Some aspects and current needs for geothermal reservoir modeling.

First results obtained with ComPASS platform.

Simon Lopez, Roland Masson, Feng Xing

some aspects and current needs for geothermal reservoir modeling

- generalities
  - a tentative classification of geothermal energies
- deep geothermal energy
- some aspects of geothermal reservoir modeling
  - « natural state » - exploration phase
  - thermal impact of the exploitation
  - on the importance of wells
- current needs

a preliminary definition

geothermal energy

=

heat stored in the Earth crust

a preliminary definition

geothermal energy

=

heat stored in the Earth crust

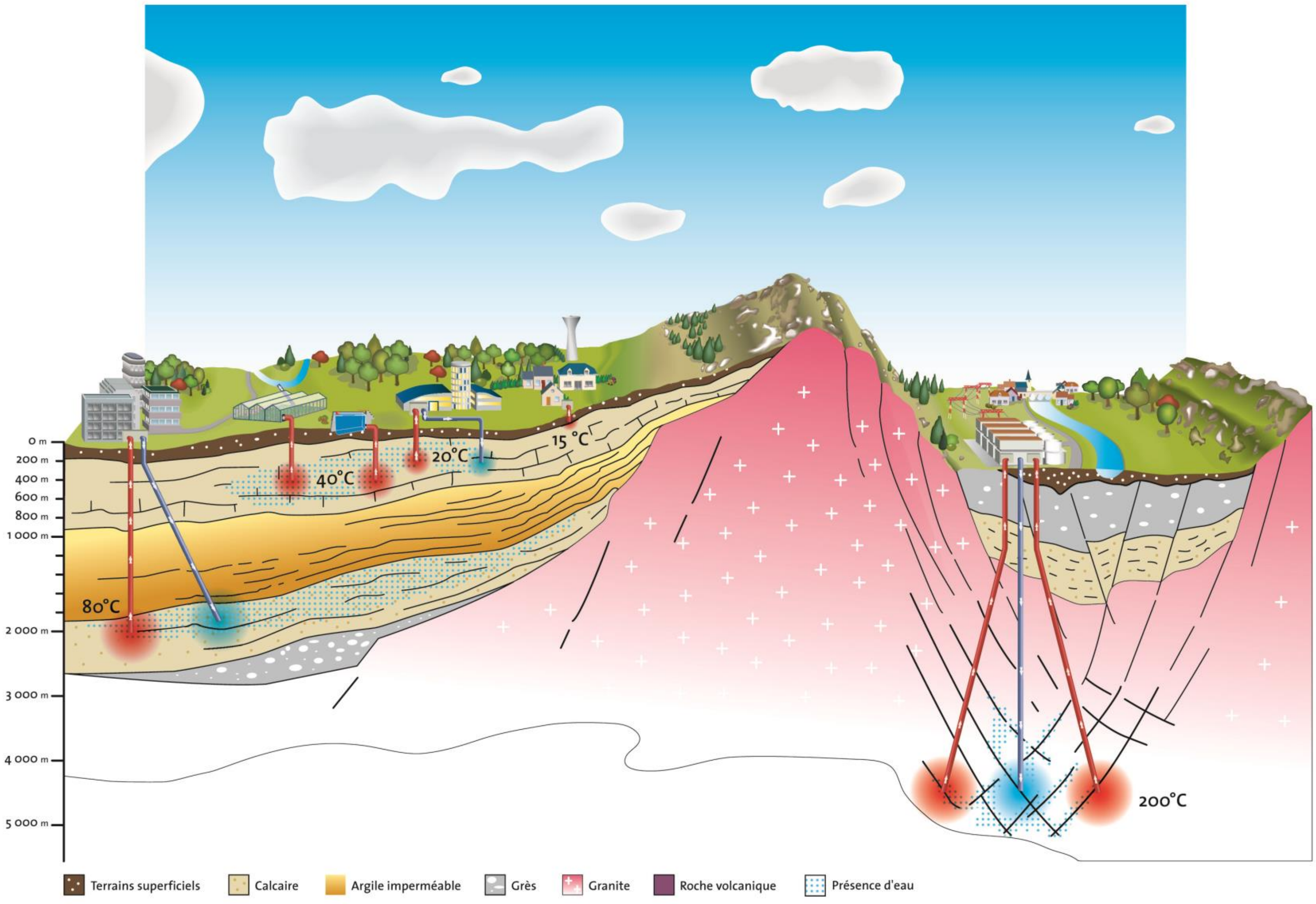
=

a huge amount of energy

can we exploit it ?

(in a sustainable way ?)

geothermal energ**ies** (in the shallow part of the crust)



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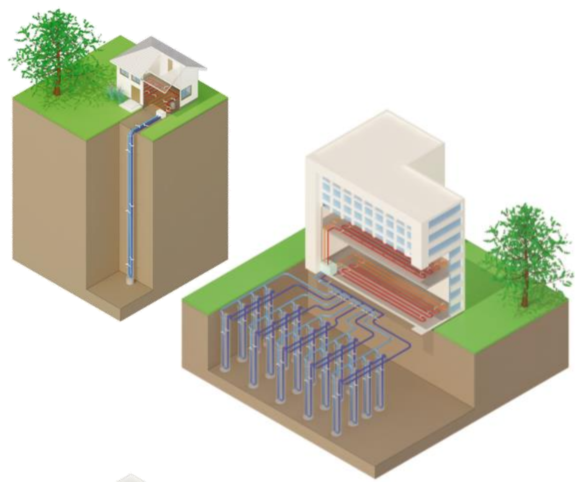
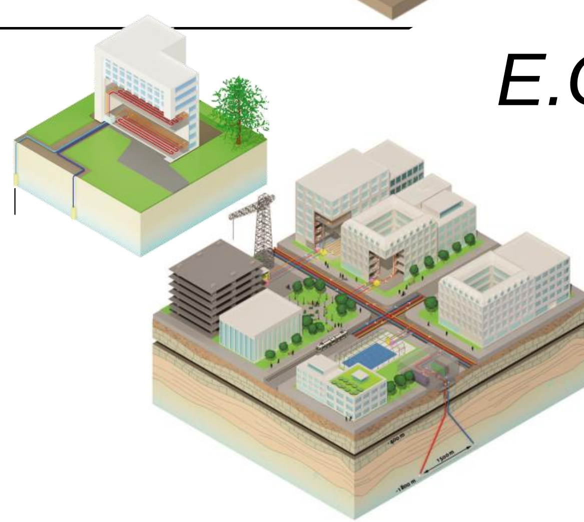
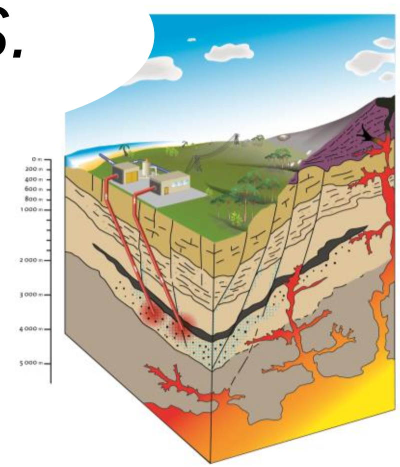
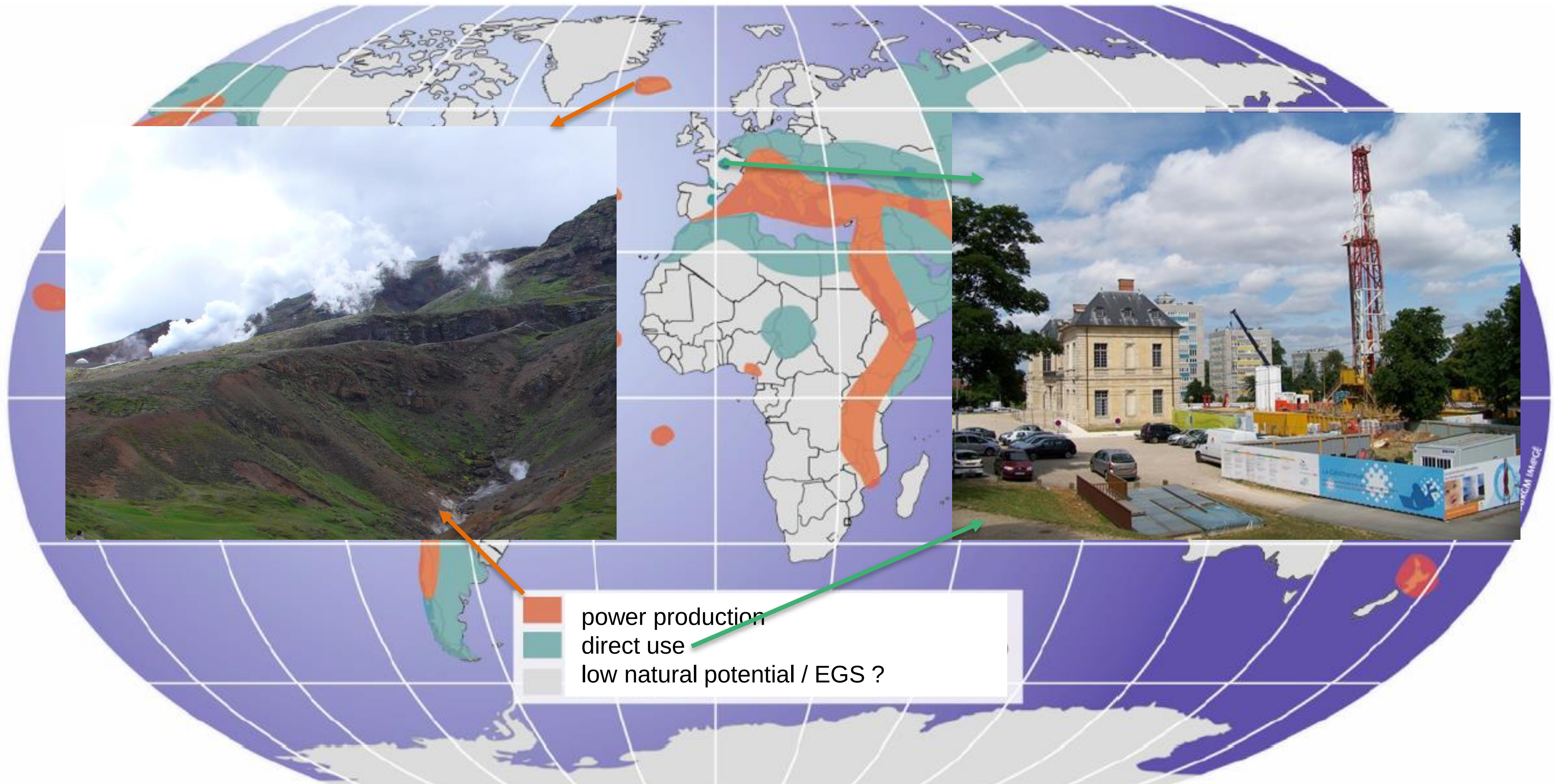
a tentative classification

		use / exchange with the *reservoir*	increasing temperature: direct use (heat)	power production (cogeneration ←)
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		E.G.S. 

