some aspects and current needs for geothermal reservoir modeling

S. Lopez, V. Hamm, E. Giuglaris,
G. Courrioux, P. Calcagno,
F. Xing, R. Masson, K. Brenner…

a preliminary definition

geothermal energy

=

heat stored in the earth crust

Géosciences pour une Terre durable

brgm

a preliminary definition

geothermal energy

=

heat stored in the earth crust

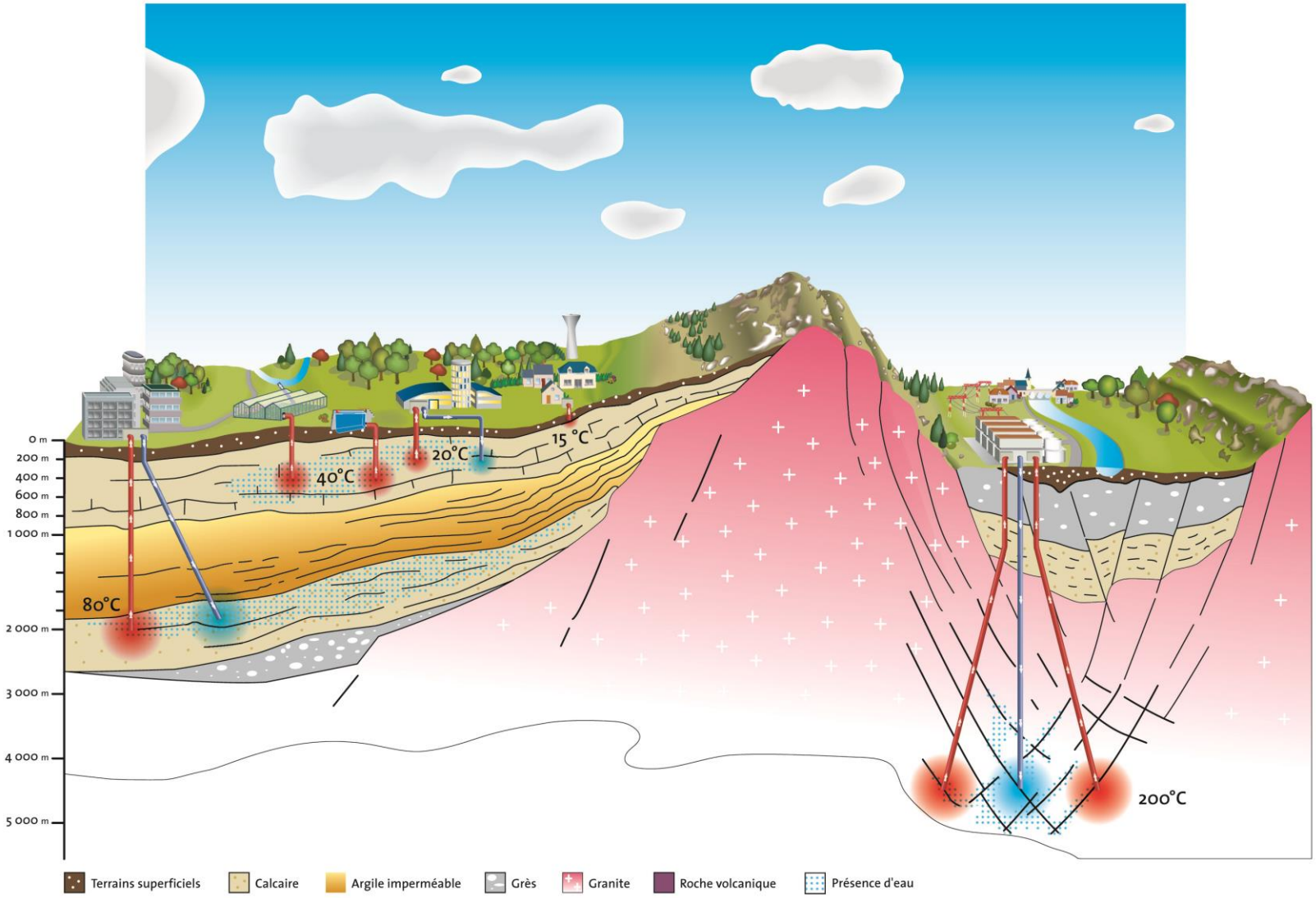
=

a huge amount of energy

can we exploit it ?

(in a sustainable way ?)

geothermal energ**ies**

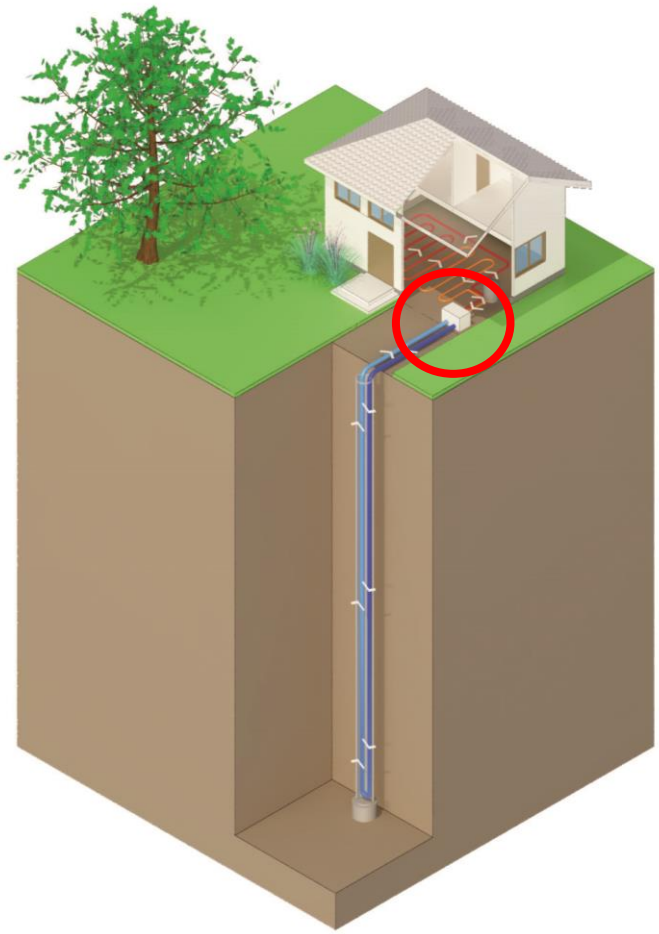


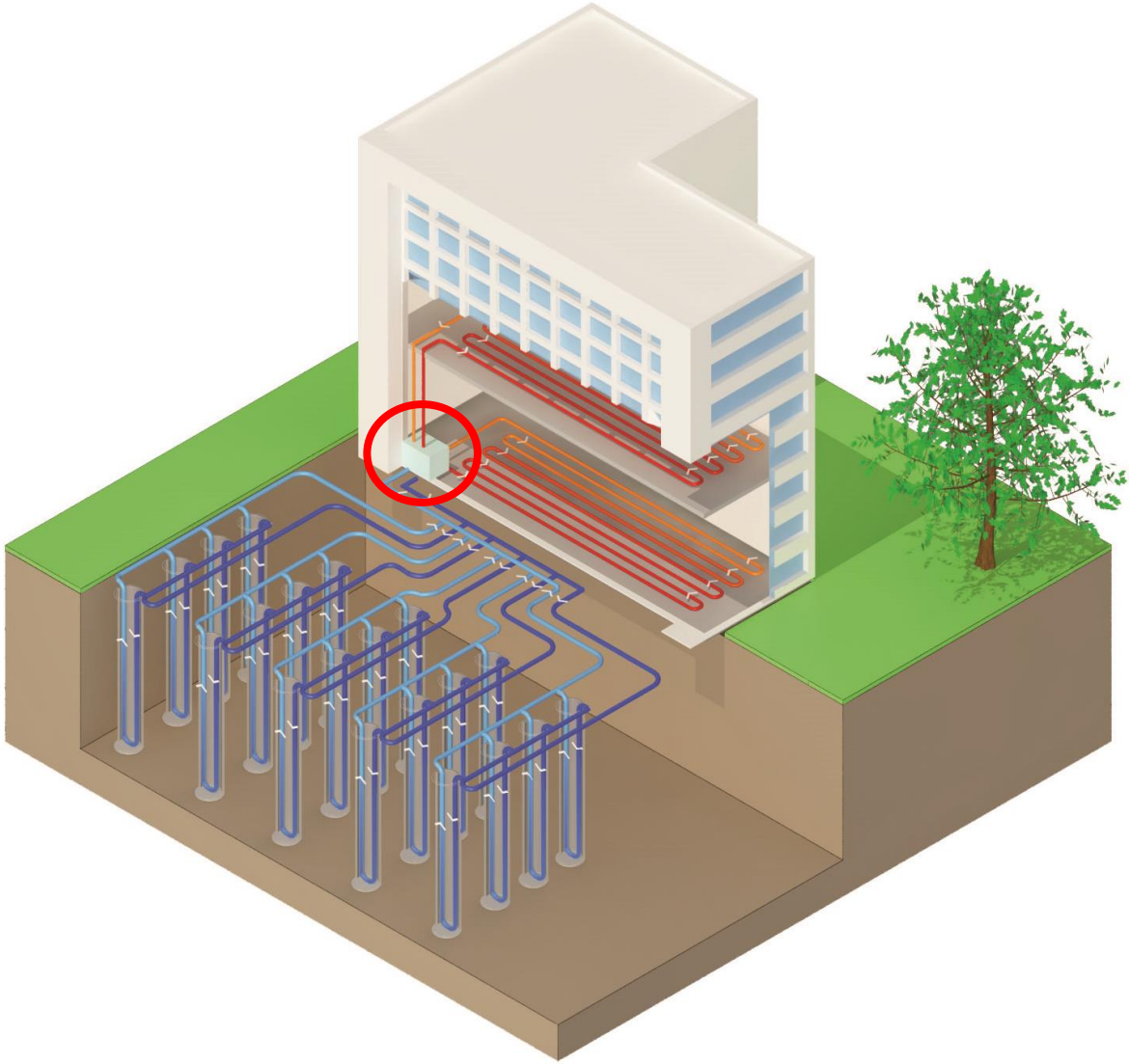
Géosciences pour une Terre durable
brgm

a tentative classification

		use / exchange with the *reservoir*	increasing temperature: direct use (heat)	increasing temperature: power production (cogeneration)
heat exchanger	closed	diffusive exchange industrial fluid makes loops in the heat exchanger	(very) low temperature geothermal energy horizontal heat exchanger geothermal probes residential heating heat pumps	almost nonexistent (<1MW) a few prototypes/projects
	open	convective exchange mass exchange with the subsurface fluids that make loops in a geothermal loop	low temperature geothermal energy deep aquifers district heating industrical processes	high temperature geothermal energy geologically specific zones (active volcanoes…) permeable network heat source and natural fluids

closed exchangers – direct use





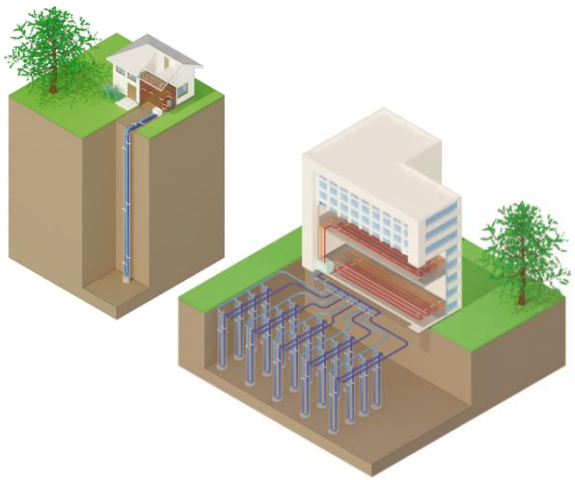
Géosciences pour une Terre durable
brgm

a tentative classification

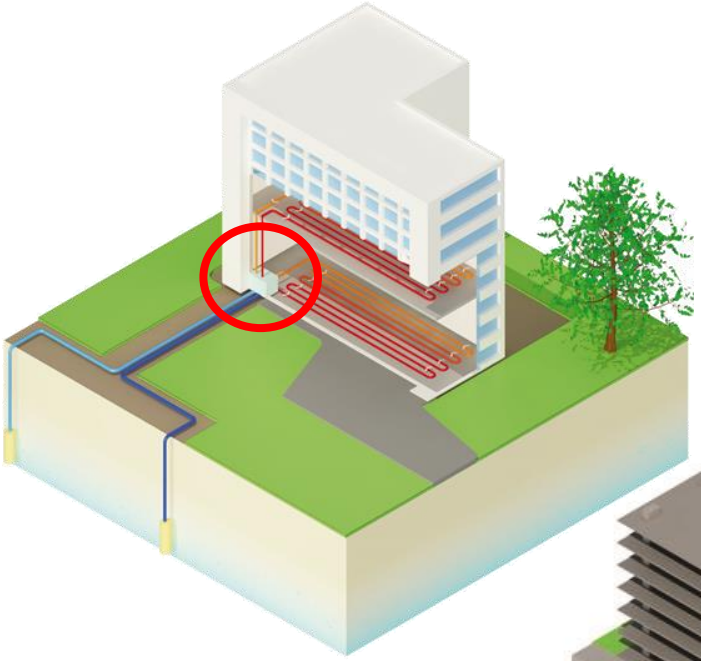
increasing temperature

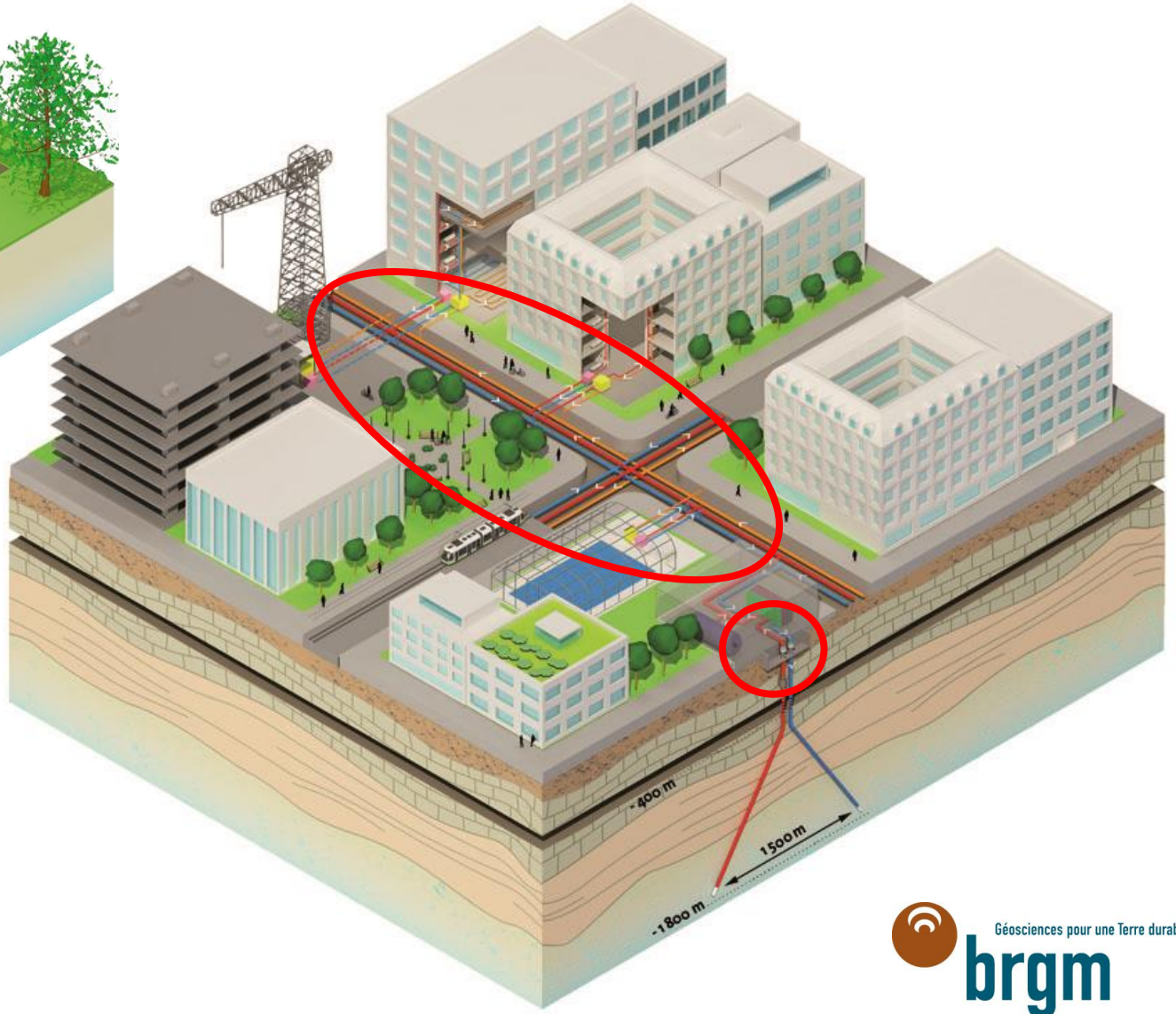
direct use (heat) → power production

cogeneration

		use / exchange with the *reservoir*		
heat exchanger	closed	diffusive exchange industrial fluid makes loops in the heat exchanger		almost nonexistent (<1MW) a few prototypes/projects
	open	convective exchange mass exchange with the subsurface fluids that make loops in a geothermal loop	low temperature geothermal energy deep aquifers district heating industrical processes	high temperature geothermal energy geologically specific zones (active volcanoes…) permeable network heat source and natural fluids

