture spacing would improve this match.

A dual-porosity approach in CMG-STARS can replicate the TOUGH MINC 4-shell model sing an increased fracture volume fraction of 7.5% (*FRFRAC), a fracture porosity of 12%, and a fracture spacing of 53 m. In TETRAD dual-porosity, a good match is accomplished using a fracture volume of 10%, fracture porosity of 90%, and fracture spacing of 45 m. Permeabilities are kept at 50 md for the fracture domain and 0.001 md for the matrix domain in both the CMG-STARS and TETRAD dual-porosity implementations. A comparison of the MINC-4 Shell model and dual-porosity is shown in Figure 5.

Additionally, dual-permeability can be used in both CMG-STARS and TETRAD to match the behavior of the 4-shell model. In these models, rather than using microdarcy-scale matrix permeability, a lower ratio between fracture and matrix permeabilities is used, representing a fairly strong interaction between matrix and fractures, akin to fractures of high permeability interacting with a damage zone of moderate permeability. Because moderate permeability is hosted in the matrix, dual-permeability is required rather than dual-porosity, with 100% matrix-matrix interactions used throughout this study.

The best match models for dual-permeability use a net-to-gross ratio of 10% in the fracture domain, 90% in the matrix domain, fracture spacing of 53 m, fracture permeability of 478 md and matrix permeability of 2.4 md (200:1 ratio). Fracture porosity is 9% and matrix porosity is 5%. In TETRAD, some rock mass is assigned to the fracture domain using 'FROCK' = 0.1. These models are shown in Figure 6 and show a good match to the long-term behavior but a faster onset of temperature decline in both the TETRAD and CMG-STARS models.

**BRADY'S HOT SPRINGS MODEL**

A simplified model of Ormat's Brady's Hot Springs (Brady's) geothermal project was used to identify a set of dual-porosity parameters than can replicate real-world temperature decline. Brady's experienced thermal breakthrough shortly after plant startup, associated with strong injection returns from a subset of injectors (Holt et al, 2004). After modifying the injection strategy, cooling was successfully reduced, and is currently at 1.4 °C/year. After seven years of production, some injection was diverted outside of the system. As observed in the field history, diverting injection outside the system caused an immediate pressure decline and a few degrees of temperature recovery. Some injection continues to be diverted to an outfield injector at the maximum rate allowable for maintaining reservoir pressure. Because of the clearly observable temperature decline and multiple changes in injection/production configuration at Brady's, this field provides useful test of applicable dual-porosity parameters.

Figure 7 shows an isometric view of the simplified Brady's model. In the single-porosity model, background rock is set to a permeability of 12.2 md. Production and injection wells delineate a central fault zone, which is set to a permeability of 10000. The boundaries are closed and recharge is supplied by multiplying the volume of blocks to the southeast by 50000 at an elevation of -400 m. This recharge is connected to moderate permeability of 152 md. A uniform 10% porosity is applied to this model. For this model, production and injection were simplified into four zones: northern shallow injection which is moderately connected to production, central shallow injection (MGI) which is strongly connected to production, shallow production, and a deep zone that was originally used for injection but converted to production after three years of production. Outfield injection is not modeled, as the lack of pressure support is evidence that it is outside the system.

**DUAL POROSITY MATCHING AT BRADY'S HOT SPRINGS**

Figure 8 shows the single-porosity models for both TOUGH2 and CMG-STARS, which have a good match to the pressure history but do not predict the observed early temperature decline and underpredict the long-term temperature stabilization. Introducing dual porosity allows for models that closely match the temperature decline history and allow for more accurate predictions of future behavior.

Using a two-shell MINC model with 1% fracture volume fraction in either TOUGH2 or CMG-STARS can be used to moderately match the temperature history at Brady's, a fracture spacing of 100 m (in TOUGH2) will over-predict the initial temperature decline and the temperature recovery when injection is diverted. As shown in Figure 9, a fracture spacing of 50 m in TOUGH2 or 22 m in CMG-STARS results in a much better temperature match than the 100 m starting point.

A four-shell MINC model (1%,5%,25%,69%) improves further on the temperature match, using fracture spacing of 50 m in TOUGH2 or 22 m in CMG-STARS (Figure 10).

Dual-porosity modeling in CMG-STARS can also replicate the temperature match, using the 7.5% fracture volume fraction (*FRFRAC) identified in the single-layer doublet model and 22 m fracture spacing. However, in this model the pressure match is lost. A better overall match is achieved by decreasing the fracture permeabilities by 60% and increasing the reliance on boundary recharge by increasing the volume modifier by 10x on the recharge blocks.

