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Hydrothermal convection beneath an inclined basement-sediment interface: application to the Rhine graben and its Soultz-sous-Forêts temperature anomaly

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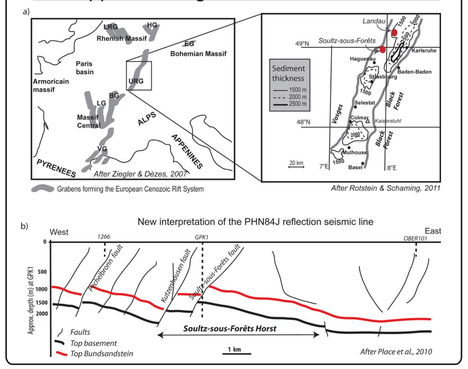
Abstract:Geothermal anomalies in sedimentary basins are strongly controlled by fluid circulation within permeable zones. Exploration of new targets requires the understanding of how and why hydrothermal circulation patterns establish in a particular zone. This study presents a new compilation of newly corrected bottom-hole temperature data in the French part of the Upper Rhine Graben, where the Soultz-sous-Forêts temperature anomaly is locked beneath a local horst structure. After a geostatistically constrained interpolation procedure, maps and crosssections are extracted from the 3D thermal block, together with the associated standard deviations. Thermal anomalies are preferentially associated with the thickest zones of the permeable fractured Buntsandstein (sandstones) formation, in apparent contradiction with previous models where two major fault zones were suggested to control fluid flow. The underlying fractured granitic basement hosts fluid circulation patterns which are apparently controlled at large-scale by the inclined basement-sediments interface. Based on these observations, numerical models of hydrothermal convection including an inclined basement-sediments interface, a local horst structure, and realistic petrophysical properties have been carried out. The depth-decrease of permeability, the inclination of the interface and the fixed heat flow condition at the base of the model, explain why only a few upwellings can be triggered. Thermal anomalies and a measured temperature profile can be reproduced when fault permeability equals 10^{-14} m². Interestingly, structure of convective patterns also exhibits a second hotter upwelling, 8 km east of the Soultz-sous-Forêts upwelling zone, where another geothermal exploration project is now underway.
The understanding of hydrothermal convection with realistic fluid and rock properties clearly appears as a predictive tool for geothermal exploration strategies.

Raw BHT data → Data selection and correction for transient disturbances → Geostatistics (variogram) and kriging (interpolation) → Maps & cross-sections → Thermal field & geology → Numerical simulations → Prediction for potentially favorable geothermal areas...

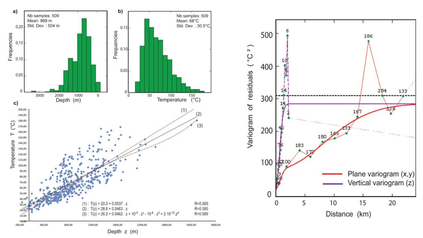
Highlights

- New compilation of corrected BHT data in the French part of the Upper Rhine Graben
- Geostatistically-constrained 3D thermal block, maps and cross-sections
- 3D view of the Soultz-sous-Forêts thermal anomaly
- Models of hydrothermal convection with an inclined basement-sediment interface
- Single large upwelling is triggered, and a neighbouring anomaly is predicted

The Upper Rhine graben and its Soultz horst



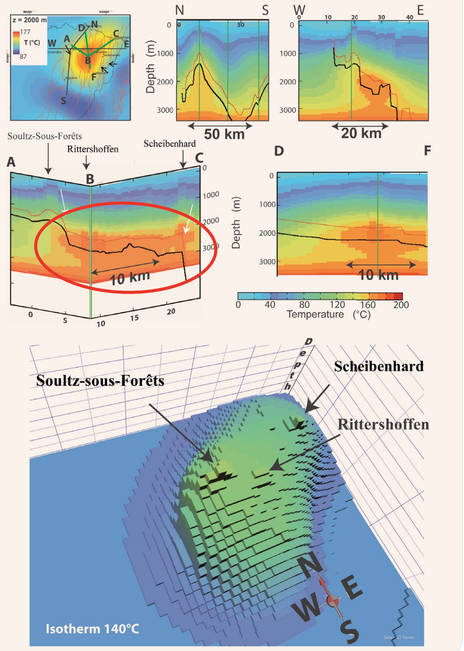
3D interpolation of newly corrected BHT data



The variogram analysis was performed on residuals after subtracting the vertical drift (here fitted with a 4th-degree polynomial).