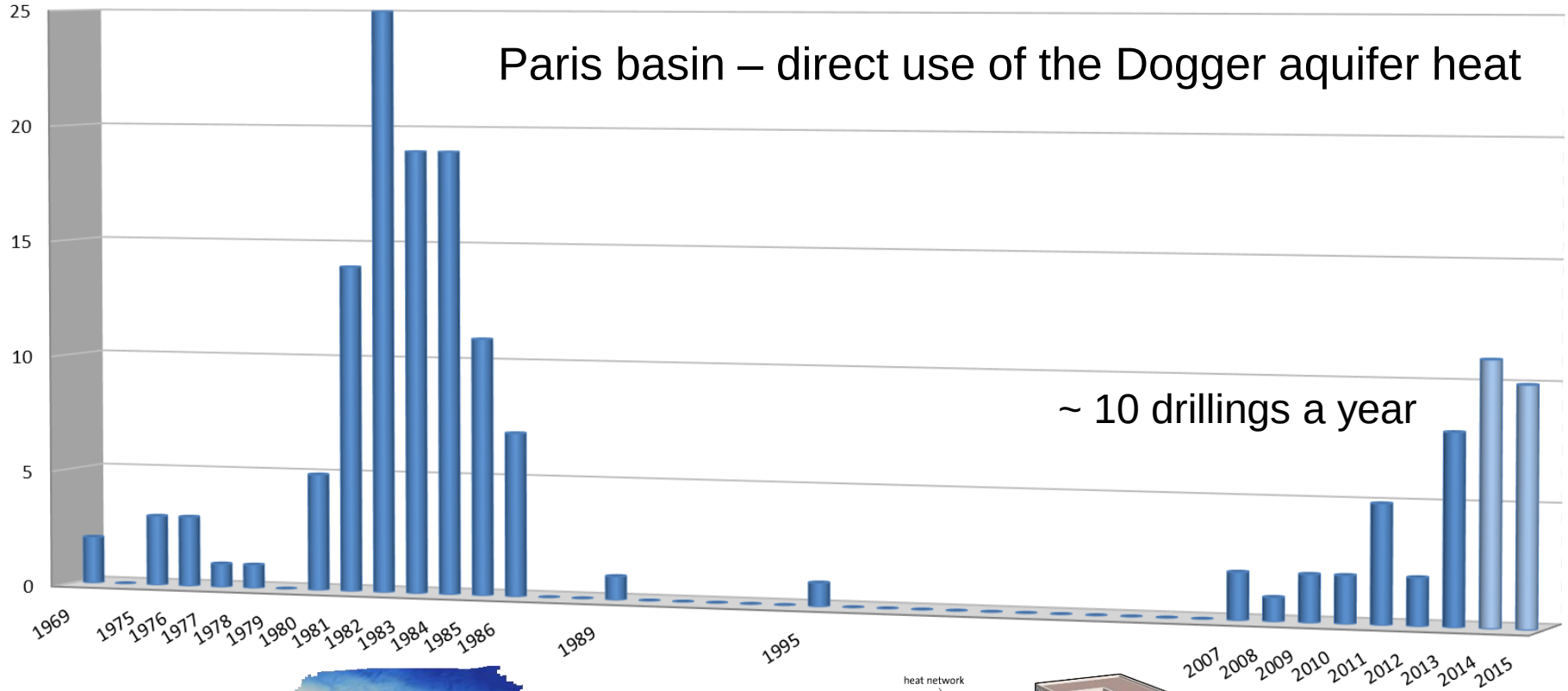
open exchanger – direct use

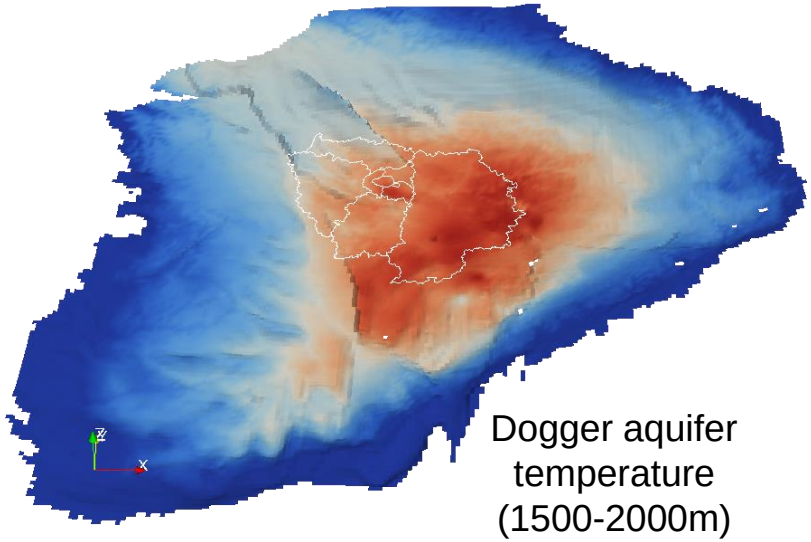




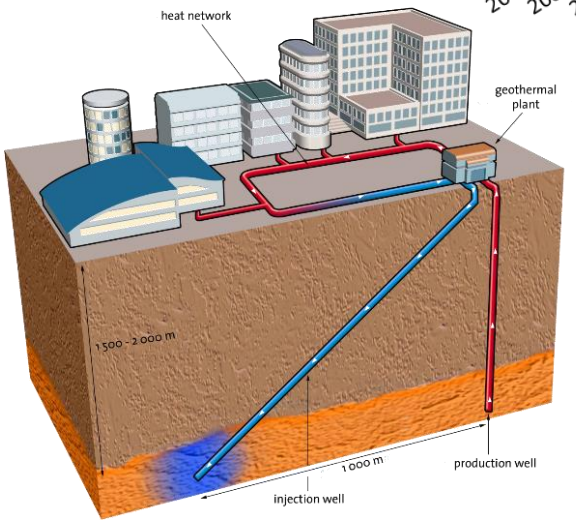
Géosciences pour une Terre durable
brgm

a Parisian digression





Dogger aquifer temperature (1500-2000m)



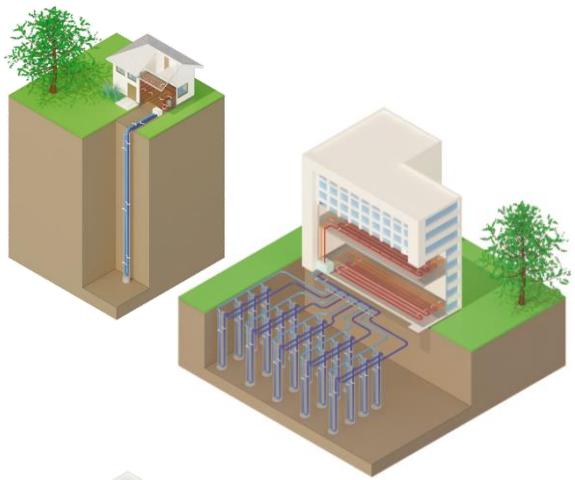
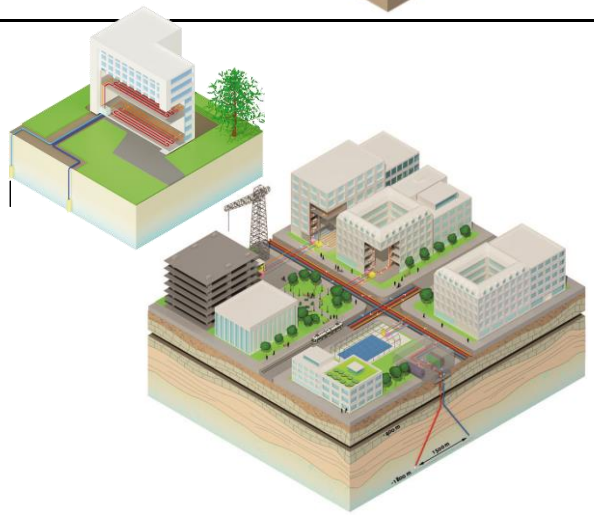
Géosciences pour une Terre durable
brgm

a tentative classification

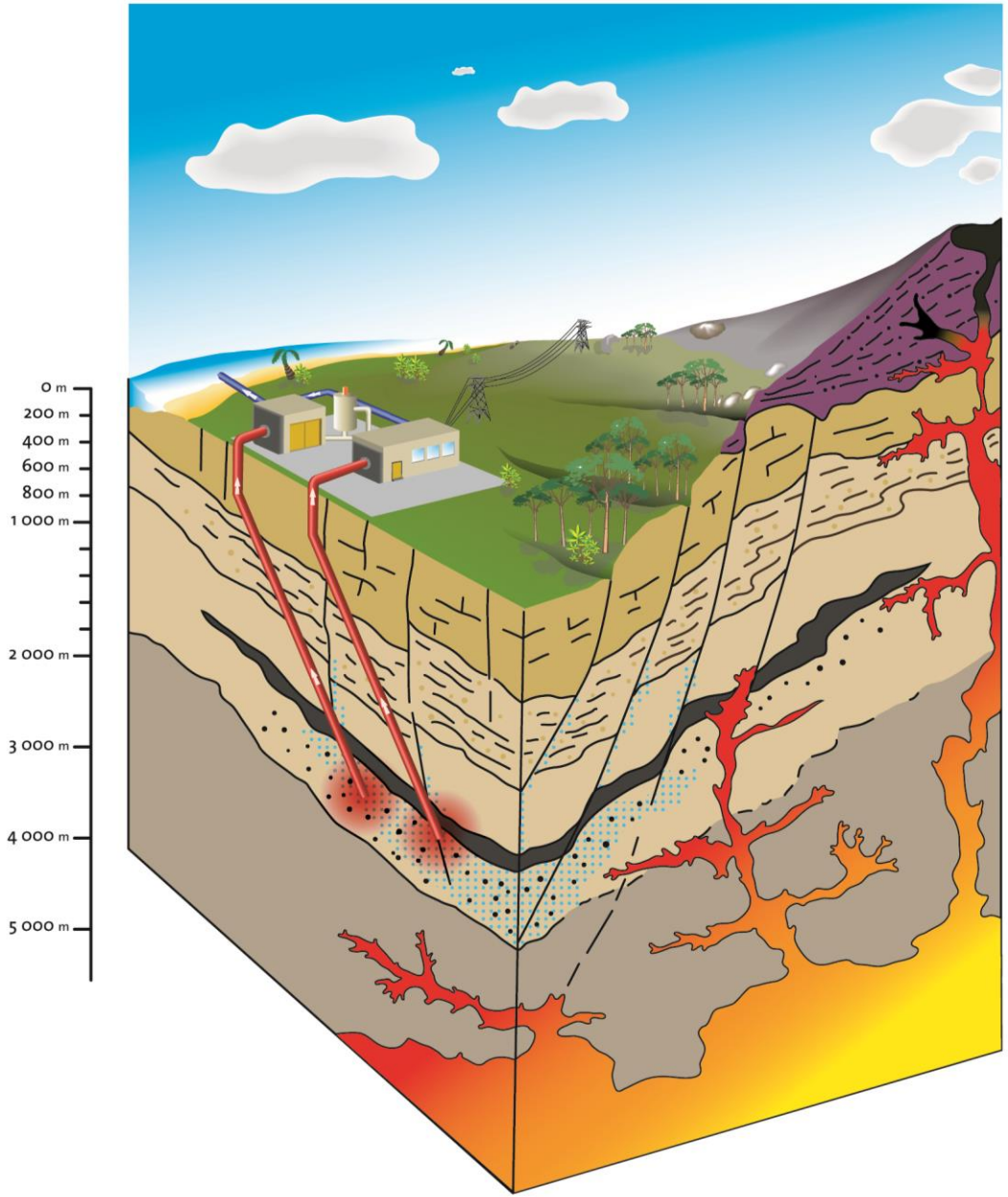
increasing temperature

direct use (heat) → power production

cogeneration

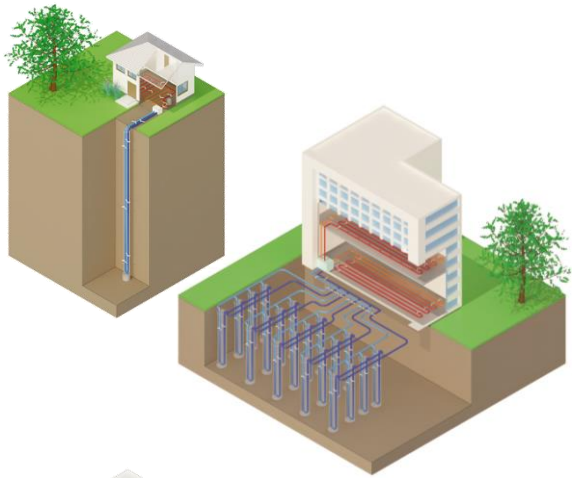
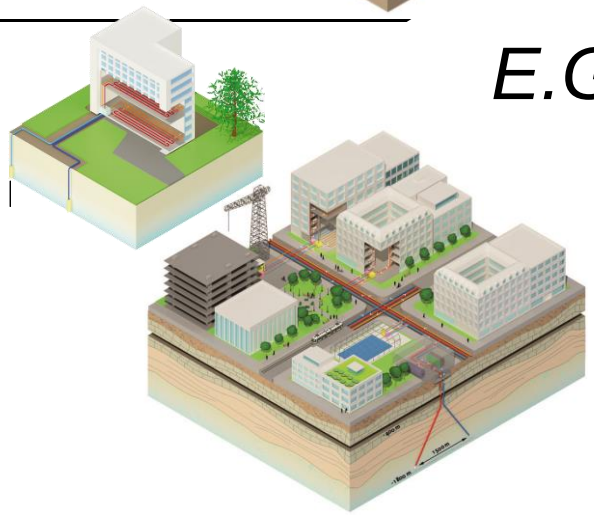
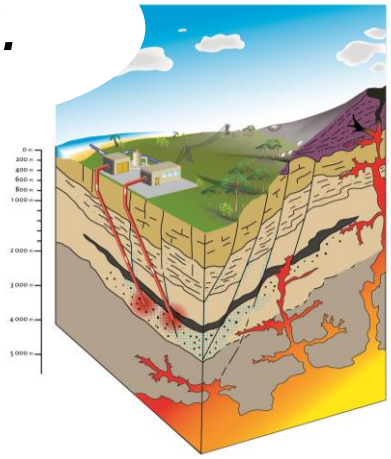
		use / exchange with the *reservoir*		
heat exchanger	closed	diffusive exchange industrial fluid makes loops in the heat exchanger		almost nonexistent (<1MW) a few prototypes/projects
	open	convective exchange mass exchange with the subsurface fluids that make loops in a geothermal loop		high temperature geothermal energy geologically specific zones (active volcanoes…) permeable network heat source and natural fluids

