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Permeability estimation conditioned to geophysical downhole log data in sandstones of the northern Galilee Basin, Queensland: Methods and application

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ABSTRACT

This study uses borehole geophysical log data of sonic velocity and electrical resistivity to estimate permeability in sandstones in the northern Galilee Basin, Queensland. The prior estimates of permeability are calculated according to the deterministic log–log linear empirical correlations between electrical resistivity and measured permeability. Both negative and positive relationships are influenced by the clay content. The prior estimates of permeability are updated in a Bayesian framework for three boreholes using both the cokriging (CK) method and a normal linear regression (NLR) approach to infer the likelihood function. The results show that the mean permeability estimated from the CK-based Bayesian method is in better agreement with the measured permeability when a fairly apparent linear relationship exists between the logarithm of permeability and sonic velocity. In contrast, the NLR-based Bayesian approach gives better estimates of permeability for boreholes where no linear relationship exists between logarithm permeability and sonic velocity.

1. Introduction

Characterization of the heterogeneity of permeability in sandstones is critical for groundwater, oil and gas exploration (De Marsily et al., 2005; Zimmerman et al., 1998). Many techniques were developed to measure permeability from microscale to macroscale in both hydrogeology and petroleum engineering, for example, tomography approaches, slug tests or drill stem tests (Al-Raoush and Willson, 2005; Bouwer and Rice, 1976; Bredehoeft, 1965). However, because these methods of direct measurement produce costly and sparse data, only limited information can be obtained in regard to understanding the spatial variability of permeability (Hyndman et al., 2000).

Borehole geophysical techniques provide low-cost means to measure geophysical properties that relate to permeability at a fine scale over broad vertical and horizontal intervals (Cassiani et al., 1998; El Idrysy and De Smedt, 2007; Gloaguen et al., 2001). The geophysical properties commonly used to infer permeability include seismic velocity (Rubin et al., 1992), electrical resistivity (Purvance and Andricevic, 2000), and ground-penetrating radar data (Cunningham, 2004; Gloaguen et al., 2001). Various mathematical approaches were employed to tie geophysical properties to permeability, such as regression analysis (Archie, 1942; Purvance and Andricevic, 2000), cokriging interpolation (Kay and Dimitrakopoulos, 2000), Bayesian inference (Chen et al., 2001), and more recently, coupled hydrogeophysical numerical simulations (Day-Lewis and Singha, 2008; Huisman et al., 2010).

Regression analysis is often used to correlate electrical resistivity with permeability, and a log–log linear relationship between these properties can in certain cases be validated theoretically and empirically (Archie, 1942; Purvance and Andricevic, 2000; Wong et al., 1984). This method is efficient, but the relationship between permeability and resistivity is possibly non-unique and ambiguous due to multiple contributing factors, for example, water saturation and clay content, and also possible scale and resolution disparity between the measurements of permeability and resistivity (Ezzedine et al., 1999). As a consequence, other approaches such as Bayesian and cokriging methods are often applied to revise the estimates of permeability.

The Bayesian technique updates the prior estimates of permeability via a likelihood function. The prior estimates of permeability can be obtained from hydrogeologic inversion (Copty et al., 1993) or ordinary kriging interpolation (Shlomi and Michalak, 2007). The likelihood function plays a key role in the Bayesian technique, which can be derived by, for example, ensemble Kalman filter (Evensen, 1994), generalized likelihood uncertainty estimation (Beven and Binley, 1992), or a normal regression model (Chen et al., 2001).

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In addition, Cokriging (CK) is a method for the linear estimation of vector random functions that considers spatial and inter-variable correlation (Myers, 1985). The CK method can be applied to estimate permeability from geophysical measurements, where the geophysical measurements are considered as a secondary variable (Ahmed et al., 1988). A simple cokriging estimator is expressed by:

$$Z_1 - \mu_1 = \sum_{i=1}^{T} \sum_{\alpha_i}^{n_i} \lambda_{\alpha_i} \left(Z_i \left(x_{\alpha_i} \right) - \mu_i \right), \tag{1}$$

where Z_i is the permeability and the geophysical variables related to the permeability, μ_i is the stationary mean of variable i, and λ_{α_i} is the weight of variable Z_i at x_{α_i} (Goovaerts, 1997). These weights can be obtained from a matrix, which is composed of covariance functions. Therefore, inference of covariance functions from the actual measurements is at the foundation of the CK method.

Another approach to estimating permeability (or hydraulic conductivity) is the coupled hydro-geophysical simulation. The basic steps of this simulation are outlined as follows: (1) prior estimates of hydraulic parameters (permeability); (2) calculation of the hydraulic variables, e.g. water saturation or salinity using fluid flow and solute transport simulation; (3) revision of the geohydrologic environments to forward geophysical properties, typically electrical resistivity; and (4) recalculation of permeability considering geophysical properties, and using them as the new input to the hydrogeologic model. These steps are repeated until both the hydrogeologic and geophysical measurements fit well with the calculated results (Day-Lewis et al., 2003; Hinnell et al., 2010; Kowalsky et al., 2011; Pollock and Cirpka, 2012).