The chosen model variogram consists in one nugget effect (25°C²) and two Gaussian structures, whose sills are respectively 60°C² and 200°C².The horizontal ranges are 1800 and 20000m, and the vertical ranges are 1200 and 1600m. Kriging has been performed with the Isatis™ geostatistical tool.

Thermal field around Soutz-sous-Forêts

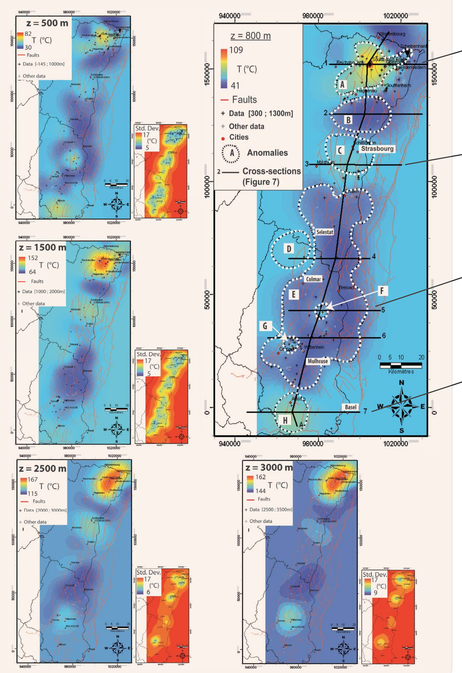


*- Development of thermal anomaly around Soultz is favored within the thickest zones of the permeable Buntsandstein formation (**red ellipses**).*

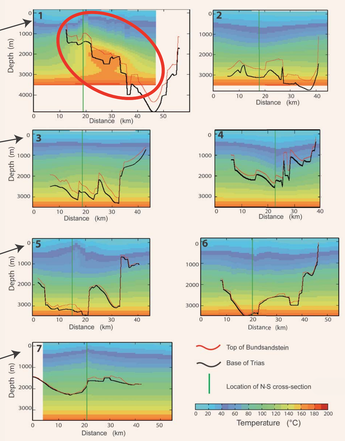
- Shape of the anomaly seems to be controlled by the inclination of the basement-sediment interface.

- Temperature profile measured at Soultz-sous-Forêts indicates that hydrothermal convection occurs within the granitic basement

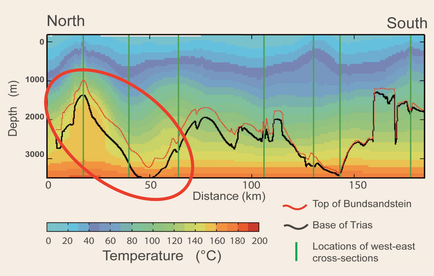
Horizontal cross-sections at different depth levels, together with standard deviation on interpolation



West-east vertical cross-section through the 3D thermal block



North-South vertical cross-section through the 3D thermal block



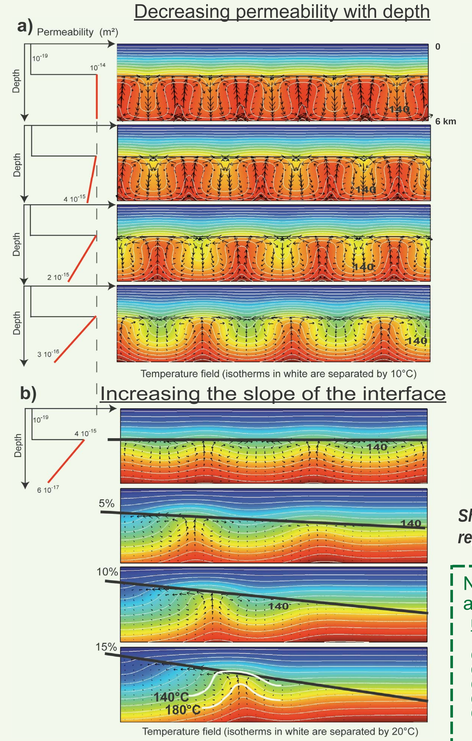
Numerical modelling of hydrothermal convection

