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A scaled perspective on permeability: How to get the best from what we have

Paul F. Worthington

Park Royd P&P (England) Limited, PO Box 4653, Ascot, Royal Berkshire, SL5 5BY, United Kingdom

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ABSTRACT

The suppression and equivalence of permeability and thickness of transmissive reservoir intervals are managed by integrating data measured at different scales. Essential requirements are estimates of effective permeability from core, logs and well tests for comparison over net reservoir intervals at key wells. The starting point is a quality-assured determination of interval transmissibility from well testing. The interval thickness is refined to effective thickness through the scale-compatible application of dynamically-conditioned net-reservoir discriminators, a process that allows effective permeability to be determined at the well-test scale. Algorithms for transforming core absolute permeability to core effective permeability form the basis for comparisons of laboratory and well-test data provided that appropriate core compaction corrections have been made with data partitioning as needed. Where core sampling is comprehensive and representative over the perforated interval, the comparison with well-tests can be made directly. Otherwise core-calibrated log data constitute an essential intermediary. In the absence of formation-damage effects, the reconciliation of petrophysically- and dynamically-derived effective permeabilities over a tested interval is diagnostic of uniform reservoir character. Beyond data shortfalls, impediments to reconciliation include formation anisotropy exacerbated by natural fractures and relatively high permeability conduits possibly in the form of "super-k" layers. A deterministic workflow for achieving reconciliation is substantiated by reference to field examples, which collectively reveal further opportunities for improved permeability characterization in integrated reservoir studies.

1. Introduction

It has long been known that measurements of subsurface physical properties are impacted by the principles of equivalence and suppression in cases where there are, respectively, moderate or severe shortfalls in the spatial resolution of the instruments that are being used to sense rock character. Suppression means simply that the character is not seen because it has a weak manifestation. Equivalence means that the measuring system can sense some combination of the size of a body and a recorded physical property. However, the measuring system cannot separate them out.

Matters of equivalence have been most prominent in the interpretation of geoelectrical survey data. For relatively conductive beds, the longitudinal conductance, i.e. the product of bed thickness and its electrical conductivity, can be inferred even where the two components of the product cannot be resolved individually. For relatively resistive beds, the transverse resistance, i.e. the ratio of bed thickness to its electrical conductivity, can be inferred even where the numerator and denominator cannot be separately resolved. Longitudinal conductance and transverse resistance are collectively known as the Dar Zarrouk parameters (Maillet, 1947).

Reported correlations of electrical and flow properties in aquifers, most notably electrical conductivity and intergranular permeability, respectively (e.g. Huntley, 1985; Purvance and Andricevic, 2000; Khalil and Monterio Santos, 2009), have served as foundations for empirical relationships between:

(i) The Dar Zarrouk parameters and transmissibility, the product of interval thickness and its hydraulic permeability (e.g. Salem, 1999; Utom et al., 2012; Singh and Singh, 2016), and
(ii) The Dar Zarrouk parameters and hydraulic resistance, the ratio of interval thickness to its hydraulic permeability, or its reciprocal, hydraulic leakance (e.g. Bradbury and Taylor, 1984; Cherkauer et al., 1987; Taylor, 1992).

Since hydraulic resistance and hydraulic leakance intuitively relate to conditions of vertical flow and therefore are more pertinent to containment and cross flow, this paper will focus on horizontal transmissibility

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E-mail address: paulfworthington@parkroyd.com.

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as analogous to longitudinal conductance with the principle of equivalence applying to both.

The paramount objective is to overcome the principle of equivalence by mapping the progression from a determined value of transmissibility to the evaluation of its constituent parameters, i.e. net layer thickness and effective permeability, for application to subsurface oil and gas reservoirs. To manage the discussion, the subject matter will focus on conventional water-wet clastic reservoirs for which quality-assured databases include well tests, conventional and special core analysis, fluids analysis, and a full suite of standard well logs, the so-called "quad-combo". A high-level workflow for data usage is shown in Fig. 1.

2. Founding concepts

Many of the earlier concepts relating to the evaluation of transmissibility are rooted in groundwater hydrology. The starting point was the work of Henri Darcy, a civil engineer in the city of Dijon, France, who formulated an expression for the permeability of a medium in terms of observed water flow under a given pressure gradient through gravel beds of known dimensions, based on experimental observations as part of filtration studies (Darcy, 1856). Other notable markers were the application of Darcy's Law to equilibrium well hydraulics in which the rate of groundwater flow to a well equals the constant rate of discharge from the well (Dupuit, 1863) with subsequent modifications to render the process more pragmatic (Thiem, 1906).