focus on…

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



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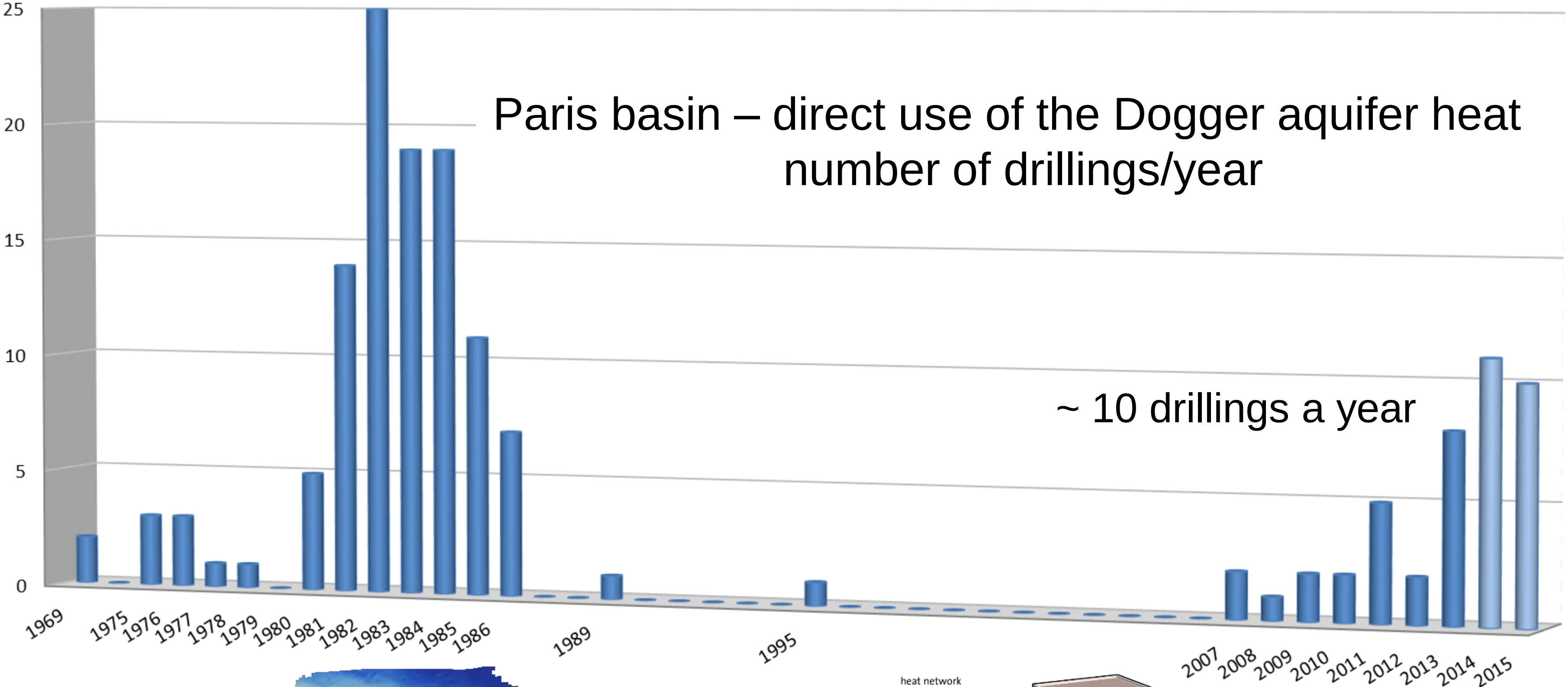
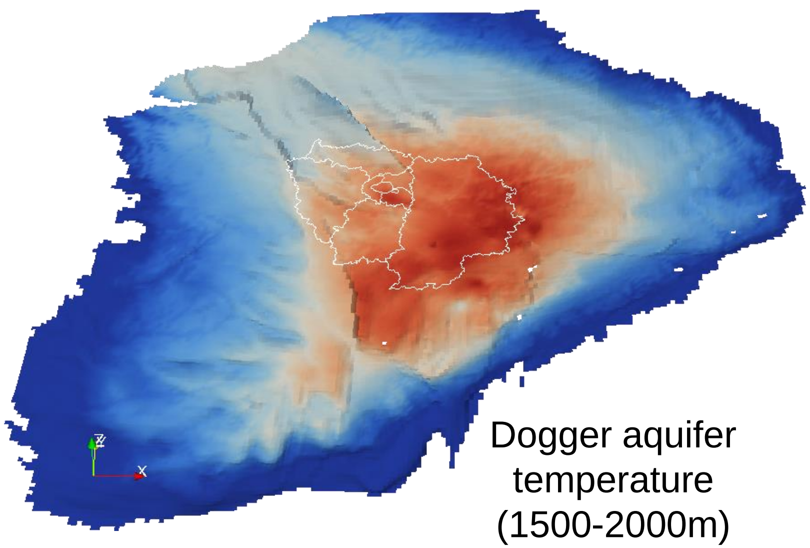
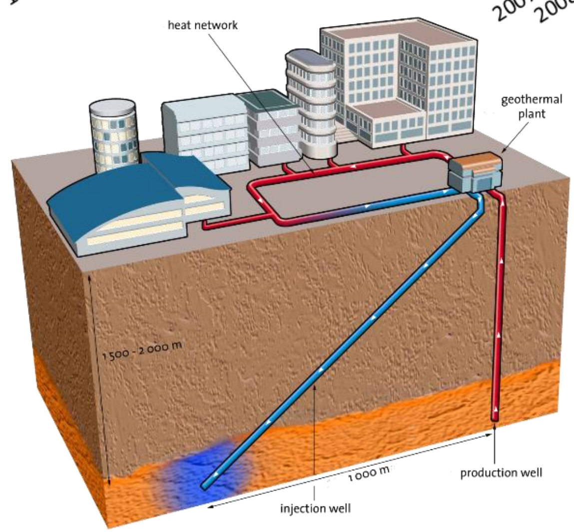
district heating in Paris suburban areas





Dogger aquifer temperature (1500-2000m)



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deep geothermal energy

- medium to high temperature geothermal systems
  - deep (overall diffusive systems) or *active* zones
- *conventional* geothermal reservoirs
  - pervasive permeable objects make production naturally possible (fractures, sedimentary bodies…) – if not: EGS (several ongoing projects, not covered here)
- mass exchange with the reservoir
  - fluid is pumped out of the reservoir and may be injected back

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geothermal reservoir ? = a subsurface feature

- intuitive concept from the surface:
  - *good productive well(s) tapping a resource below with steady production flow-rate and temperature*
  - hot water in the subsurface: spatial extent may be hard to define in the subsurface (isotherm)
- definitions (adapted from Grant & Bixley, 2011)
  - *geothermal system*: all part of the flow paths associated with a geothermal resource
  - *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
- some similarities with oil and gas reservoir
  - « genesis » of the (high temperature) geothermal ressource is much more recent and is (most often) linked with a present day hydrosystem
  - oil reservoir extent may be somewhat easier to define
  - geothermal production flow-rates are often much higher (which implies specific rock properties)

what we are interested in

- understand the geological controls on the spatial distribution of the ressource (temperature and permeable rocks/conduits)
  - characterization of an initial/natural state : exploration phase
- understanding, reproducing and forecasting the impact of ressource exploitation
  - field management, lifetime, sustainability, exhaustion/recovery
  - -> *preserve as long as possible production flowrate (pressure of the reservoir) & temperature*

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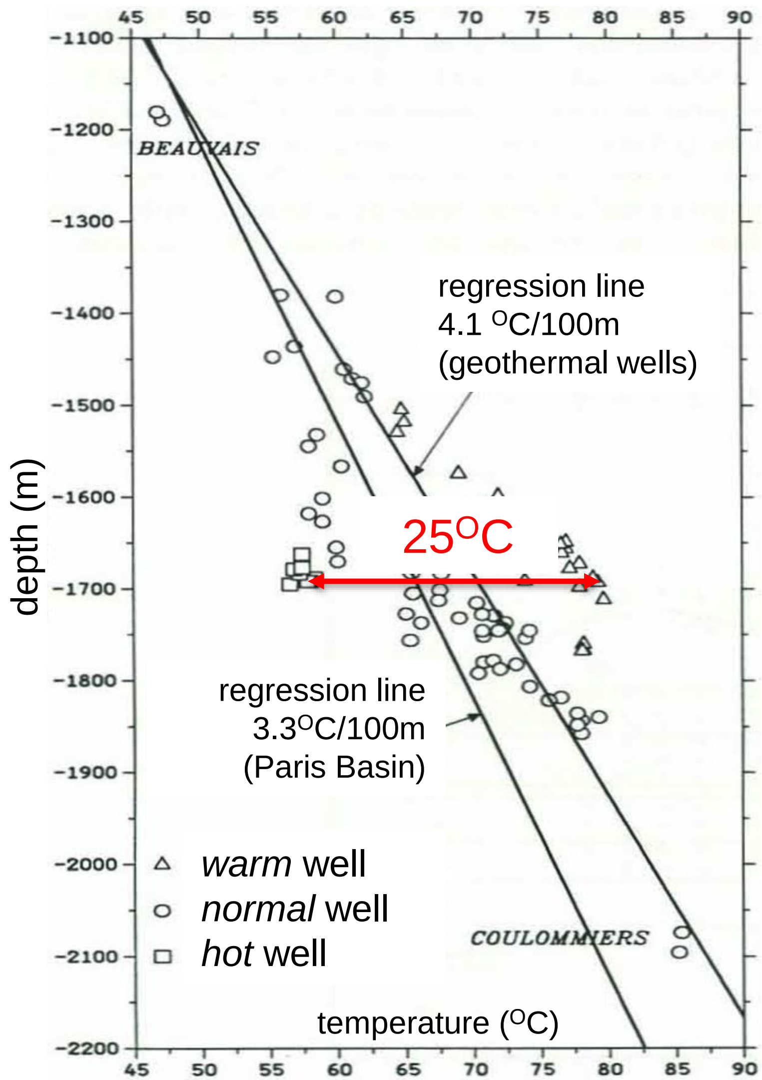
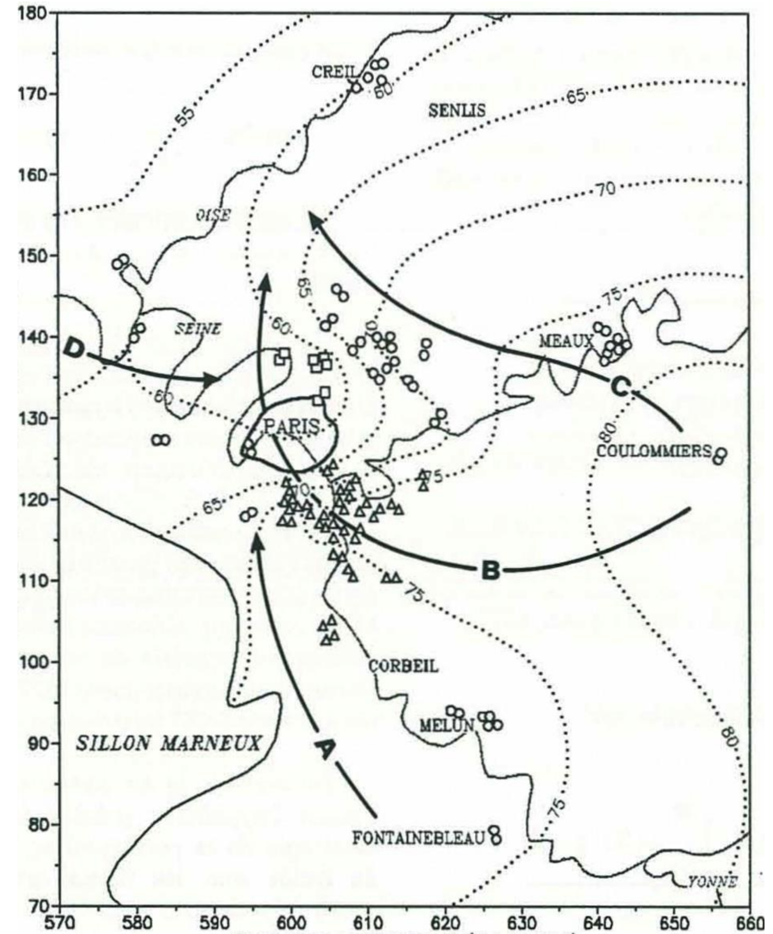
initial/natural state

- 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
  - in terms of temperature/heat fluxes (« diffusive » systems)
  - in terms of pressure/mass fluxes (« convective » systems)

temperature variations in « diffusive » systems



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



(Rojas et al.,1989)