(west-east cross-section, 5-6 km deep)

- Darcy law
- Heat transfer equation
- Density and viscosity vary with T
- Permeability decreases with depth
- Other physical properties taken from measurements

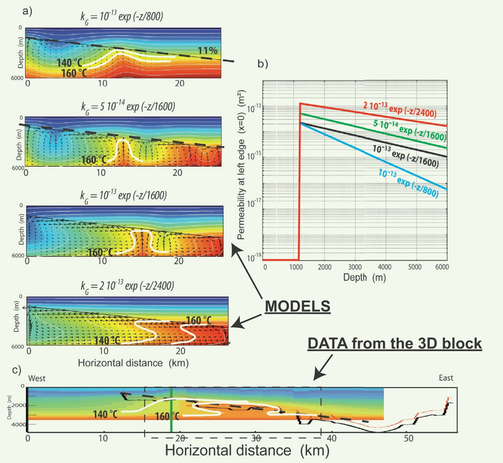
Use of the Comsol Multiphysics™ software, with classical boundary conditions, the objective being to reproduce
- surface heat flow data,
- spatial features observed in the 3D thermal block,
- temperature profile measured at Soultz-sous-Forêts.

Decreasing permeability with depth



Both effects (a and b) act to decrease the number of convective upwellings.

Tests of different permeability laws with an inclined interface



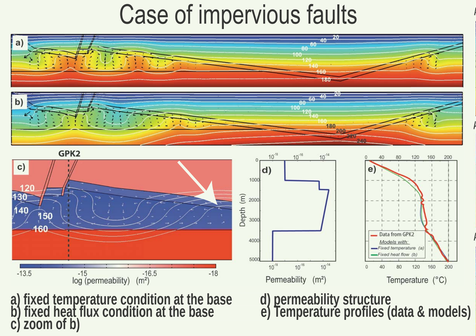
Shapes of the 140°C and 160°C isotherms (white thick lines) are satisfactorily reproduced with the two extreme (top and bottom) permeability laws.

Numerical model at the Rhine graben scale, with adapted geometry and realistic petrophysical properties of main lithological formations

Unit	Depth (Soultz)	Porosity	Thermal conductivity	Permeability	Heat production
	m	%	W/m/K	m²	µW/m³
(1)	0-800	15	1.4	10^{-17}	1.0
(2)	800-1000	15	2.1	10^{-16}	1.0
(3)	1000-1400	15	2.5	$5\ 10^{-15} - 10^{-14}$	1.0
(4)	1400-3700	9	3.0	$k_{top} \exp(-z/\delta)$	6.0 (top) to 2.7 (bottom)
(5)	3700-5000	1	3.0	10^{-18}	2.7
Faults		15	2.5	$10^{-17} - 3\ 10^{-14}$	1.0

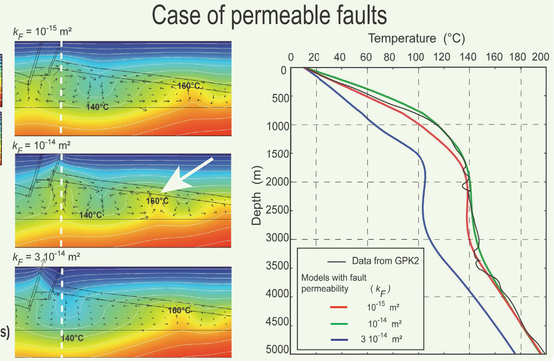
Physical properties attributed to the basin-scale models, and corresponding to laboratory measurements on core samples of geothermal boreholes at Soultz-sous-Forêts.
Units: (1) Pechelbronn oil layers and Jurassic limestones; (2) Keuper and Mushelkalk formations; (3) Buntsandstein sandstones; (4) Permeable part of the granitic basement; (5) less permeable granitic basement.

Case of impervious faults



a) fixed temperature condition at the base
b) fixed heat flux condition at the base
c) zoom of b)
d) permeability structure
e) Temperature profiles (data & models)

Case of permeable faults



White arrows show a neighbouring thermal anomaly, hotter and shallower than that of Soultz-sous-Forêts (dashed lines), and corresponds to the Rittershoffen area, where a vertical geothermal drillhole GRT-1 is ongoing.

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