The extension of the equilibrium theory to non-equilibrium well hydraulics introduced storativity within an exponential integral equation that quantified pressure drawdown in an observation well as a function of time and formed the basis for a curve-fitting methodology (Theis, 1935). The early part of such a theoretical curve was distorted primarily by wellbore storage effects whereas the later part was susceptible to departures caused by leakage through or cross-flow from adjacent beds or by the presence of (sub-)vertical barriers to flow within the subsurface volume potentially drainable by the well. The complexity of the Theis equation led to straight-line approximations to the central, theoretically-compliant portion of the Theis drawdown curve, which reflects reservoir behaviour, in order to facilitate the analysis of drawdown data at observation wells for transmissibility and for storativity (Cooper and Jacob, 1946). However, the degree of manifestation of the central portion of the Theis curve for straight-line analysis is highly variable (Bruin and Hudson, 1955).

> "The transition into the straight line may always be expected to occur but it may be hard to recognize because it sometimes passes very quickly and other times endures for an extended period."

In extreme cases, it might never occur at all.

The concept of linear approximation was applied to the estimation of transmissibility through analysis of pressure build-up behaviour at oil wells for which there were no observation-well data (Horner, 1951). This development heralded the first era of well-test or pressure-transient analysis in the petroleum industry (e.g. Gringarten, 2008). The emergence of electronic computers opened the door to computationally-intensive solutions to the build-up equation, primarily through the matching of pressure-transient data for a single well to generic or customized type plots of pressure versus time (Ramey, 1970). This extension to whole-curve analysis allowed the identification of hydrocarbon flow regimes, particularly the central portion of a build-up curve that could be analysed using a linear approximation method (Earlougher and Kersch, 1974; Ramey, 1976): it marked the second era. Ambiguities associated with type-curve matching focused attention on the derivative of build-up pressure to expose more detailed character in pressure vs time plots (Tiab and Crichlow, 1979). The subsequent introduction of type curves based on the derivative of dimensionless pressure with respect to the logarithm of dimensionless time signalled the third era of well-test analysis (Bourdet et al., 1983). More recently, the deconvolution of well-test data (Hutchinson and Sikora, 1959) has evolved into an additional practical tool for transforming variable-rate pressure data into equivalent pressure data that would have been obtained with an initial drawdown if the well had flowed at constant rate for the duration of a test (Von Schroeter et al., 2004; Levitan, 2005). Deconvolution is seen as the fourth era. Throughout the four eras there is a common aim of evaluating reservoir transmissibility most definitively. Practical aspects of well-test analysis have been reviewed by Gringarten (2012).

3. Degree of confidence in transmissibility

In essence, the degree of confidence in transmissibility determined from well-test analysis is governed by the manifestation of the Horner-

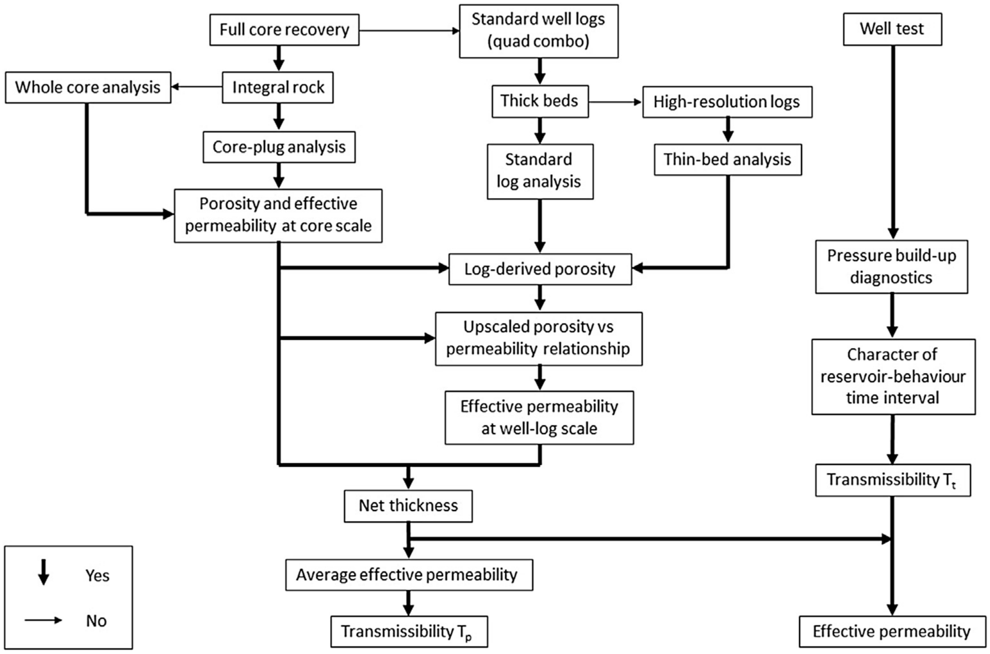

Fig. 1. High-level workflow for data usage in permeability estimation. T_p is transmissibility from petrophysics: T_t is transmissibility from well testing.