open exchanger – power production



Géosciences pour une Terre durable
brgm

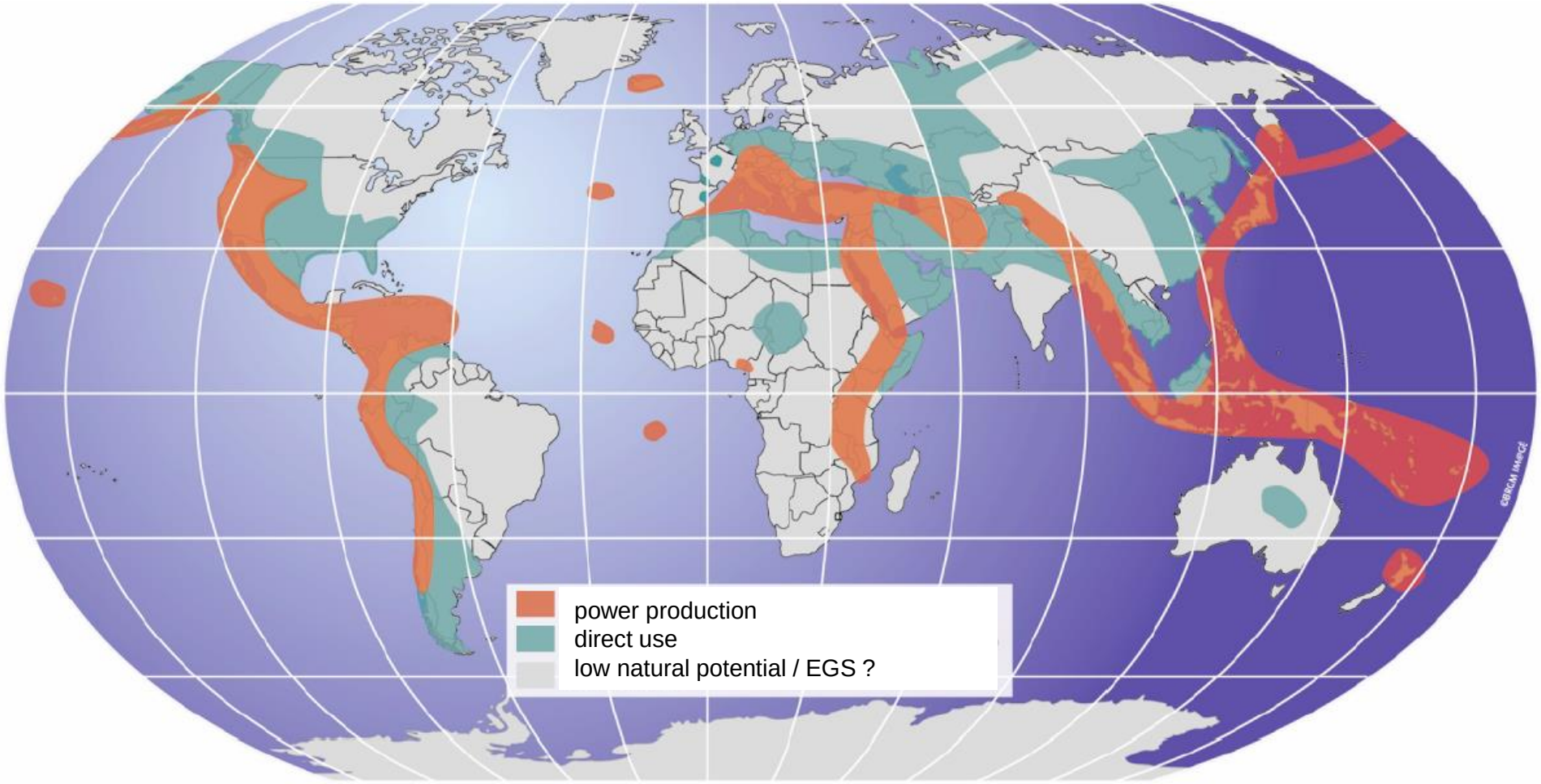
a tentative classification

		use / exchange with the *reservoir*	increasing temperature: direct use (heat)	increasing temperature: power production (cogeneration)
heat exchanger	closed	diffusive exchange industrial fluid makes loops in the heat exchanger		almost nonexistent (<1MW) a few prototypes/projects
heat exchanger	open	convective exchange mass exchange with the subsurface fluids that make loops in a geothermal loop		

E.G.S.

focus on…

- high temperature geothermal systems
  - deep (overall diffusive systems) or *active* zones



Géosciences pour une Terre durable
brgm

focus on…

- high temperature geothermal systems
  - deep (overall diffusive systems) or *active* zones
- *conventional* geothermal reservoirs
  - pervasive permeable objects make production naturally possible (fractures, sedimentary bodies…)
- mass exchange with the reservoir
  - fluid is pumped out of the reservoir and may be injected back

Géosciences pour une Terre durable
brgm

focus on…

- high temperature geothermal systems
  - deep (overall diffusive systems) or *active* zones
- *conventional* geothermal reservoirs
  - pervasive permeable objects make production naturally possible (fractures, sedimentary bodies…)
- mass exchange with the reservoir
  - fluid is pumped out of the reservoir and may be injected back
- a few concepts about reservoir evolution / modeling
  - based on France deep (conventional) geothermal projects :
    - deep sedimentary aquifers (Paris and Aquitain basins)
    - Bouillante field (Guadeloupe)
    - … and a few examples from larger well-documented fields
    - far from being exhaustive
  - hydrothermal aspects (HT, no M, no C… but a pinch of G)

Géosciences pour une Terre durable
brgm

geothermal reservoir ?

- intuitive concept from the surface:
  - *good productive well(s) tapping a resource below*
  - spatial extent may be harder to define in the subsurface
- a few definitions (Grant & Bixley, 2011)
  - *geothermal field*: convenient geographic description
  - *geothermal system*: all part of the flow paths associated with geothermal field(s)
  - *geothermal reservoir*: part of the geothermal system that is so hot and so permeable that it can be economically exploited for the production of fluid or/*and* heat
- economical considerations
  - economical thresholds that may evolve according to technological possibilities

what we are interested in

- departure from an initial/natural state
  - exploration, field development
- understanding, reproducing and forecasting pressure and temperature transients
- wellbore models
- field management, lifetime, sustainability, exhaustion/recovery
- …

Géosciences pour une Terre durable
brgm

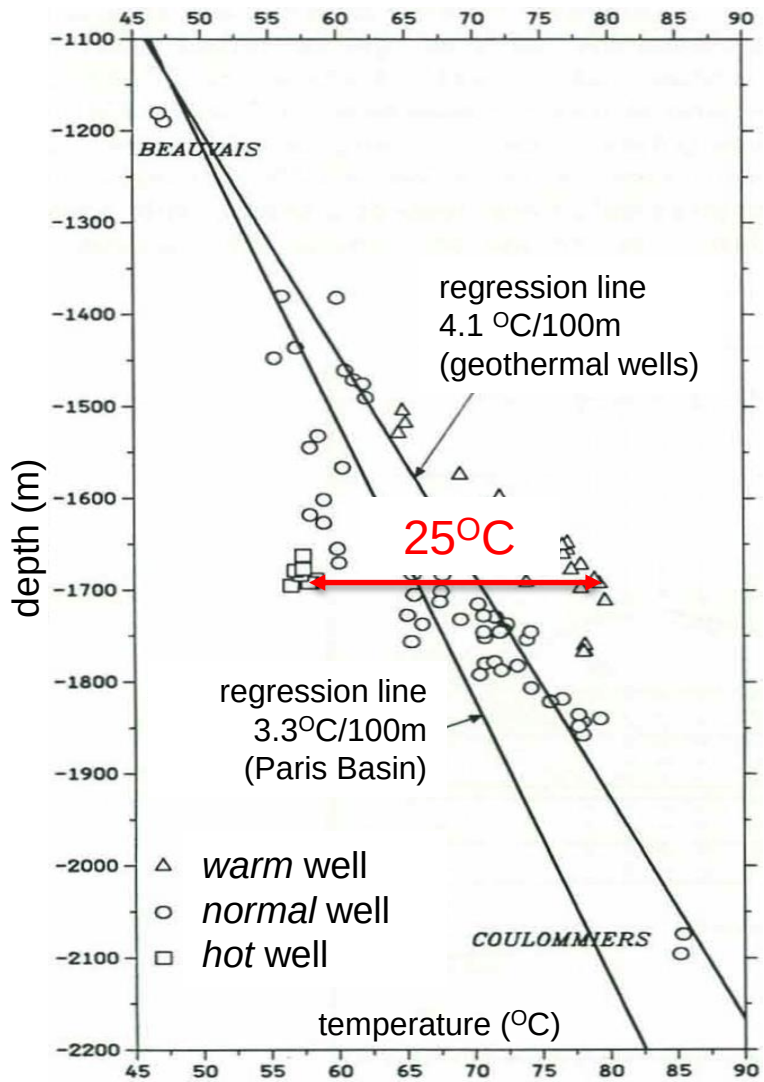
initial/natural state

- often supposed to be a stationary state
  - ok for the purpose of modeling the exploitation of the resource
  - more likely to be a transient state at the geological timescale
    - understanding this transient state will help to understand the resource but it is hardly constrainable
- a matter of boundary conditions

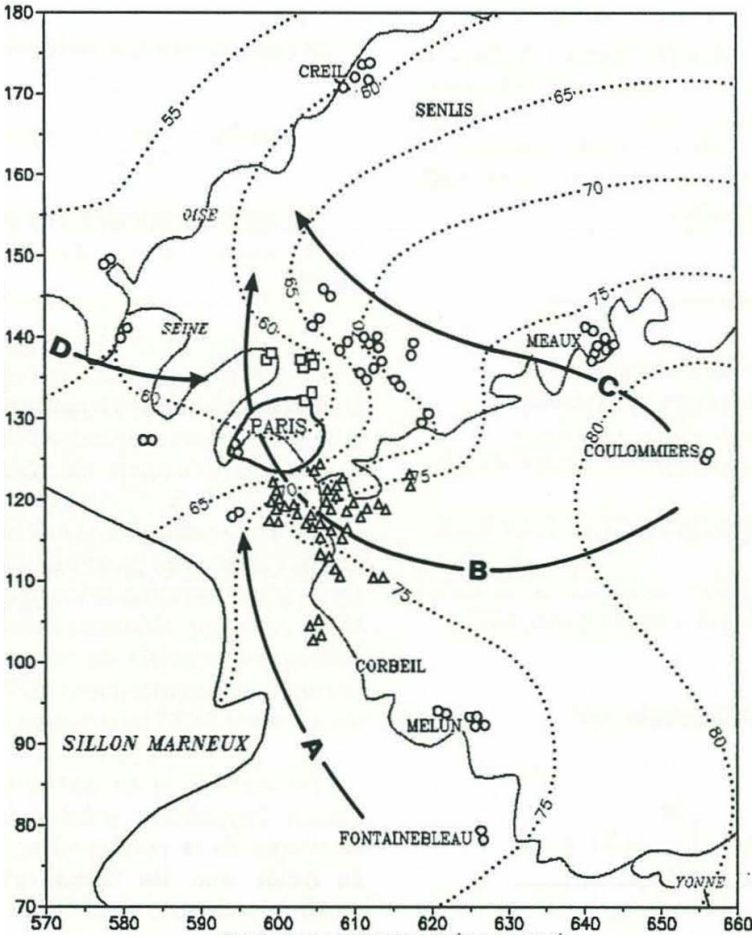
natural state of « conductive systems »

- a fixed temperature at the top boundary and a prescribed (geothermal) flux at the bottom boundary
  - linear contribution of the geothermal flux may be locally filtered out considering a uniform initial temperature
- typical case of the Dogger aquifer
  - « ok for government work » but…

departures from this conceptual model



(Dentzer 2014, modified from Rojas et al.,1989)