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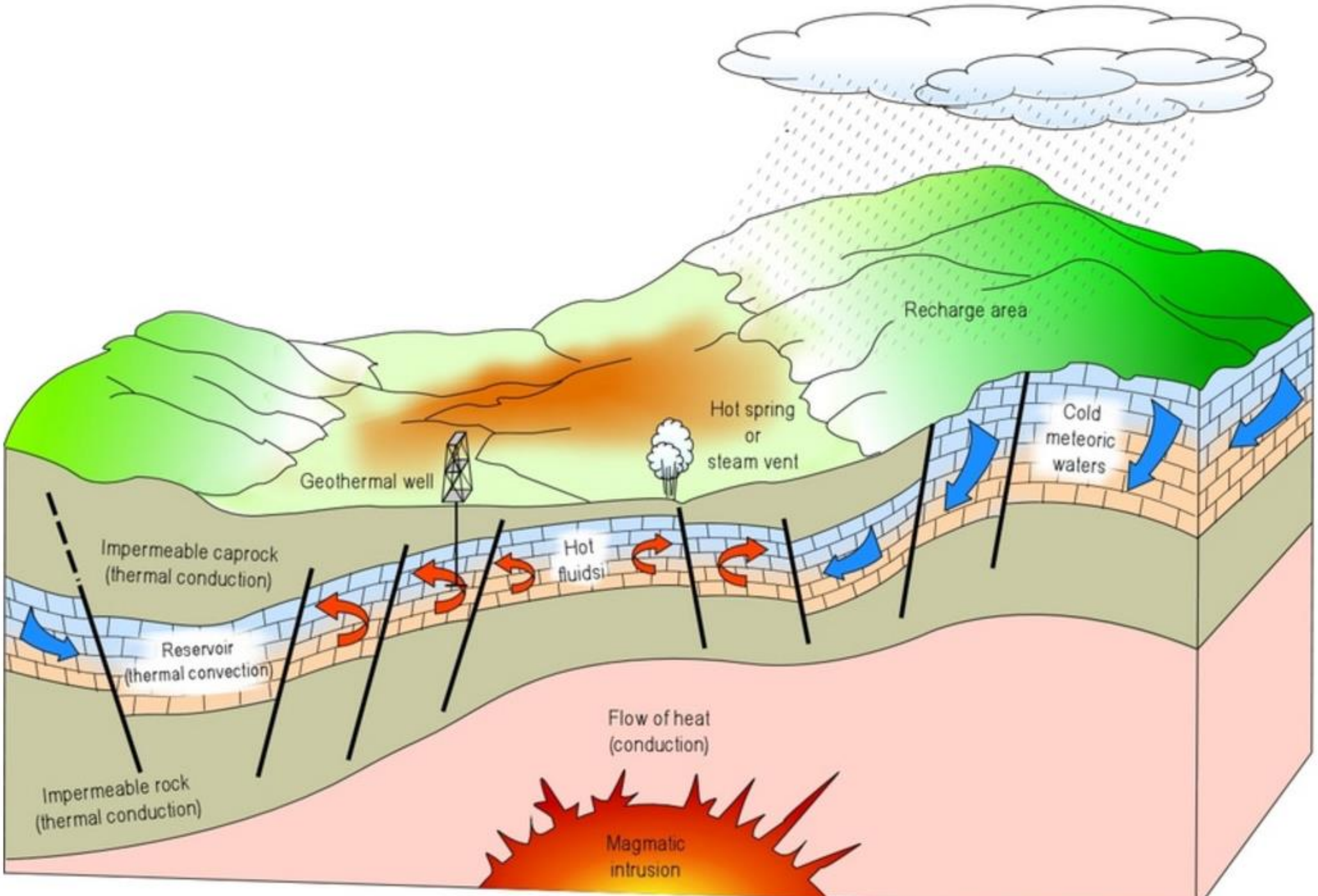
natural state of « convective systems »

- 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

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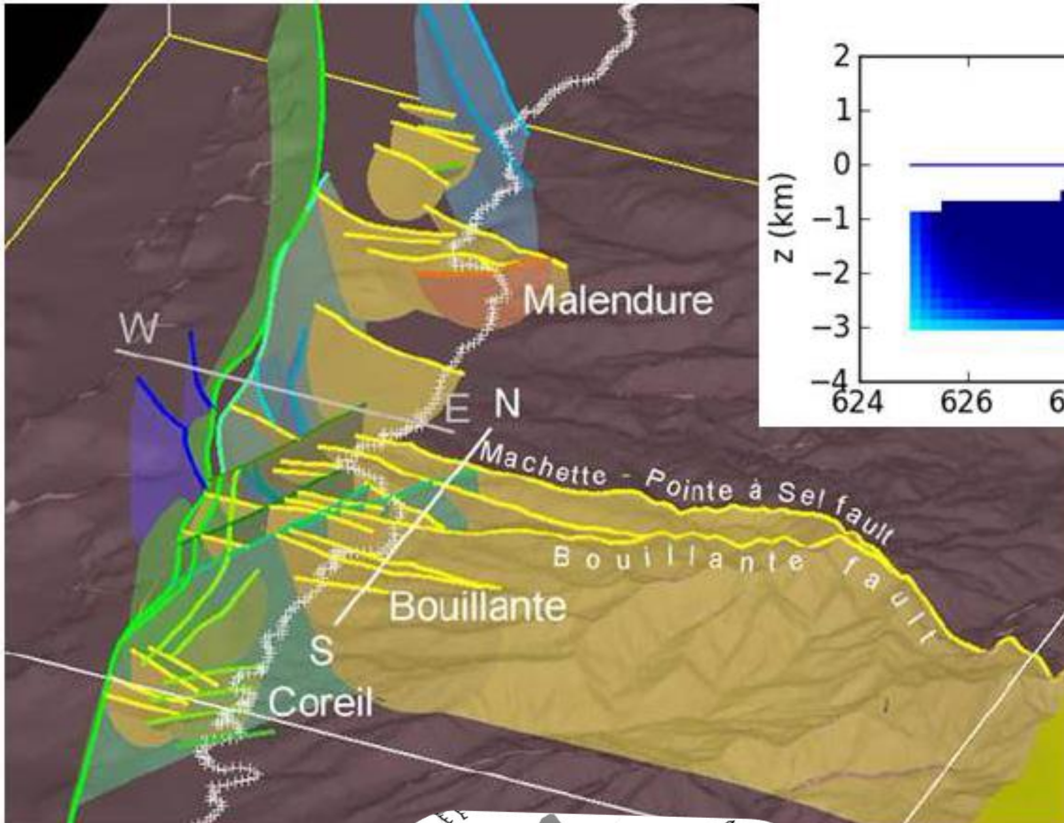
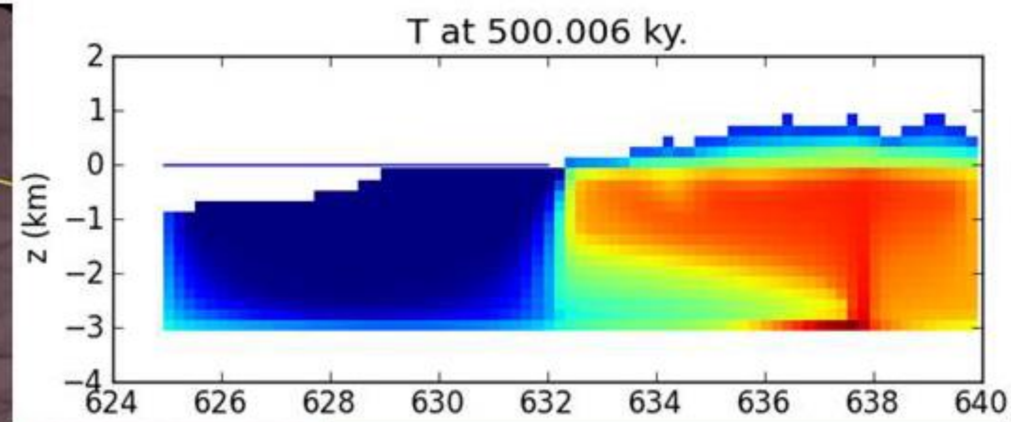
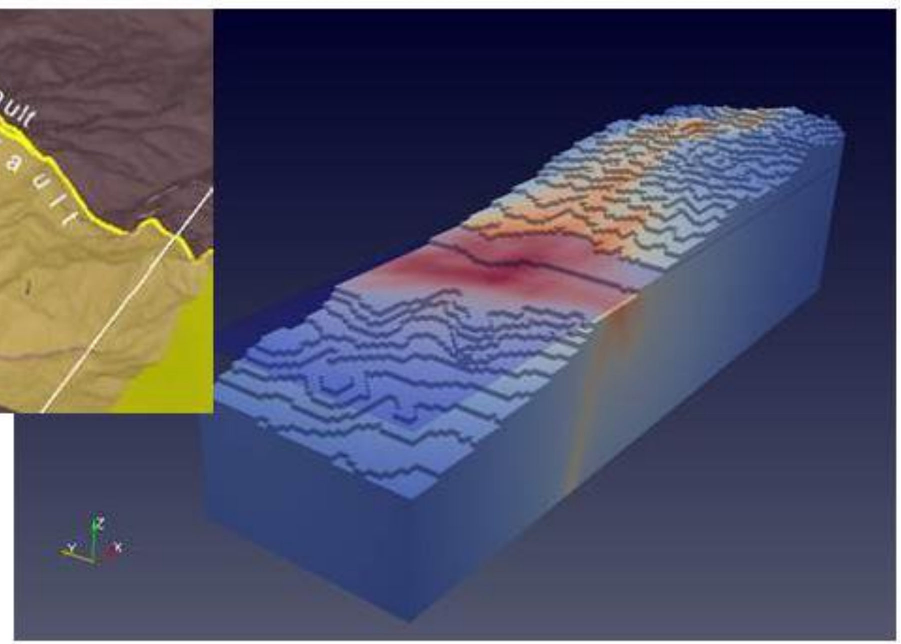
natural state of « convective systems »

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

Bouillante example

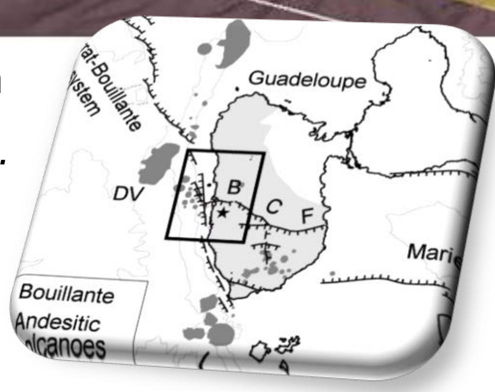






15 x 16 x 2 km

Calcagno *et al.* 2012



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…

what we are interested in

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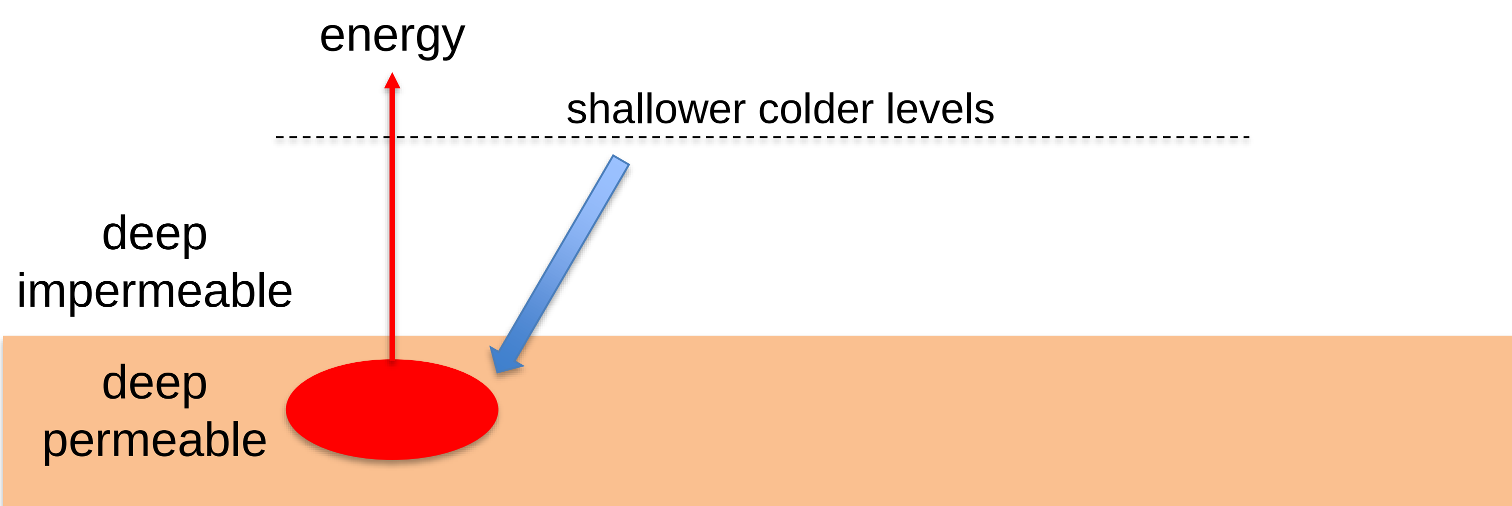
thermal evolution of the reservoir - exploitation

