Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Getting into Numerical Modeling and Simulation to Help Mitigate Geological and Associated Financial Risks by Better Tackling Geothermal Resource Uncertainty Issues at the Earliest at Exploration or Prefeasibility Stage

Michel H. GARCIA[1], Jean-Baptiste MATHIEU[1], Florine GARCIA[1] + GEOTREF team (43 scientists and engineers)

1. KIDOVA, 155 avenue Roger Salengro, 92370 Chaville, France

michel.garcia@kidova.com

Keywords: Resource assessment, Geological risk, Numerical conceptual model, Phenomenological modeling, Well-layout optimization, Numerical simulation, GEOTREF, Guadeloupe, TOUGH2, HYDROTHERM, SKUA-GOCAD, Software platform.

ABSTRACT

As part of the GEOTREF research project dedicated to deep geothermal energy and fractured reservoirs, a cost-effective approach relying on innovative software tools is proposed to carry out prefeasibility studies prior drilling based on numerical conceptual models associated with phenomenological modeling and well-layout optimization.

The numerical conceptual models are intended to be 3D structural, geological and geothermal numerical models that integrate at best all understanding, interpretations and data about the geothermal reservoir. They are defined at a scale where relevant boundary conditions can be specified, including recharge, basal heat flux and heat sources.

Scenarios are used to formalize the uncertainty about numerical conceptual models, whether it is related to data values or interpretations, model assumptions or simplifications, or geothermal reservoir model components. Each scenario determines a numerical conceptual model as a possible representation of the actual geothermal reservoir.

Phenomenological modeling is carried out by numerically simulating the geothermal systems corresponding to various scenarios.

Results provide information to determine and understand the structural, geological and geothermal conditions that should be met to explain the presence of a geothermal resource. The geothermal potential of hot scenarios is then assessed by seeking optimal production and injection well locations that maximize the production of electrical power from the available geothermal energy.

The application of the approach is presented for the GEOTREF demonstration case study, which is located in Basse-Terre Island , the highest volcanic island of Guadeloupe.

1. INTRODUCTION

Geothermal energy is a green and partly renewable energy easily available in many regions in the world. It shows several advantages compared with other sources of renewable energy, which very often face storage issues to match production and needs. Geological risk remains the main issue, however, to interest investors in financing exploration well drilling that must provide complementary subsurface information to confirm the existence of a resource and decide about the way it can be exploited at best.

Existing approaches are used to address geothermal resource assessment at prefeasibility stage before drilling. They are based on available surface data (i.e. geological, outcrop, geophysical and geochemical data). Geophysical and geochemical evidences or indicators of the presence of a geothermal resource are sought, schematic conceptual models are provided to explain the understanding of the geothermal system (Cumming, 2009), and simple analytical methods are used to assess the geothermal resource potential (AGRCC, 2010; Grant, 2015; Williams, 2014). Monte Carlo sampling is also used to provide a probabilistic estimate of the geothermal reservoir potential, which can be expressed in terms of thermal energy, exergy (available work) or electric power generation. Based on simple (uniformly porous and permeable) geothermal reservoir models, empirical thermal recovery factors and poorly known probability distributions attached to model parameters, the results are approximate, if not biased, and not necessarily appropriate to decide with enough confidence whether exploration wells are to be drilled or not.

Instead, a new cost-effective approach is proposed based on numerical conceptual modeling to formalize model uncertainty, phenomenological modeling to perform sensitivity analysis, and well-layout optimization to account for wells. It relies on the principle that multiple and complex uncertainties are better addressed by understanding and properly evaluating the effects of uncertainty on the (geothermal) resource potential, rather than (falsely) trying to quantify its probability distribution for decision making. The four steps of the proposed numerical approach are illustrated in Figure 1. This approach is expected to help mitigate geological and associated financial risks by better tackling geothermal resource uncertainty issues at the earliest at exploration or prefeasibility stage.

This work is part of the GEOTREF[1] research project. After comparing the standard and proposed methods for geothermal resource assessment, this paper presents the main methodological aspects of the four steps of the approach, then its application to the

[1] GEOTREF: French acronym for “multidisciplinary platform for innovation and demonstration activities for the exploration and development of high geothermal energy in fractured reservoirs”.

GEOTREF demonstration case study, which takes place in Basse-Terre Island, the highest volcanic island of Guadeloupe. Conclusions are finally drawn about the proposed numerical approach and its implementation to make it cost-effective.

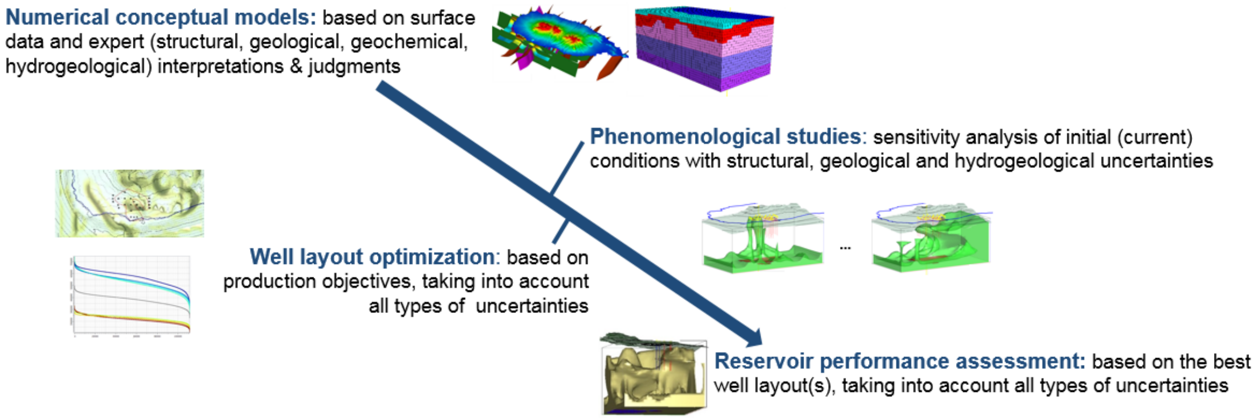

Figure 1: Proposed numerical approach.

2. GEOTHERMAL RESOURCE ASSESSMENT BEFORE DRILLING

2.1 Volume method

In prefeasibility studies prior drilling, the assessment of geothermal resource potential generally involves handmade conceptual model sketches and the use of an analytical volume or equivalent method (Grant, 2015, Williams, 2014, AGRRC, 2010) associated with Monte Carlo sampling to provide probabilistic assessment from which mean, median, confidence interval or other statistics can be estimated. Based on simple (uniformly porous and permeable) geothermal reservoir models, empirical thermal recovery factors and poorly known probability distributions attached to model parameters, the results are approximate, if not biased, and not necessarily appropriate to decide with enough confidence whether exploration wells are to be drilled or not.

Using the analytical volume method, the geothermal reservoir or resource potential is assessed in terms of energy. The following energies can be calculated (Williams, 2014).

- Thermal energy at reservoir conditions: $E_t(R) = \rho CV(T_R - T_0)$.
- Thermal energy recovered at well-head conditions: $E_t(WH) = R_g E_t(R)$
- Exergy (available work): $E_w = m_{WH}\big(H_{WH} - H_0 - T_0(s_{WH} - s_0)\big)$
- Electric energy: $W_e = \eta_u E_w$

Where:

- C: specific heat.
- H_0, s_0: enthalpy and entropy at T_0.
- H_{WH}, s_{WH}: enthalpy and entropy at well-head conditions.
- m_{WH}: extractable mass at well-head conditions.
- η_u: utilization efficiency.
- R: reservoir conditions.
- R_g: recovery factor function of reservoir properties.
- T_0: reference temperature.
- T_R: reservoir temperature.
- V: reservoir volume.
- WH: well-head conditions.
- ρ: bulk density.

Applied to simple box-shaped reservoir models, assuming homogeneous (averaged) reservoir properties and temperature, these resource assessment methods appear as facing important limitations.

- They ignore structural, geological and petrophysical complexities.
- They ignore recharge and other flow or thermal boundary conditions.
- They ignore the reservoir pressure, which is of paramount importance to convert thermal energy into electric energy.
- They ignore the wells in terms of number, location and reinjected fluid.
- They finally do not provide any information that can help better understand and validate the conceptual models and the assumptions made.