Dual porosity using the net-to-gross approach results in an unsatisfactory match at Brady's Hot Springs, with the best match achieved using 50 m fracture spacing, but ultimately shows a temperature recovery that was not observed in field data. Three dual-porosity models are shown in Figure 11.

A dual-permeability model in CMG-STARS was tested, and the best match results were achieved using a 20% fracture volume fraction (using net-to-gross), 80% matrix, and a 10:1 fracture to matrix permeability ratio. With these ratios, the fracture permeability must be increased by 2.15x to maintain the pressure match. Although this results in a good match to the initial temperature behavior, temperature recovery is over-predicted by this model.

Finally, a DFN model was tested against the Brady's temperature history. In this model, two discrete fractures are introduced to a single-porosity grid. These fractures were vertical and replace the high-permeability fault zone, with one discrete fracture in each vertical layer that was formerly fault-zone. Accordingly, the fault-zone permeability in the main grid was reduced to 100 md. The best-match model was achieved using fracture apertures of 5 meters and permeabilities of 10000 md. The result is similar to the dual-permeability model, with an excellent match to initial temperature decline but an over-prediction of temperature recovery. This can be slightly improved by reducing the density of the rock in the main grid by half, limiting the stored heat available to recharge to the modeled discrete fracture. In this improved model, the aperture was kept at 5 m, the DFN permeability was reduced to 6000 md, and the fault-zone permeability in the main grid was increased to 200 md. The dual-permeability and DFN models are shown in Figure 12.

Although the net-to-gross model dual-porosity model, the dual-permeability model, and the DFN models were not good matches to the temperature recovery at Brady's in this simple model, they could still be used in a more complete history matching process with a more complicated permeability structure.

## CONCLUSION

This comparison between dual-porosity behavior in the TOUGH2, CMG-STARS, and TETRAD reservoir simulators highlights the need to adjust several parameters to accurately compare temperature decline predictions. MINC models are comparable across simulators with a simple adjustment to the fracture spacing and MINC models can be compared to dual-porosity models by allowing for differences in fracture spacing and fracture volume fractions. Dual-permeability models with increased matrix permeabilities and DFN models were also able to replicate temperature breakthrough and decline.

When modeling the Brady's Hot Springs field, a four-shell MINC model with small fracture spacings or a dual-porosity model with 7.5% fracture volume and small fracture spacing resulted in the best match models. While Brady's is a useful analog for a fault-hosted system with initially unfavorable temperature decline, testing parameters in other geologic settings with well-documented temperature histories would provide better constraints for dual-porosity parameters when simulating a geothermal system before the onset of thermal breakthrough.

## ACKNOWLEDGEMENTS

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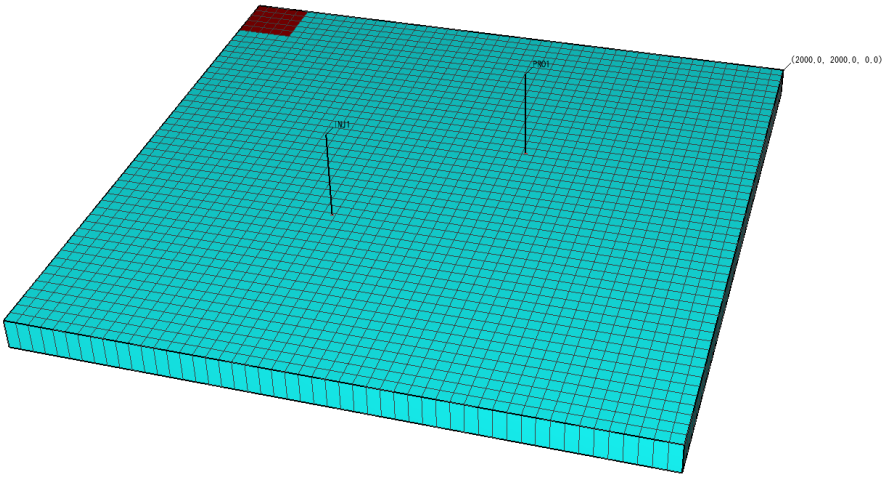