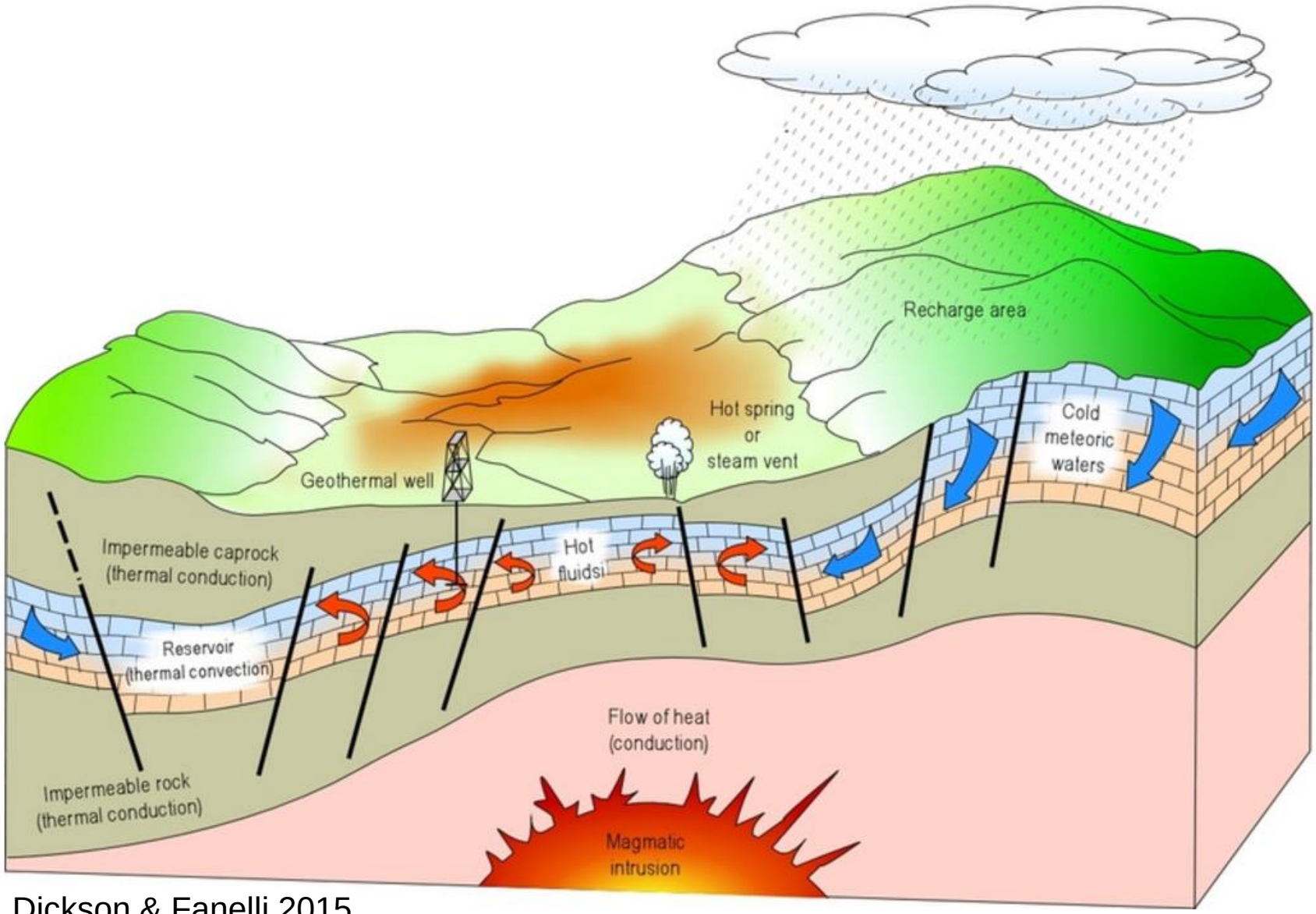
(Rojas et al.,1989)

Géosciences pour une Terre durable
brgm

natural state of « convective systems »

- hot upflows from deeper part of the geothermal system
  - problem may be tedious to tackle at the geothermal system scale

the classical conceptual model



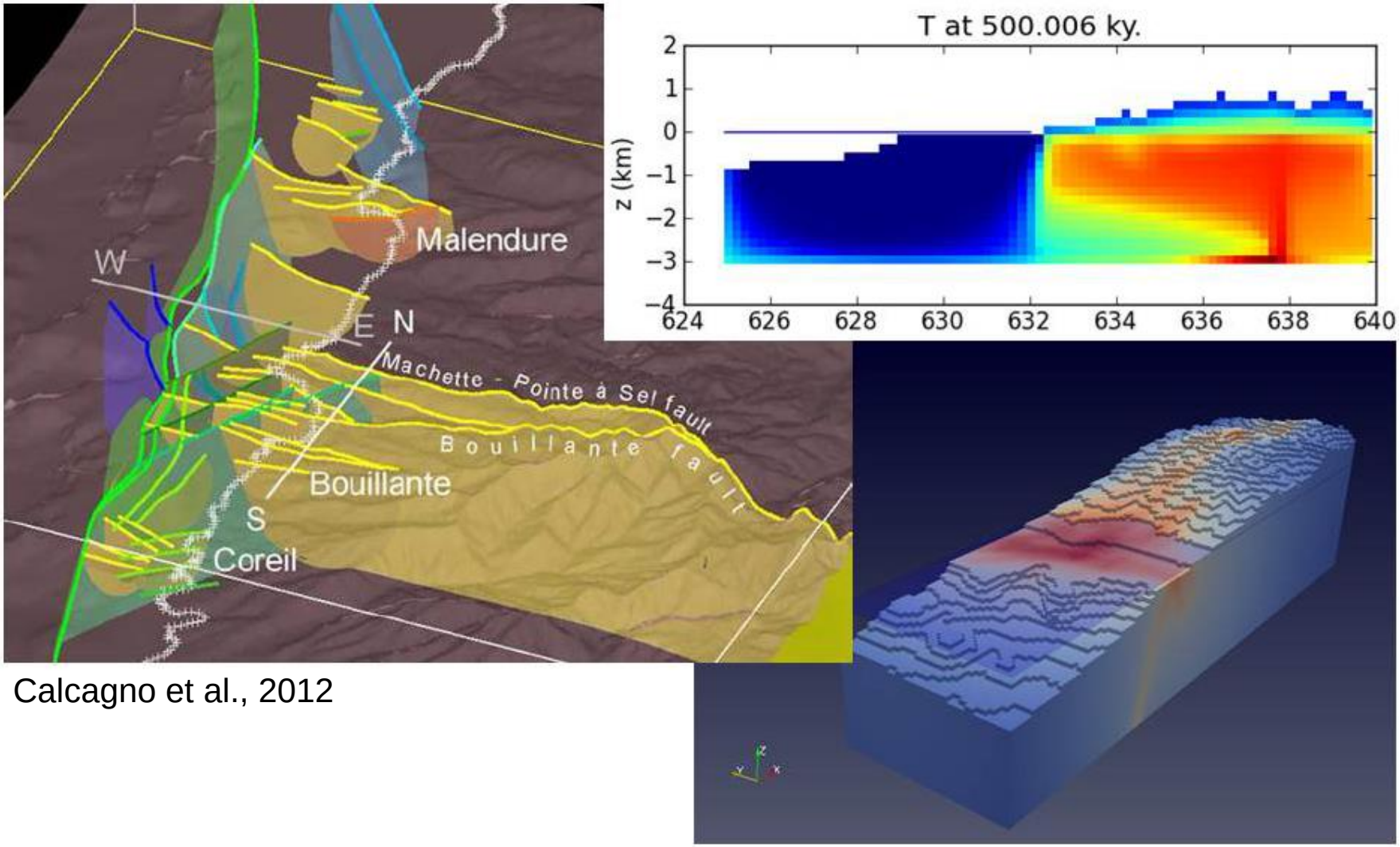
Dickson & Fanelli 2015

Géosciences pour une Terre durable
brgm

natural state of « convective systems »

- hot upflows from deeper part of the geothermal system
  - problem may be tedious to tackle at the geothermal system scale
  - highly nonlinear physics (potentially complex thermodynamics, phase changes…): instabilities, computationally intensive, (much too small) time steps…
  - multiscale geological objects

Bouillante example



Calcagno et al., 2012

Géosciences pour une Terre durable
brgm

natural state of « convective systems »

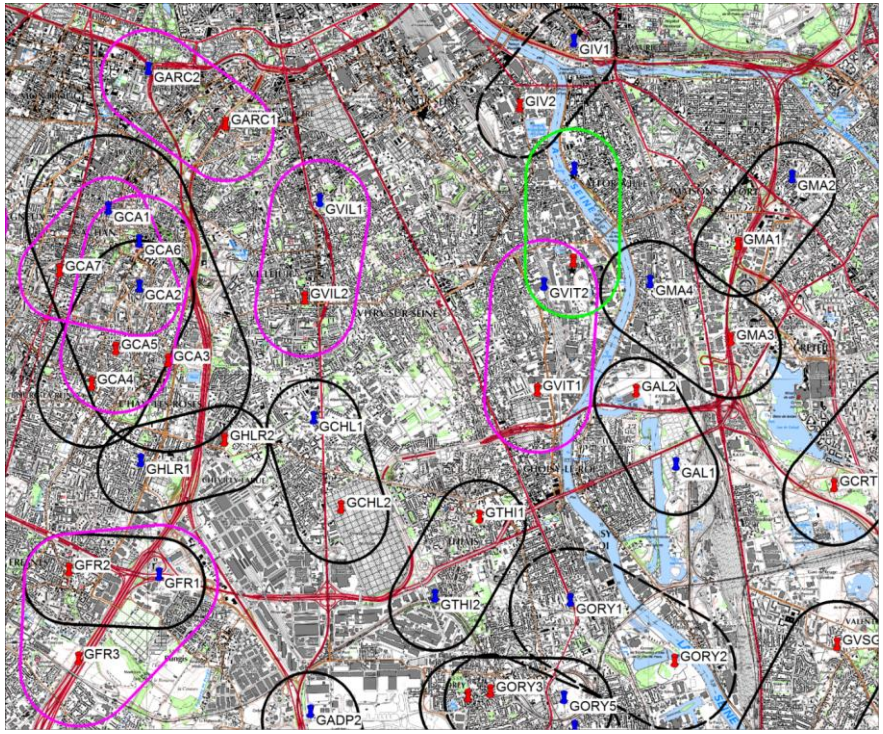
- hot upflows from deeper part of the geothermal system
- Bouillante example
- … the practical way
  - “roots of the geothermal system” are rarely considered nor are shallow levels (vadose zone)
  - find the *ad-hoc* boundary conditions (hot fluids input) to match the data inside (temperature, well tests…) the “reservoir box” integrating the geological model as well as can be…

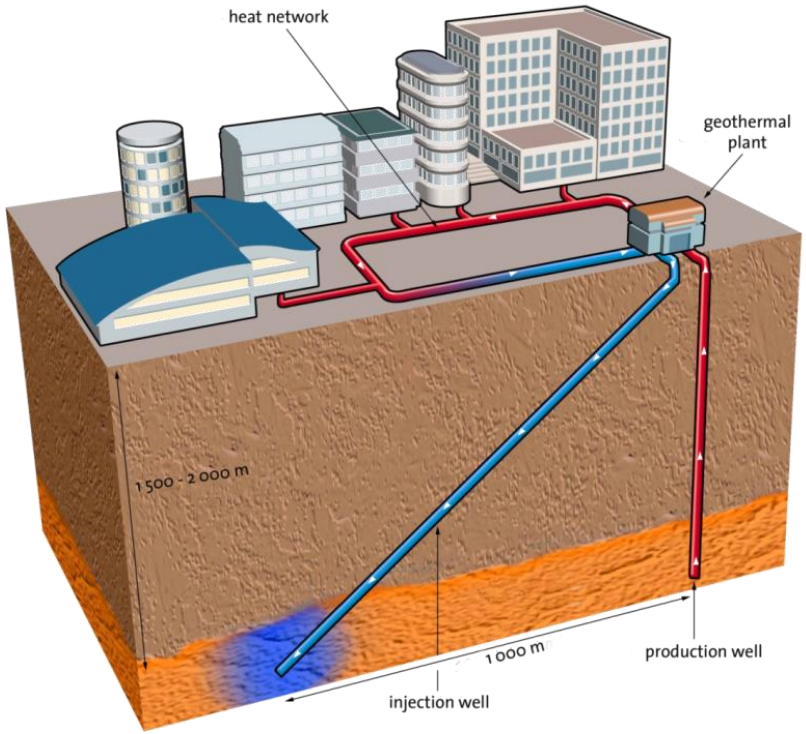
pressure transients

- resource exploitation implies a pressure drop
  - reservoir often reacts as a whole because of pervasive permeable units
  - linked to the amount of fluid resource used
  - may (or may not) stabilize, depending on recharge, reservoir state…
  - may impact the resource exploitability but injection schemes can mitigate these adverse effects

optimal well siting / resource management

- geothermal doublets targeting the Dogger aquifer

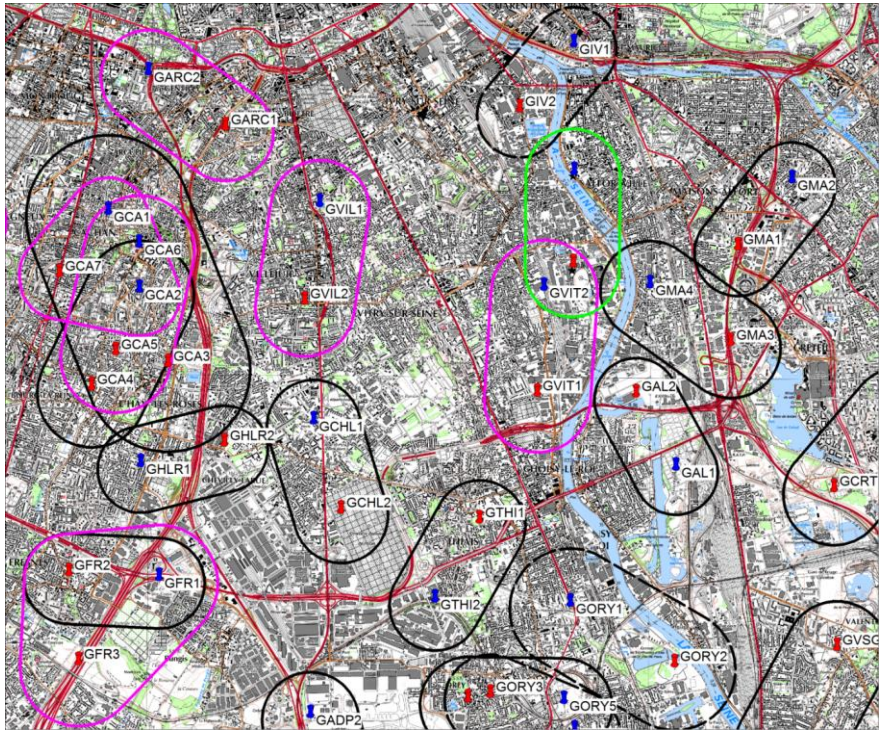


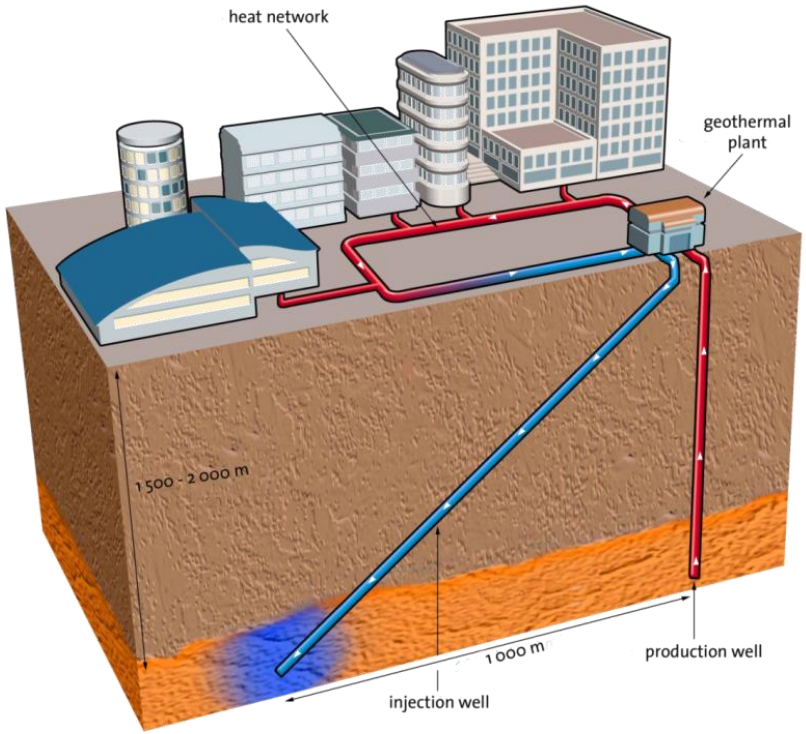


Géosciences pour une Terre durable
brgm

optimal well siting / resource management

- geothermal doublets targeting the Dogger aquifer





- the Geysers field exploitation showed that there was an optimal well spacing and that, at some point, additional drilling was not economical (Sanyal, 2000)