- temperature drop may occur without cold brine reinjection
  - cold inflows may also come from overlying or peripheral aquifers
  - boiling
    - may temporarily increase the energetic content of the fluid
    - steam cap may develop with gravity drainage



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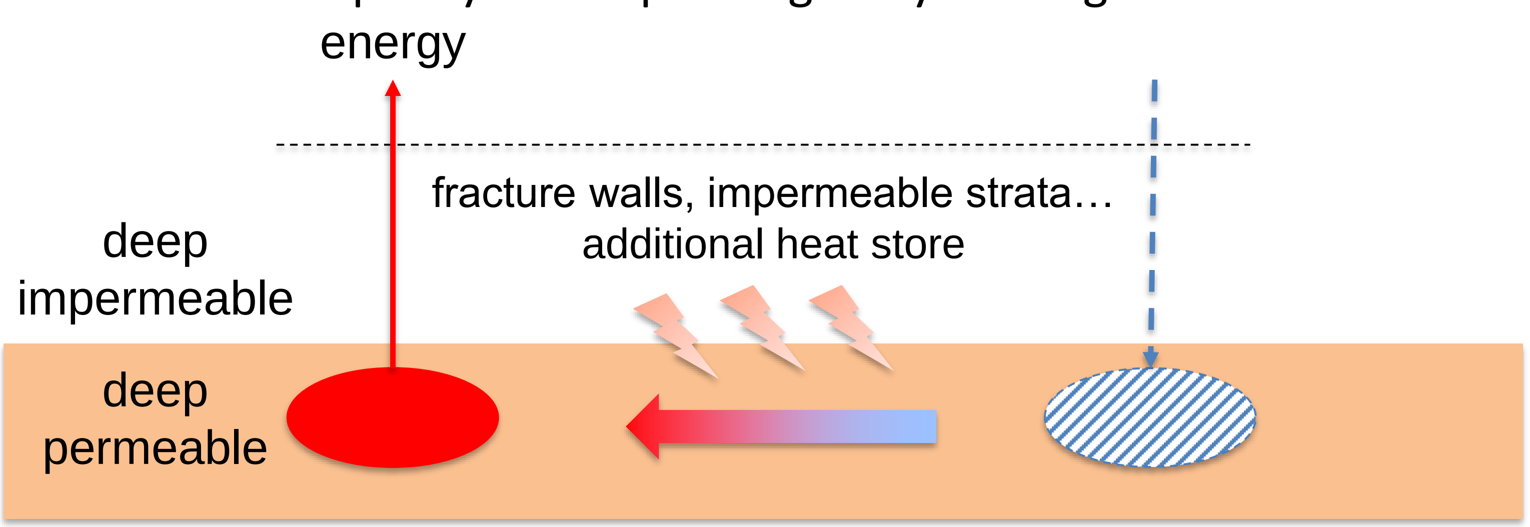

thermal evolution of the reservoir

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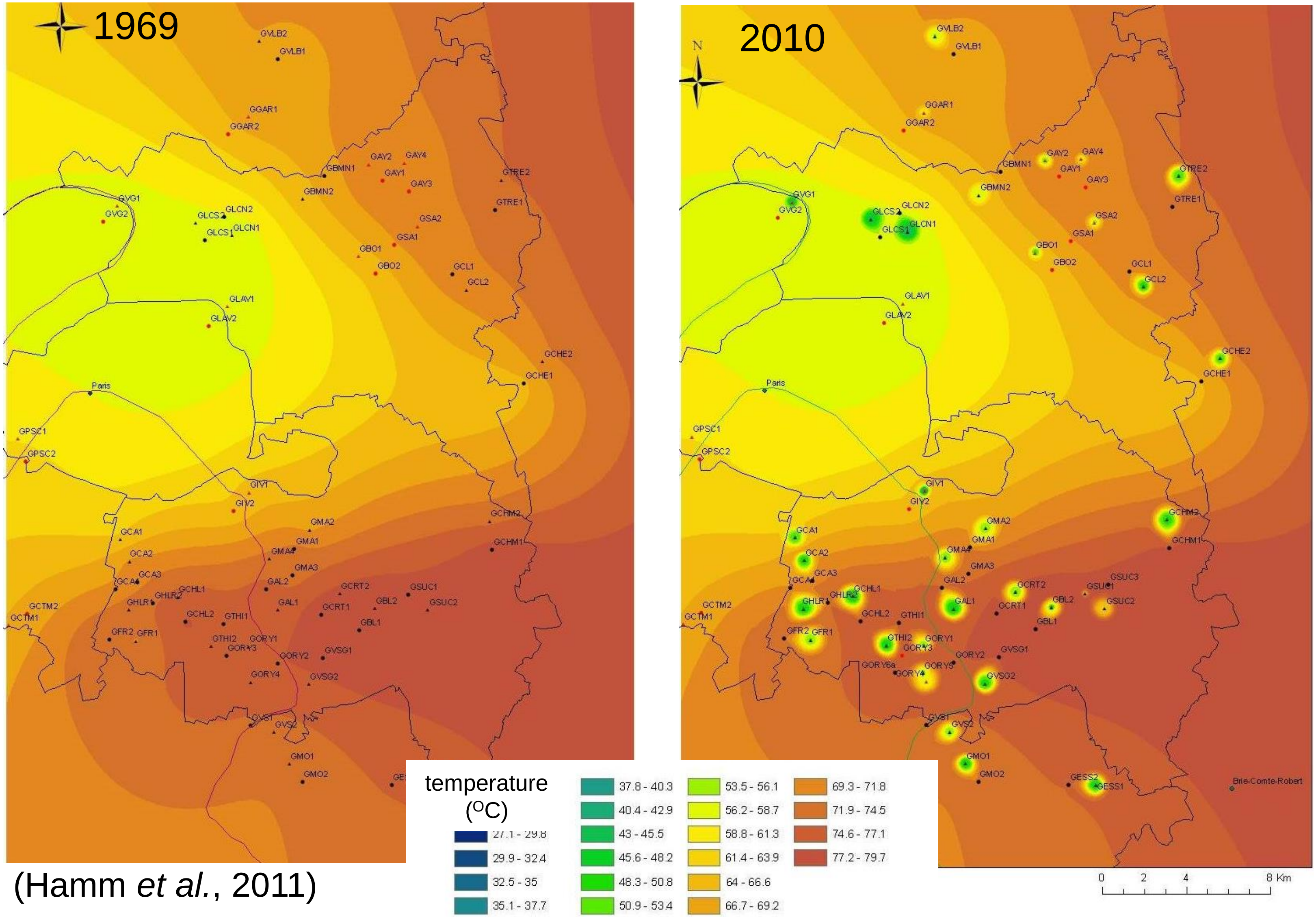
  - boiling
    - may temporarily increase the energetic content of the fluid
    - steam cap may develop with gravity drainage
- in-field reinjection implies the possibility of thermal breakthrough
  - tracer tests may provide chemical precursors and are useful to identify flow paths
  - if the convective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

monitoring the resource at regional scale



(Hamm *et al.*, 2011)

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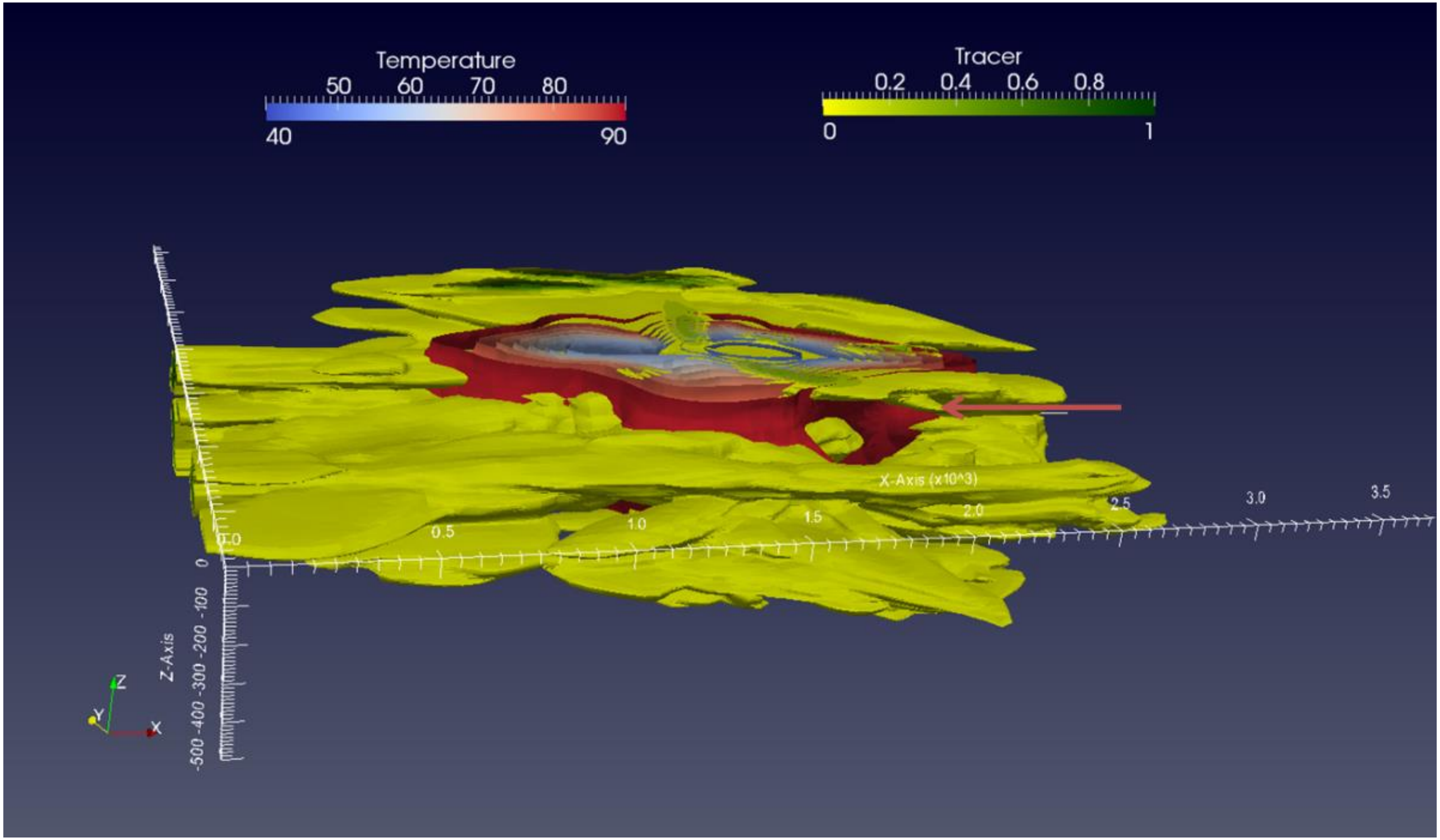
geothermal doublet in a sandstone aquifer