**Figure 1: One-Layer Simulation Grid with Recharge Blocks Highlighted**

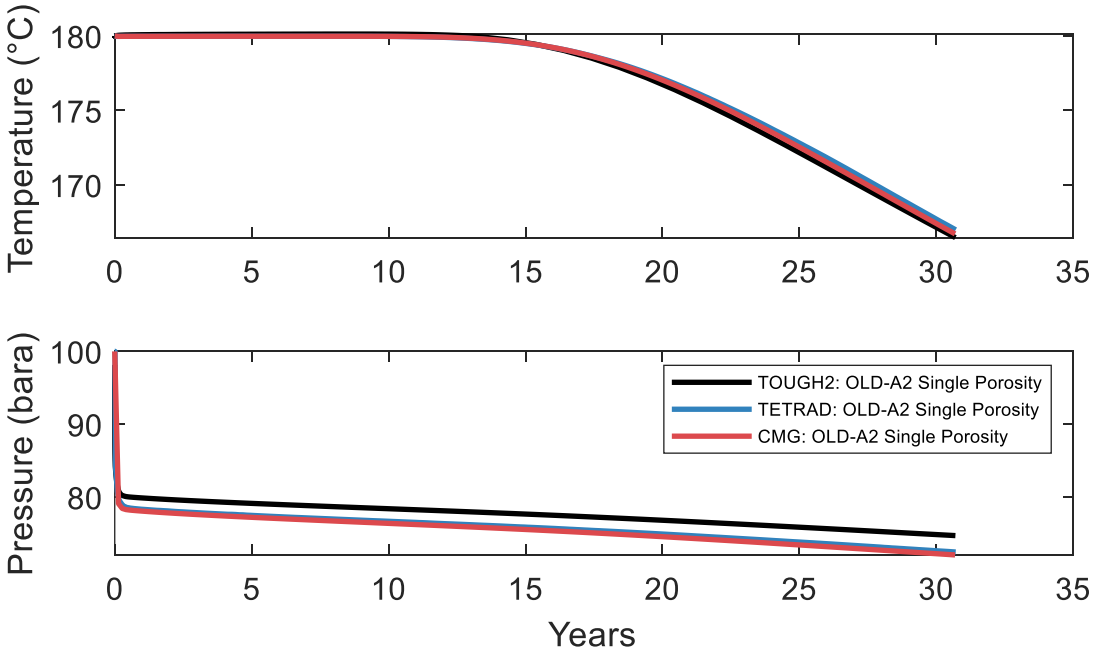


**Figure 2: Single Porosity Comparison**

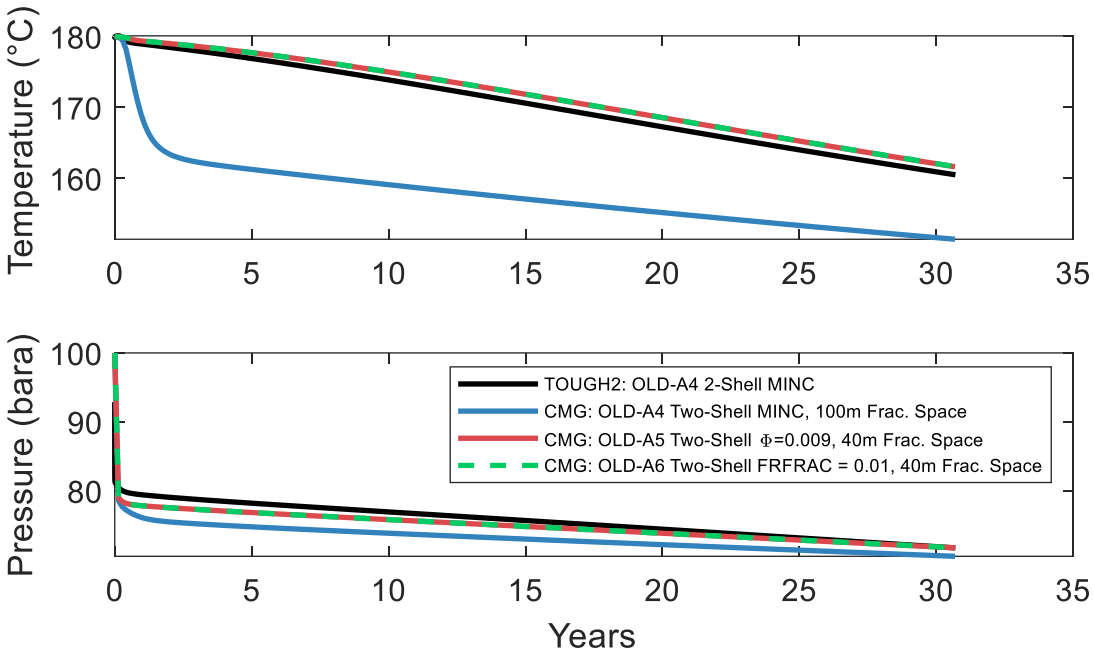


