Outcrop Analogue Studies for Reservoir Characterization of Deep Geothermal Systems in Upper Jurassic Limestone Formations (South Germany)*

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Abstract

The utilization of deep geothermal systems is based on a detailed knowledge of their distinct reservoir characteristics. In the early stages of hydrothermal reservoir exploration, the thermo-physical characterization of the reservoir is mainly accomplished by evaluation of already existing drilling data and seismic surveys in the vicinity of the target area. For reservoir predictions, geothermal parameters such as permeability, thermal conductivity, specific heat capacity and reservoir heat flow have to be quantified. In addition to these thermo-physical parameters, in-situ stress field analysis through uniaxial stress testing and structural tectonic data are important to assess. Outcrop analogue studies enable the determination and correlation of the thermo-physical parameters and structural geology data with distinct facies patterns, therefore the geothermal exploration concept becomes more precise and descriptive. For the economic utilization of deep geothermal reservoirs, a sufficient high flow rate of thermal waters throughout the reservoir to the production well is necessary. This flow rate is mainly controlled by the reservoir permeability. The outcrops of the Swabian and Franconian Alb as well as the transition zone of these two facies areas represent the target formations of the adjacent Molasse Basin. In the Molasse Basin, the limestone formations of the Upper Jurassic contain the main flow paths through tectonic elements and typically for limestone formations through karstification.

A high variation of thermo-physical parameters is recognized within one facies zone or stratigraphic unit; variations even occur within one outcrop. However, general trends indicate that the hydraulic flow patterns are related to tectonically created weak zones in the formations and that the matrix permeability has only a minor effect on the reservoirs sustainability. On the one hand these preliminary results show the necessity to gather more data from the target formations for setting up a reliable thermofacies model. On the other hand comparing our data with already existing data confirms that the applied methodology is appropriate and very productive.

The facies related characterization and prediction of geothermal reservoir parameters is a powerful tool for the maintenance, operation and quality management of an existing geothermal reservoir. Thus, the results of this study will also be used for further drilling design plans and reservoir enhancement measures.

Selected References

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Theme V: Carbonates and Fractured Reservoirs

Motivation

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Scientific

Reservoir characterization with determining thermo-physical parameters including permeability and thermal conductivity data which are rarely available measured at the same sample.

3D prognosis of reservoir properties by applying facies models to the deeper subsurface can be implemented as an additional exploration tool.

Engineering

Geothermal reservoir properties serve to distinguish between enhanced (petrothermal) and hydrothermal systems and can be used for optimized drilling design.

Economic

Outcrop analogue studies offer effective opportunities to gain data to be transferred to greater depths and higher temperatures which lead to a better understanding of production capacities of geothermal reservoirs.

Geothermal *vs.* Hydrocarbon Reservoir

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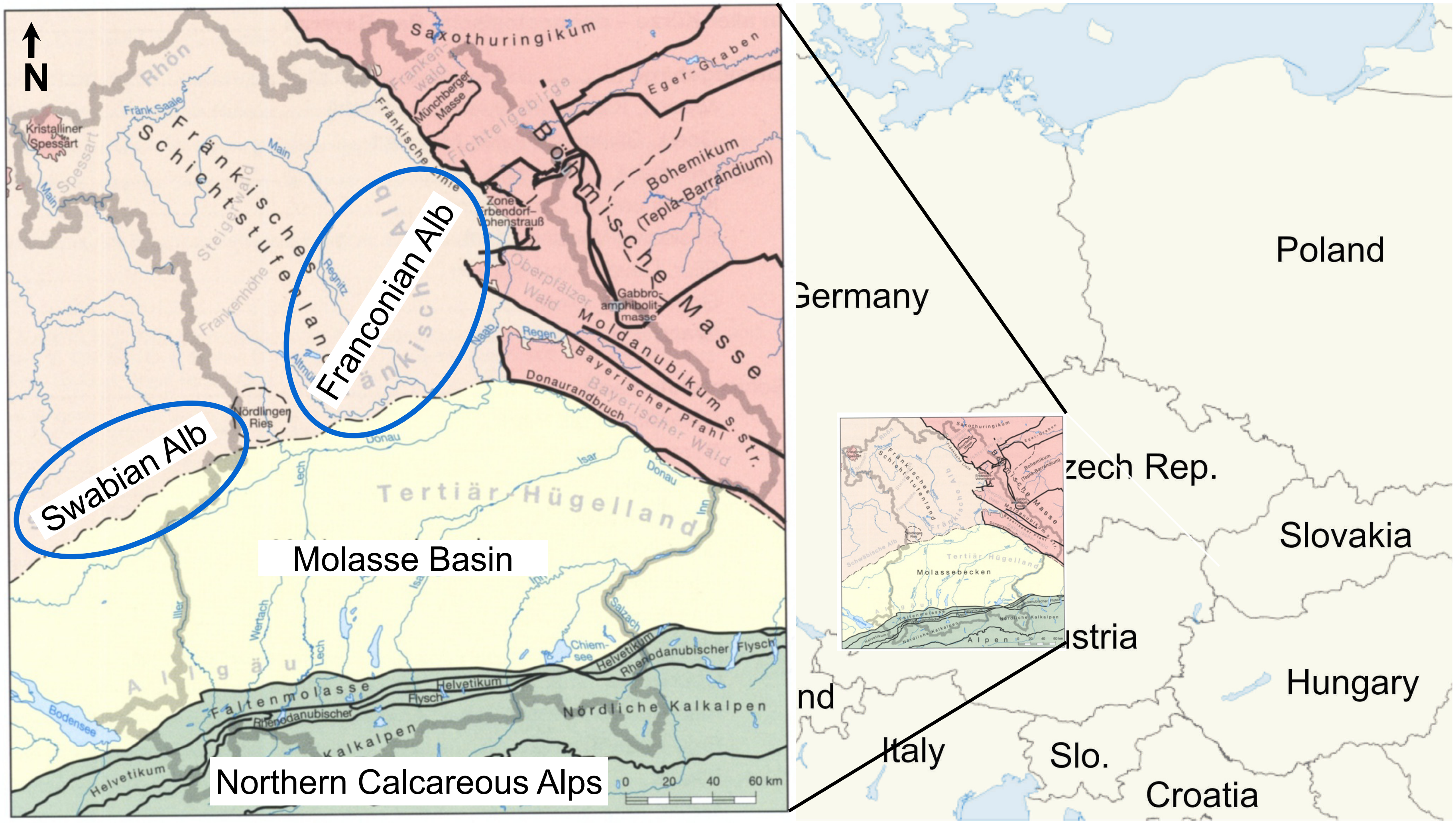
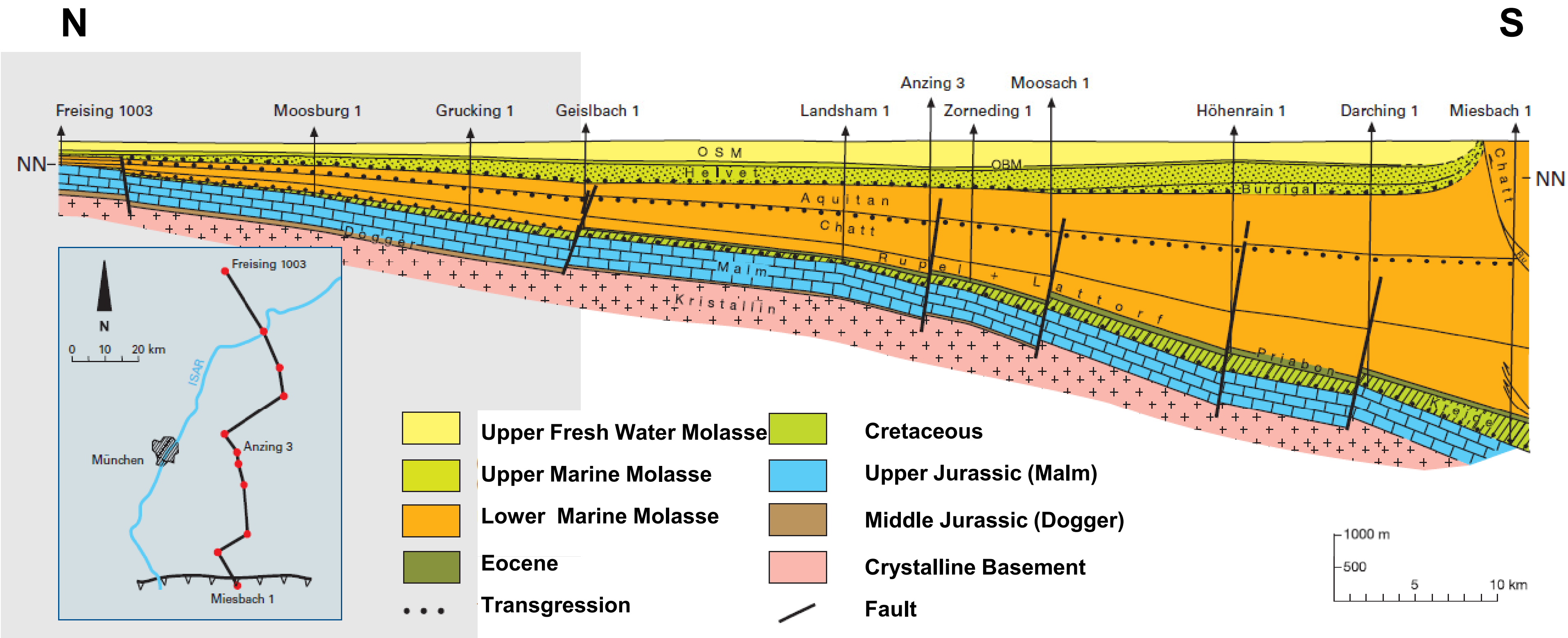
Reservoir Characteristics