Using Monte Carlo (MC) simulation to derive resource assessment uncertainty from reservoir model uncertainties, can falsely give the impression that the estimated uncertainty reliably accounts for all types of model uncertainties: uncertainty on model parameters and uncertainty on the assumptions and simplifications made. This is all but correct. Instead, great care must be taken with Monte Carlo simulation results for the following reasons.

- The reservoir model assumptions and simplifications are likely to lead to estimation biases, which means potentially erroneous results.
- MC simulation is very sensitive to the distribution models attached to the uncertain reservoir model variables. This includes both the type of distribution models (e.g. uniform, Gaussian, triangular…) and the distribution model parameter values.

- MC simulation must take into account correlation or relationships between variables. Ignoring them may lead to highly overestimated resource assessment uncertainty.
- It follows that confidence interval and other statistics about resource assessment inferred from MC simulation results are all but reliable statistics. Cautions must be taken before to use them for decision making.

Nevertheless, most prefeasibility studies continue to provide this type of resource assessment, which remains a reference in the geothermal field. They are justified as relying on recovery factors that result from geothermal industry feedbacks.

Charroy et al. (2020) present the application of this type of approach to the same demonstration case study than the one presented here in §4 to illustrate the proposed numerical approach.

2.1 Proposed method

In reality, geothermal systems are geologically and dynamically complex systems that are not accommodated by simple reservoir models. Examples are given in Figure 2, which show two reservoir models that cannot easily be summarized to equivalent homogeneous bloc-shaped reservoir models associated with average reservoir temperatures.

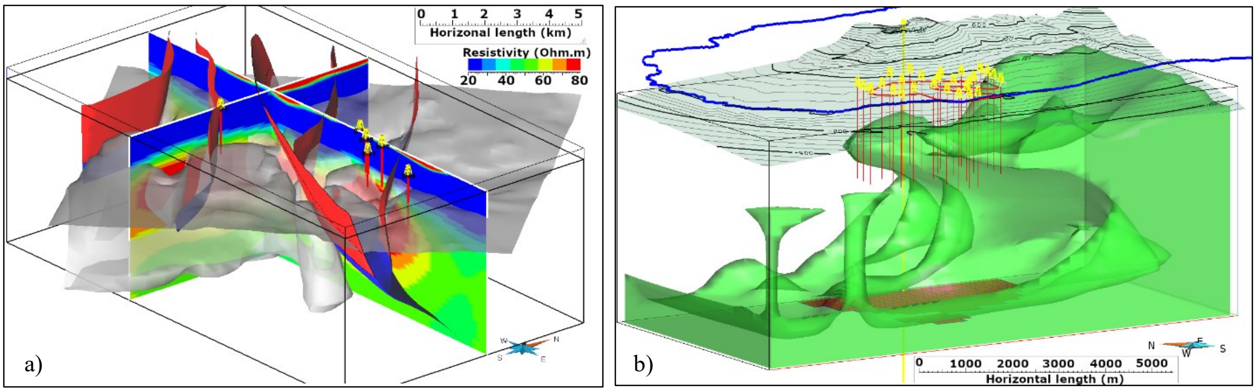

Figure 2: Examples of actual reservoir models showing complex geothermal systems, a) two-phase geothermal system (Andean Altiplano) showing compartments and convective cells (iso-surface of T = 240°C), b) single (liquid) phase geothermal system (Caribbean island) showing complex hot fluid flow paths (iso-surface of T = 180°C).

In the proposed numerical approach that is detailed in the following sections, producer and injector wells are taken into account to assess the geothermal reservoir potential. The latter can be expressed in different ways to be used as objective function to optimize well layouts, or to assess geothermal reservoir performances based on optimal well locations. The reservoir potential assessment functions are presented in (Lu et al., 2018). They all consist of assessing the remaining potential of the geothermal resource after it has been produced during a targeted period of time (e.g., 30 years producing 40 MWe). These functions can be summarized as follows, considering a well layout WL that defines the locations and perforation intervals of all producer and injector wells.

- Available thermal exergy: $E_\gamma = \sum_{\propto \in WL} Q_\alpha \big(h_\alpha - h_0 - T_0(s_\alpha - s_0)\big)$.
- Leftover energy rate: $L_\gamma = \sum_{\propto \in WL} h_\alpha Q_\alpha$.
- Electric power output for a single flash power plant: $W_{st} = \eta_t \times \eta_g \times \dot{m}_s \times \left(h_{t_{in}} - h_{t_{out}}\right)$.
- Electric power output for a binary power plant: $W_t = \frac{(0.18 \times T_{ev\_in} - 10) \times (h_{ev\_in} - h_{ev\_out}) \times \dot{m}_f}{218}$.

Where:

- h_0, s_0: enthalpy and entropy at T_0.
- h_α, s_α: specific enthalpy and specific entropy of the fluid produced from well α.
- $h_{t\_in} - h_{t\_out}$: difference of enthalpy, between the inlet and outlet of the turbine, in kJ/kg.
- h_{ev_in}, h_{ev_out}: enthalpies of the geothermal fluid at evaporator/exchanger inlet & outlet, respectively.
- $\dot{m}_f$: total primary geothermal fluid mass rate in kg/s, produced by the wells.
- $\dot{m}_s$: total mass flow rate of steam in kg/s at turbine inlet conditions.
- Q_α: fluid mass rate of production well α.
- T_0: reject or turbine outlet temperature.
- T_{ev_in}: temperature of the geothermal fluid at the evaporator/exchanger inlet.
- W_{st}: steam turbine power output in kilowatt equivalent (kWe).
- W_t: electric power generated by the turbine in kWe.
- η_g: generator efficiency.
- η_t: turbine efficiency.

Control of the fluid mass rates Q_α by the bottom-hole pressure is required to ensure minimum well-head pressures that are required by the power plant and surface facilities. The minimum bottom-hole pressures are calculated by using previously simulated pressure and enthalpy loss tables along the wells. The fluid mass rates Q_α are then calculated as:

$$Q_\alpha = \frac{1}{\mu_l} \rho_l PI_\alpha \left(P_{\frac{gb}{\alpha}} - P_{wb/min/\alpha}\right)$$

where,

- $PI_\alpha = \frac{2\pi k_{h(\alpha)}}{ln(r_{e(\alpha)}/r_w)-1/2}$: productivity index of well α.
- $k_{h(\alpha)}$: horizontal permeability of the grid-block where well α is opened.
- $P_{gb/\alpha}$, $P_{wb/min/\alpha}$: simulated gridblock pressure and minimum (required) bottom-hole pressure, respectively.
- r_w is the well radius, and $r_{e(\alpha)}$ is the equivalent radius of the grid-block where well α is opened.
- ρ_l, μ_l: liquid density and dynamic viscosity at $P_{gb/\alpha}$ and $T_{gb/\alpha}$.

Results obtained using the leftover energy rate and the electric power output for a single flash power plant are presented in §4 on the application of the proposed approach to the GEOTREF demonstration case study.

3. METHODOLOGICAL ASPECTS

The main methodological aspects that are required to address the four steps of the proposed numerical approach are detailed in the following sections. They all target the same objectives of making the proposed approach relevant by helping produce useful results for decision making and having it time and cost-effective to be successfully implemented in prefeasibility studies.

3.1 Numerical conceptual models

Numerical conceptual models refer to the numerical translation of the usual schematic handmade conceptual models. Numerical modeling is considered at early prefeasibility stage as an efficient way:

- to understand the geothermal system,
- to provide answers to questions about the relevance and consequences of possible interpretations and assumptions that can be made by geologists, geophysicists, geochemists, hydrogeologists or reservoir engineers using surface data,
- to quantify their effects in terms of resource potential.

Building numerical conceptual models at prefeasibility stage is all but the usual practice. Recommendations can be found in the literature to do it after drilling once well data are available (Mortensen and Axelsson, 2013) but not before drilling.

Numerical conceptual models make sense and are possible before drilling, however, providing the reservoir model uncertainties are formalized and parametrized in a relevant way to carry out phenomenological studies that can provide answers to questions and quantitative results.

The reservoir model uncertainties are addressed in the following way.