**Figure 3: Two-Shell MINC**

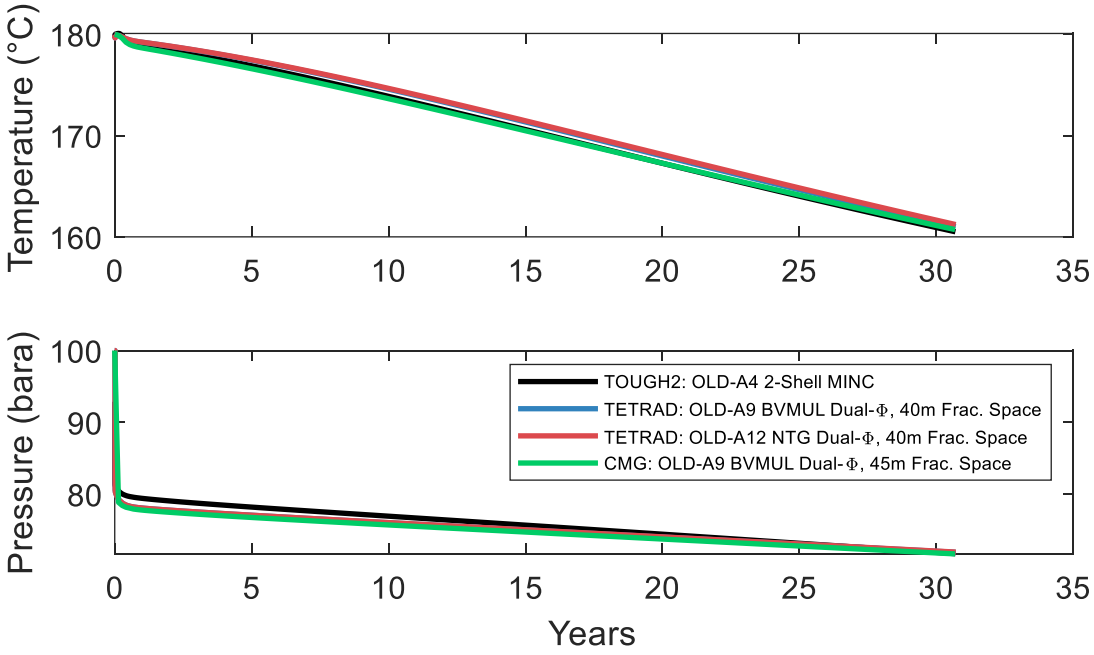


**Figure 4: Two-Shell MINC and Dual-Porosity**

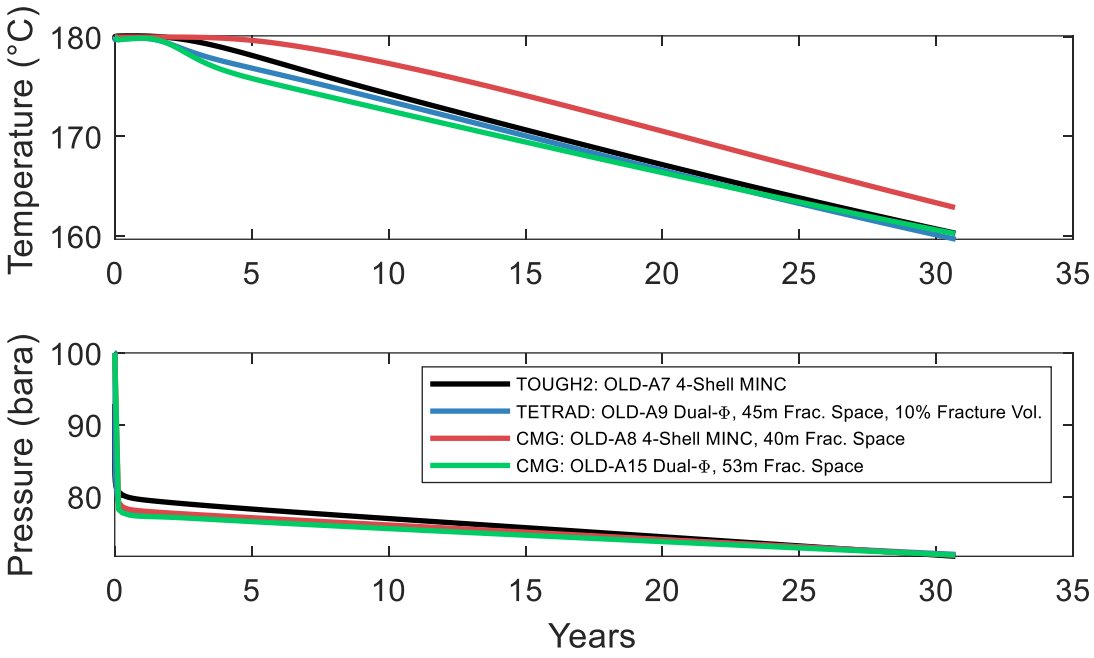