Géosciences pour une Terre durable
brgm

lumped parameters models

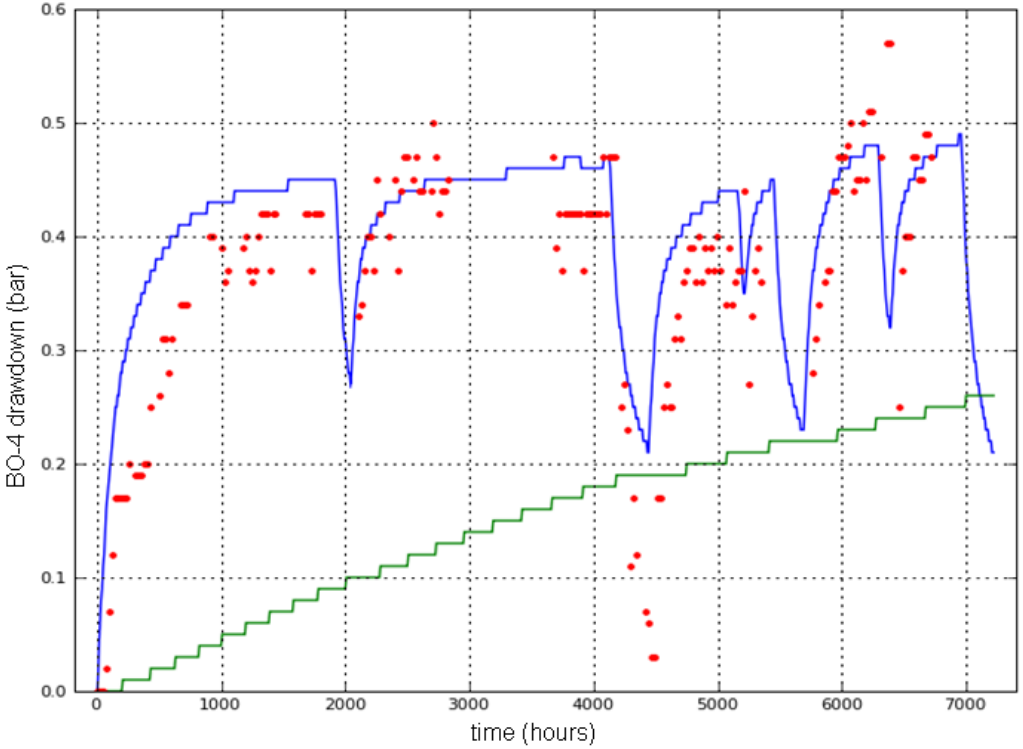
- « black-box models » that do not integrate processes and cannot forecast long-term evolution or deviation from the fitted trend
- different models fitted on the same date may eventually diverge
- easy to fit to data (least square regression)
- often provide the best short-term pressure forecast
- have proven to be valuable tools in studying quantitatively sustainability issues
- **not very satisfactory nor interesting from a *physical point of view***

Géosciences pour une Terre durable
brgm

reservoir simulation

- TOUGH2 family of codes has been the geothermal standard for 25 years now
  - dedicated to geothermal applications from the beginning
  - detailed fluid physics (several EOS modules) but limited range of validity (T<350°C)
  - wide (code) diffusion… as many versions as users
  - Two Point Flux Approximation
  - (really) poor numerical performances

Bouillante numerical reservoir model



Lopez et al., 2010

reproducing interferences tests
using Tough2:
MINC module
(dual porosity/permeability)
reservoir is an isolated cube
with regular discretisation
(no geology…)

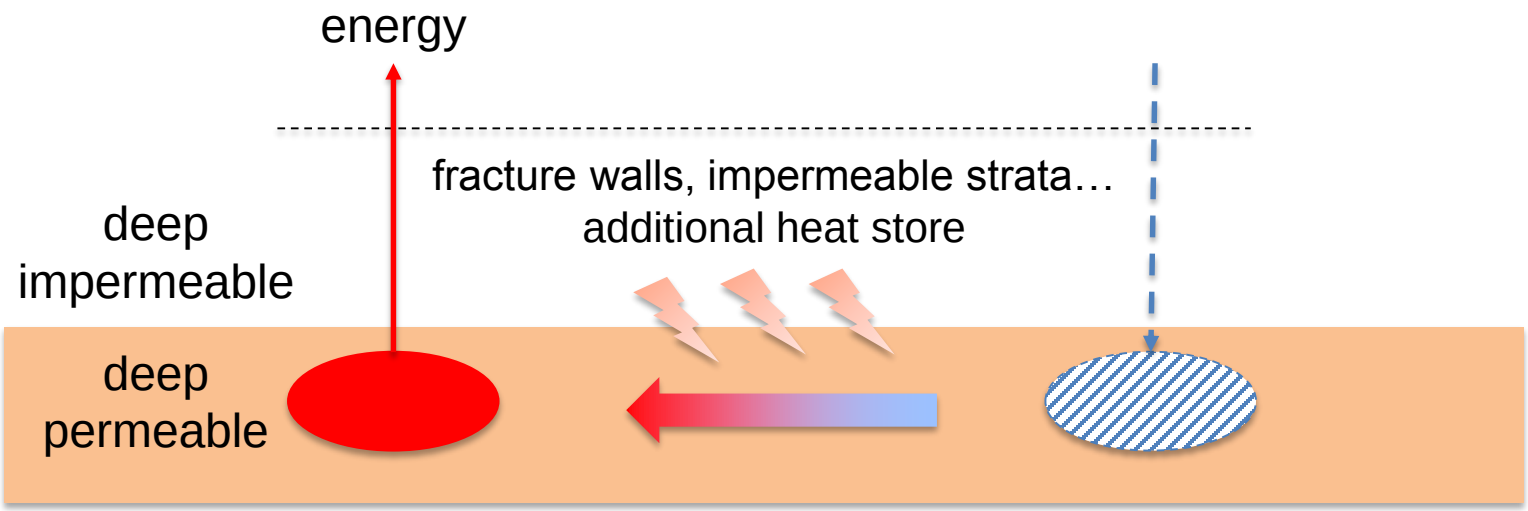
data
fracture pressure
matrix pressure

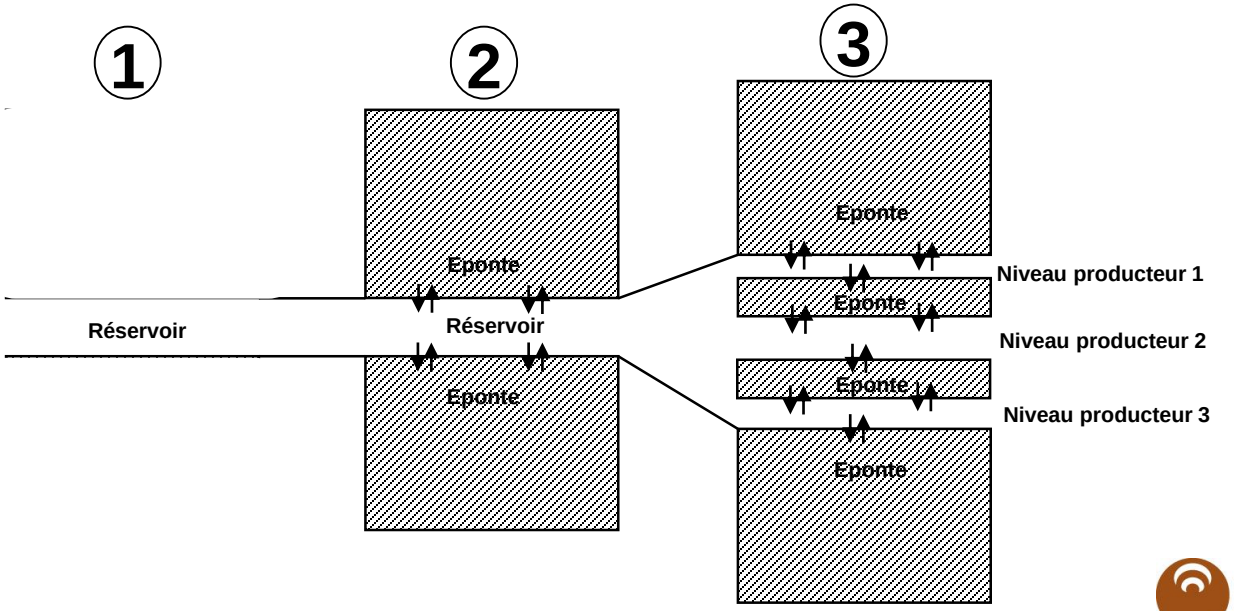
Géosciences pour une Terre durable
brgm

thermal evolution of the reservoir

- temperature drop may occur without cold brine reinjection
  - boiling
    - may temporarily increase the energetic content of the fluid
    - steam cap may develop with gravity drainage
  - cold inflows may also come from overlying or peripheral aquifers
- in-field reinjection implies the possibility of thermal breakthrough
  - tracer tests may provide chemical precursors and are useful to identify flow paths
  - if the convective flow path are not too fast, impermeable bodies may provide appreciable additional heat store