1. Key elements of the numerical conceptual model are identified first, in collaboration with all experts (geologists, geophysicists…) involved in study, based on preliminary interpretations and understanding of the geothermal resource. Typical conceptual model elements are the following.
    - Lithology in terms of flow units (e.g., surface aquifer, clay-cap or cap-rock, one or several reservoir units, fragile-ductile transition zone, ductile zone…).
    - Large-scale (structural) discontinuities under the form of discontinuity sets according to their orientation, nature (faults, fracture or deformation corridors…), or other distinguishing aspects.
    - Small-scale fractures under the form of fracture-sets according to their orientation, nature or other aspects.
    - Petrophysical properties of each flow unit.
    - Petrophysical properties of each set of large-scale discontinuities.
    - Geometric and flow properties of small-scale discontinuities.
    - Recharge.
    - Heat sources.
2. For each conceptual model element, scenarios are defined as corresponding to different interpretations, assumptions, or understanding of the complexity of the element. Each scenario is supposed to capture possible features of the geothermal system. Examples of scenarios are the following.
    - Different sets of surfaces that correspond to different interpretations of large-scale discontinuities.
    - Different complexities of the lithological model, whether spatial variations of facies or rock types are taken into account or not within the flow units.
    - Different complexities of the petrophysical property model, assuming uniform properties or spatial trends.
    - Different complexities of the recharge model, depending on the way it is spatially distributed or defined in the numerical reservoir model.
    - Different assumptions about the heat sources that are present at some locations, or not.
3. Associated with each scenario, the uncertain reservoir model variables are defined. Whether a reservoir model variable is constant or spatially varying at the reservoir model scale, the uncertainty is parametrized differently, but with the same objective of being able to derive optimistic, pessimistic, and intermediate solutions.
    - For constant variables: ranges corresponding to minimum and maximum values are provided.
    - For spatially varying variables: stochastic realizations, corresponding to grid properties stochastically simulated using a geostatistical or other relevant method, are properly sorted based on local or spatial statistics that ensure gradual variations of their flow responses from one realization to the next. See for instance (Gervais and Ravalec, 2018) for information about this type of parametrization.

The reservoir elements and the associated scenarios being defined, the numerical conceptual models are built as 3D structural, geological and geothermal numerical models that integrate at best all understanding, interpretations and data about the geothermal reservoir.

1. They are extended enough to include relevant (well defined) flow and heat transfer boundary conditions (recharge, basal heat flux, heat sources).
2. A very fine geological grid is used to model the geological units and all petrophysical properties.
3. New and relevant (multivariate statistical and geostatistical) methods are used to model the geological units and the spatially varying (i.e., nonstationary) properties.

The application of this step to the GEOTREF demonstration case study is illustrated in §4.3.

3.2 Phenomenological studies

Phenomenological modeling is carried out by numerically simulating the geothermal systems (i.e. pressure, temperature and enthalpy fields) corresponding to various scenarios in order to determine and understand the structural, geological and geothermal conditions that should be met to explain the presence of a geothermal resource. This requires an efficient numerical reservoir simulation strategy, which can be summarized as follows.

1. The simulation domain is extended enough according to the numerical conceptual models to reach well defined boundary conditions.
2. Two reservoir simulation grids covering the extended domain are created to speed up the simulation run times. One is very coarse, the other one fine enough to properly capture all relevant and consequential reservoir heterogeneities.
3. Appropriate upscaling methods are used to calculate units and reservoir gridblock properties from the very fine geological grid containing the numerical conceptual models to the two reservoir simulation grids. Especially, the upscaling of lithological units is performed in such a way to preserve flow barriers (clay-cap or cap rock, non-conductive discontinuities) and preferential flow paths (conductive discontinuities, schistosity planes…). This task is automated to be automatically repeated with each numerical conceptual model to be simulated.
4. The very coarse reservoir simulation grid is used to simulate rapidly but roughly the current (initial) geothermal system (up to hundreds of thousands of simulated years from a cold state). This simulation step allows one to identify scenarios that are hot enough to be further studied, and to discard the others. The simulation run time is expected to be less than 1 hour to reach stabilization.
5. The simulation of hot scenarios is continued using the finer reservoir simulation grid, which better capture the reservoir heterogeneities, to fine tune the simulated temperature, pressure and enthalpy fields, using those simulated with the coarser grid as initial conditions. The simulation run time is expected not to exceed one or a few hours to stabilize again.
6. Given a structural and geological scenario, the simulations based on basal heat fluxes are carried out first, then used to progressively introduce the heat sources. The recharge reaching the reservoir is progressively increased as long as the reservoir temperature remains high enough.

Analyzing the simulation results obtained with different scenarios, as well as the impact of reservoir elements or features on the pressure, temperature or enthalpy at key locations, help understand and confirm the relevance of some interpretations or assumptions, compared to others.

The application of this step to the GEOTREF demonstration case study is illustrated in §4.4.

3.3 Well-layout optimization

Hot enough scenarios having been identified, their geothermal resource potential is assessed by taking into account production and injection wells. Before getting into reservoir performance assessment, optimal well layouts must be determined. They may be different from one scenario to another. The method presented in (Lu et al., 2018) is implemented in the following way.

1. The simulation domain is restricted to the final zone of interest to speed up the simulations.
2. A fine enough reservoir simulation grid, covering this zone and properly integrating all relevant reservoir heterogeneities, is created.
3. Upscaling of the lithological units and of petrophysical properties is carried out from the fine geological grid to the restricted reservoir simulation grid, the same way is done for the phenomenological studies.
4. The simulation results of the phenomenological studies are used to initialize and set the boundary conditions of the restricted reservoir simulation grid.
5. The simulation of the initial conditions is resumed, with prescribed boundary conditions, to fine tune the temperature, pressure and enthalpy fields in the restricted reservoir simulation grid until to stabilize again.
6. Numbers of producer wells and injector wells are chosen, based on the targeted production and industry standards.
7. Possible locations and perforation depths are identified for the producer and injector wells. Their combinations define all the possible well layouts to be tested, whose number can be huge, counted in millions.
8. Optimal production and injection wells or well platforms are then sought among the possible locations and depths. Millions of well layouts can rapidly be tested using an innovative method based on the principle of superposition.
9. Optimal well layouts can be found taking into account multiple scenarios separately, to obtain specific well layouts, or together to find well layouts that accommodate at best with reservoir model uncertainty.

The application of this step to the GEOTREF demonstration case study is illustrated in §4.5.

3.4 Reservoir performance assessment

Relevant (hot) scenarios having been identified together with optimal well layouts. Production histories can be simulated, and from there reservoir performances can be assessed using the functions presented in §2.1.

The restricted reservoir simulation grid, associated with the initial conditions fine-tuned at the previous step to optimize the well layout, are used to simulate the production history.

The application of this step to the GEOTREF demonstration case study is illustrated in §4.6.

3.5 Flow and heat transport simulator

The proposed approach is general and can be implemented using any geothermal reservoir simulator able to simulate flow and heat transport. The choice of a simulator depends, however, on the complexity of the geothermal system to simulate at the different steps of the approach. The following aspects must be considered.

1. Being able to simulate very high temperatures, including super critical fluids to account for heat sources.
2. Being able to simulate multiphase flows if required.
3. Being able to integrate relevant reservoir heterogeneities that are likely to control flow and heat transport, as defined in structural and geological models that can be complex. This includes lithology, rock types or facies, discontinuities of various small to large scales, and rock and fracture properties.
4. Being able to reproduce the behavior of large scale discontinuities that can be faults, fracture corridors, deformation corridors, or schistosity planes resulting from pressure-solution mechanisms (Favier et al., 2020). Some can act as preferential flow paths associated with convective heat transport, whereas others are flow barriers only allowing diffusive heat transport.
5. Being able to integrate relevant flow and heat boundary conditions.
6. Being able to integrate production and injection wells.

Different simulators can be used if required at different steps of the approach. For example, simulating very high temperatures and critical fluids may be required at the phenomenological study step, whereas wells are to be taken into account only at the resource evaluation step. This is illustrated in the case study presented later. A well simulator is also required to calculate enthalpy and pressure loss tables along the wells.

A geothermal dual-medium reservoir simulator and a geothermal well simulator are developed in the framework of the GEOTREF research project (Rajeh, 2019; Thiagalingam et al., 2017).

4. APPLICATION TO THE GEOTREF DEMONSTRATION CASE STUDY

4.1 Presentation of the case study

The demonstration case study is located in Basse-Terre Island, the highest volcanic island of Guadeloupe (Figure 3).

The available exploration data include the following: field data, geophysical data (MT, gravimetric, magnetic…), lab data on rock samples (outcrops), geochemical data (water, rock), but also exhumed potential analogs of the deep reservoir.