**Figure 5: MINC 4-Shell and Dual-Porosity Comparisons**

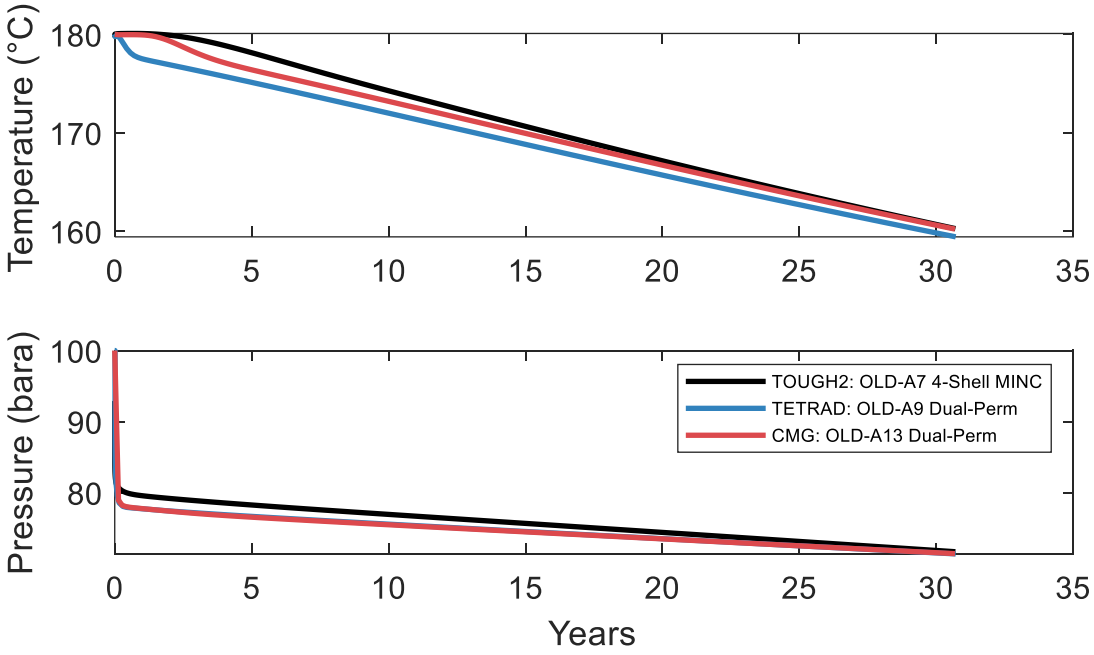


**Figure 6: MINC 4-Shell and Dual-Permeability Comparison**

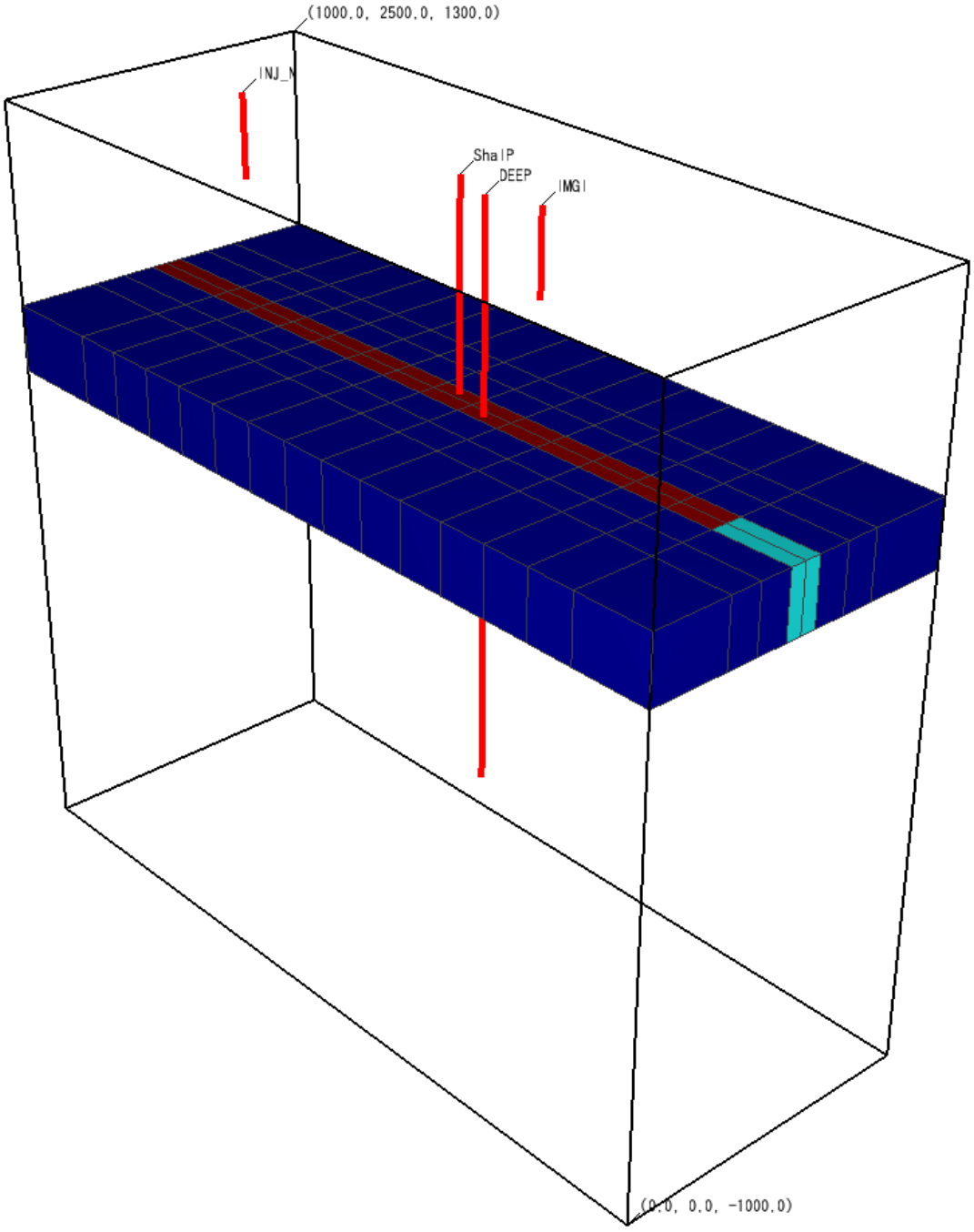