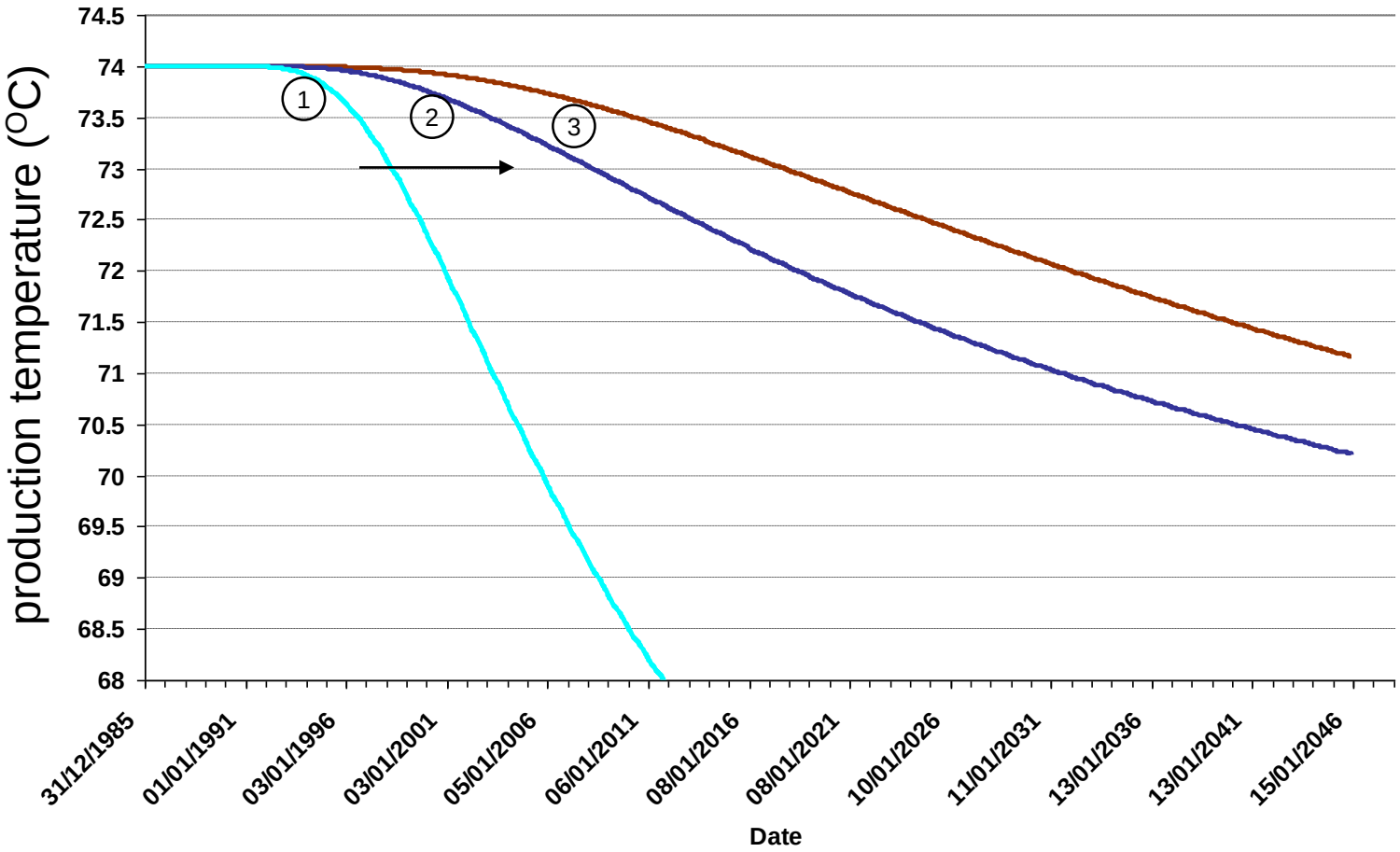
thermal evolution – Dogger aquifer





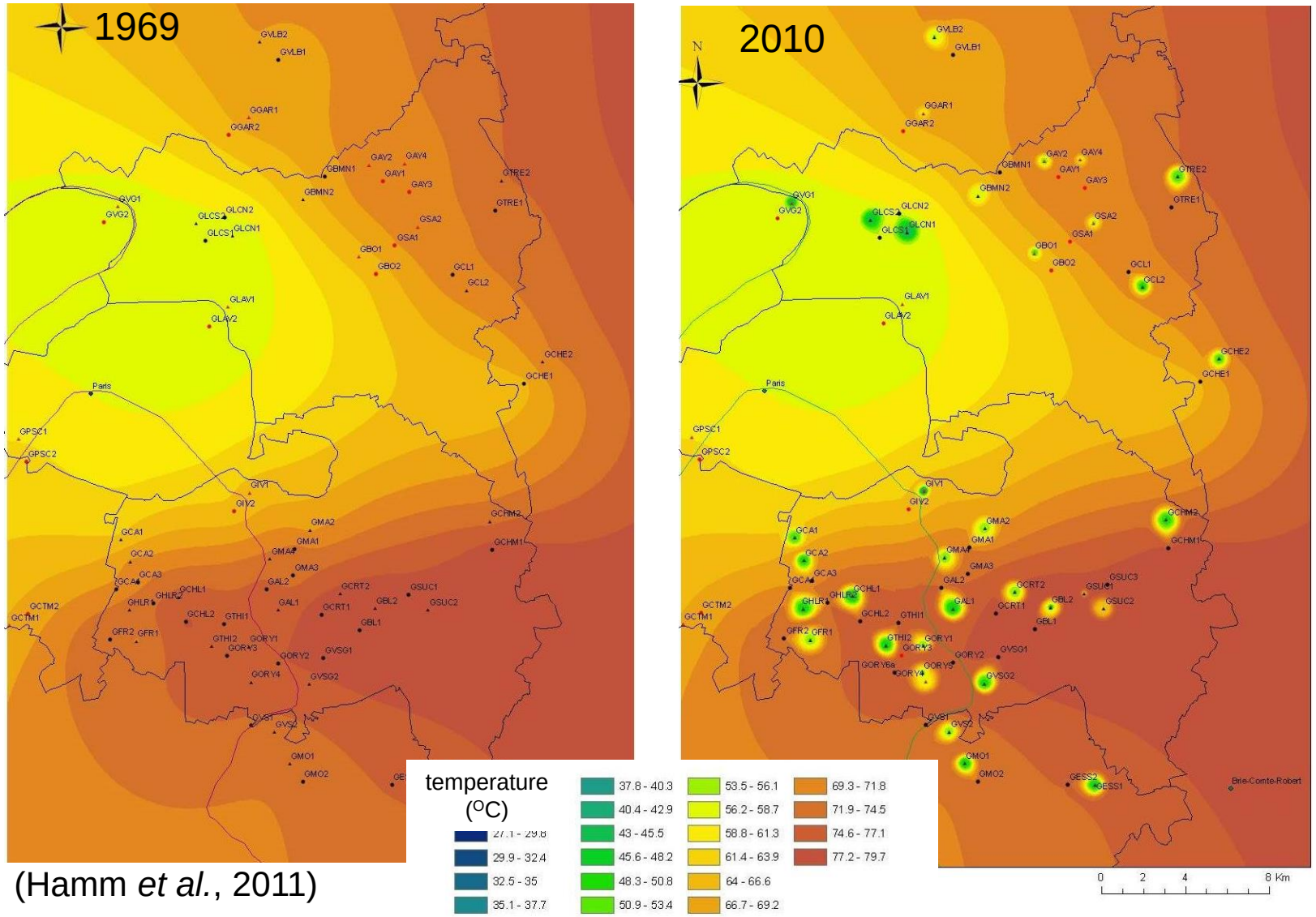
Géosciences pour une Terre durable
brgm

thermal breakthrough in the Dogger aquifer



Géosciences pour une Terre durable
brgm

monitoring the resource at regional scale

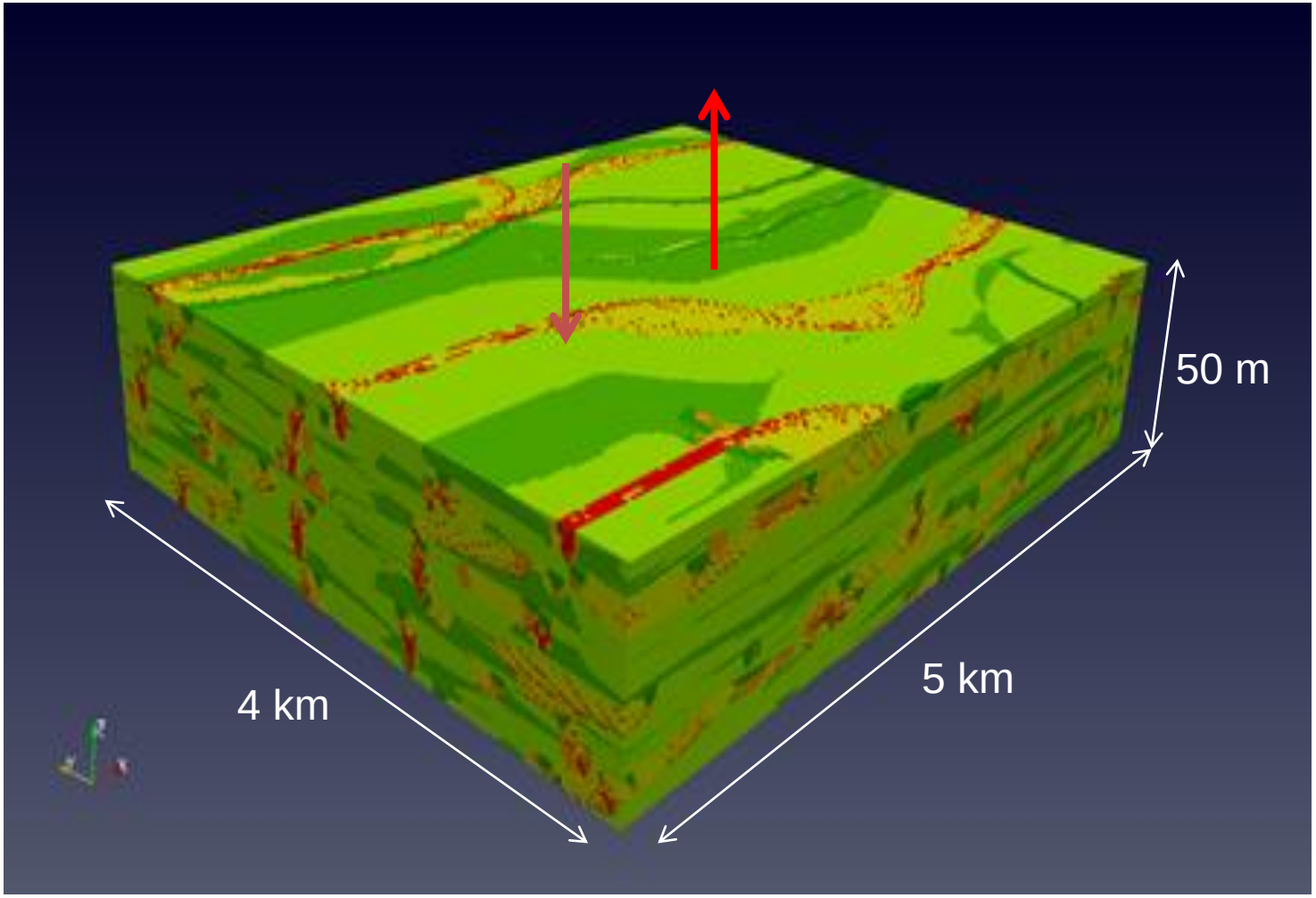


(Hamm *et al.*, 2011)

Géosciences pour une Terre durable
brgm

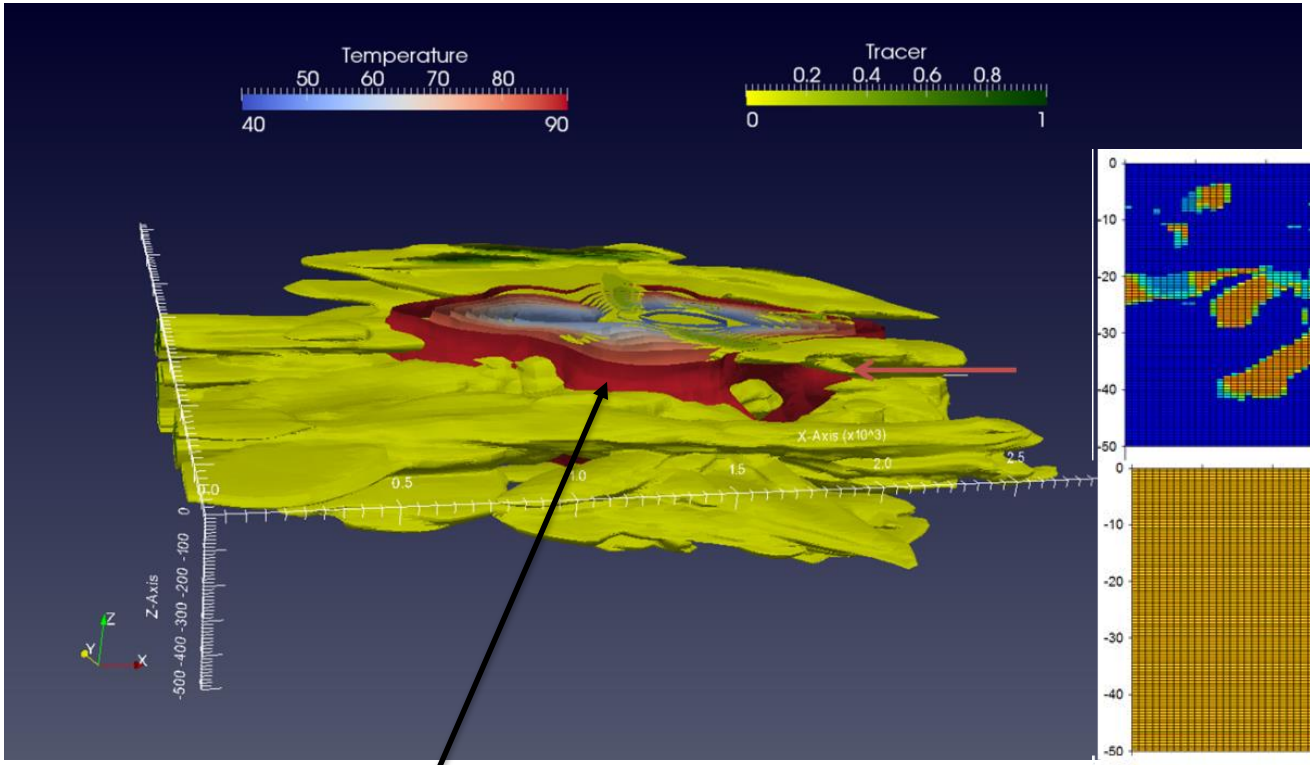
geothermal doublet in a sandstone aquifer

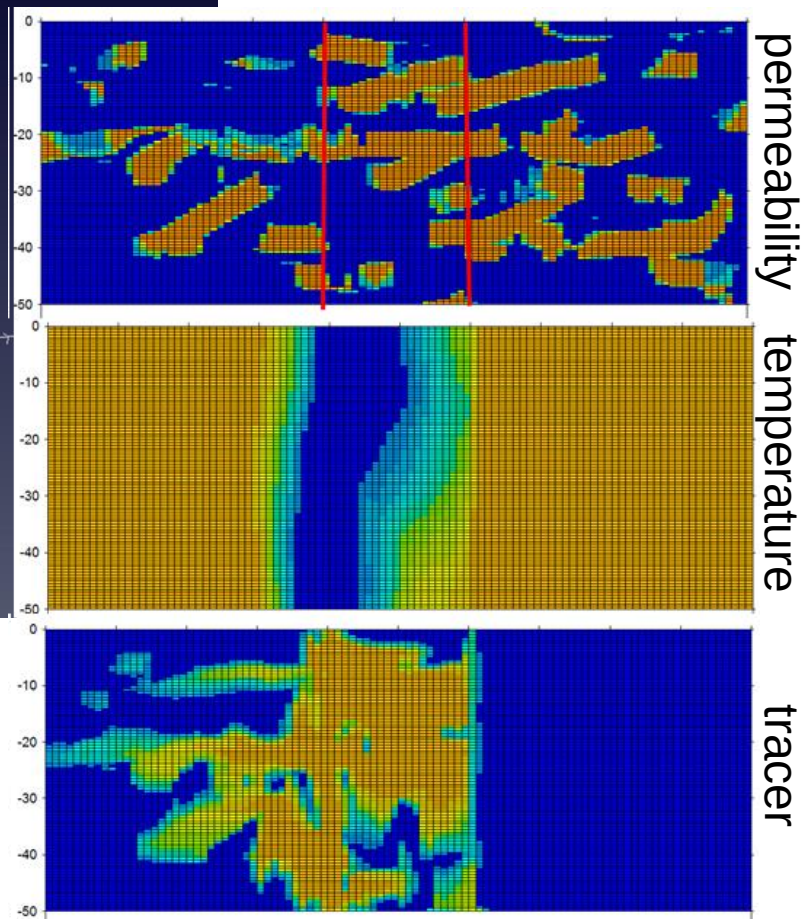
impact of geological heterogeneities



Géosciences pour une Terre durable
brgm

geothermal doublet in a sandstone aquifer





Hamm & Lopez, 2012

temperature diffusion smoothens thermal impact of heterogeneities

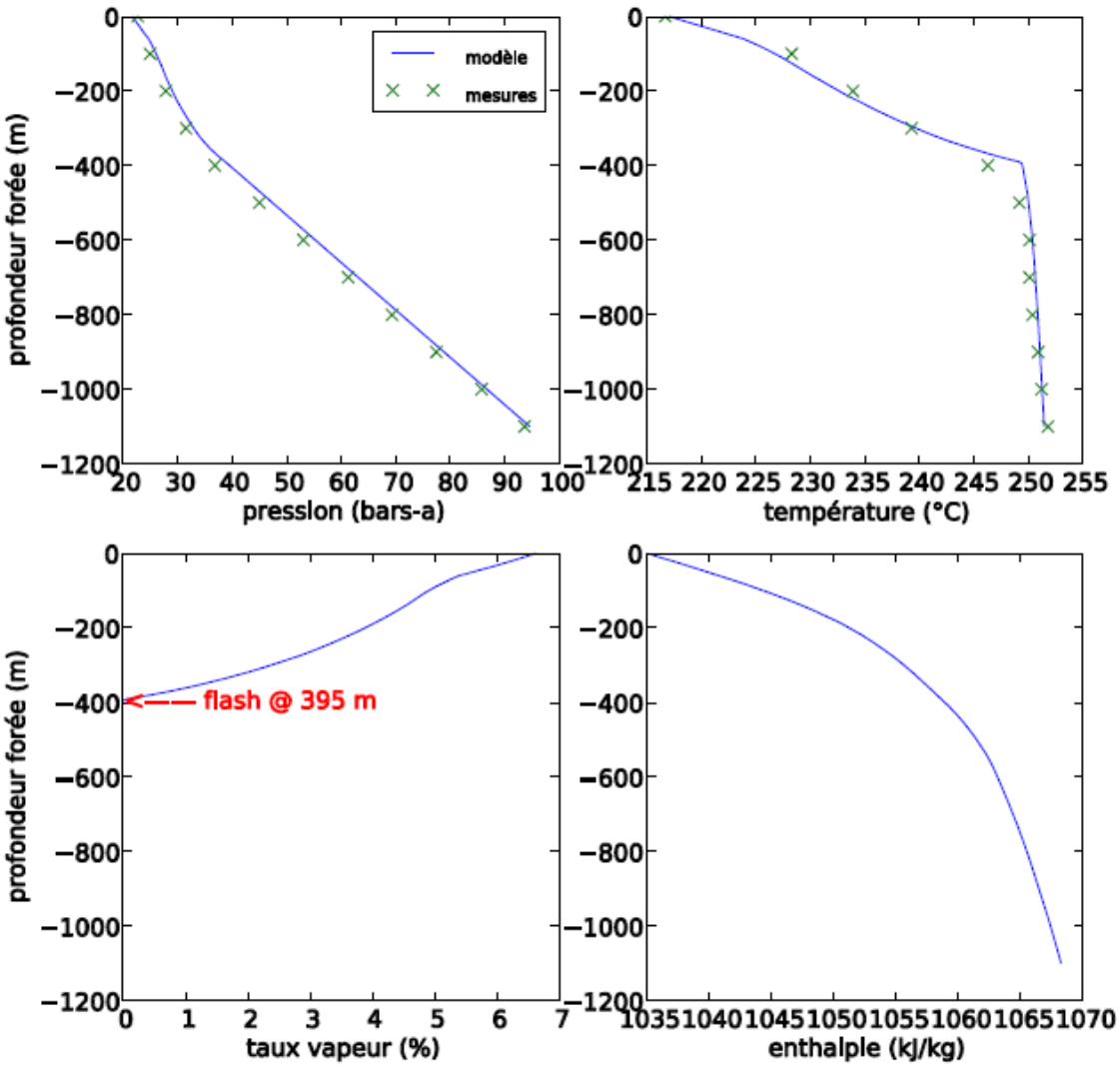
10 years

Géosciences pour une Terre durable
brgm

wellbore models

- wells are where change is detected
- wellbore models are necessary tools to monitor reservoir evolution from the well head
- if the fluid stays monophasic
  - essentially head losses and conductive heat losses
  - simple transfer function (but density effects and convective perturbations)
- if the fluid is boiling inside the wellbore
  - things may get much more complex
- coupling reservoir and wellbore models is a desirable thing but a hard problem (stiffness)