Details about the GEOTREF demonstration case study and the available data can be found in the associated conference papers of Charroy et al. (2020), Favier et al. (2020), Géraud et al. (2020), Ledésert et al. (2020), Mercier de Lepinay et al. (2020), as well as in Navelot et al. (2018).

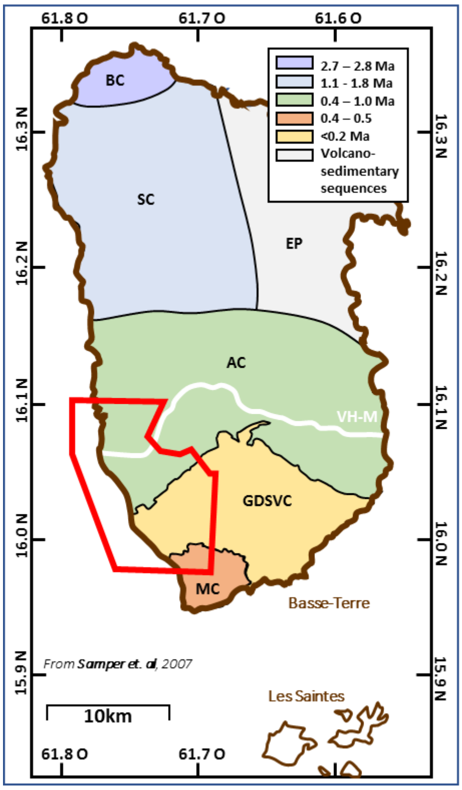

Figure 3: Map of Basse-Terre Island, the highest volcanic island of Guadeloupe, with in red the exploration license area corresponding to the GEOTREF demonstration case study.

4.2 Presentation of the numerical simulators

Two geothermal reservoir simulators have been used at different steps of the approach.

- HYDROTHERM (Kipp et al., 2008) to simulate very high (critical) temperatures in heat sources and ductile zones.
- TOUGH2 (Pruess et al., 2012) to simulate temperatures up to 360°C but with more complete integration of reservoir heterogeneities.

Two well simulators have also been used: HOLA (Björnsson and Arason, 1993) and W1D (Thiagalingam et al., 2017), whose development is part of the GEOTREF project.

4.3 Step 1: numerical conceptual models

The numerical conceptual models have been defined based on:

- all the available data,
- reservoir heterogeneities that have been identified as potentially controlling flow and heat transport,
- interpretations and assumptions that require to be confirmed or unconfirmed as illustrated on the schematic conceptual models shown in Figure 4,
- questions that the phenomenological studies, carried out using the numerical conceptual models should help answer.

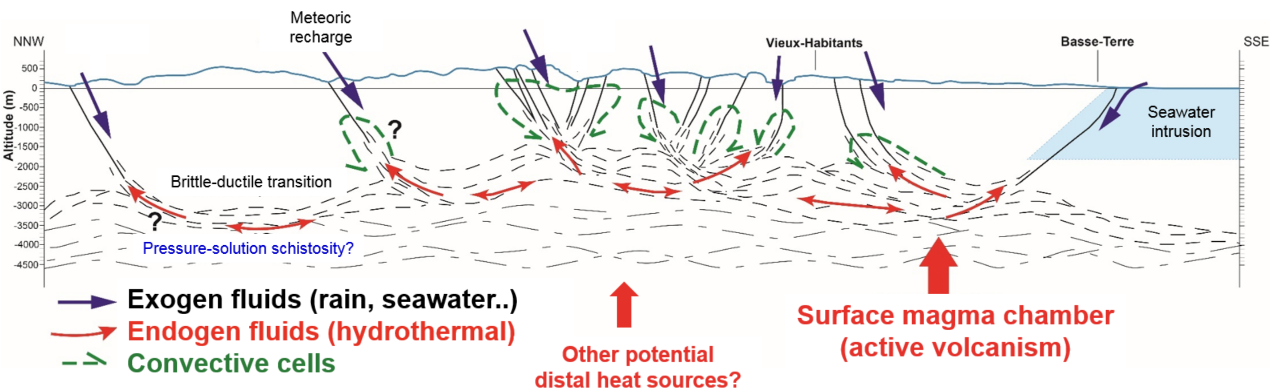

Figure 4: understanding and questioning about the geothermal system as illustrated in the conceptual model of the deeper part of the Basse-Terre island geothermal reservoir. Modified after (Favier et al., 2020).

The key elements of the numerical conceptual models are the following.

- The geological model defining the flow units (Figure 5.a).
- The deformation corridors derived from fault traces (Figure 5.b).
- The petrophysical properties that are the purpose of different scenarios, one being based on horizontal and vertical trends (Figure 5.c).
- The heat sources that also are the purpose of different scenarios, one being known, the others resulting from possible assumptions (Figure 5.d).

They are used to define the scenarios presented in Table 1 and to parametrize the reservoir model uncertainties as detailed in Table 2. The parametrization of model uncertainty is designed in such a way that the permeability of deformation corridors is the reference permeability. The permeability of other flow units is related to it by using factors, which provide easy control of permeability contrasts.

A numerical conceptual model is then the combination of a scenario and uncertainty options. They are built using a very fine geological grid that is extended enough to reach well-defined boundary conditions that are the sea and a major flow-barrier fault located at the boundary of the groundwater basin (Figure 6).

The so obtained numerical conceptual models are used to carry out the phenomenological studies in step 2 of the approach.

Table 1: scenarios defining different model complexities and assumptions.

Key element	Scenario name	Description
Reservoir petrophysical properties	PropTrend1	Homogeneous petrophysical properties
	PropTrend2	Horizontal spatial trends from emission points (*K*, *Φ, Cth)*
	PropTrend3	Horizontal and vertical spatial trends (*K*, *Φ, Cth)*
Petrophysical properties of deformation corridors	KdcAniso1	Isotropic *K* in deformation corridors
	KdcAniso2	Anisotropic *K* in deformation corridors
	KdcAniso3	Anisotropic *K* in deformation corridors + vertical spatial trend
Recharge	Recharge1	Neglected meteoric recharge
	Recharge2	Based on effective groundwater recharge
	Recharge3	Prescribed at the top of the cap-rock
Heat sources	HeatSource1	Only basal heat flux
	HeatSource2	Single distal heat source below Soufrière + basal heat flux
	HeatSource3	Multiple distal heat sources + basal heat flux