**Figure 7: Brady's Hot Spring Simulation Grid (Permeability Shown on Log Scale)**

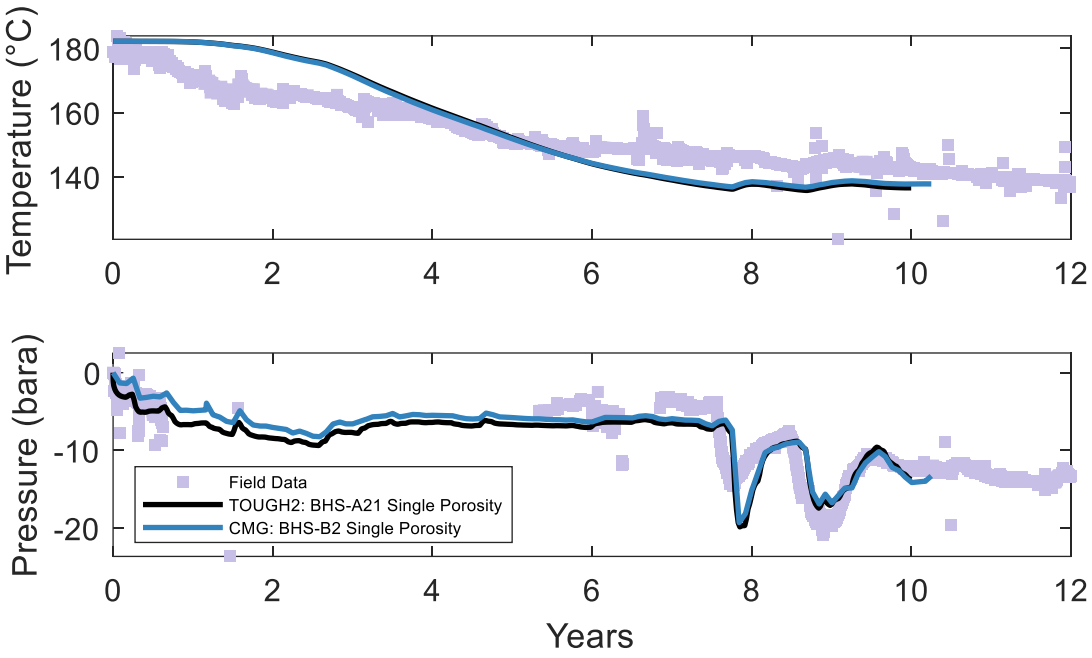


**Figure 8: Single-Porosity Brady's Hot Spring Models**

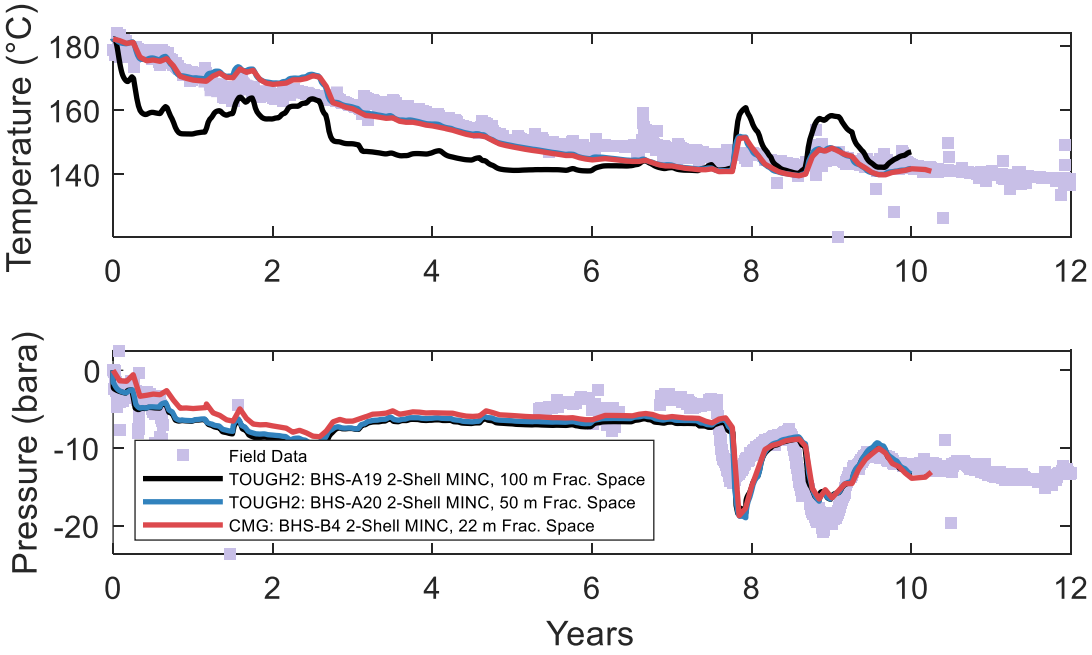


