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THE THERMOFACIES CONCEPT

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ABSTRACT

The investigation and exploration of potential deep geothermal systems is based on detailed knowledge of their distinct reservoir characteristics. This is especially important in the exploration of potentially engineered geothermal systems and of mid to low enthalpy reservoir formations in greater depths, resp. In the early stages of geothermal reservoir exploration, characterization of the reservoir is mainly accomplished by evaluation of drilling data and seismic surveys. However, for the prognosis of 3D reservoir properties, the main geothermal parameters such as (1) permeability, (2) thermal conductivity, and (3) reservoir heat flow have to be quantified with respect to a 3D structural model.
Outcrop analogue studies enable the determination and correlation of the necessary parameters, and based on detailed facies analysis, the geothermal exploration concept becomes more precise and descriptive. Finally, the detection of the spatio-temporal development of sedimentary facies within a specific exploration area may contribute to establish integrated structural 3D reservoir models. Thus, thermofacies – the facies dependence of geothermal parameters – become a key feature for reservoir prognosis, reservoir stimulation, and efficient reservoir utilisation. Here, a thermofacies approach on reservoir characterisation is presented and discussed.

INTRODUCTION

The scientific motivation to undergo 3D prognosis of reservoir properties by facies models to be applied to the deeper subsurface is that permeability and thermal conductivity data are rarely available measured at the same samples. From the engineering point of view geothermal facies concepts serve to distinguish between enhanced (petrothermal) and hydrothermal systems. Furthermore, the economic part is that outcrop analogue studies offer effective opportunities to gain data to be transferred to greater depths and higher temperatures.

Future geothermal utilization will depend on exploration of comparatively deep reservoirs which may be characterized as intermediate to high enthalpy resources (discussed in Dickson and Fanelli, 2003). At the early stage of a project, characterization of a reservoir is difficult because direct and indirect survey data are lacking. Investigation drillings are extremely costly due to their depths between 3.000 and 5.000 m and deeper. There is an economic necessity to utilize exploratory drillings later on as a production or injection well. This makes sufficient reservoir property prognosis necessary based on quantitative data sets. Facies concepts have to be integrated by outcrop analogue investigations to obtain a three dimensional image of the system as well as measured thermo-physical formation properties. The measurement of the thermo-physical rock properties itself then requires a high level of accuracy with a good reproducibility. Therefore, a statistically relevant number of outcrop analogue data is required. The approach to use measured data from outcrop samples requires furthermore the prediction of the impact of reservoir pressure, temperature and natural fracture fabric on permeability and thermal conductivity. A matter of further investigations is to quantify the impact of hydrothermal alteration. Generally, outcrops are not exposed to alteration as long and intense such as deeply buried reservoir formations. Furthermore, hydrothermal altered samples show higher permeability and a lower thermal conductivity in comparison to unaltered or weakly altered rocks of the same formation (Mielke et al., 2010). The prognosis of alteration cannot be obtained from a facies related concept.
This study introduces the conceptual framework to predict reservoir characteristics based on facies. Data from ongoing field and laboratory studies are introduced to test whether a 3D prognosis of facies may be taken as a reliable method to explore geothermal reservoir properties of the deep subsurface.