wellbore models

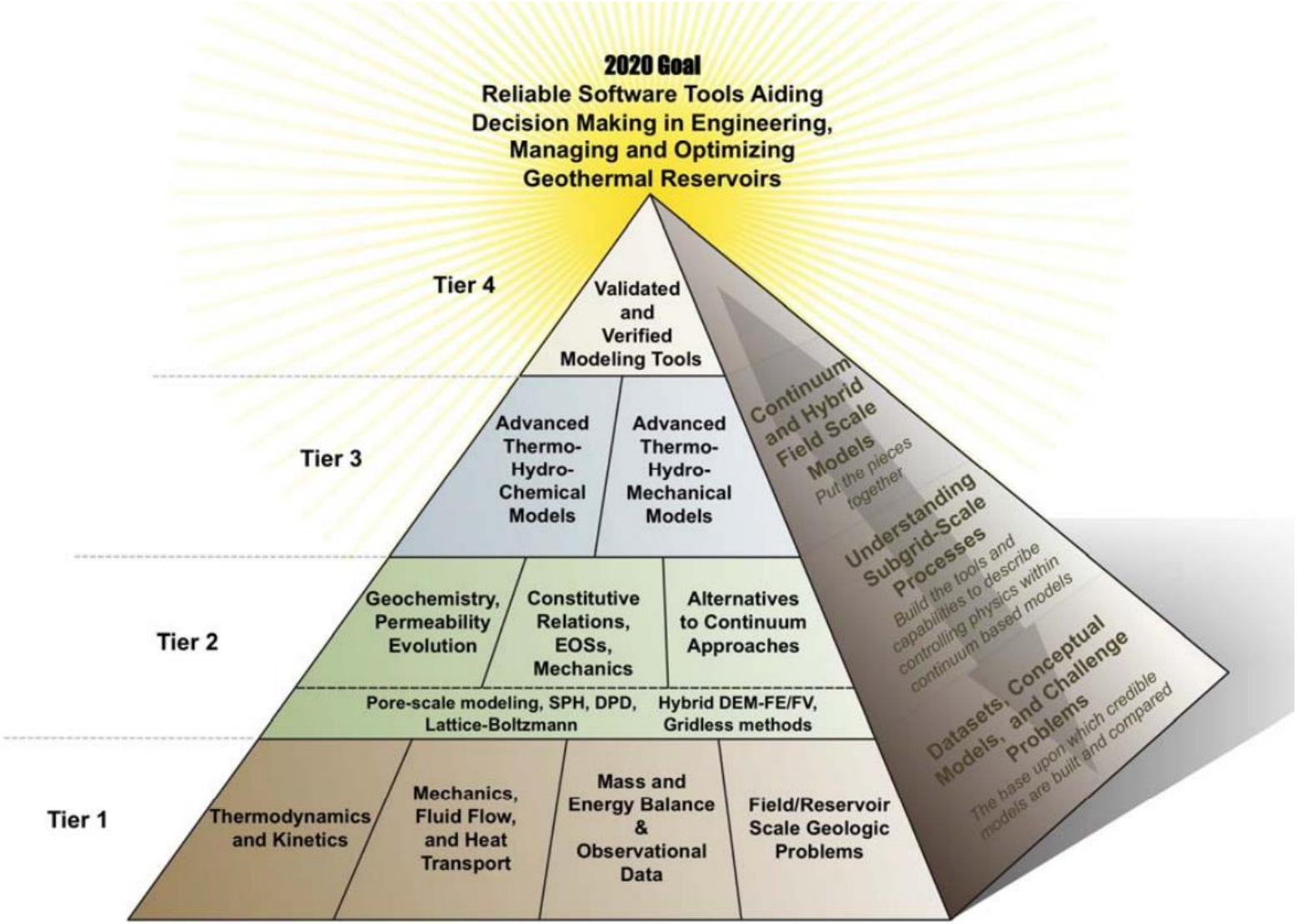


BO-4 dynamic logs from Bouillante field reproduced with GNACL

Giuglaris & Lopez, 2012

Géosciences pour une Terre durable
brgm

current needs



International Partnership for Geothermal Technology (IPGT) white paper on geothermal reservoir modeling (2012)

Géosciences pour une Terre durable
brgm

current needs

- IPGT white paper (2012)
- several initiatives worldwide towards new modern geothermal reservoir modeling tools among wich:
  - Tough2 evolutions
  - CSMP++ platform (ETH Zurich, Leoben, Herit-Watt University)
  - Geothermal Supermodels (open initiative/New Zealand)
  - OpenGeoSys
  - …
  - what about a French one?

(ideally) we would like to be able to

1. (quickly) build structural models involving geological bodies of any shape and with the occurrence of discontinuities,

2. (quickly) produce conformable quality meshes of such models,

3. (quickly) perform multiphase thermo-hydraulic simulations with phase change on these meshes without numerical artefacts.

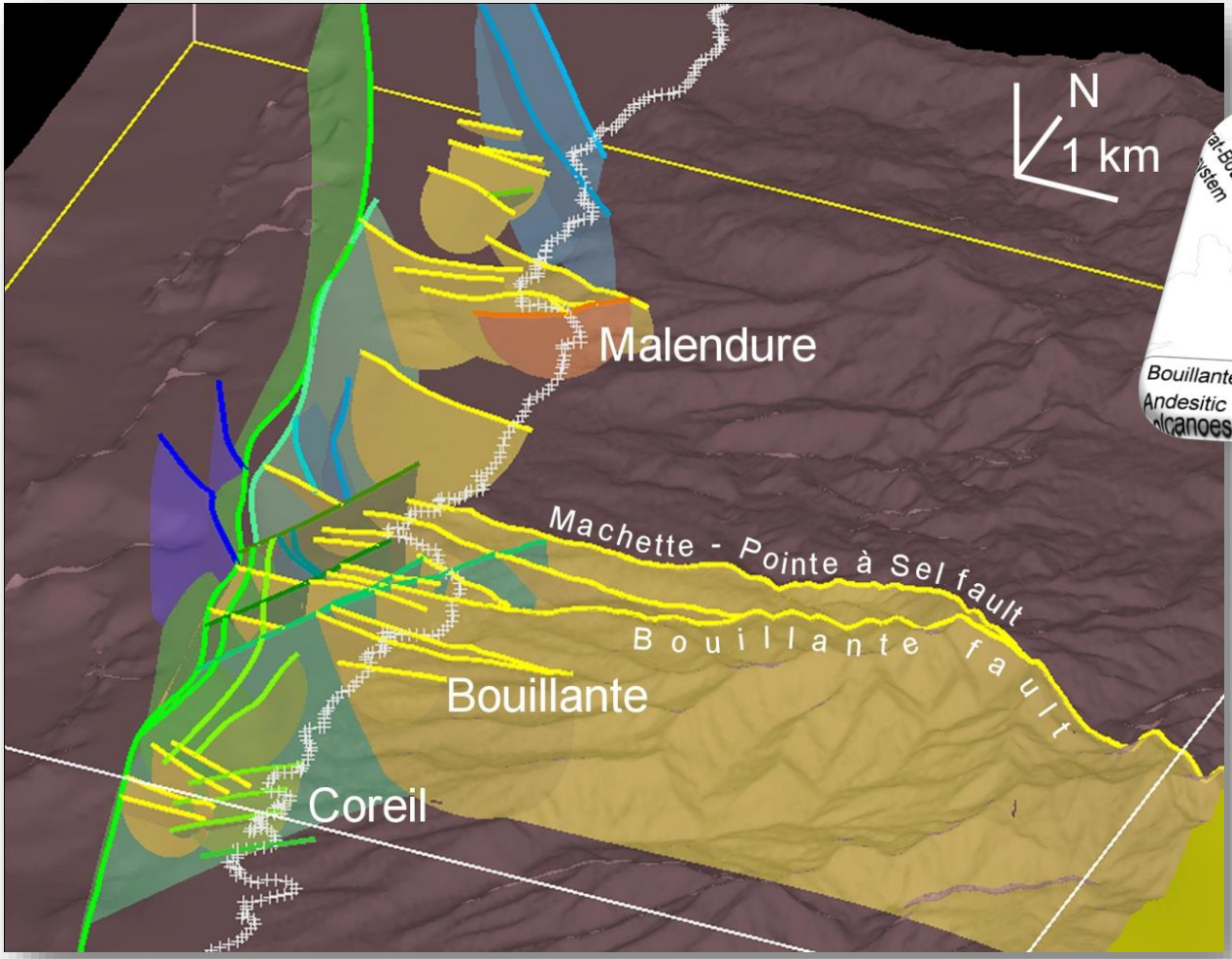
(4.) close the loop: sensistivity analysis, inversion …

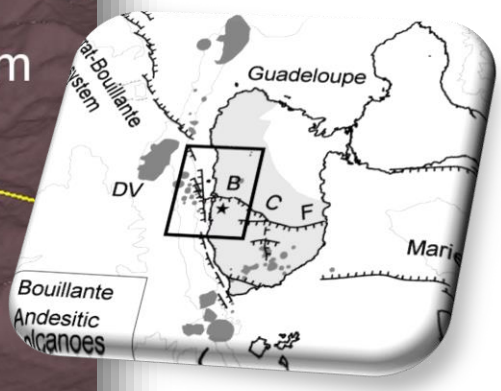
Géosciences pour une Terre durable
brgm

goal #1 structural models

implicit techniques: well-proven approach

e.g. GeoModeller: potential field modeling and interaction rules between implicit surfaces (Lajaunie *et al.* 1997, Calcagno *et al.* 2008)





15 x 16 x 2 km

Calcagno *et al.* 2012

GeoModeller 2014

Géosciences pour une Terre durable
brgm

goal #2 (quality) meshes

- obtain a 3D tetrahedral mesh of geological formations which is conformal to (all) boundaries (fractures) as described by the implicit functions model
- the main requirements for an appropriate reconstruction of implicit surfaces and volumes are:
  - the respect of geological singularities (sharp angles at intersecting surfaces, faults displacements),
  - the respect of cell size and shape criteria (user given),
  - the respect of topological constraints.

CGAL 3D mesh generation package

- CGAL (Computational Geometry Algorithms Library) is a product of GeometryFactory, initiated at Geometrica research group from INRIA Sophia-Antipolis
- designed to mesh implicit domains (no other alternative ?)
- mesh generation based on progressive Delaunay mesh refinement until proximity and size criteria are reached
  - produce bad quality cells (slivers) which must be removed through an optimization phase
- generic programming paradigm (C++ templates)
  - the user must implement an « oracle » which returns domain indexes (geological formations) found at a given location and surface indexes that a given ray may intersect (faults, geological interfaces…)

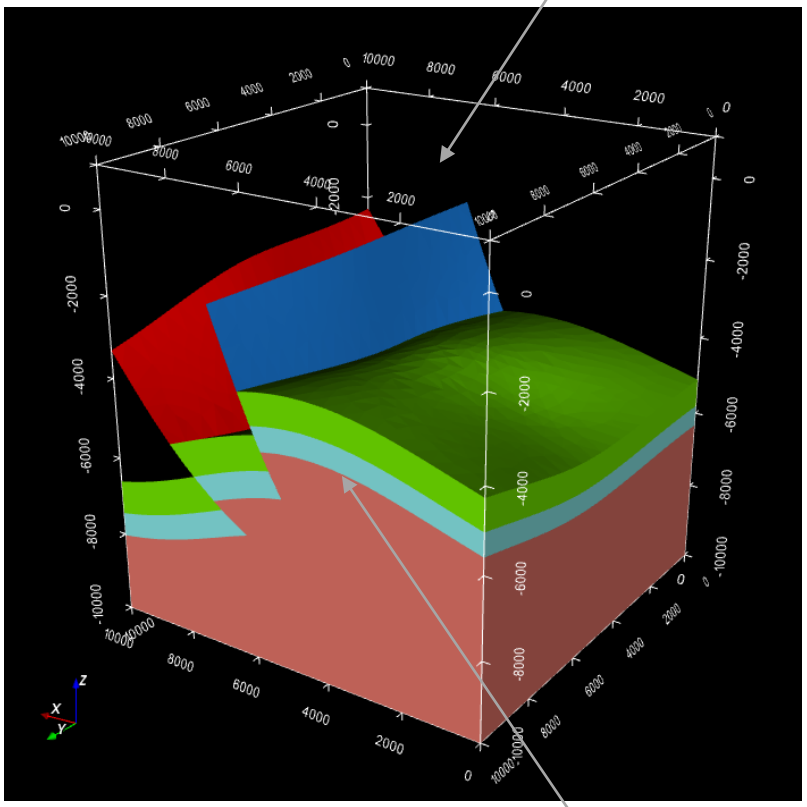
goal #3 speed-up simulations

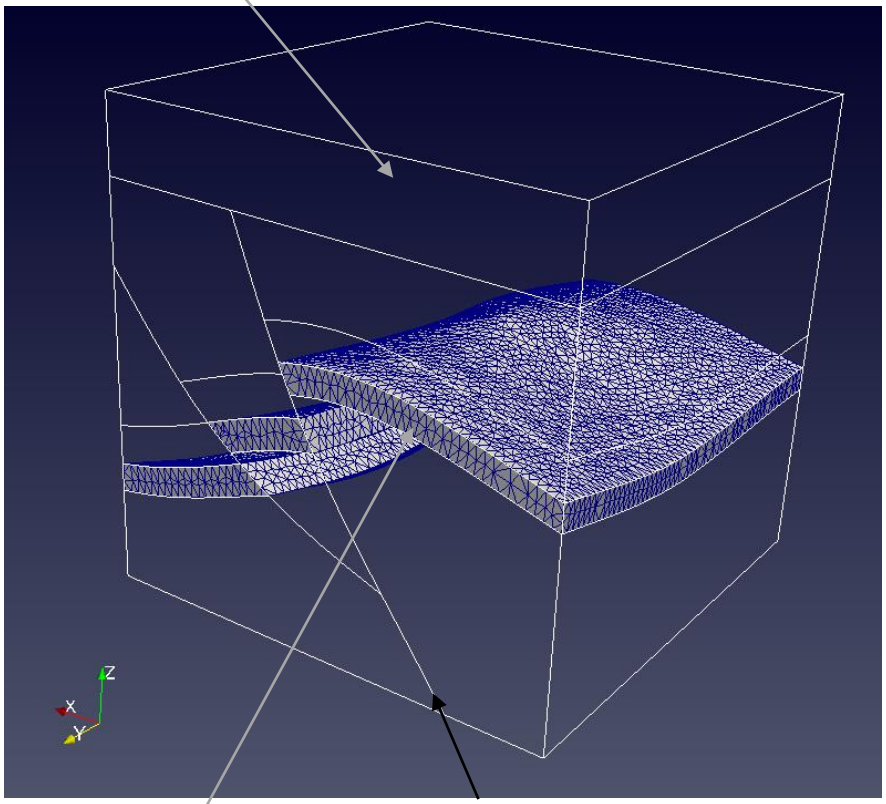
- ongoing developments on the ComPASS platform
  - Dalissier et al. 2013: parallel version of the VAG/SUSHI schemes for the pressure equation
  - interCarnot BRGM/INRIA postdoctoral position : Feng Xing 2015-2016
    - parallel version of a hybrid Darcy model (matrix/fractures)
    - passive tracer advection