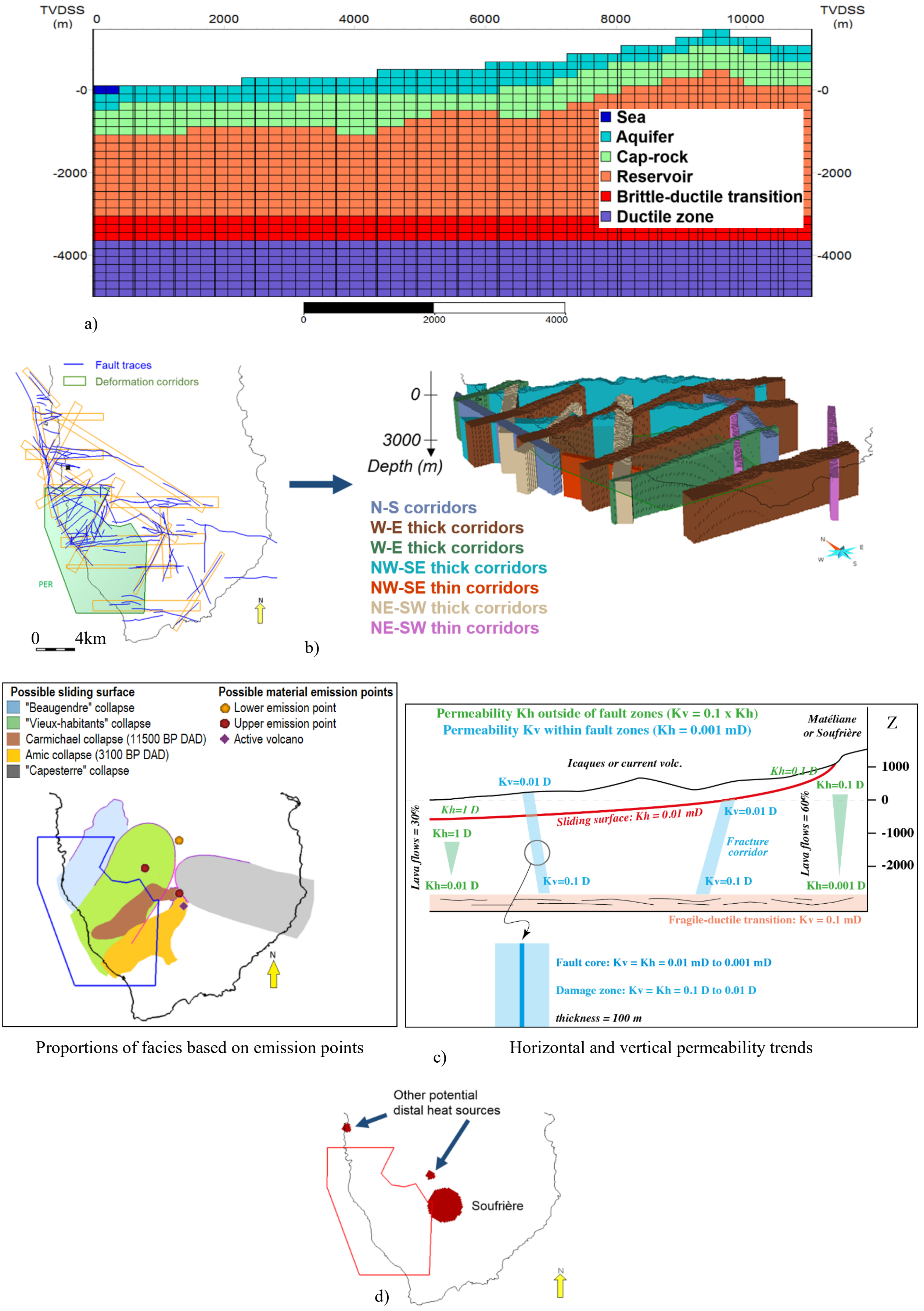

Figure 5: key elements of the numerical conceptual model including a) the geological model (cross-section) defining the flow units, b) the deformation corridors based on interpreted fault traces, c) the rock petrophysical properties that some scenarios predict as being subject to horizontal and vertical trends, after (Navelot et al., 2018), d) the known and assumed heat sources.

Table 2: parametrization of the reservoir model uncertainties.

Type	Variable or parameter	Description	Denomination	Value
Mean permeability	**Kdc**	Deformation corridor permeability = reference permeability	Kdc1 Kdc2 Kdc3	1 mD 10 mD 100 mD
	KresFact	Factor defining the reservoir permeability as **Kres** = KresFact × **Kdc**	KresFact1 KresFact2 KresFact3	1 0.1 0.01
	KbdtFact	Factor defining the permeability of the brittle-ductile transition zone as **Kbdt** = KbdtFact × **Kdc**	KbdtFact0 KbdtFact1 KbdtFact2 KbdtFact3	0.1 1 10 100
	KcrdcBase	Factor defining the cap-rock permeability as **Kcrdc** = Kcr + **KcrdcBase** × Ndc	KcrdcBase0 KcrdcBase*X*	0 *X* ranging in]0; 1]
Basal thermal flux	**HeatFlux**	Uniformly distributed at the bottom of the reservoir model	HeatFlux1 HeatFlux2 HeatFlux3	60 mW/m² 100 mW/m² 120 mW/m²

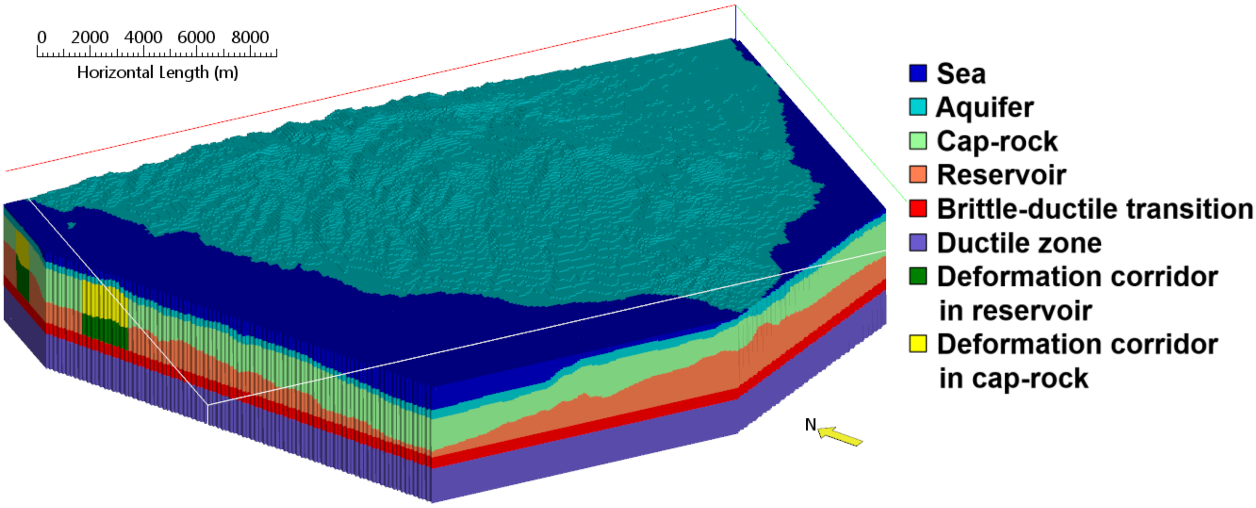

Figure 6: 3D view of geological model built in very fine grid of 7.5 M cells. The grid is extended enough to reach the sea and a major flow-barrier fault, located at the boundary of the groundwater basin, which are well-defined boundary conditions.

4.4 Step 2: phenomenological studies

The phenomenological studies consist of simulating initial (nowadays) geothermal conditions for different conceptual models that represent different scenarios and uncertainty options. Starting with a groundwater model in hydrostatic conditions at a cold (atmospheric) temperature, the geothermal system is heated up by applying basal thermal flux and heat sources. Hundreds of thousands of years are to be simulated.

As explained in §3.2, several grids are to be used to speed up the simulation run times. This is required to rapidly identify good and bad numerical conceptual models as being associated with the presence or not of a geothermal resource. Two reservoir simulation grids were used (Figure 7). Figure 8 shows the upscaling of the geological model, which preserves the preferential flow paths and the flow barriers defined in the very fine geological grid.

HYDROTHERM was used to simulate the initial conditions with temperatures of 800°C in the heat sources. The simulation with the coarse grid of hundreds of thousands of years to heat up the geothermal system and reach some stabilization conditions takes less than 30 minutes on a mid-range laptop. This is to be compared with the simulation of a few thousand years using the fine reservoir simulation grid to fine tune the simulation results. These simulations take between one and a few hours. They are only performed, however, for the numerical conceptual models that show high enough temperatures at the end of the reservoir simulation on the coarse grid.

Two areas of interest are depicted in Figure 8. Area 1 is located in the exploration license area of the GEOTREF demonstration case study. Area 2 is another far away zone where well data are available showing high temperatures of 250°C (Lachassagne et al., 2009).

Sensitivity analysis results can be derived from the many numerical conceptual models simulated. Table 3 provides such sensitivity analysis results. Figure 9 shows the impact of four numerical conceptual models on the simulated temperature field. All these results are helpful to quantify and interpret the effects of different scenarios or uncertainty options on the temperature at various locations.

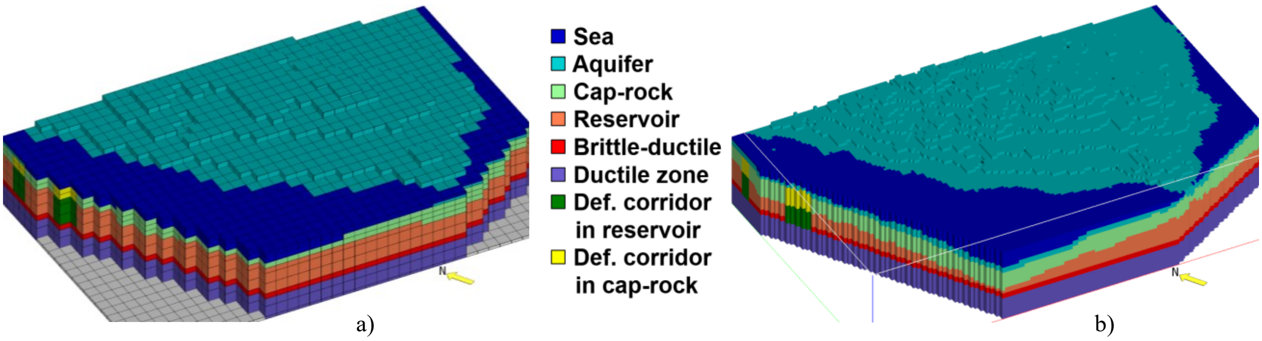

Figure 7: 3D views of the two a) coarse and b) fine simulation grids that were used to speed up the simulation of the initial geothermal conditions of multiple numerical conceptual models. Coarse grid = 9.4 K cells. Fine grid = 335K cells.