Geothermal Reservoir	Hydrocarbon Reservoir
High porosity and permeability	High porosity and permeability
Reservoir rock = host rock	Reservoir rock ≠ host rock
High temperature	Low temperature
Low/high reaction rate with water	Low reaction rate with HC
Good connectivity with faults	No connectivity with faults
High thermal conductivity	Low thermal conductivity
Circulation/Capture structure	Capture structure (cap rock)

Study Area – SE Germany (Molasse Basin)



Cross Section – Molasse Basin

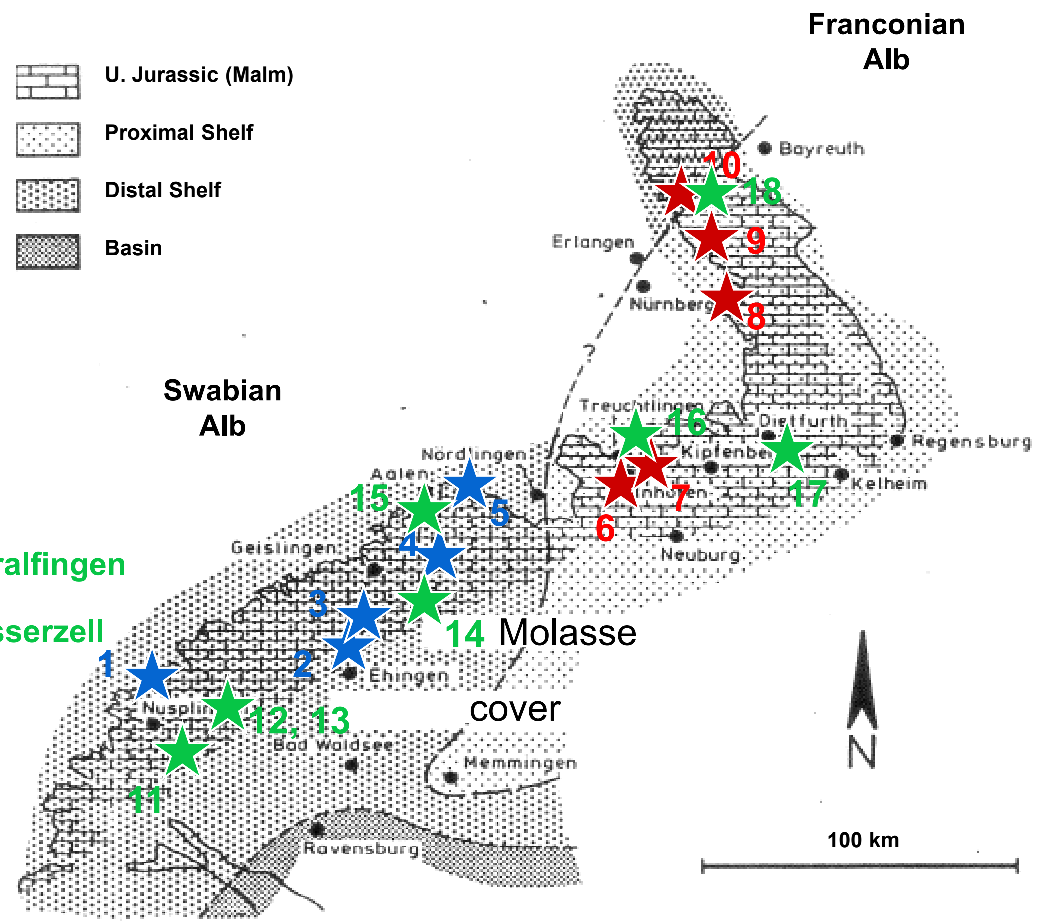


Bavarian Geothermal Atlas, 2010

Swabian and Franconian Alb

Field campaign 2011:

