

Unraveling the effects of tortuosity and fractal dimension on the electrical resistivity-porosity relationship in porous rocks: A digital rock physics study

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SUMMARY

Electrical resistivity is sensitive to the presence of fluids. Therefore, it can be a good indicator of the distribution of geofluids in the upper crust. Using rock physics models, we can estimate the water content from resistivity data obtained from electromagnetic observations. Such rock physics models have been proposed by assuming different equivalent pore geometries. However, the predicted results are strongly dependent on the choice of model, with some empirical parameters related to the assumed pore structure.

In this study, we evaluated the resistivity and current tortuosity based on a simulated local electric current for different types of digitized porous rocks. Digital rock models with a wide range of porosities were collected from different CT images. The local electric current was simulated from the potential difference between the inlet and outlet boundaries using the finite element method. To account for the anisotropy of the microstructure, we calculated the directional anisotropy of the resistivity and tortuosity in three directions (x-, y-, and z-axes) by changing the applied voltage direction. In this analysis, the fluid and solid were modeled with conductivities of 5 S/m and 10^{-5} S/m, respectively. To characterize the pore structure quantitatively, we also calculated the pore fractal dimensions using the box-counting method.

The simulation results demonstrated an increase in resistivity and its anisotropy with decreasing porosity. The increasing tortuosity and decreasing pore fractal dimension with decreasing porosity further explains the evolution of the resistivity. This suggests that smaller pore volumes (i.e., porosities) prevent pore connectivity, enhance tortuosity, and reduce the pore fractal dimension, resulting in higher resistivity and anisotropy.

The resistivity exhibited a log-linear relationship with the porosity. The resistivities at high- and low- porosity data were fitted by two separate power-law equations. The resistivities at high-porosity samples were fitted by Archie's equation with empirical parameter previously reported, whereas low-porosity samples were not. This indicates the difficulty of applying Archie's equation to low-porosity rocks. The resistivity estimated by the model using fractal dimension also could not explain the resistivity of the low porosity models. On the other hand, the equivalent channel model using the estimated tortuosity reproduced the resistivity over a wide porosity range. Our results suggest that tortuosity is a key factor in controlling electrical properties.

Keywords: Rock resistivity, Tortuosity, Digital rock physics, Effective medium theory, Fractal dimension
