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# Upscaling thermal conductivities of sedimentary formations for geothermal exploration

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ABSTRACT

An important issue in the numerical simulation of geothermal reservoirs is the problem of scales. Data are collected at a scale usually smaller than the one used to discretise the sedimentological units in the numerical model. For instance, thermal conductivities sampled from field scale cores have measurement support in the order of centimeters to meters, whereas numerical models for heat flow require conductivities representative of scales ranging between tens to hundreds of meters. We present a study aimed at demonstrating the upscaling of thermal conductivities. Based on the spatial characteristics of a large sample data set of thermal conductivities of permo-carboniferous sedimentary rocks, 10 different realizations of the system are randomly generated at a fine scale of resolution and are then upscaled to four different resolutions using diverse averaging procedures (based on arithmetic, geometric, or harmonic averaging) as well as renormalization. Results show that upscaling based on harmonic averaging of local values is superior in reproducing the original values while renormalization gives the poorest results. Generally it is demonstrated that the specific kind of upscaling has only a small impact on the resulting temperature distribution. Due to the diffusive character of heat conduction all results tend towards the arithmetic mean value associated with the data.

## 1. Introduction

Geothermal models for simulating heat and mass transfer are a key tool for geothermal exploration and planning (e.g. Rühaak et al., 2010; Sippel et al., 2013; Huenges et al., 2013). Inputs to such models include information/data on parameters such as permeability and thermal conductivity. Knowledge of the details of the spatial distribution of these system parameters is typically very limited. Measurements are associated with diverse sources and are distributed on a multiplicity of scales. These data can be obtained from different sources, including but not limited to well-logs, outcrop analogues, plugs, or thin sections (Fig. 1).

Remarkable databases of petrophysical properties in geothermal reservoirs have been maintained in the past (e.g. Sass et al., 1971; Haenel and Staroste, 1988; Williams and Anderson, 1990; Clauser and Huenges, 1995; Bär et al., 2011; Homuth et al., 2014).

Depending on the approach and data type availability, projecting these measurements onto reservoir models requires, for example, geostatistical/stochastic modeling, upscaling and possibly also downscaling. A key requirement associated with all these approaches is the intention to keep as much of the small scale information as possible while projecting their effect onto the model scale.

Several well-established modeling and upscaling techniques for petrophysical properties in hydrocarbon reservoirs can be found, a short review is added in this text. Few works exist about the upscaling of thermal conductivity for geothermal modeling (e.g. focusing

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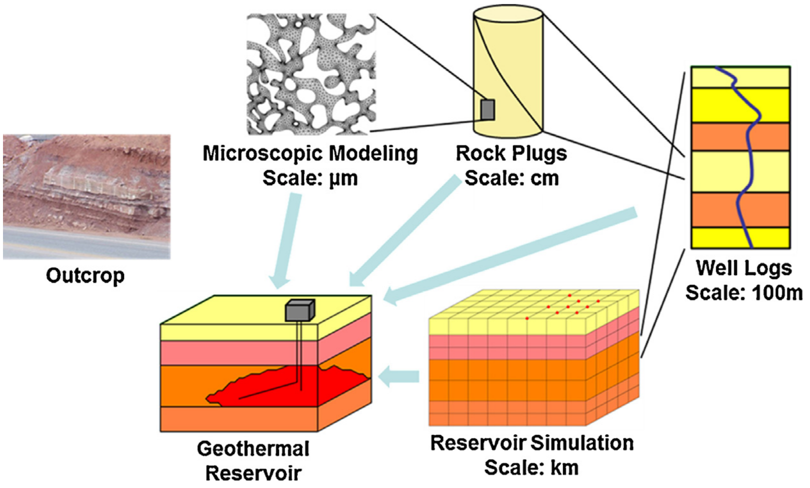

**Fig. 1.** The concept of upscaling from diverse scales to a desired model scale.

on crystalline rocks, Sundberg et al., 2009), but no established procedure exists.

Yet, geothermal reservoirs have a much tighter margin to be economically profitable. Therefore, being able to reliably model and upscale petrophysical properties in such reservoirs is of critical importance to reliably forecast heat in place and energy extraction.