impact of geological heterogeneities



Hamm & Lopez, 2012

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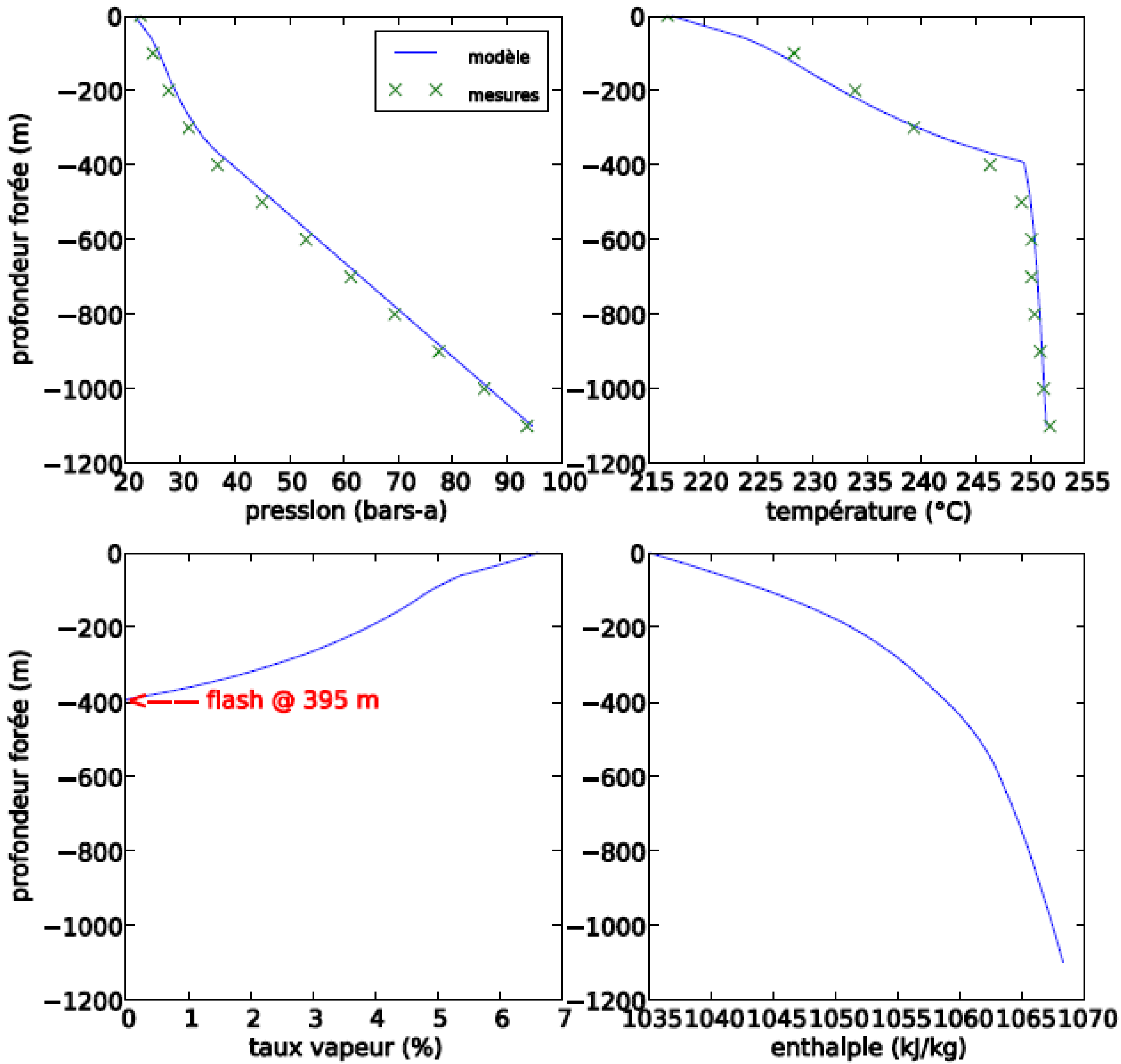
on the importance of wells

- wells are where change is detected
  - “windows” on the subsurface and reservoir behavior: variations in reservoir pressure, well head pressure, enthalpy, flow rate…
- wellbore models are necessary tools to monitor reservoir evolution from the well head

on the importance of wells

- 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 may occur)
- if the fluid is boiling inside the wellbore
  - things may get much more complex

wellbore models



Giuglaris & Lopez, 2012

BO-4 dynamic logs from Bouillante field reproduced with GNACL

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on the importance of wells

- wells are where change is detected
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- if the fluid stays monophasic
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- 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 challenging problem

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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
  - poor numerical performances

current needs

- International Partnership for Geothermal Technology (IPGT) white paper on geothermal reservoir modeling (2012)
- several initiatives worldwide towards new modern geothermal reservoir modeling tools among wich:
  - Tough2 evolutions
  - CSMP++ platform (ETH Zurich, Leoben, Heriott-Watt University)
  - Geothermal Supermodels (open initiative/New Zealand)
  - OpenGeoSys
  - …
  - ComPASS
- integration of geological modeling and reservoir and wellbore simulation

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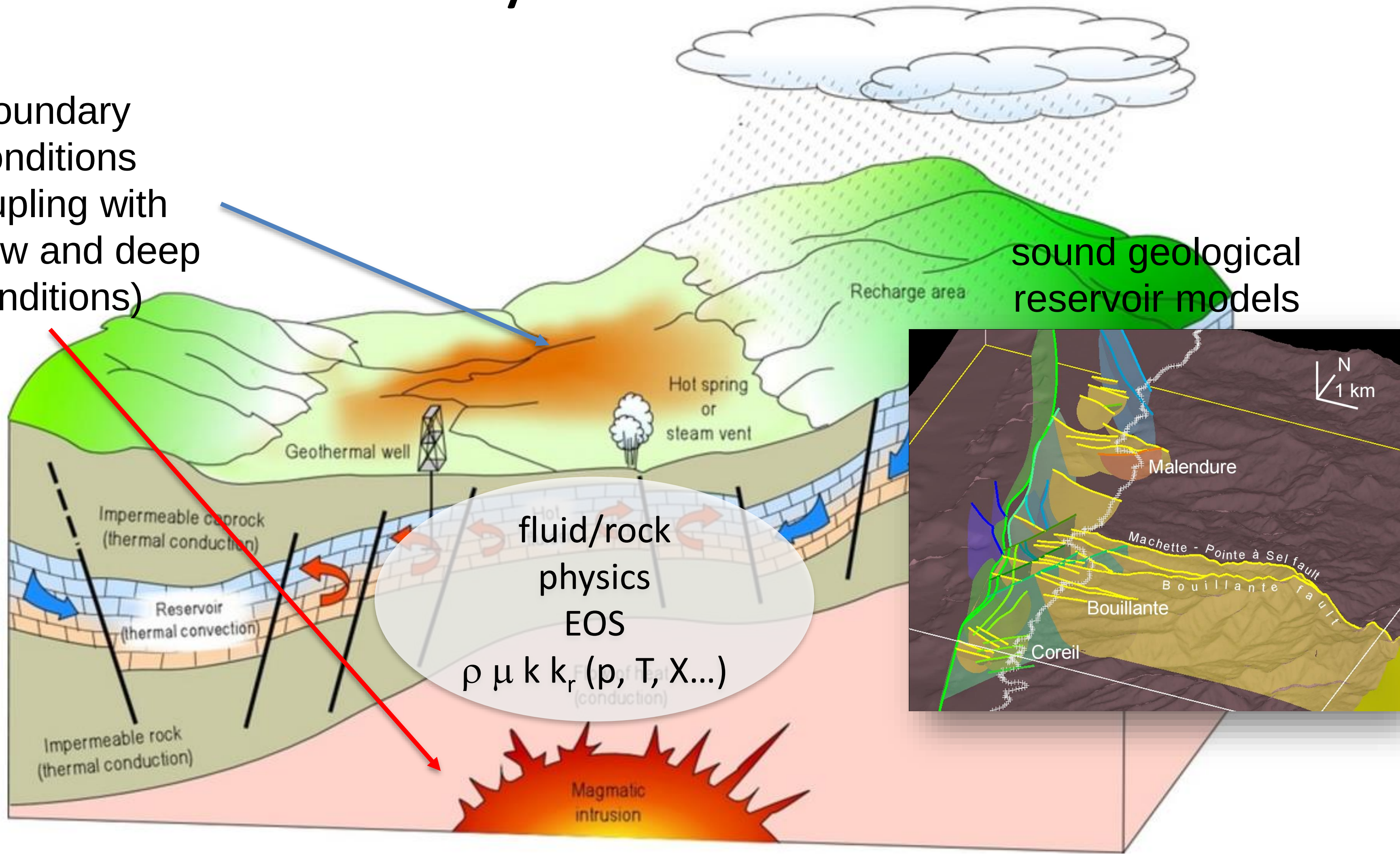
a tentative summary

boundary conditions (coupling with shallow and deep conditions)

sound geological reservoir models



fluid/rock
physics
EOS
$\rho\ \mu\ k\ k_r\ (p, T, X\ldots)$

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

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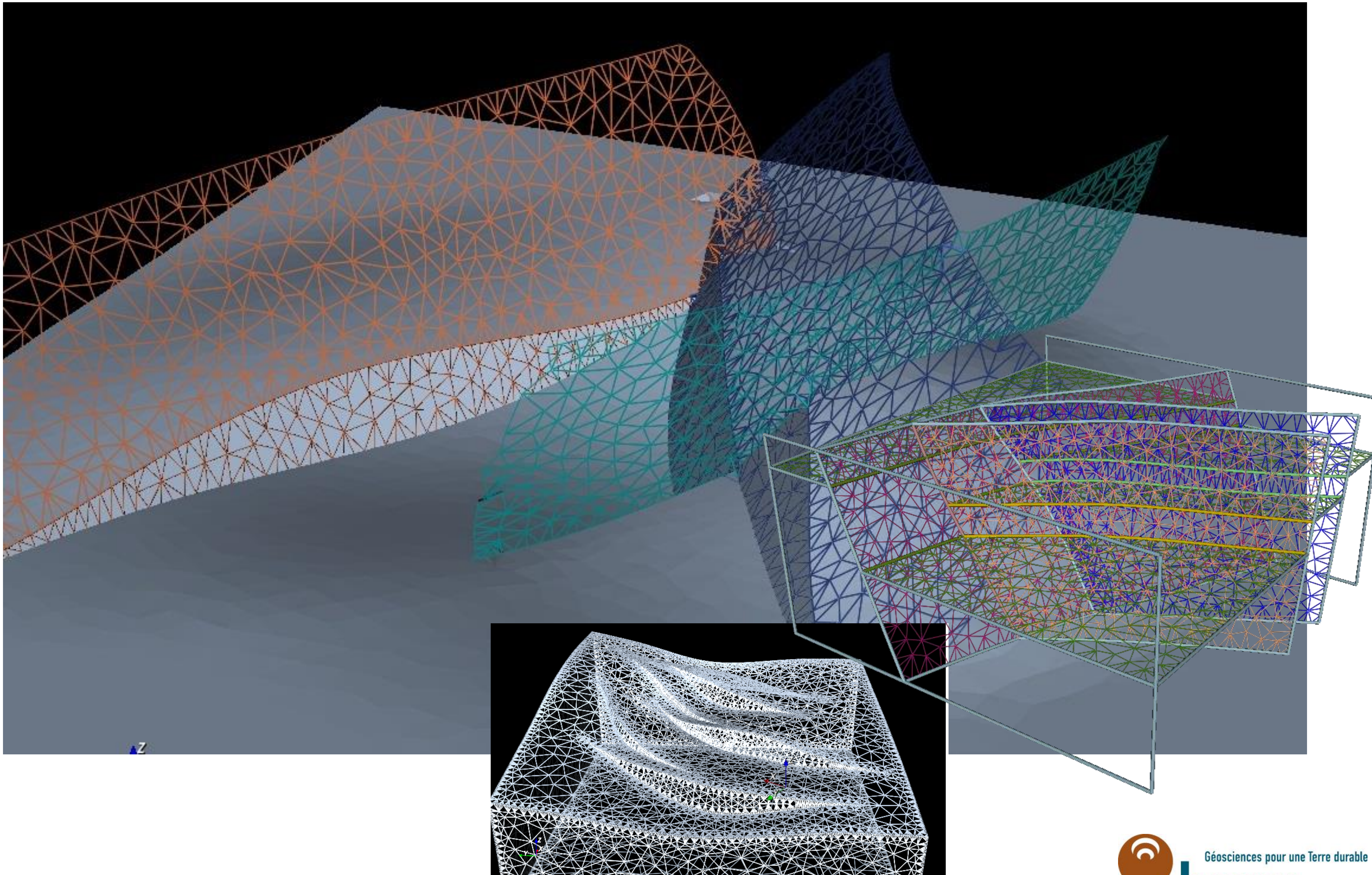
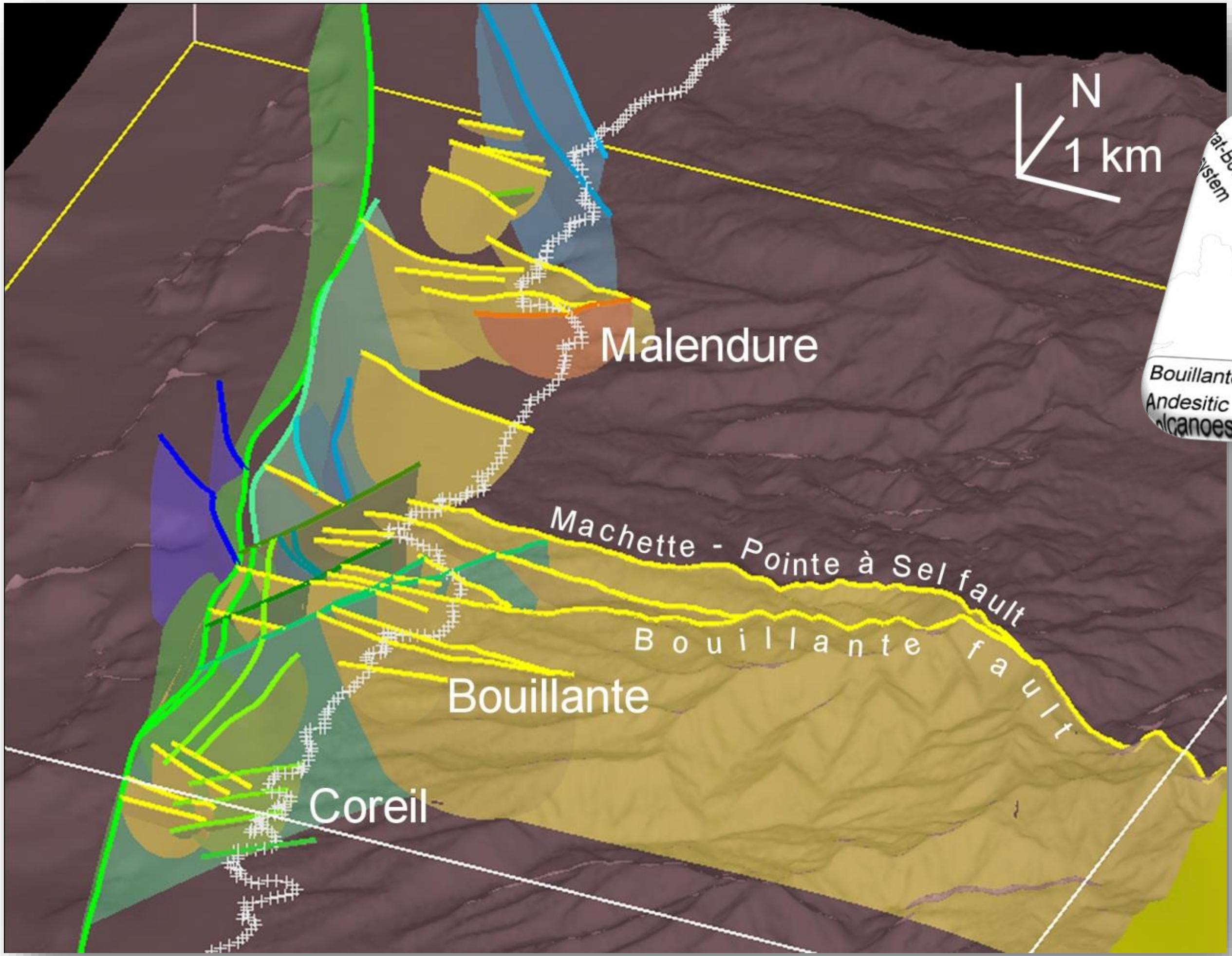