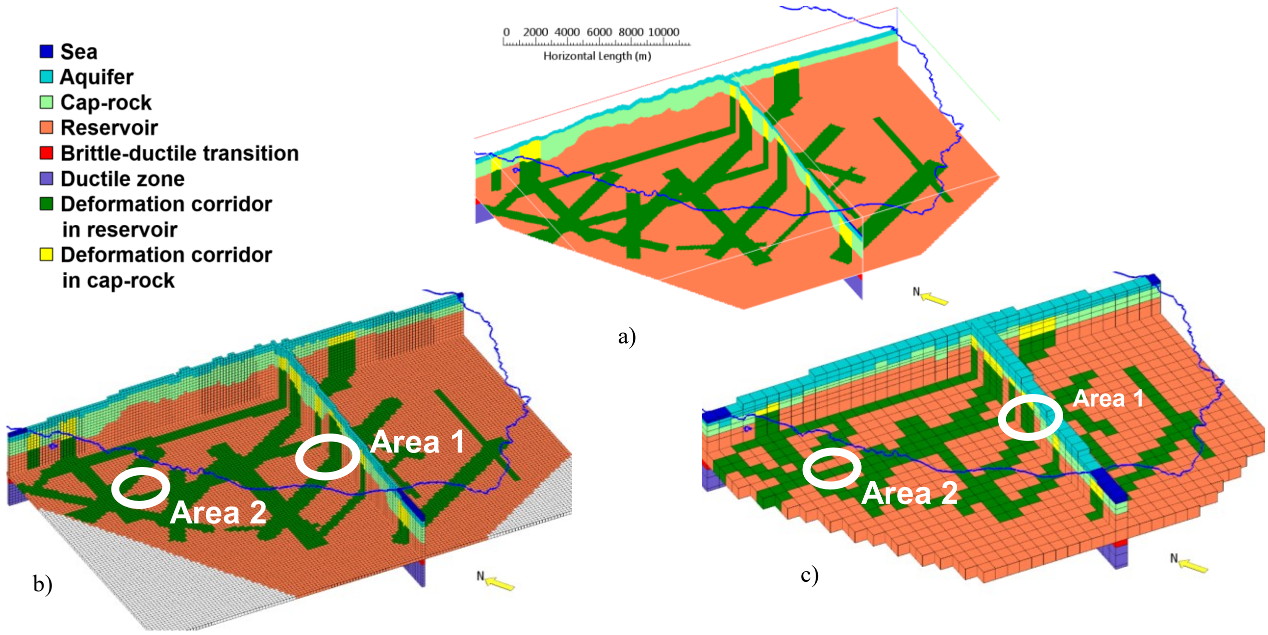

Figure 8: 3D views of a) the geological model built in the very fine geological grid, and b) the upscaled geological model defined in the fine simulation grid, c) the upscaled geological model defined in the coarse simulation grid. Areas of interest are indicated with white lines, area 1 being located in the exploration license area of the GEOTREF demonstration case study.

Table 3: sensitivity analysis results based on 80 (coarse-grid) simulations. They provide information about the effects of a single parameter on the temperature at different locations.

Sensitivity parameter	**Mean T°C area 1** Min | Mean | Max	**Mean T°C area 2** Min | Mean | Max	**Mean T°C TFD** Min | Mean | Max	**Mean T°C cap-rock** Min | Mean | Max	**Nb cases**
Soufrière heat-source added	87 | 165 | 288	0 | 32 | 72	30 | 70 | 94	56 | 74 | 103	18
Other heat-sources added	0 | 10 | 80	10 | 49 | 112	0 | 10 | 58	0 | 9 | 42	21
Basal heat flux from 60 to 100 mW/m²	61 | 81 | 99	110 | 121 | 132	56 | 68 | 81	54 | 58 | 60	4
Basal heat flux from 100 to 120 mW/m²	15 | 16 | 18	22 | 22 | 22	20 | 21 | 23	16 | 17 | 18	2
Factor KresFact divided by 10	-49 | 7 | 96	-34 | 12 | 78	-30 | 7 | 52	-24 | 1 | 26	69
Factor KresFact divided by 100	-60 | 25 | 63	-19 | 27 | 101	-26 | 23 | 51	-13 | 6 | 31	19
Factor KbdtFact divided by 10	-49 | 0 | 97	-55 | 3 | 78	-30 | 0 | 52	-34 | 0 | 23	70
Factor KbdtFact divided by 100	-60 | 5 | 57	-59 | 2 | 101	-26 | 1 | 25	-37 | -2 | 14	20

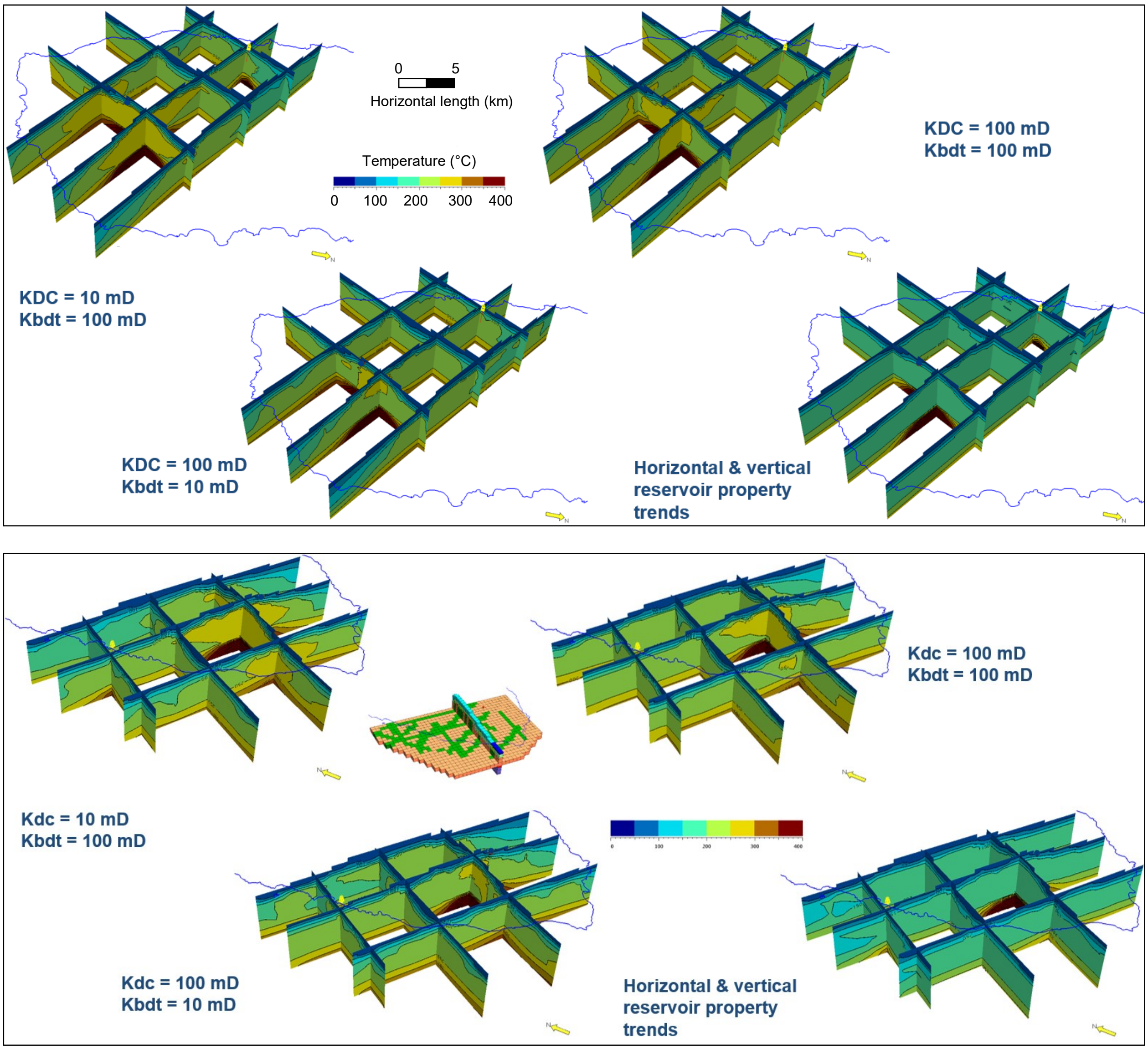

Figure 9: 3D views in two directions of the temperature fields simulated with four numerical conceptual models.