The accuracy of permeability estimated by the above methods depends on the sufficiency of actual permeability measurements. In order to overcome the problem of under-sampling in this study, the CK method is coupled with a Bayesian framework to calculate the likelihood function. Both sonic and electrical log data are used to infer the permeability in this coupled method, assuming that the covariances of permeability and the resistivity are the same.

This study initially introduces the geology of the northern Galilee Basin, followed by a description of Bayesian framework and cokriging theory. The coupled CK–Bayesian method is then tested on three boreholes in the northern Galilee Basin (Fig. 1). The performance of the CK–Bayesian method is compared with another deterministic Bayesian method based on normal linear regression. Finally, the main results are discussed.

2. Study area and data description

2.1. General geological setting

The Galilee Basin is a large intracratonic basin of the Late Carboniferous to Triassic period located in central Queensland, Australia (Fig. 1a). Sediments of the northern Galilee Basin were deposited in two regional depressions, the Koburra Trough and Lovelle Depression,

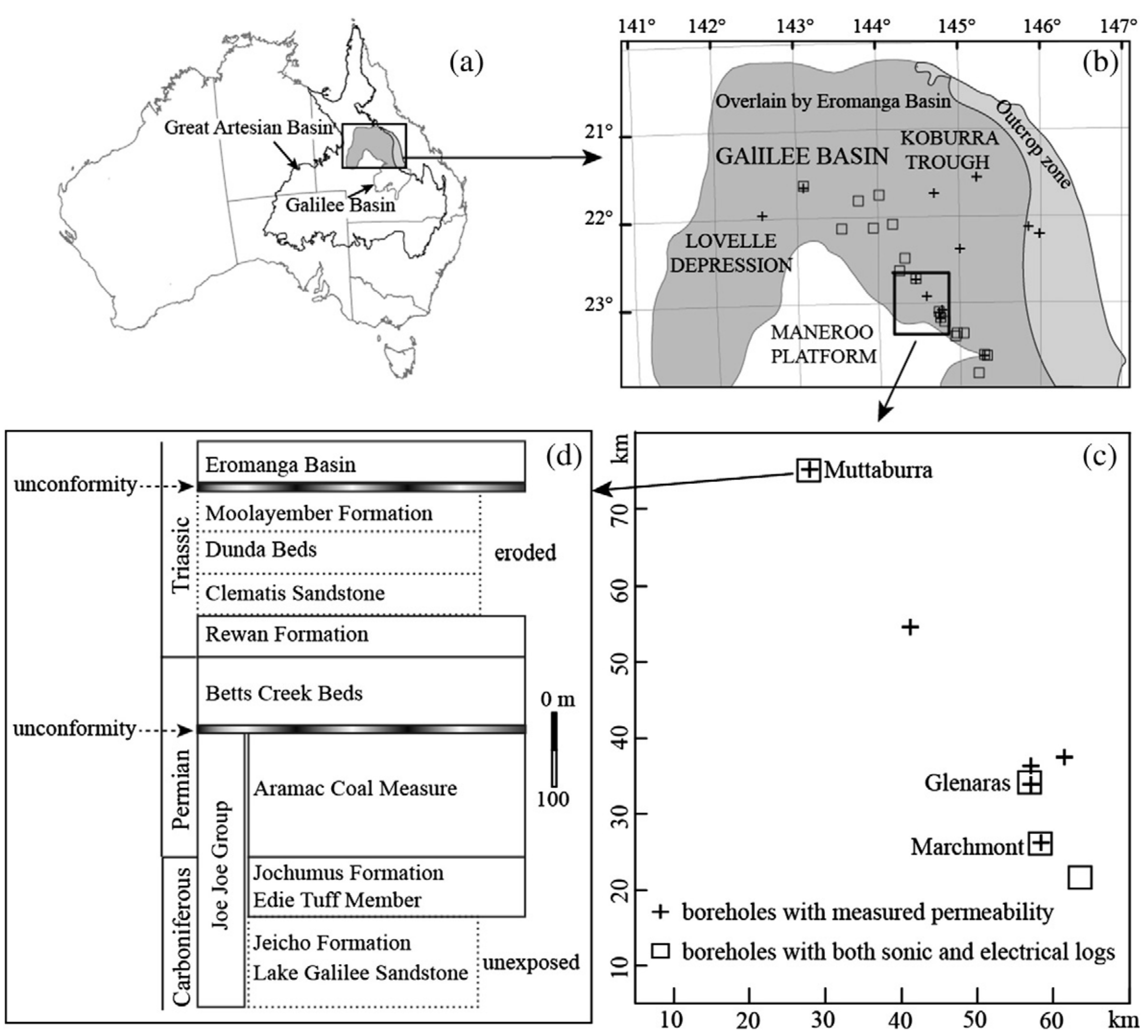

Fig. 1. Location map showing (a) the study area within the northern Galilee Basin, (b, c) boreholes with geophysical logs and permeability measurements, and (d) a schematic column showing the general stratigraphy in the northern Galilee Basin.