goal #1 structural models

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

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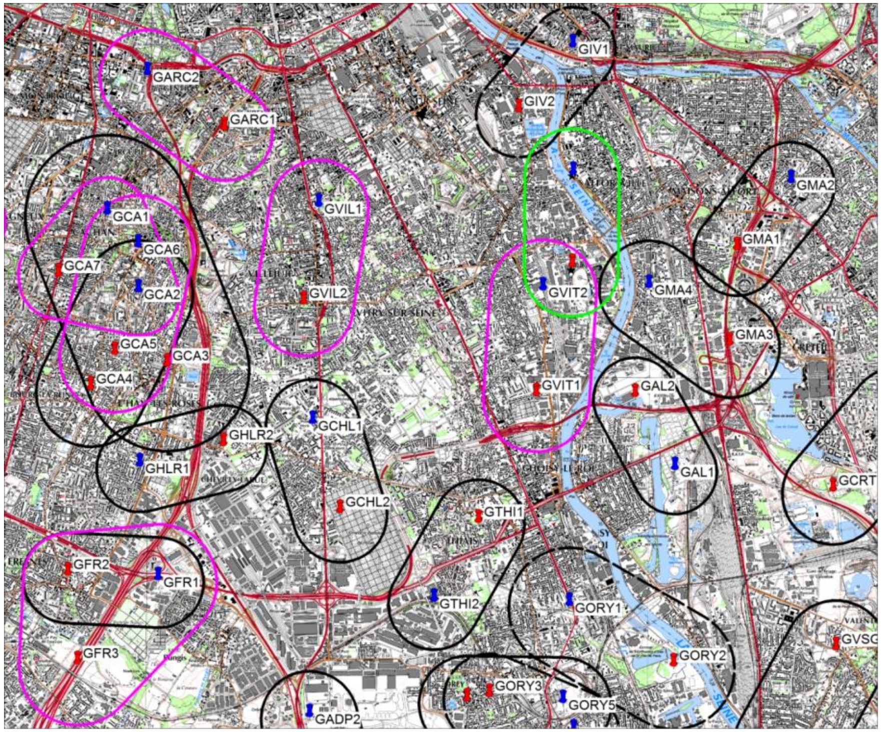
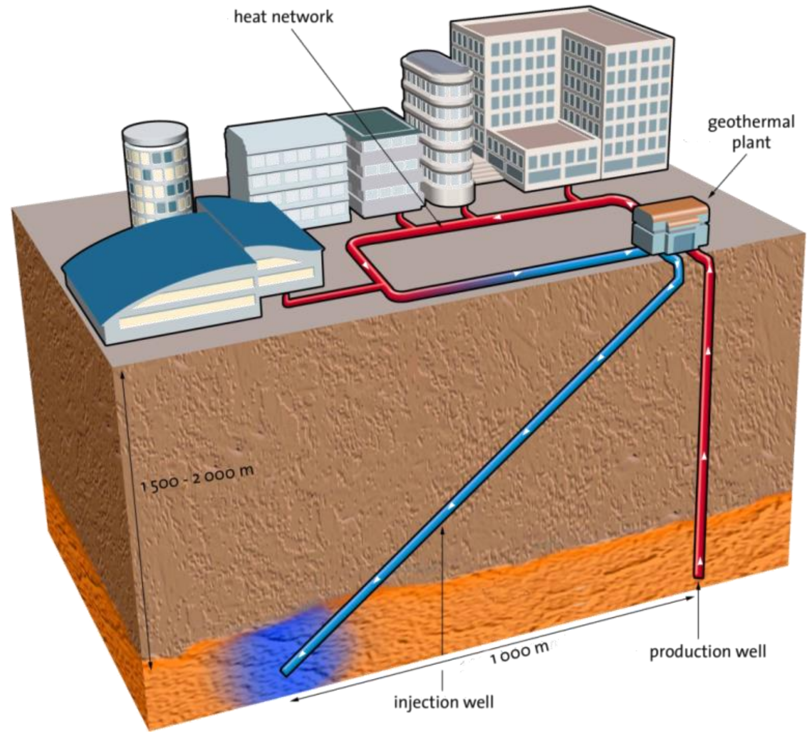
pressure transients

- 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





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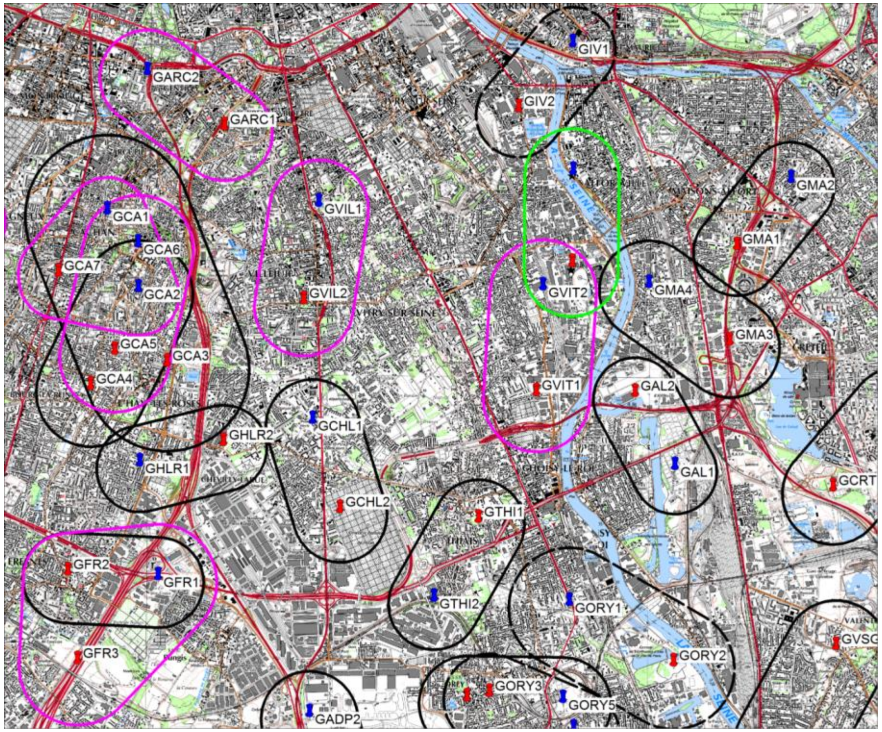
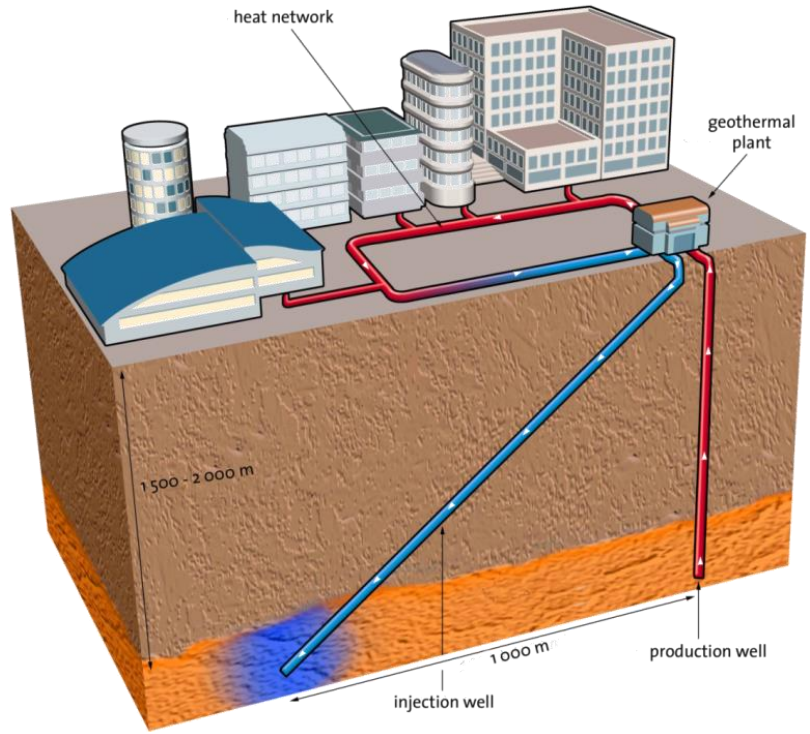
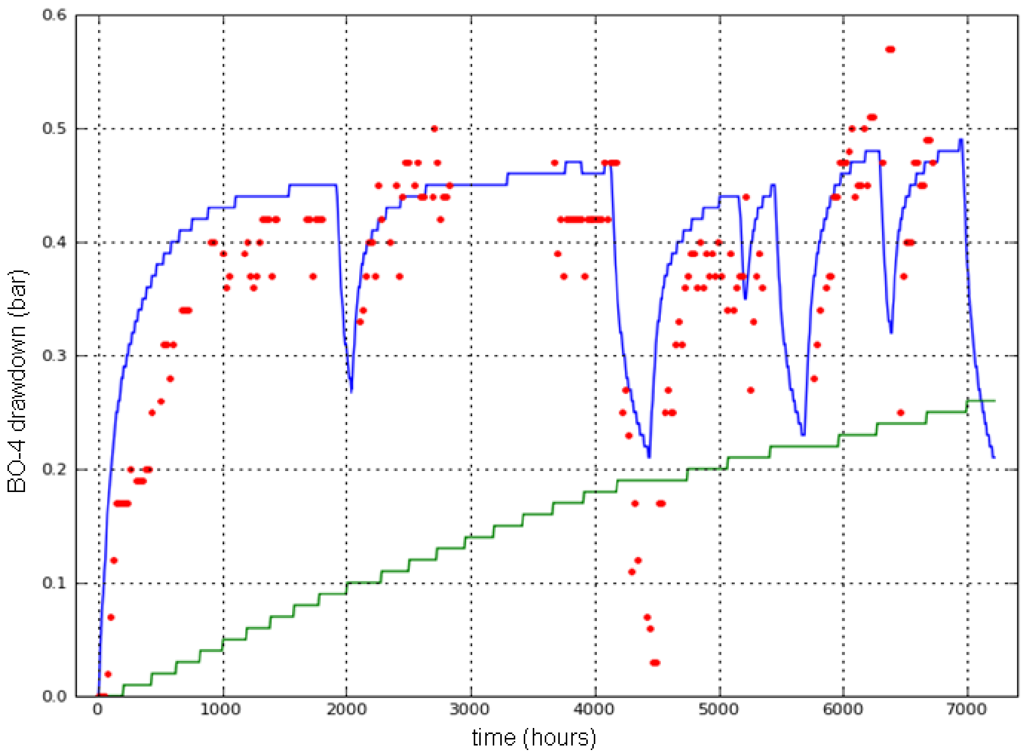