4.5 Step 3: well-layout optimization

The phenomenological study carried out at the previous step showed that relevant numerical conceptual models, based on realistic assumptions, are hot enough to provide a geothermal resource. Some of them were selected to assess their geothermal potential. Optimal well layouts must be found first, however, before to get into reservoir performance assessment.

The optimization of well layout relies on the following choices.

- Well production plan
  - 4 producer wells.
  - 2 injector wells.
  - Reinjection rate = 90% of production rate.
  - Minimum production well-head pressure = 7.5 bar.
  - Targeted power plant production: 20 MWe with a duration of 30 years.
- Predefined well locations and depths
  - 26 possible well locations.
  - Different perforation depths for production and injection wells.
- Targeted area: area 1 located in the exploration license area of the GEOTREF demonstration case study (Figure 8).

Based on these choices, the well-layout optimization requires testing up to 4,858,750 possible layouts. Fortunately, using the superposition principle, the method presented by (Lu et al., 2018) only requires 52 + 1 transient simulations to successfully sort all the possible well layouts. Best ranked well layouts are then the optimal ones.

The simulation domain is restricted to area 1 and its neighborhood. A locally refined grid of 84 K cells is used (Figure 10). The initial conditional and boundary conditions applying to the grid are retrieved from the simulation on the fine grid of the corresponding numerical conceptual model. Fine-tuning of the initial conditions are obtained by resuming the initial condition simulation using the geothermal reservoir simulator TOUGH2, which can better capture some reservoir heterogeneities and take into account well models.

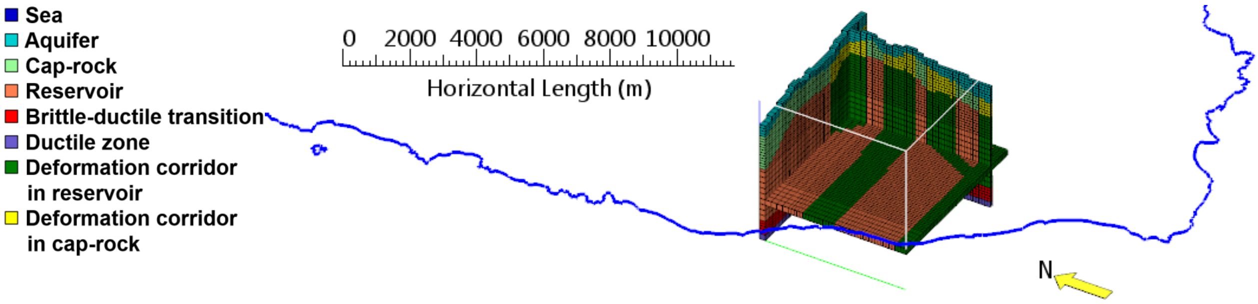

Figure 10: locally refined grid of 84 K cells covering the restricted simulation domain.

Well-layout sorting results are presented in Figure 11 for two reservoir performance functions, the leftover performance and the simple flash performance. They are related to the numerical conceptual model Kcd = 10 mD and Kbdt = 100 mD in Figure 9. The highly contrasted performances of the well layouts can be noticed with only a few having very good performances.

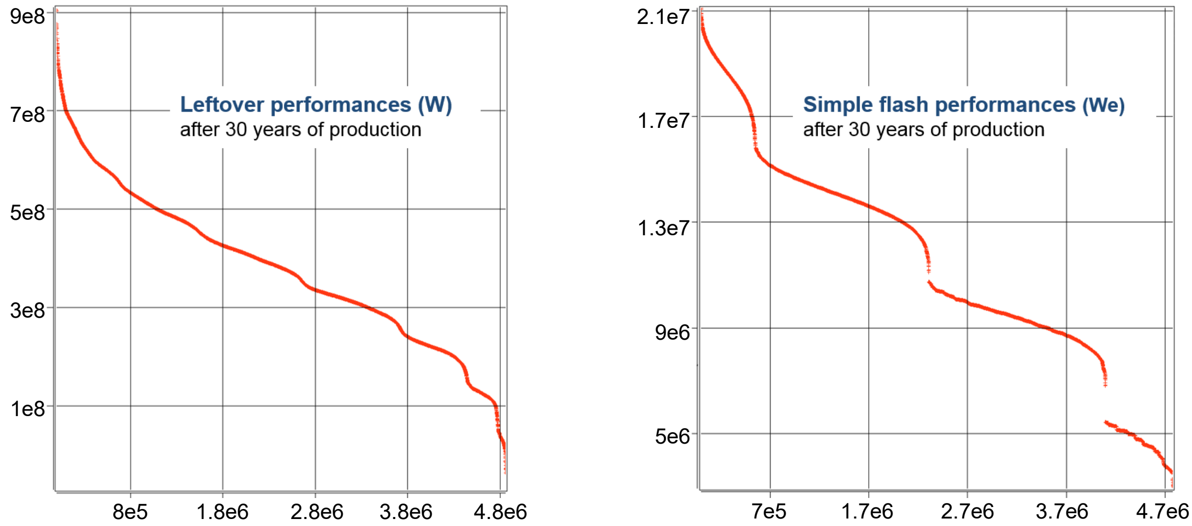

Figure 11: sorting of all possible well layouts using the leftover and simple flash performance functions.

Beyond the optimal well layouts, the analysis of well-layout optimization results also provides information about good and bad locations and depths for production and injection perforations. This is illustrated in Figure 12, under the form of performance indexes that are calculated and standardized to range between 0 and 1. Locations in maroon are the best, those in dark blue are the worst. These types of plots are useful to decide about new borehole drilling locations.

4.6 Step 4: reservoir performance assessment

Once numerical reservoir models are selected and best well locations are identified, everything is almost ready to assess the potential of the geothermal resource in terms of reservoir performances. The following production history has been simulated.

- Total fluid production: 200 kg/s.
- Production period: 30 years.
- Power plant: single flash.
- Minimum well-head pressure: 7.5 bar.

For the numerical reservoir model corresponding to Kcd = 10 mD and Kbdt = 100 mD presented in §4.5, the following electric productions are found for the best well-layouts based on leftover or single flash performances.

- Best well-layout based on leftover performances: 18.4 MWe.
- Best well-layout based on single flash performances: 21.1 MWe.

As expected, the electric production is higher with the best well-layout that is based on single flash performances, consistently with the choice of a single flash power plant.