**Figure 9: MINC 2-Shell Brady's Hot Spring Models**

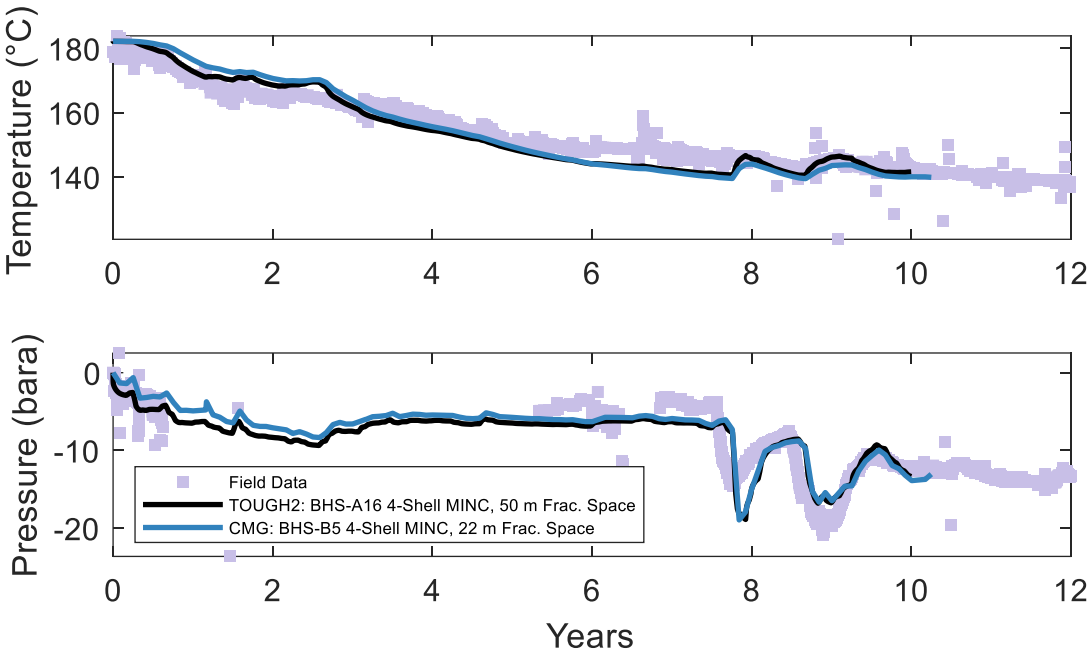


**Figure 10: MINC 4-Shell Brady's Hot Spring Models**

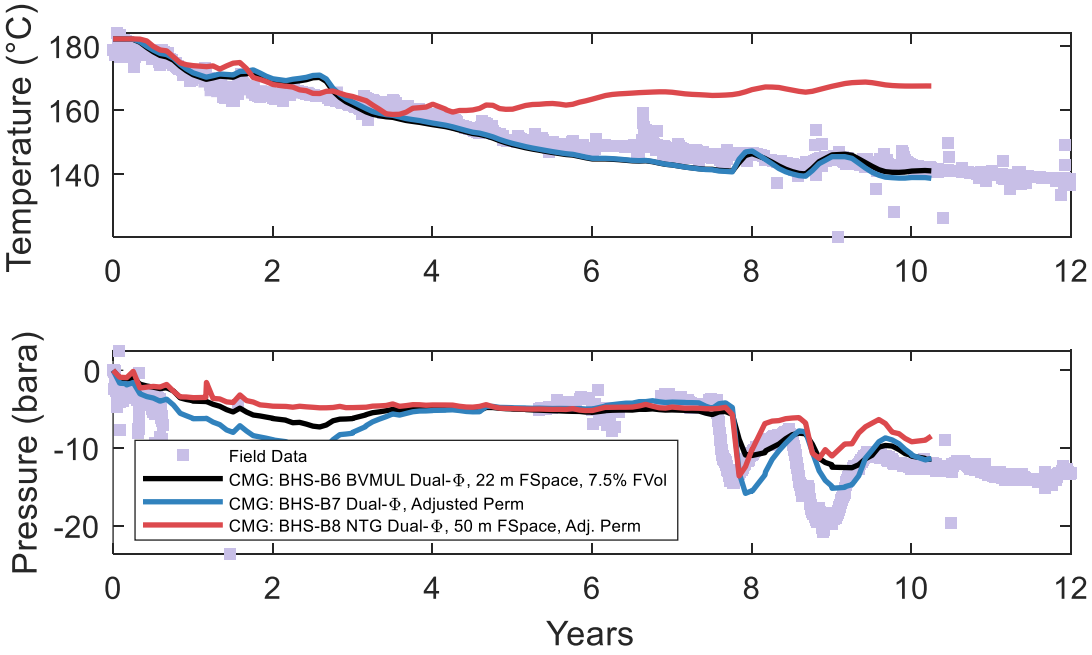