Géosciences pour une Terre durable
brgm

a synthetic (slightly geological) example

caprock layer





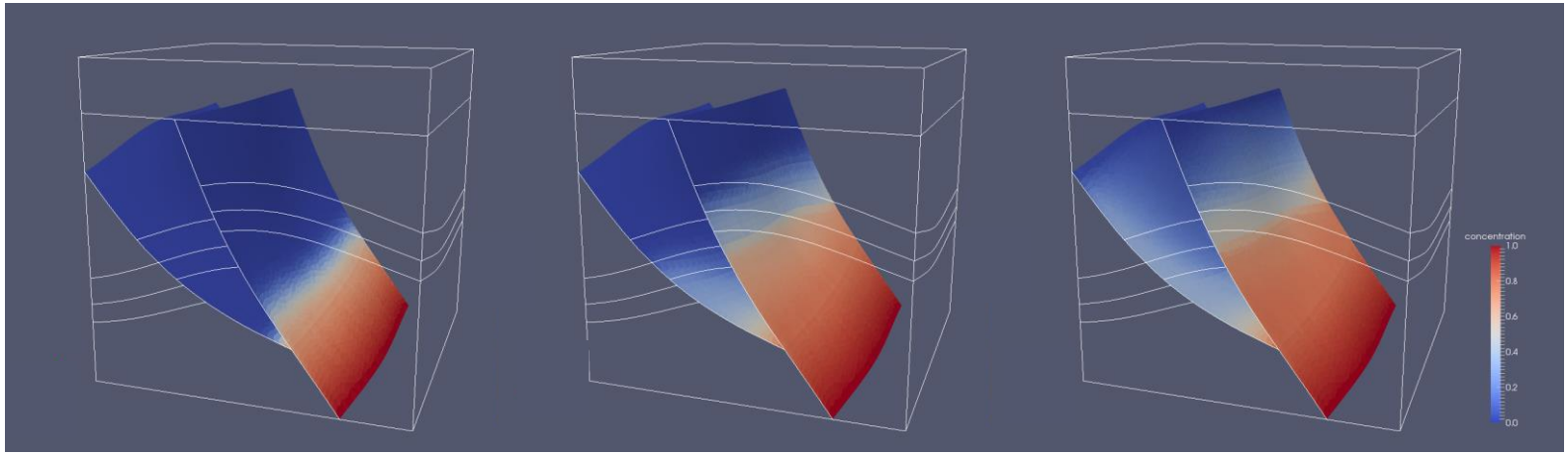
tracer injection
along the fault

aquifer layer

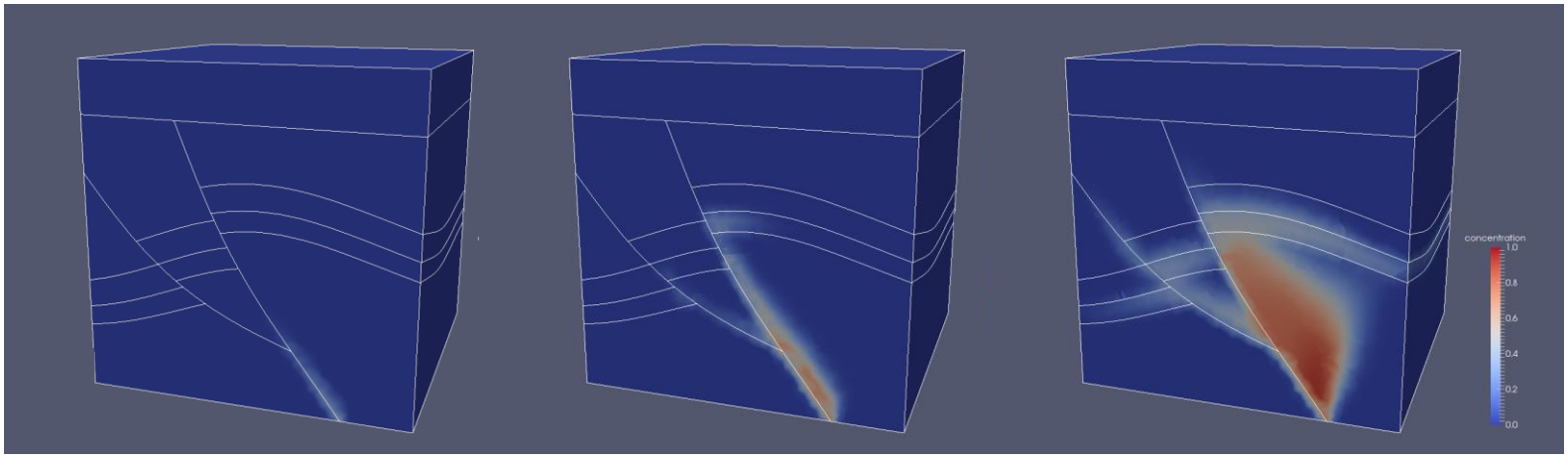
Géosciences pour une Terre durable
brgm

tracer advection

tracer concentration in the fractures



tracer concentration in the matrix

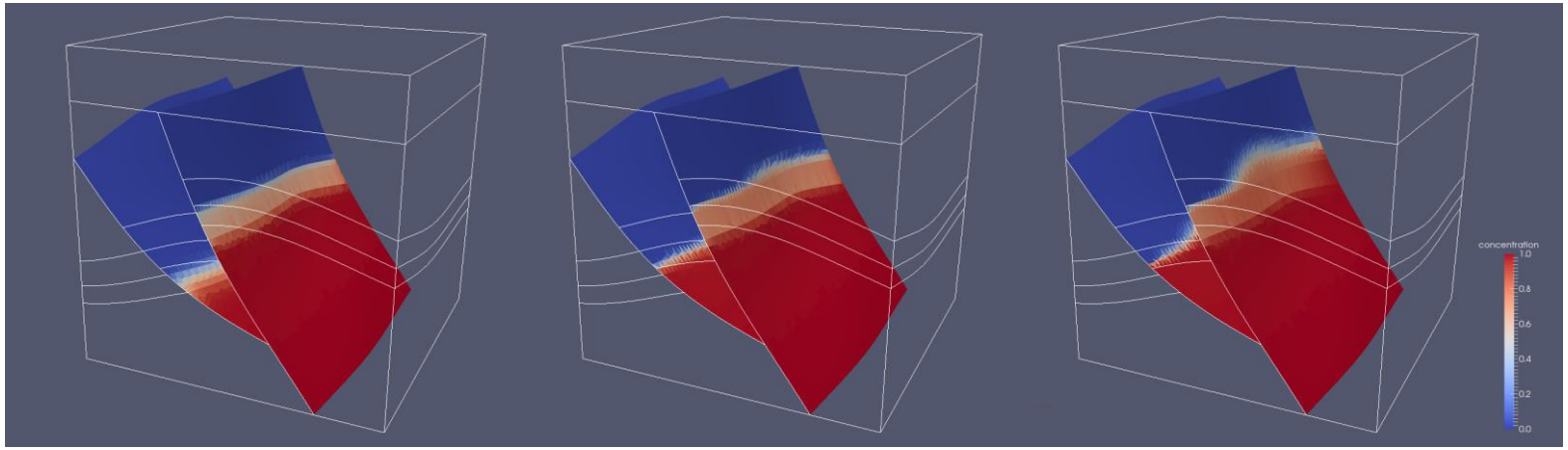


low permeability contrast
(aquifer / host rock)

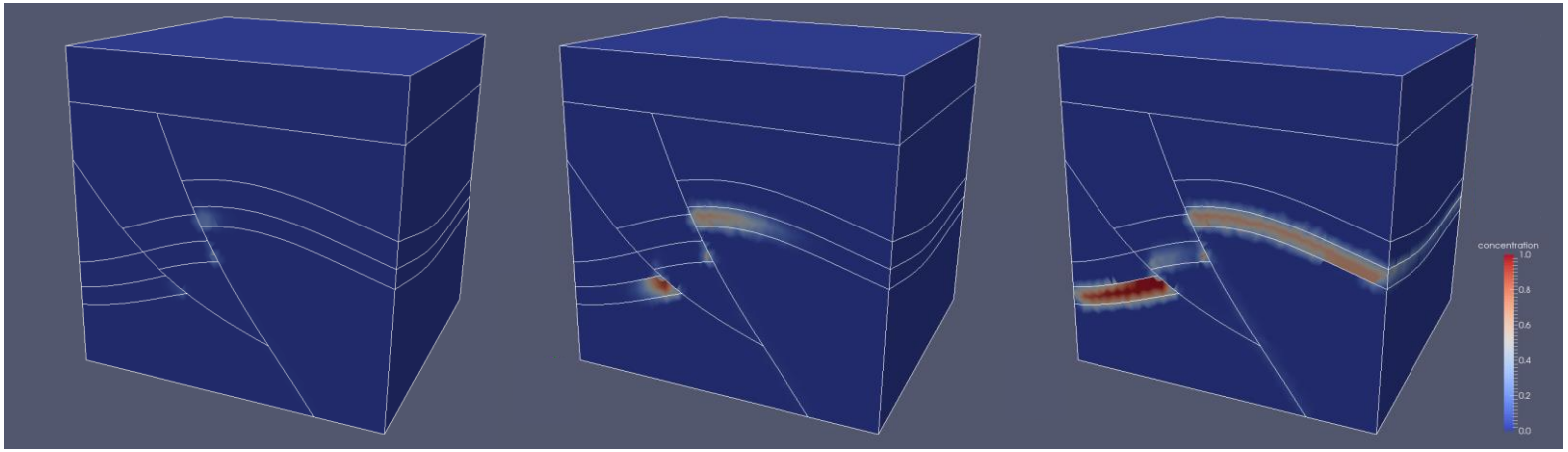
Géosciences pour une Terre durable
brgm

tracer advection

tracer concentration in the fractures



tracer concentration in the matrix



high permeability contrast
(aquifer / host rock)

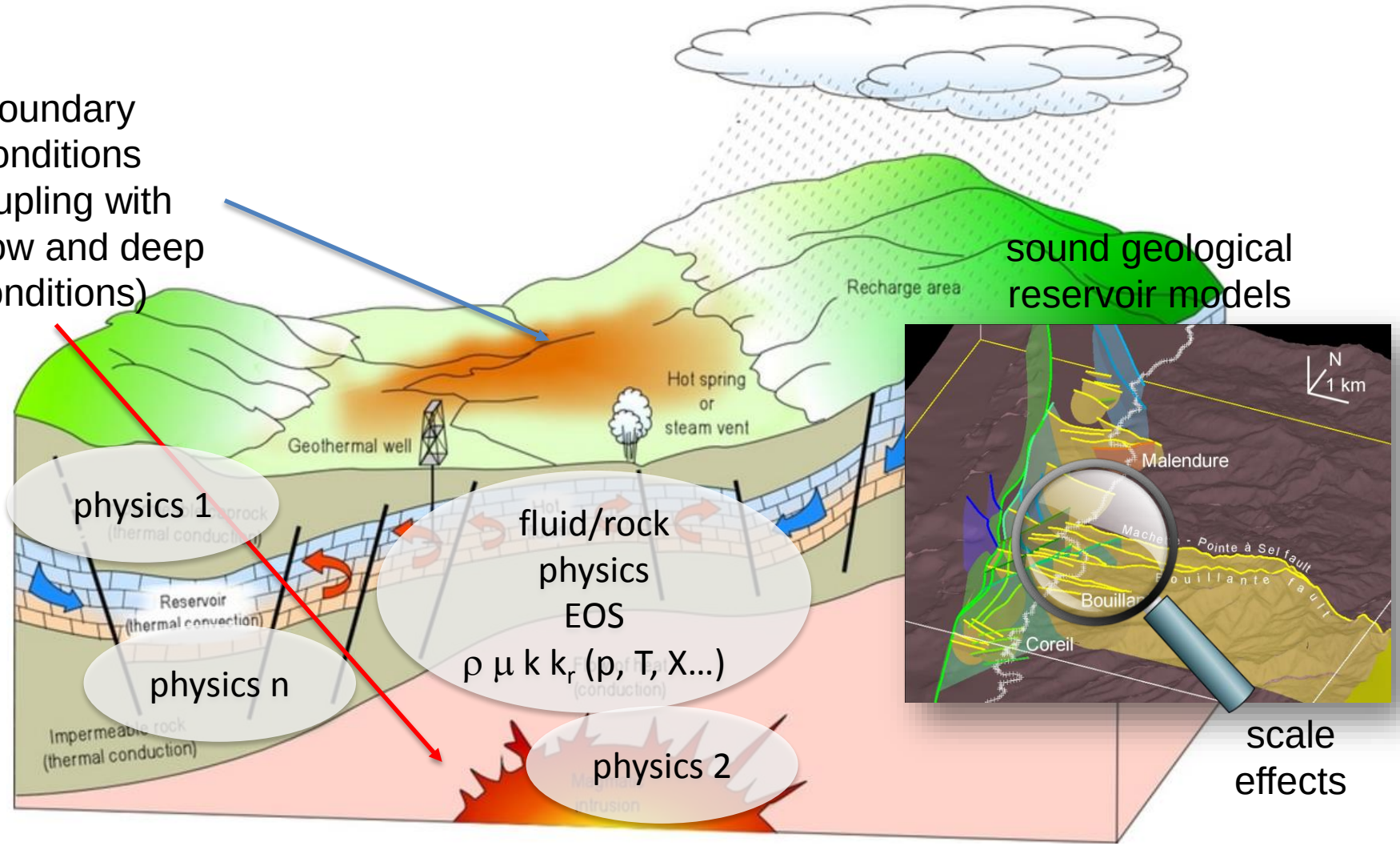
Géosciences pour une Terre durable
brgm

goal #3 speed-up simulations

- ongoing developments on the ComPASS platform
  - Dalissier et al. 2013: parallel version of the VAG/SUSHI schemes for the pressure equation
  - interCarnot BRGM/INRIA postdoctoral position : Feng Xing 2015-2016
    - parallel version of hybrid Darcy model (matrix/fractures)
    - passive tracer advection
    - ongoing work: parallel implementation of non isothermal multiphase multicomponent transfers
    - 2016: validation and application on the Bouillante geothermal reservoir model

some conclusions

boundary conditions (coupling with shallow and deep conditions)



sound geological reservoir models

scale effects

towards new conceptual reservoir models that integrate constraints from both static and dynamic models:

→ regional assessment of geothermal fields

→ reliable natural state for modeling reservoir exploitation

Géosciences pour une Terre durable
brgm

some conclusions

- geothermal reservoirs are dynamic systems which are naturally evolving on timescales much larger than the exploitation timescales, many developments are needed concerning:
  - robustness
  - integration of complex physics in a flexible way
  - computanional efficiency/HPC
  - flexible geological models/and their discretization with quality meshes
  - numerous boundary conditions types
    - coupling with deep or shallow environments
  - wellbore models and their coupling to the reservoir model

some conclusions and perspectives

- reliability is a real concern
  - so that *reasonable* models run to completion (and are reproducible)
- practical aspects (IO…) are not to be overlooked
- then, inversion/uncertainty analysis would be great
  - should also/mainly concern the static geological model (both architectural and petrophysical aspects)
  - subsurface phenomena are loosely constrained: modeling reservoir evolution is a matter of assumptions – the fewer that are made, the better
- coupling different models/physics (THMC…)
- all developments can be directly adapted to EGS modeling