- the Geysers field exploitation showed that there was an optimal well spacing and that, at some point, additional drilling was not economical (Sanyal, 2000)

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

data
fracture pressure
matrix pressure

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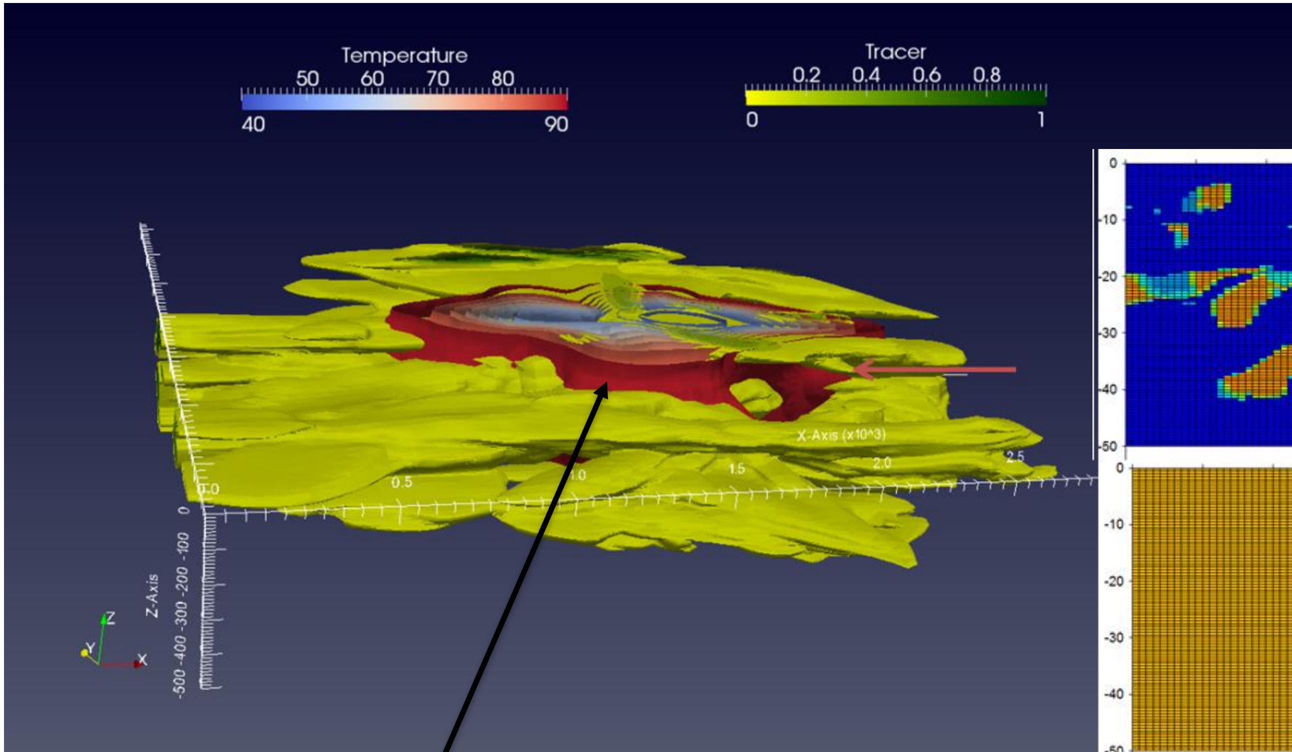
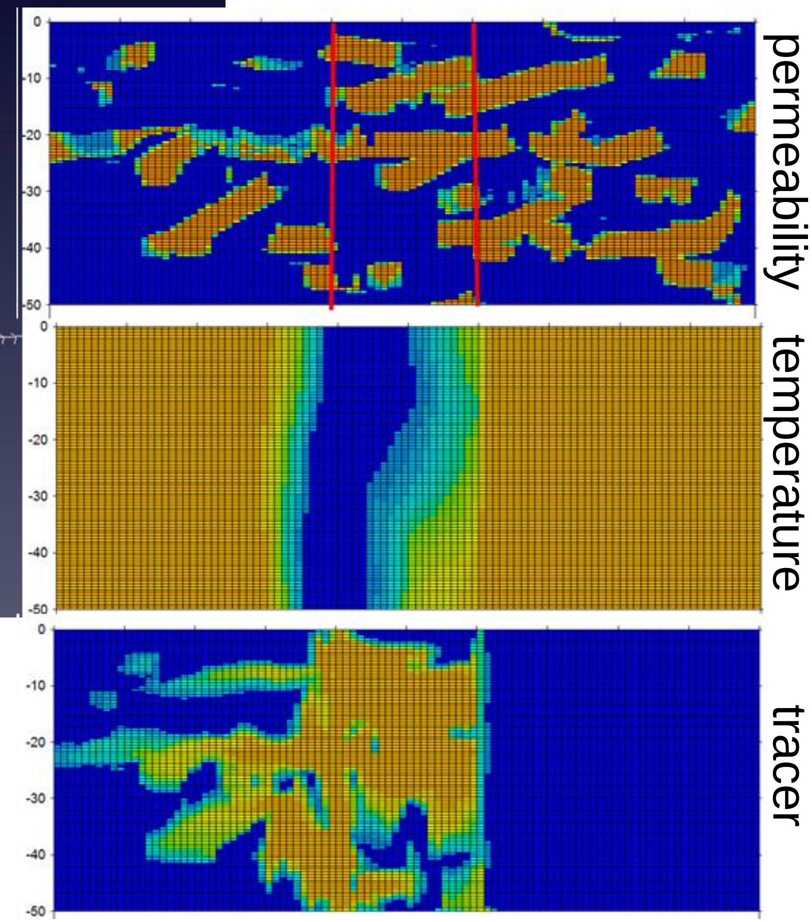
geothermal doublet in a sandstone aquifer





Hamm & Lopez, 2012

10 years

temperature diffusion
smoothens thermal impact
of heterogeneities

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we would like to be able to

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

2. produce conformable quality meshes of such models,

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

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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…)

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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

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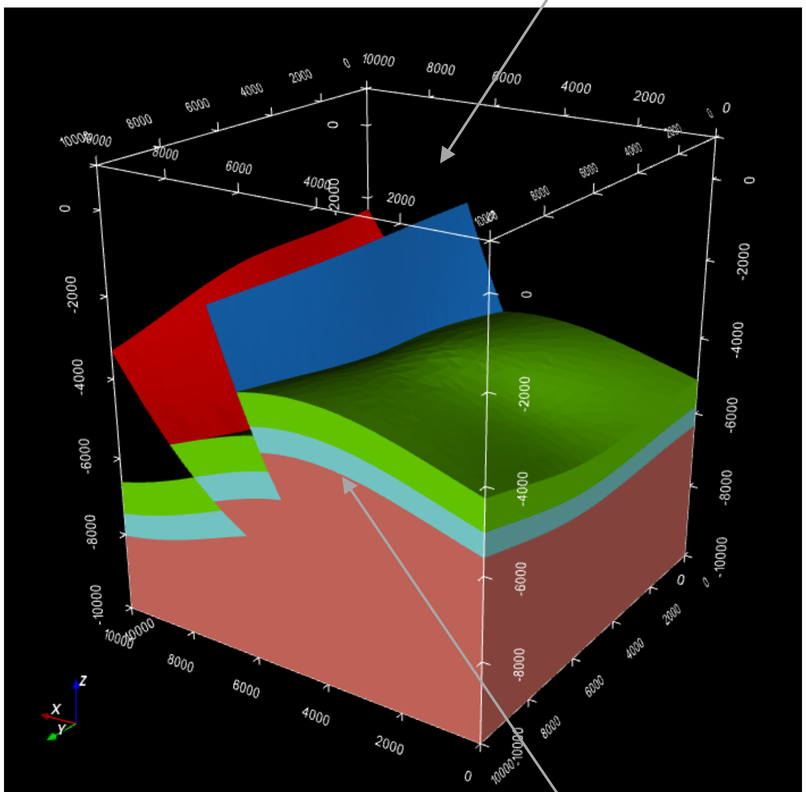
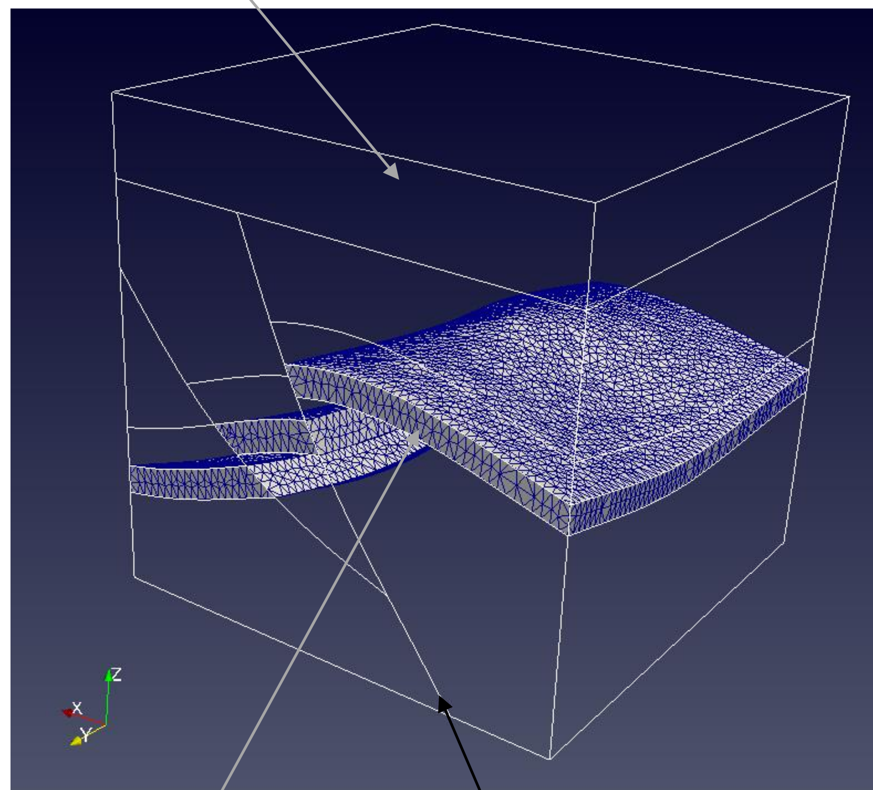
a synthetic (slightly geological) example

