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Inference of hydraulic permeability and thermal conductivity from NMR and borehole logging

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Hydraulic permeability and thermal conductivity are the transport properties governing heat advection and heat conduction, respectively, in rock. Therefore, geothermal heat production requires information on these parameters. At the same time they are difficult to measure directly in situ, and in situ values can be inferred from laboratory measurements only with care due to the inherent scale problem. This uncertainty comprises one of the major uncertainties in energy yield predictions and corresponding economic calculations for new installations of geothermal energy use.

In this situation, permeability prediction from NMR well logs or mobile NMR core-scanner data is attractive since measurements can be performed directly in the formation and on fresh cores right after drilling, respectively. Besides, the method is fast and non-destructive. In contrast to T_1 relaxation time distributions of longitudinal magnetization, commonly measured T_2 distributions of transversal magnetization are influenced by external and internal magnetic field gradients. Internal magnetic field gradients arise from magnetic susceptibility contrasts between rock mineral surfaces and the pore fluid. Resulting diffusion effects result in shorter T_2 values and thus in apparently smaller pore sizes. In the case of typical reservoir rocks with high porosity, the influence of diffusion due to internal magnetic field gradients can be neglected and permeability can be predicted by a standard equation developed by Kenyon et al. (1988) which is commonly used in NMR logging. With a mobile NMR core scanner which provides a nearly homogeneous static magnetic field we performed two-dimensional T_1 and T_2 relaxation experiments on Rhaetian sandstone samples with low porosity and small pore radii. Because small pore radii are associated with high internal magnetic field gradients diffusion effects become more important and standard methods from NMR logging in the oil industry cannot be applied for an accurate permeability prediction. Based on model theory with regard to a field gradient interlayer which fits the inner side of the pore wall, we can relate an effective pore radius to each T_2 distribution curve with both an analytical and a more practical empirical equation. In a next step, permeability can then be predicted accurately from the physically based Kozeny-Carman equation (Konzeny, 1927; Carman, 1937). Here, the formation factor for hydraulic flow provides an additional contribution towards an accurate permeability prediction. All calculated permeability values are verified based on results from gas flow measurements.

We inferred thermal conductivity from other petrophysical properties based on core data from the South German Molasse basin. A correlation study of thermal conductivity, sonic velocity, bulk density, and porosity yields an accuracy for the predicted thermal conductivity of ± 0.2 W/(m K). For predictions of in situ thermal conductivity based on wireline data a mixing law approach is used. The most appropriate mixing law based on porosity was determined in a review of existing laws. Also, a two-parameter mixing law is analyzed which is based on porosity and an additional structural parameter. For water-saturated, granular rocks the geometric mixing law is appropriate. For dry samples, the structure of the rock cannot be neglected and should be taken into account. The computation of thermal conductivity from wireline data is performed for a borehole from the South German Molasse basin. Two inverse algorithms of varying complexity are used and the results are tested against core data from the same borehole. The accuracy of the prediction is ± 0.3 W/(m K). This is larger than for controlled laboratory conditions due to problems of core-log matching, different spatial resolution of measurements, and changes in sample properties which may occur during coring. The analysis shows that the computation is feasible and may be extended to include the inversion of temperature data in a joint inversion algorithm. This has requirements different from conventional algorithms for petrophysical inversion as it requires solving the differential equation for transient heat diffusion, resulting in a more complex forward problem. The inverse problem is solved by a Quasi-Newton iterative scheme with a Bayesian type regularization. Use of the technique of matrix compression may improve drastically the performance of the algorithm, depending on the particular inverse problem studied. Those involving transient heat conduction cannot be compressed efficiently whereas purely petrophysical problems have a much higher compression ratio.

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