**Figure 11: Dual-Porosity Models of Brady's Hot Springs**

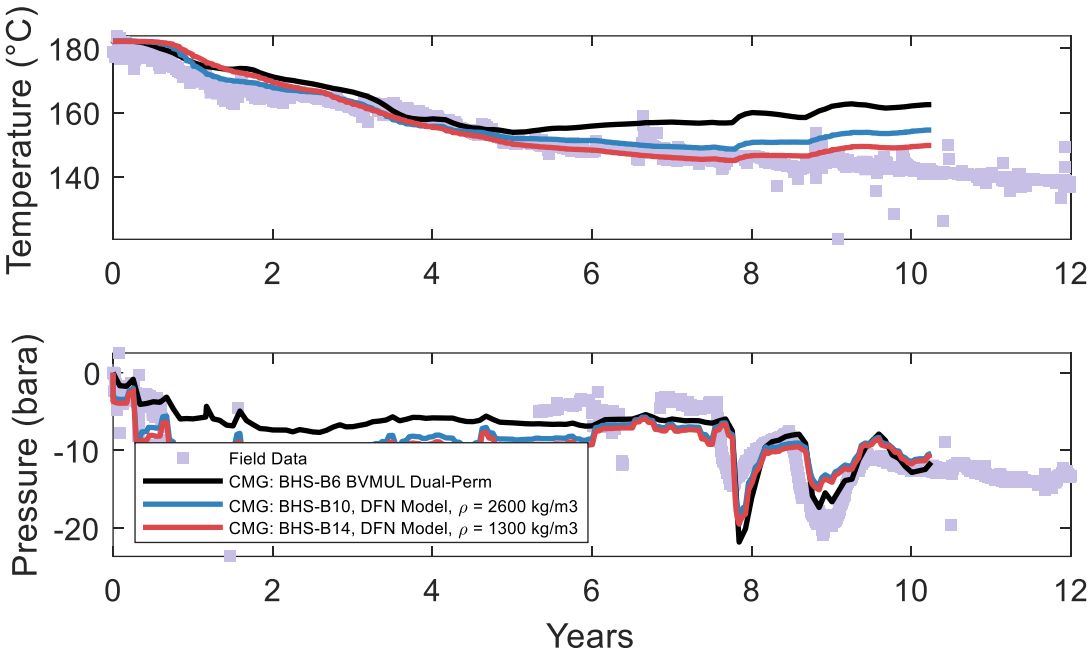


**Figure 12: Dual-Permeability and DFN Models of Brady's Hot Springs**