11 ★ Liptingen
12 ★ Staßberg
13 ★ Thiergarten
14 ★ Herrlingen
15 ★ Aalen-Wasseralfingen
16 ★ Eichstätt-Wasserzell
17 ★ Köttingwörth
18 ★ Simmeldorf



Selg & Wagenplast (1990)

Field campaign 2010:

1 ★ Plettenberg
2 ★ Vohenbronnen
3 ★ Gerhausen
4 ★ Mergelstetten
5 ★ Hülen

6 ★ Solnhofen
7 ★ Kinding
8 ★ Vilshofen
9 ★ Drügendorf
10 ★ Gräfenberg

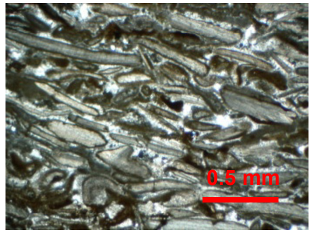
Upper Jurassic: Malm $\alpha - \zeta_3$

Concept

Outcrop

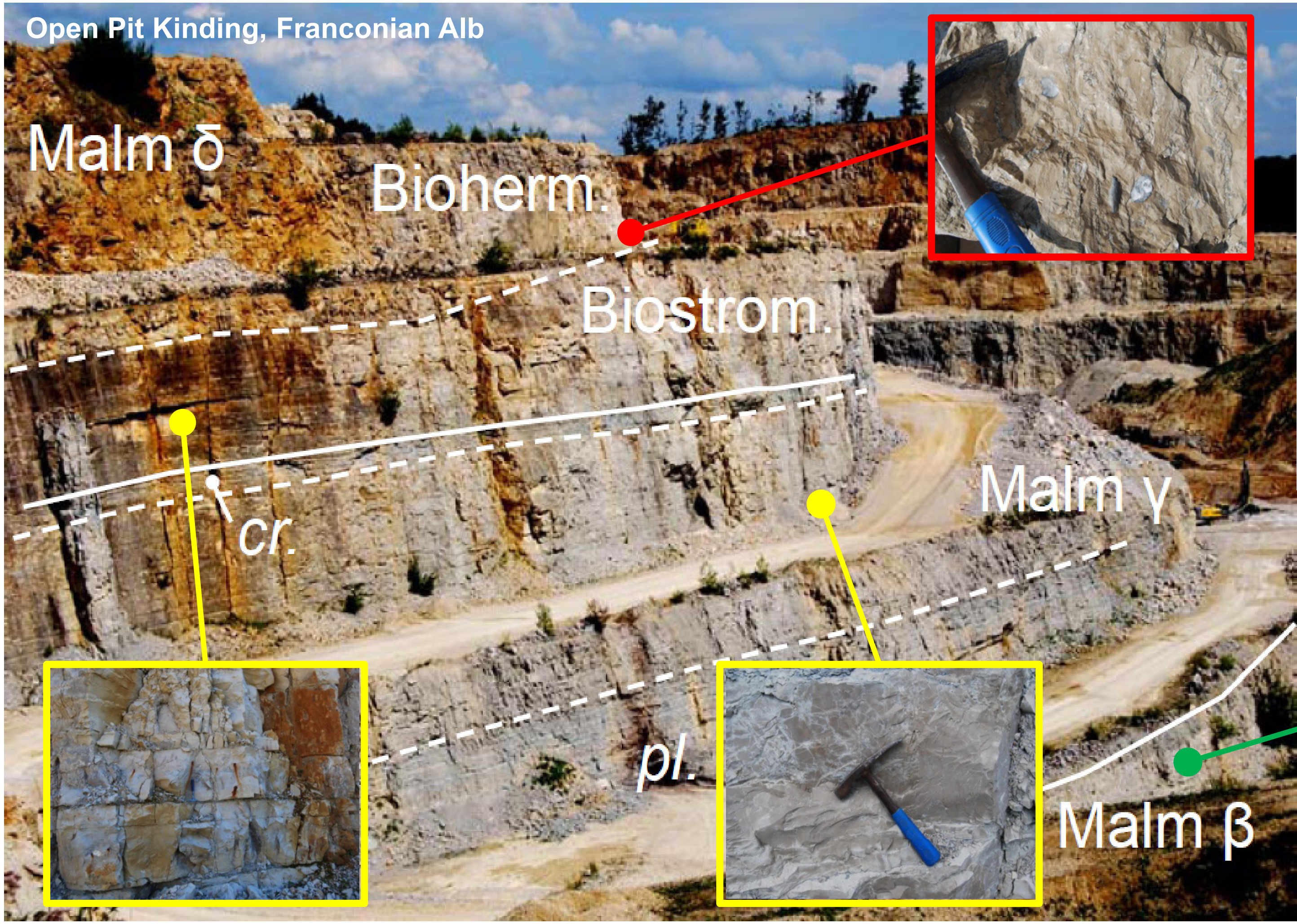
Core Samples

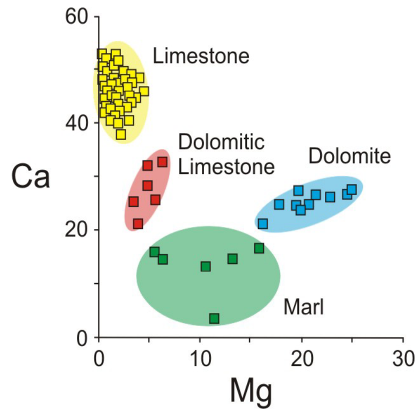
Thin Sections



Macro Scale → **Meso Scale** → **Micro Scale**

Outcrop Analogue Studies





Sampling and Measurements

Oriented Drill cores (wherever possible)

Representative samples

Thermo-physical parameter determination done with Thermal Conductivity Scanner , Gas-Permeameter and Porosimeter

Thermo-physical Matrix Parameters (Franconian Facies)