caprock layer





tracer injection
along the fault

aquifer layer

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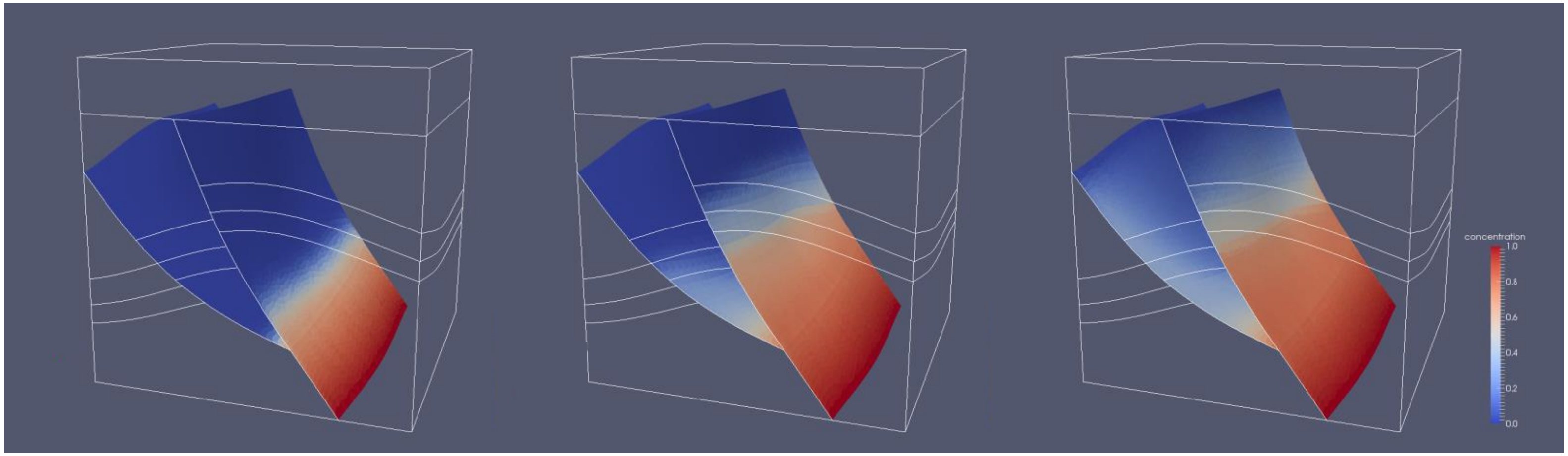
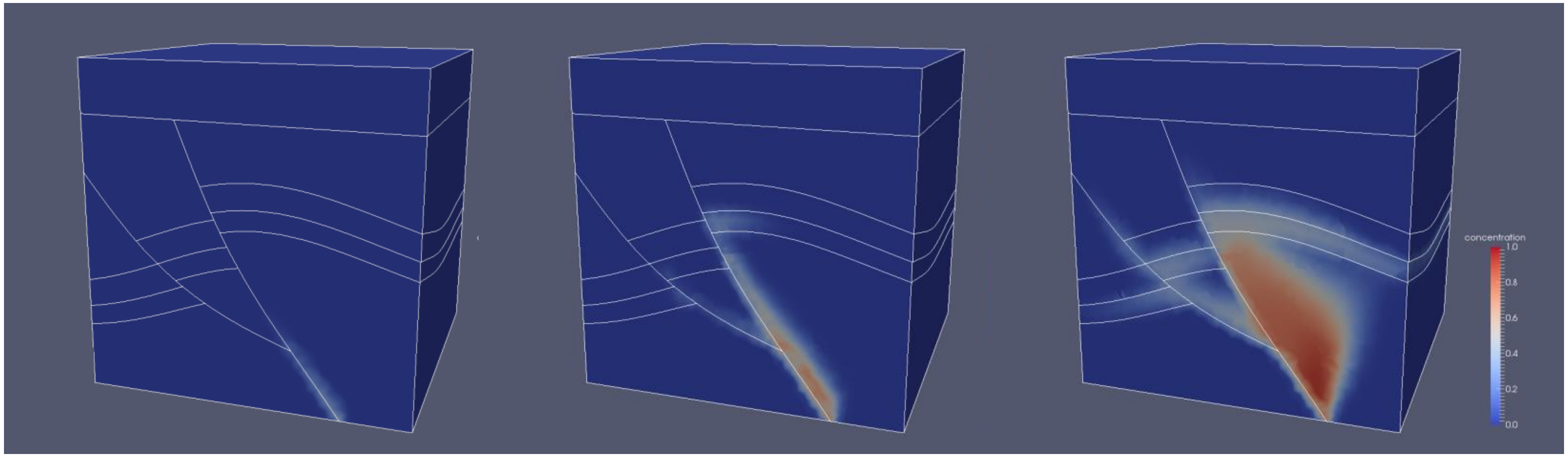
tracer advection

tracer concentration in the fractures



tracer concentration in the matrix



low permeability contrast
(aquifer / host rock)

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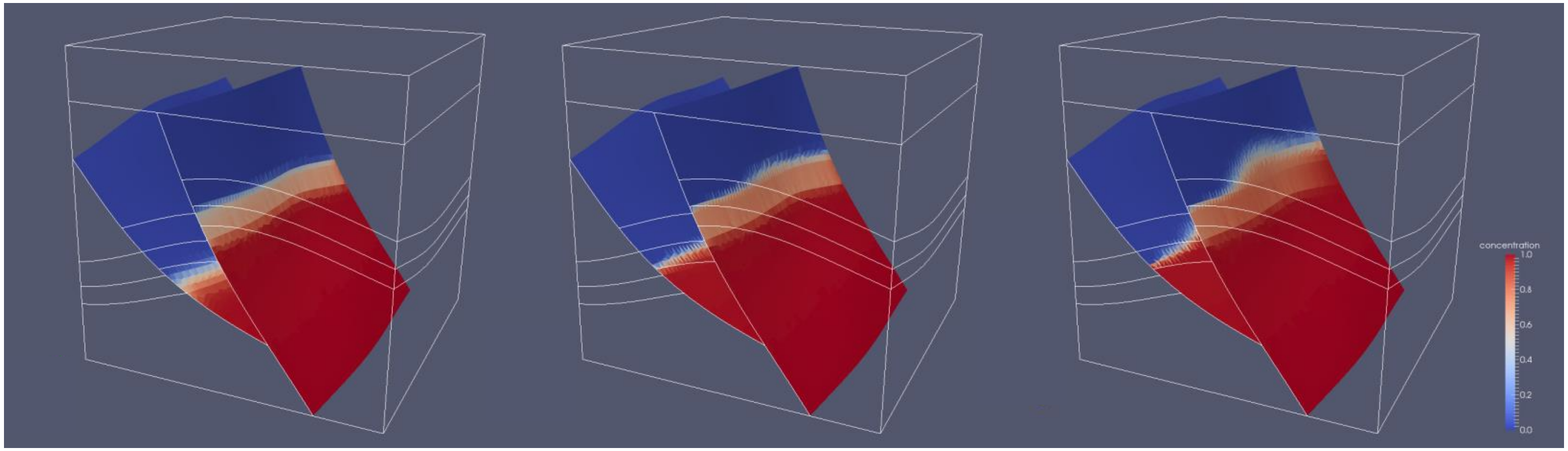
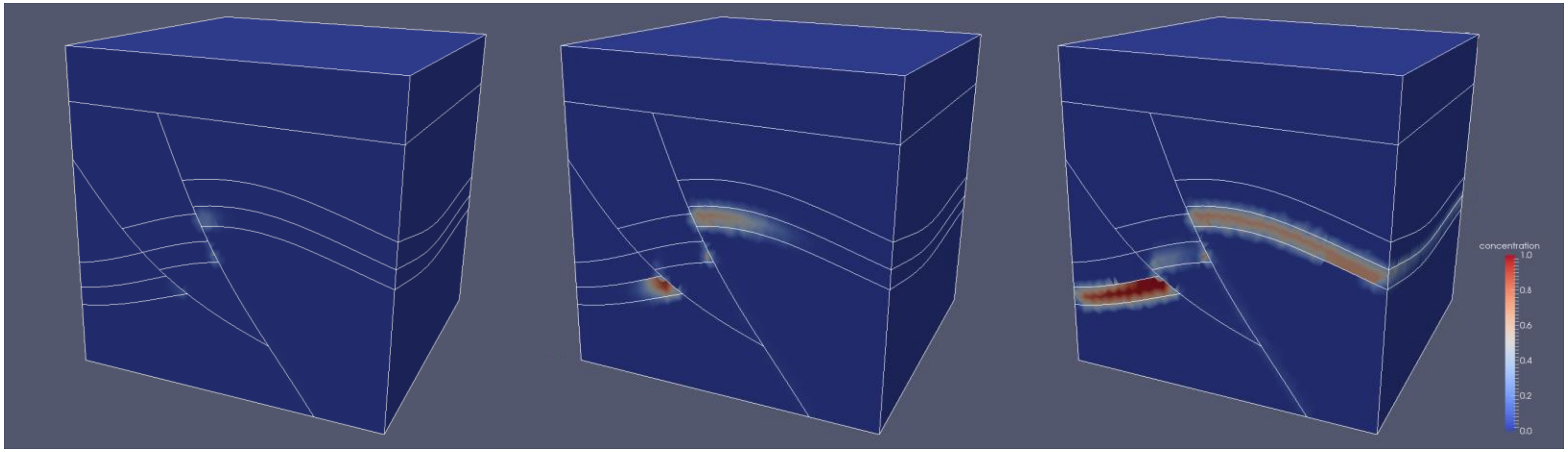
tracer advection

tracer concentration in the fractures



tracer concentration in the matrix



high permeability contrast
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    - 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

(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,
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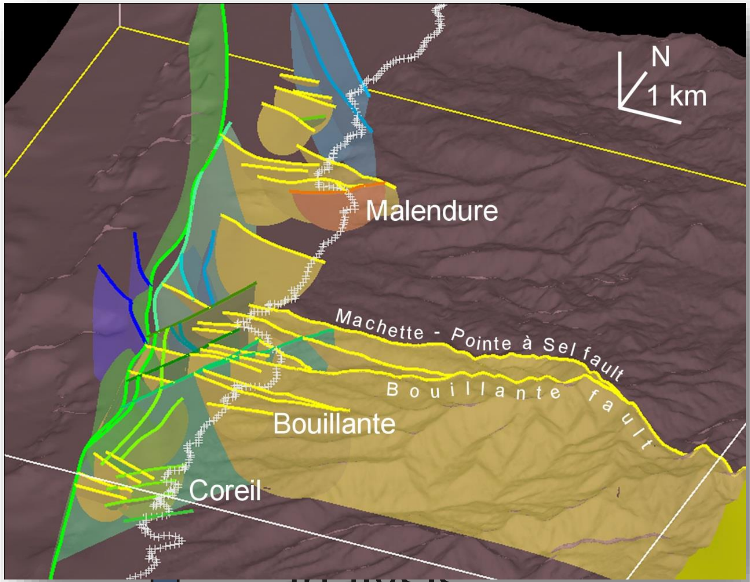

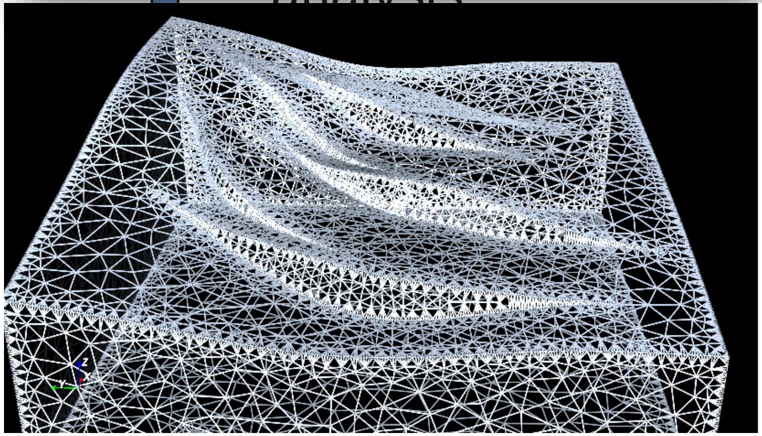

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