There are diverse approaches to parameter upscaling. Numerical models with scales of several kilometers are discretized through a set of grid blocks; upscaling has to be performed for each grid block with typical sizes of tens to hundredth of meters. One approach is simply based on some type of averaging. However, the selection of the appropriate method of averaging (i.e., arithmetic, geometric, harmonic) depending on scale and flow conditions is not trivial and is a matter of the corresponding scale (Hartmann et al., 2005).

The following scales are typically defined and considered in numerical modeling and theoretical studies:

- Microscale (X-ray computer tomography, nuclear magnetic resonance (NMR), thin-sections, electron microscopy, mineralogy, fissures, microcracks).
- Mesoscale (rock-samples, cores, borehole-geophysics, NMR, positron emission tomography (PET), laboratory measurements of thermal conductivity, permeability, porosity, fractures, small scale modelling).
- Macroscale (seismics, gravimetry, magnetics, helicopter electromagnetics (HEM), fault zones, outcrop studies, remote sensing, medium–large scale modelling).

Following Scheibe and Yabusaki (1998) the aim of this work is to demonstrate the effects of thermal conductivity upscaling in general, rather than determining rules for upscaling and/or values of parameters for general use.

## 2. Upscaling of thermal and hydraulic conductivity

### 2.1. Constitutive relations

Several thermo-physical properties are relevant for assessing and planning geothermal exploration and production. Among these parameters, bulk permeability and thermal conductivity are critical for the assessment of the subsurface distribution of fluids and temperature field. A detailed analysis of the way upscaling strategies for thermal conductivity might impact temperature and pressure distributions and the assessment of the sustainability of a geothermal reservoir is still missing.

For example, Fig. 2 depicts the ranges of thermal conductivity values documented for diverse rock types and indicates the typical degree of spatial variability of this parameter.

Based on Fourier's law (Eq. (1)) the thermal conductivity $\lambda$ ($\mathrm{W\,m^{-1}\,K^{-1}}$) controls the rate of heat flow $q$ ($\mathrm{W\,m^{-2}}$) which results from a given temperature gradient $\nabla T$ ($^\circ\mathrm{C\,m^{-1}}$):

$$\mathbf{q} = -\boldsymbol{\lambda}\nabla T. \tag{1}$$

Heat transport equation in a geological formation occurs by a combination of convective and conductive processes. It is frequently modelled by the following equation (e.g. Nield and Bejan, 1999).

$$(\rho c)_g \frac{\partial T}{\partial t} = \nabla \cdot \left(\lambda_g \nabla T - (\rho c)_f \mathbf{v} T\right) + H \tag{2}$$

Here, $T$ (°C) is temperature, $c$ is specific heat capacity ($\mathrm{J\,kg^{-1}\,K^{-1}}$), $\rho$ is density ($\mathrm{kg\,m^{-3}}$), $\lambda$ is thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$), $\mathbf{v}$ is Darcy velocity ($\mathrm{m\,s^{-1}}$), and $H$ ($\mathrm{W\,m^{-3}}$) represents sink/source terms. Subscripts $f$ and $g$ denote fluid and bulk properties, respectively.

Since heat transport in the subsurface is governed by the joint effects of conductive and convective processes, as seen in Eq. (2), a simple deduction of the thermal conductivity based on temperature or heat flow space–time distributions is fraught with theoretical and conceptual difficulties and can lead to ambiguous results.

As we are here interested in analyzing upscaling of thermal conductivity, $\lambda$, which is fundamentally different from upscaling of hydraulic conductivity as we illustrate in Section 2.2, we consider only pure conduction in Eq. (2) (i.e., when $\lambda_g \nabla T \gg (\rho c)_f \mathbf{v} T$). From a practical point of view, such situations can take place when the permeability of the host formation is approximately $10^{-15}\,\mathrm{m^2}$ or less (Hayba and Ingebritsen, 1997). Basin modelling studies often consider only conductive heat transport (e.g. Förster and Merriam, 1999; Beardsmore and Cull, 2001).

### 2.2. Key differences between upscaling of hydraulic and thermal conductivities

Upscaling of permeability and porosity has been the subject of several studies in the field of oil and gas exploration (Farmer, 2002) as well as in the groundwater hydrology literature.

Starting from the work of Clauser (1992) detailed reviews of the diverse upscaling techniques for hydraulic conductivity and permeability where provided, e.g. by Wen and Gomez-Hernandez (1996) and Renard and de Marsily (1997). Stochastic and deterministic