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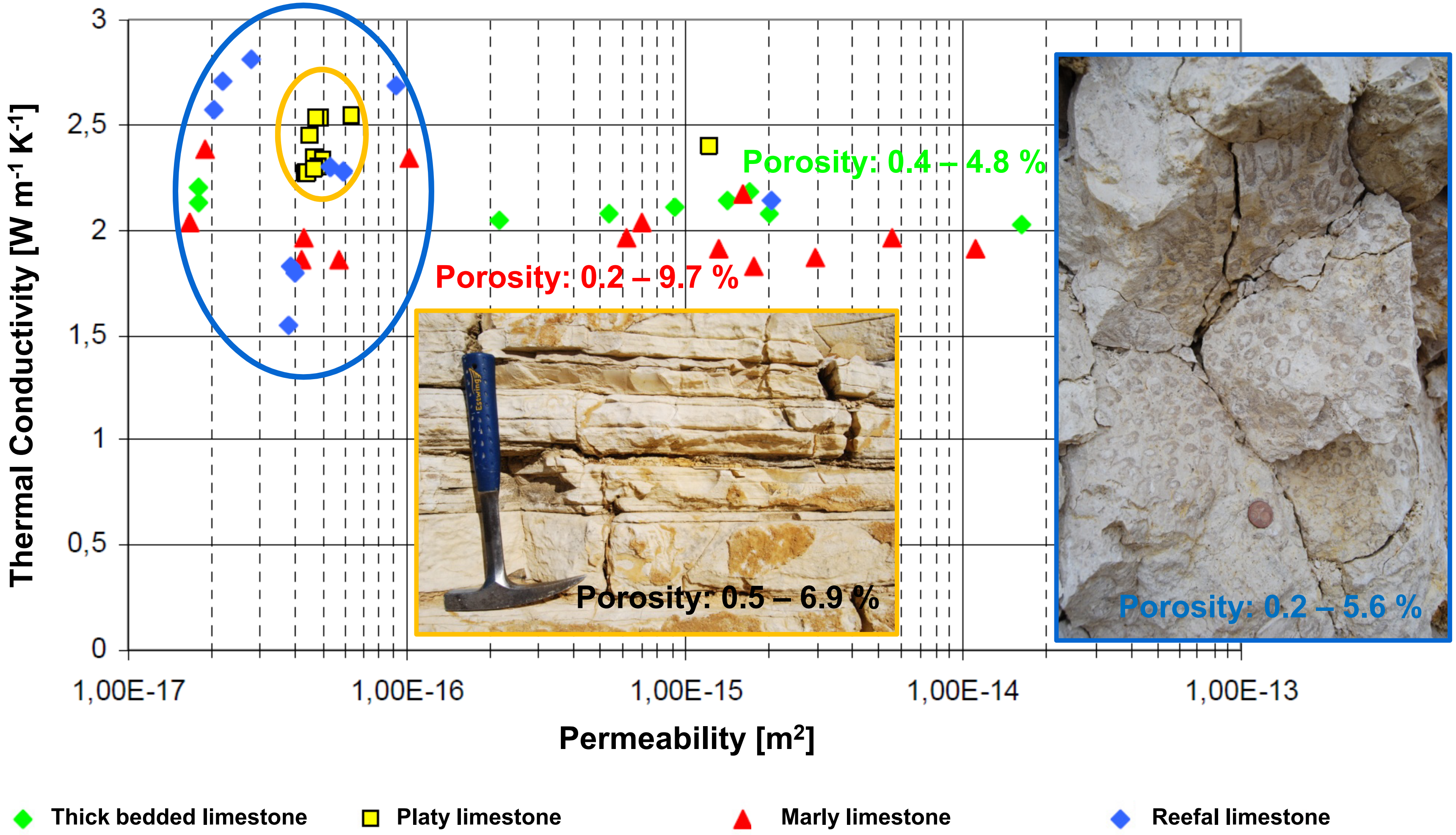

Thermo-physical Matrix Parameters (Swabian Facies)

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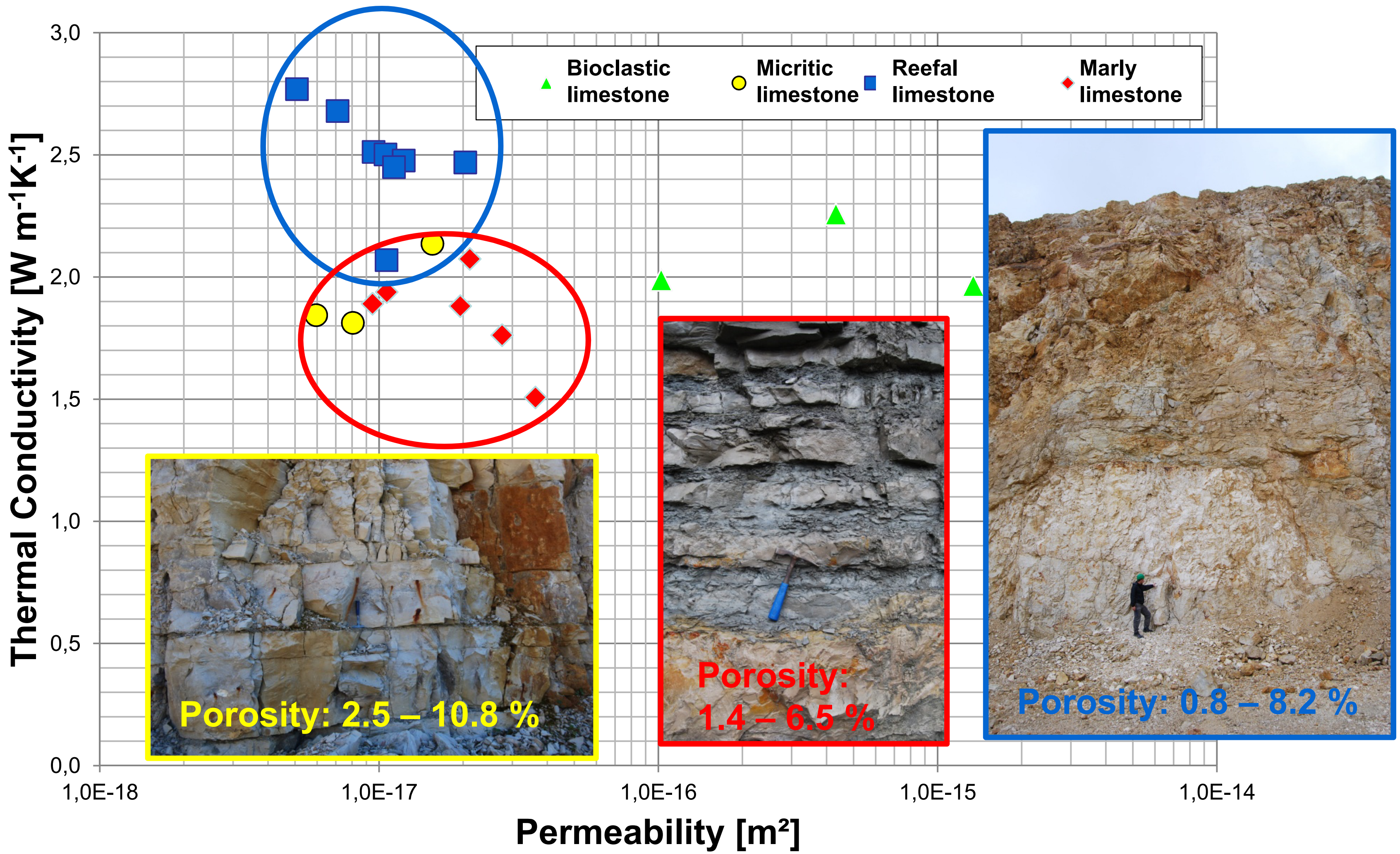