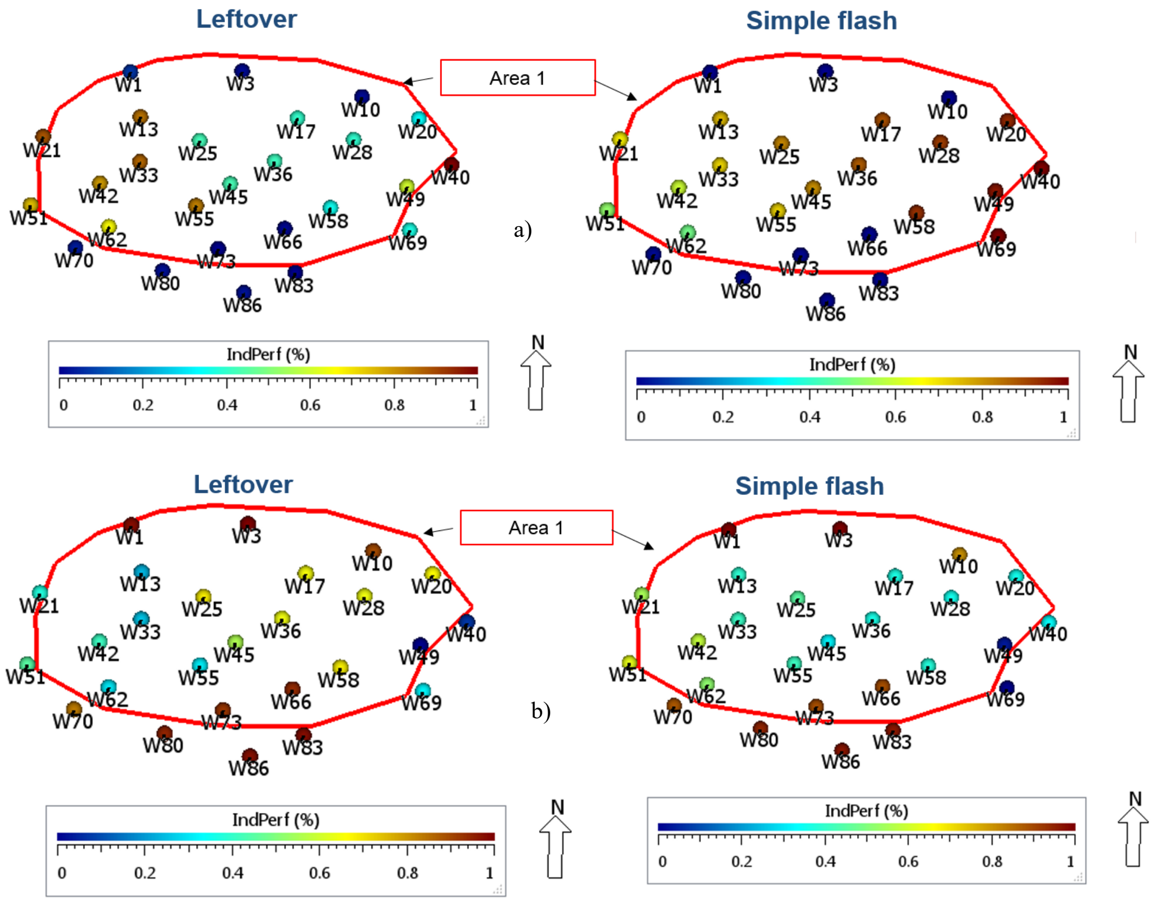

Figure 12: performance indexes of a) production and b) injection perforations.

CONCLUSIONS

This paper presents a numerical approach that has been developed within the framework of the GEOTREF research project to help better assess the potential of geothermal resources at prefeasibility stage. The steps of the approach are presented as well as their application in the GEOTREF demonstration case study. All the presented results are still preliminary results that give an overview of the benefits that can be expected from such an approach. More complete results are in preparation and will be confronted to subsurface well data that should be available soon.

Beyond the presentation and demonstration of the proposed numerical approach, the aim of this paper is also to provide answers to several questions regarding the fact that reservoir modeling is one, if not the only, solution for reliable geothermal reservoir performance assessments prior drilling.

What for?

- Testing, understanding and validating conceptual models, assumptions and uncertainties.
- Better evaluating geothermal resources by taking into account wells.

For which results?

- Sensitivity analysis results.
- Well-layout optimization and well production assessment.
- Providing reservoir models ready to help interpret exploration well data.

How?

- Using efficient tools: purpose of the GEOTREF software platform.

At which cost?

- To be carried out rapidly (1 to 3 months).

AKNOWLEDGEMENTS

The authors wish to thank the Investissements d'Avenir and ADEME for supporting this work as part of the GEOTREF research project. We are also grateful to all GEOTREF partners that contribute in one way or another to the design or development of the proposed approach. Partners of the GEOTREF project are Teranov, KIDOVA, Mines ParisTech, ENS Paris, GeoAzur, Georessources, IMFT, IPGS, LHyGes, UA, and UCP-GEC. Paradigm/Emerson is also thanked for providing all GEOTREF partners with SKUA-GOCAD user or development licenses.

REFERENCES

AGRCC: Geothermal Lexicon For Resources and Reserves Definition and Reporting, 2nd ed, (2010).

Björnsson, H., and Arason, Þ.: The wellbore simulator HOLA, Version 3.1 , User Guide.

Charroy, J., Haffen, S., Viard, S., Gérard, F., and GEOTREF team: The Matouba geothermal prospect: a newly-discovered inferred geothermal resource on Guadeloupe Island, French West Indies, *Proceedings*, World Geothermal Conference, Reykjavik, Islande (2020).

Cumming, W.: Geothermal reousrce conceptual models using surface exploration data, *Proceedings*, Thirty-Fourth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California (2009).

Favier, A., Lardeaux, J.-M., Verati, C., Corsini, M., Münch, P., and Ventalon, S.: The Concept of Exhumed Analogue for Characterization of High-Energy Geothermal Reservoir: an Example from Les Saintes Island (Guadeloupe Archipelago, Lesser Antilles) and Consequences for Exploration, *Proceedings*, World Geothermal Conference, Reykjavik, Islande (2020).

Géraud, Y., Navelot, V., and Diraison, M.: Fluids and Heat Transfer Properties and Associated Petrophysical Properties for Different Structural and Petrographic Facies of Volcanic Formations, Contribution to Building a High Temperature Geothermal Reservoir Model, *Proceedings*, World Geothermal Conference, Reykjavik, Islande (2020).

Gervais, V., and Ravalec, M.L.: Identifying influence areas with connectivity analysis – application to the local perturbation of heterogeneity distribution for history matching. *Computational Geosciences*, **22**, (2018), 3–28.

Grant, M.A.: Resource assessment, a review with reference to the Australian code, *Proceedings*, World Geothermal Congress 2015, Melbourne, Australia (2015).

Kipp, K.L., Hsieh, P.A., and Charlton, S.R.: Guide to the Revised Ground-Water Flow and Heat Transport Simulator: HYDROTHERM - Version 3 (Report), Techniques and Methods, , U.S. Geological Survey, (2008).

Lachassagne, P., Marechal, J.C., and Sanjuan, B.: Hydrogeological model of a high-energy geothermal field (Bouillante area, Guadeloupe, French West Indies). *Hydrogeology Journal*, **17**, (2009), 1589–1606.

Ledésert, B., Hébert, R., Azzimani, Y., Beauchamps, G., Bartier, D., and GEOTREF TEAM: Characterization of Reservoir Properties of Andesitic Rocks on Basse Terre de Guadeloupe (French West Indies) in the Framework of Geotref Geothermal Program, *Proceedings*, World Geothermal Conference, Reykjavik, Islande (2020).

Lu, M., Siffert, D., Mathieu, J.-B., Garcia, M.H., and Gosselin, O.R.: Testing and Improvement of Well Layout Optimisation Methods for Geothermal Reservoir Production, in: SPE Europec Featured at 80th EAGE Conference and Exhibition, , *Proceedings*, SPE Europec featured at 80th EAGE Conference and Exhibition, Society of Petroleum Engineers, Copenhagen, Denmark (2018).

Mercier de Lepinay, J., Navelot, V., Munschy, M., Géraud, Y., Diraison, M., and GEOTREF TEAM: Imaging of a Geothermal Reservoir in Volcanic Environment with Magnetic Data Supported by Structural and Petrophysical Analyses, *Proceedings*, World Geothermal Conference, Reykjavik, Islande (2020).

Mortensen, A.K., and Axelsson, G.: Developing a conceptual model of a geothermal system, *Proceedings*, Short Course on Conceptual Modelling of Geothermal Systems, UNU-GTP and LaGeo, Santa Tecla, El Salvador (2013).

Navelot, V., Géraud, Y., Favier, A., Diraison, M., Corsini, M., Lardeaux, J.-M., Verati, C., Mercier de Lépinay, J., Legendre, L., and Beauchamps, G.: Petrophysical properties of volcanic rocks and impacts of hydrothermal alteration in the Guadeloupe Archipelago (West Indies). *Journal of Volcanology and Geothermal Research*, **360**, (2018), 1–21.

Pruess, K., Oldenburg, C., and Moridis, G.: TOUGH2 User's Guide, Version 2.1, Lawrence Berkeley National Laboratory, Berkeley, Calif., (2012).

Rajeh, T.: Modeling flow in fractured geological media: upscaling and application to geothermal reservoirs (Ph.D. thesis), University of Toulouse, Toulouse, (2019).

Thiagalingam, I., Bergez, W., and Colin, C.: Thermodynamic analysis of water boiling in presence of non-condensable gas, the carbone dioxide (CO2): application to geothermal flows in wellbores, *Proceedings*, 13th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, Portoroz, Slovenia (2017).

Williams, C.F.: Evaluating the volume method in the assessment of identified geothermal resources. *GRC Transactions*, **38**, (2014), 967–974.