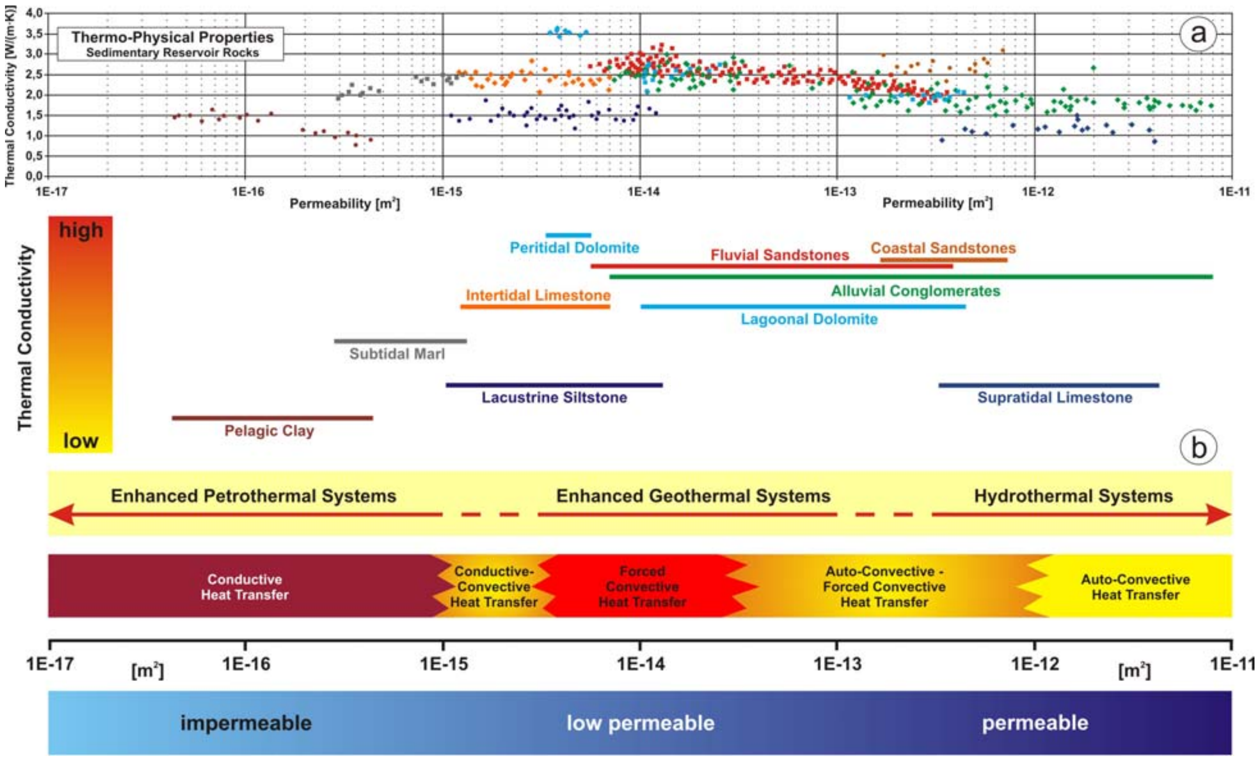

*Figure 1: Conceptual thermofacies approach: facies types of sedimentary rocks in relation to the three major geothermal system types; **a** – thermo-physical properties (error bars not plotted) from Palaeozoic, Mesozoic and Cenozoic sedimentary series of central Europe (Sass and Götz 2008; Török et al., 2008; Sass and Götz, 2010; Bär et al., 2010) and **b** – correlation to a general geothermal system characterization, depending on the major heat transfer mechanism (convective vs. conductive).*

MATERIAL AND METHODS

Samples from outcrops and drill cores which are appropriate to define matrix properties are analysed. Tectonic patterns such as fissures and faults are typically not sampled. The thermal conductivity and the intrinsic permeability are investigated at oven dried samples. A high sample number and a good consistency of the optical scanning data are required. Furthermore, permeability and thermal conductivity has to be measured at the same point of a sample. Permeability data obtained from water flow based Darcy experiments result in averages for the entire sample or core, which is insufficient to correlate thermal conductivity with permeability.

The outcrops are selected to offer the best "unweathered" conditions to be found. It is required to sample representative beds with respect to specific lithologies within a well section or an outcrop succession.

As known from reservoir engineering (Vosteen et al., 2003), the correlation between porosity and permeability is in many cases poor to very poor. Porosity concepts which seem to be appropriate to a thermofacies approach are therefore not applicable.

The problem of conventional permeability measurements was that the well known standard methods allow only to determine the bulk sample permeability of a drill core specimen etc., resulting in a wide range of permeability data.

For the concept shown in this study it was necessary to correlate punctual permeability data with linear (resp. quasi-punctual) thermal conductivity data. For this purpose a gas-pressure permeameter and a mini-permeameter were combined and used for measurements on thousands of plug samples drilled from outcrop and core samples. Thermal conductivity was measured applying the method of optical scanning introduced by Popov et al. (1999).

THERMOPHYSICAL ROCK PROPERTIES AND SEDIMENTARY FACIES

Selected rock types of different depositional environments and different stratigraphic ages were measured and plotted in the permeability-thermal conductivity diagram (Fig. 1a). A strong correlation between facies, representing distinct depositional conditions, and thermo-physical rock properties is recognized. Fine-grained pelagic clays show the lowest values of permeability and thermal conductivity because they are characterized by a high density (low permeability) and show a high content of inner crystalline water (low thermal conductivity). Coastal and terrestrial sandstones and conglomerates represent deposits characteristic of highest permeability and thermal conductivity, because they show the highest flow effective porosity (high permeability) and high quartz contents. Additional silica cements lead to the highest thermal conductivity values within this group.

If the relation between facies and thermo-physical properties is stated, it will be justified to correlate geothermal reservoir types with facies types as shown in Figure 1b. Enhanced (or engineered) geothermal systems (EGS) operate with artificial permeability improvement (Tester et al., 2005; Huenges, 2010). The target is to use thermal water as a heat carrier since the conductive heat transfer in petrothermal systems (naturally nearly impermeable with very limited availability of natural thermal water) is economically unfeasible. Natural hydrothermal systems have permeability where natural un-forced convection may take place if the thermal gradients will be large enough. Enhancement of a reservoir means to bring a rock formation as close to that natural situation as possible. If one applies the concept of the Darcy-modified Raleigh number on the range of transition from un-forced convection to applied hydraulic gradient driven convection, one will find critical permeabilities about 10^{-13} to 10^{-14} m². That is the most feasible range for EGS and it fits to medium to fine-grained sediments, e.g. dolomites and fluvial sandstones.

A data set based on about 9.000 measured samples (facies, permeability, thermal conductivity) supported by some hundreds of thin section analyses and poro-perm investigations allows to propose a thermofacies concept as shown in Figure. 1. Ongoing investigations include plutonic rocks to characterize mineral parageneses, their alteration pattern and their thermo-physical reservoir properties. First results indicate that the alteration stage seems to have similar importance as distinct sedimentary facies types of siliciclastics and carbonates.

IMPLICATIONS ON GEOTHERMAL EXPLORATION

The reservoir characteristics define the type of geothermal system (hydrothermal, petrothermal, enhanced/engineered) and therefore determine the basic direction of geothermal technology.

Facies concepts are applied as an exploration tool producing conservative results, since secondary porosities, karstification, and a distinct stress field will mostly lead to higher reservoir capacities. Thus, thermofacies may become an additional key feature for reservoir prognosis, reservoir stimulation, and efficient reservoir utilization.

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