Facies-related Correlation

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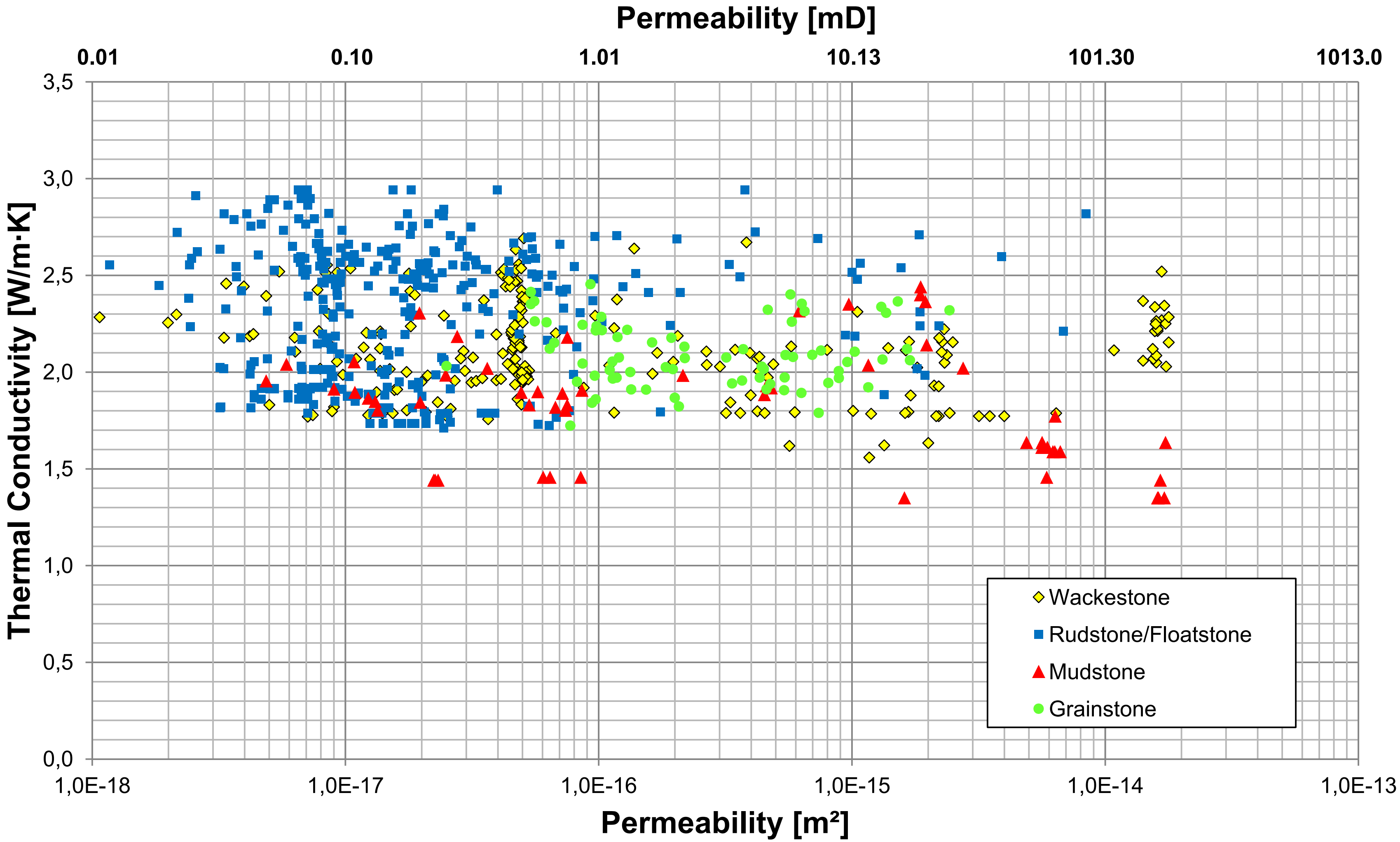
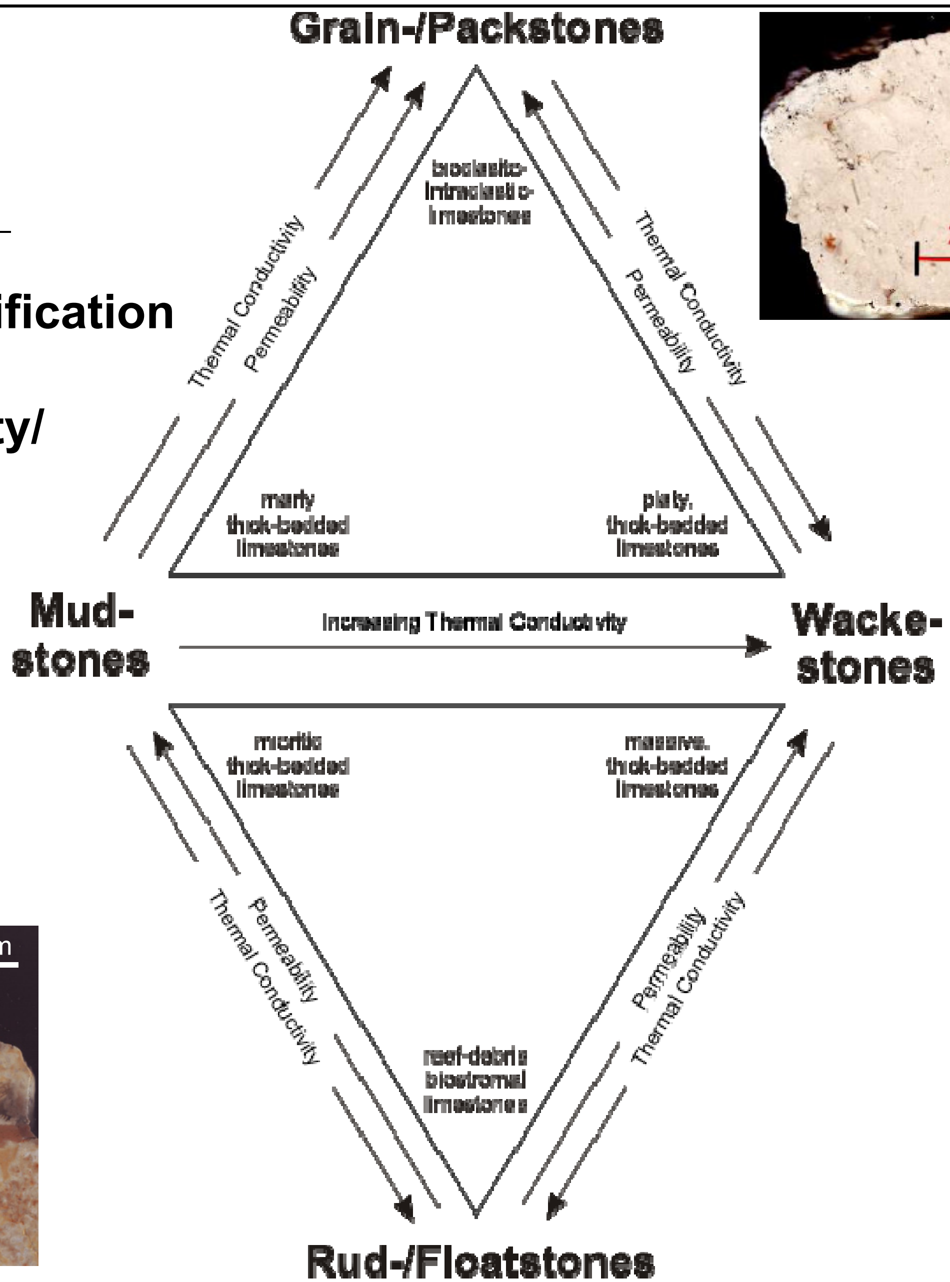
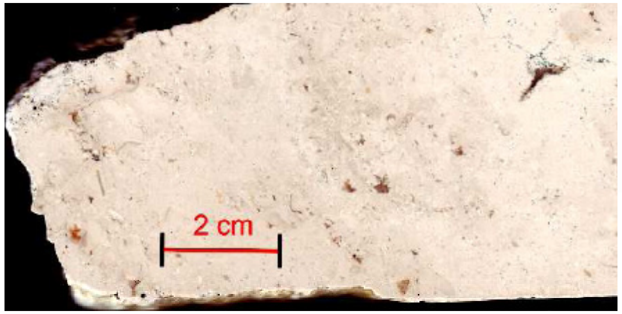
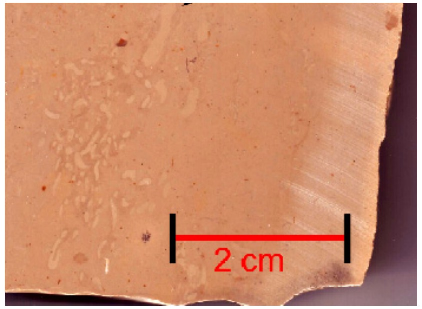


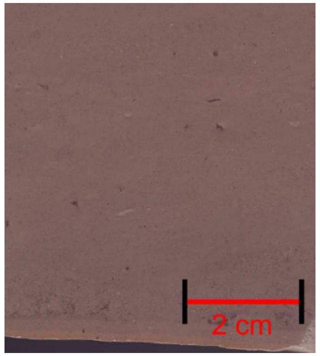
Classification

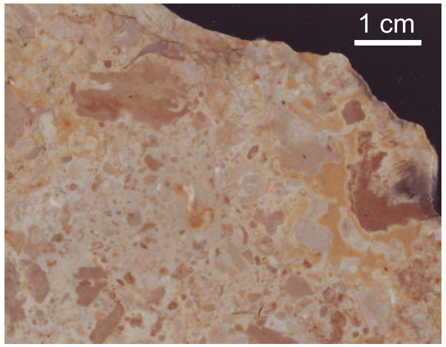
Thermofacies classification of carbonates (thermal conductivity/ permeability)



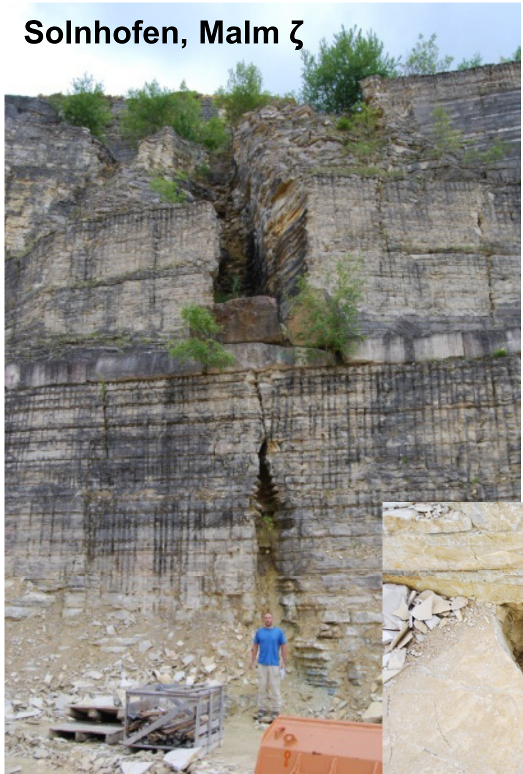








Karst Phenomena



Reefal/fossil-rich limestone:

Primary and secondary porosity

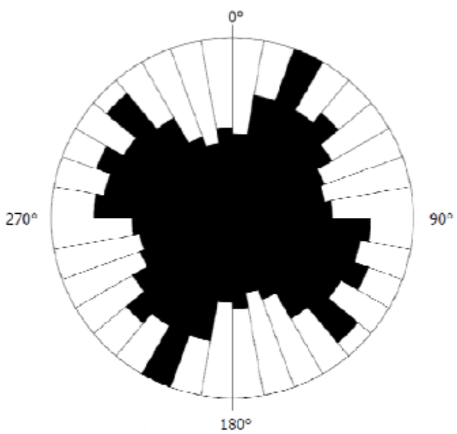
Karstification on a larger scale

Thick-bedded/platy limestone:

Karstification along faults and major joints

Structural Data

Assessing:
- **joint/fault opening width**
- **roughness of joints**
- **joint surfaces**
- **kind of fillings**
- **joint texture**
- **distribution of joints**

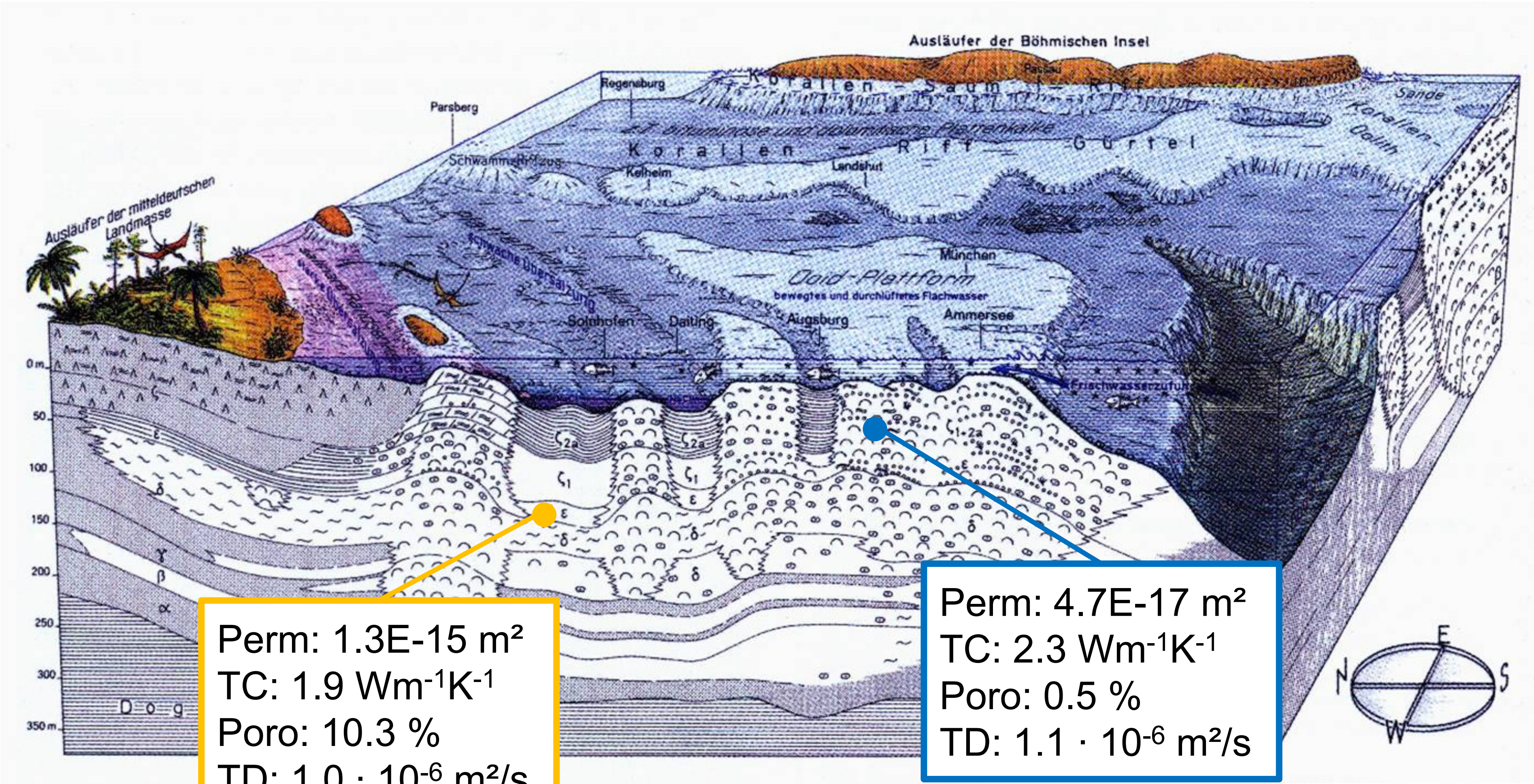


Strike direction, N=1004
Largest petal: 42.5 values
Largest petal: 4.2% of all values

Structural data combined with stress field data will give insight into the fracture system in the reservoir formation

In addition pumping test data of the target formation are analysed to evaluate the *in-situ* hydraulic performance

Facies Model – Upper Jurassic (Malm)



nach Meyer (1980)

Depth-related Correction of Parameters

The measured matrix parameters are obtained from dried cores under laboratory conditions.

To simulate reservoir conditions temperature, pressure and water saturation occuring in the geothermal reservoir have to be considered.

➡ **Different transfer models for water saturated rocks under pressure and temperature conditions for relevant depth exist (e. g. Pape et al., 2000; Vosteen & Schellschmidt, 2003; Popov et al., 2003) and can be validated by Thermo-Triaxial tests.**

High Pressure - High Temperature Triaxial Cell

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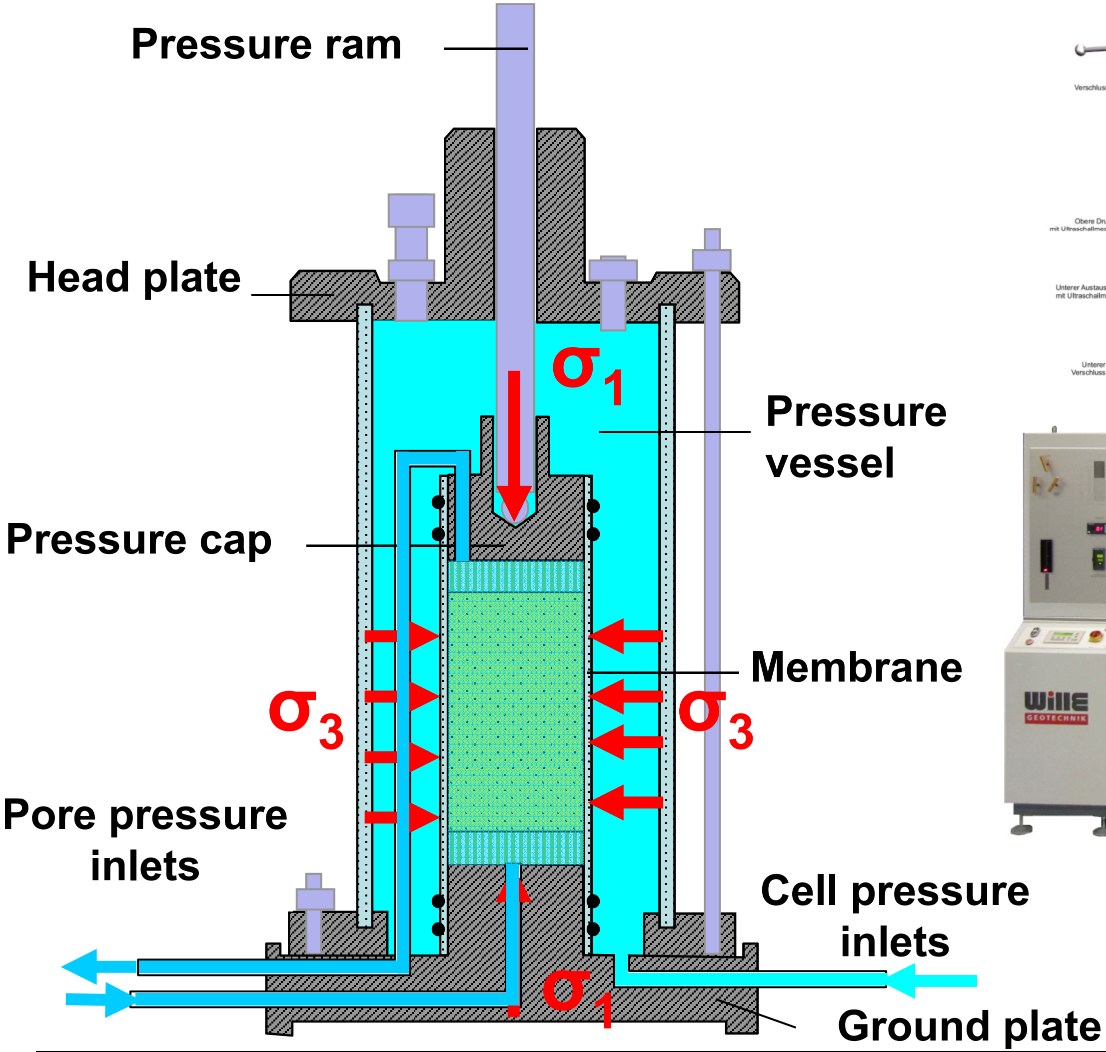

Vertical pressure: 500 MPa
Horizontal pressure: 60 MPa
Temperature: up to 200°C
Permeability range: $10^{-9} – 10^{-16} m^2$

Conclusions

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Outcrop analogue studies provide a sufficient data base to determine thermo-physical reservoir characteristics of the matrix of geothermal reservoir formations.

Facies concepts are applied as exploration tool producing conservative results. By adding information on secondary porosities, karstification, stress field higher reservoir capacities can be inferred.

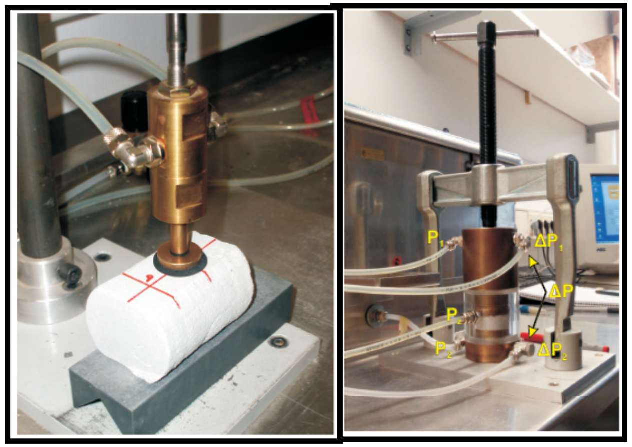
To create reliable predictions and 3D reservoir models structural geology and pumping test data as well as validated transfer models have to be included in the reservoir assessment.

The key feature for reliable reservoir prognosis, reservoir stimulation measures, and sustainable reservoir utilization is to integrate facies, thermo-physical, hydrogeolocial and structural geology data into 3D reservoir models.

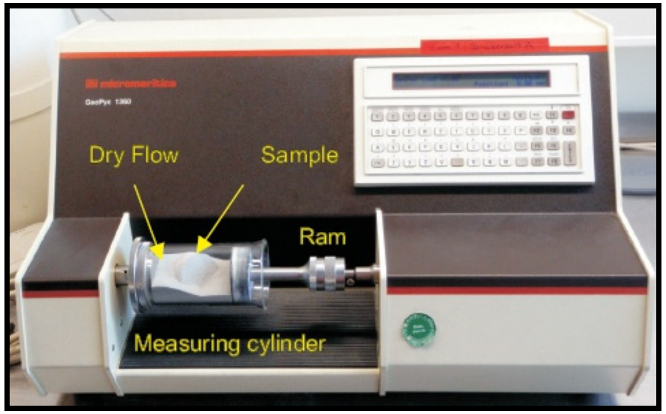
THANK YOU VERY MUCH FOR YOUR ATTENTION

Determination of Reservoir Properties

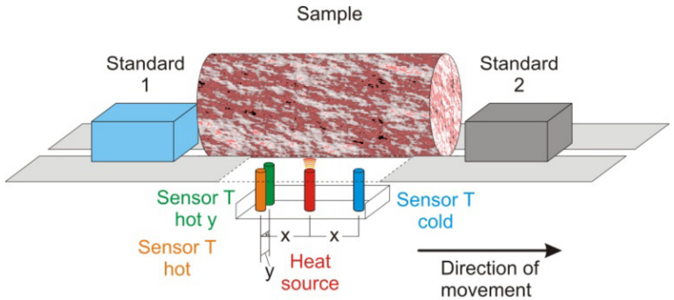
Uniaxial strength tests

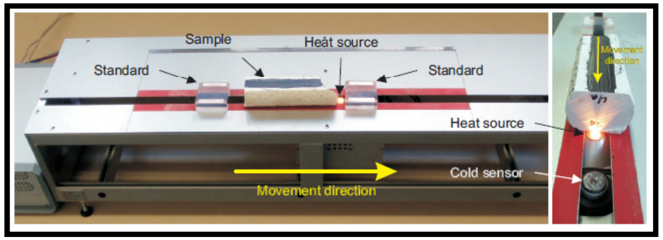


Gas-Permeameter



Porosimeter





Thermal Conductivity Scanner