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ORIGINAL PAPER

Near Surface Electrical Characterization of Hydraulic Conductivity: From Petrophysical Properties to Aquifer Geometries—A Review

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Abstract This paper reviews the recent geophysical literature addressing the estimation of saturated hydraulic conductivity (*K*) from static low frequency electrical measurements (electrical resistivity, induced polarization (IP) and spectral induced polarization (SIP)). In the first part of this paper, research describing how petrophysical relations between electrical properties and effective (i.e. controlling fluid transport) properties of (a) the interconnected pore volumes and interconnected pore surfaces, have been exploited to estimate *K* at both the core and field scale is reviewed. We start with electrical resistivity measurements, which are shown to be inherently limited in *K* estimation as, although resistivity is sensitive to both pore volume and pore surface area properties, the two contributions cannot be separated. Efforts to utilize the unique sensitivity of IP and SIP measurements to physical parameters that describe the interconnected pore surface area are subsequently introduced and the incorporation of such data into electrical based Kozeny–Carman type models of *K* estimation is reviewed. In the second part of this review, efforts to invert geophysical datasets for spatial patterns of *K* variability (e.g. aquifer geometries) at the field-scale are considered. Inversions, based on the conversion of an image of a geophysical property to a hydrological property assuming a valid petrophysical relationship, as well as joint/constrained inversion methods, whereby multiple geophysical and hydrological data are inverted simultaneously, are briefly covered. This review demonstrates that there currently exists an opportunity to link, (1) the petrophysics relating low frequency electrical measurements to effective hydraulic properties, with (2) the joint inversion strategies developed in recent years, in order to obtain more meaningful estimates of spatial patterns of *K* variability than previously reported.

Keywords Hydrogeophysics · Electrical resistivity · Induced polarization · Hydraulic conductivity · Joint inversion

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1 Introduction

Hydrogeophysical applications of geophysical methods are now widely reported and have been a primary focus of many previous reviews of electrical geophysical methods as applied to near-surface/environmental studies (Nobes 1996; Tezkan 1999; Pellerin 2002). More recent reviews have focused on the petrophysical relationships between electrical and hydraulic properties forming the backbone of hydrogeophysics (Lesmes and Friedman 2005), whereas other reviews have focused on linkages between geophysics and hydrogeology at the field scale (Linde et al. 2006a). This review specifically focuses on the efforts that have been made to estimate the hydraulic conductivity from electrical properties inferred from static geophysical measurements. The potential merit of time-lapse geoelectrical measurements is only considered briefly in the concluding remarks in the interests of brevity. This review is unique in that it first introduces, with reference to the pertinent literature, a petrophysical basis for linking electrical and hydraulic properties and then reviews laboratory and field based geophysical studies within this framework.

The possibility of predicting the hydraulic conductivity from geoelectrical measurements has resulted in a large volume of literature focused on this objective over the last 60 years. These research efforts have been largely motivated by the fact that, although the distribution of hydraulic conductivity is critical to modeling groundwater flow and solute transport, it is non-trivial parameter to measure directly. Furthermore, any direct measurements that may exist are often sparsely distributed or at scales inappropriate for modeling flow processes that may be of interest. A critical issue in hydrogeology is determining a representative hydraulic conductivity, being a value that controls the average behavior of groundwater flow within an aquifer at a given scale (e.g. Sánchez-Vila et al. 2006) A closely related concept is that of 'equivalent hydraulic conductivity', that relates the spatial averages of flux and head gradient within a given volume of an aquifer (e.g. Renard and Marsily 1997, for review) Field measurements, most commonly being pumping tests or slug tests, yield the interpreted hydraulic conductivity (defined in this review as K) of a portion of an aquifer or for small isolated sections of boreholes. These field measurements may often be closely linked to the equivalent hydraulic conductivity (Sánchez-Vila et al. 2006). Although large-scale equivalent transmissivity can be obtained from the interpretation of a pumping test (e.g. Meier et al. 1998), pumping tests do not typically provide detailed information about the hydraulic conductivity distribution in the horizontal (good vertical resolution may be obtained by isolating sections of a borehole). Slug tests can be used to estimate K in the vicinity of a single well although they are often biased due to perturbations caused by drilling (see for review, Butler 1998). Newer technologies, based on direct-push methods, e.g. the direct push permeameter (e.g. Butler et al. 2002), appear to offer improved estimates of K variation in the vertical (see Butler 2005 for review).

With any invasive hydrogeologic test, the number and distribution of wells determines how precisely the subsurface K variability is resolved. Obviously, large networks of wells are needed to define the spatial distribution and correlation structure (i.e. the continuity of lithologic units of similar K) from pumping tests. Small-scale measurements of K may be available, for example, from laboratory Darcy tests or in-well flowmeter measurements. However, such small-scale measurements may be too biased to be useful in the development of site-scale flow models (e.g. Barlebo et al. 2004). It is usually uncertain how such small-scale measurements of K will represent upscaled values required to characterize flow and transport in the field, although upscaling strategies have been developed (e.g.

Sánchez-Vila et al. 1995, for review). The limited availability of representative hydraulic conductivity data at the appropriate scale means that groundwater modelers rely heavily on model calibration, whereby model outputs (e.g. heads, concentrations) are compared to measurements. Although well calibrated models may be reliable, the difficulty of defining the intrinsic spatial continuity of K needed to correctly model flow and transport in the earth remains a fundamental limitation of model development (Sánchez-Vila et al. 2006); the spatially continuous datasets provided from geophysics offer the potential to reduce this difficulty. The increasing complexity of 2D/3D flow and transport models requires 2D/3D distributions of K estimates that are typically only available at very well characterized, high profile, sites (e.g. Sudicky 1986; Hess et al. 1992: Rehfeldt et al. 1992). Recent advances in hydraulic tomography, a sequential aquifer test whereby hydraulic head is measured in multiple (typically 5–10) wells for sequential pump tests on isolated vertical sections of an aquifer, have yielded spatial estimates of K structure when applying appropriate inverse methods (Gottlieb and Dietrich 1995; Butler et al. 1999; .Yeh and Liu 2000; Meier et al. 2001; Liu et al. 2002; Butler 2005). However, hydraulic tomography requires multiple boreholes, time-consuming and expensive testing on multiple isolated intervals and may be ineffective in some environments.

Given that geophysics provides a minimally invasive approach to obtaining spatially continuous datasets, at a relatively high temporal and spatial sampling density, it is unsurprising that geophysicists have, over the years, taken up the challenge of trying to predict K from geophysical measurements. A geophysical approach to K estimation is attractive for numerous reasons, (1) non-invasive (when applied from the earth surface) or minimally invasive (when applied from a small number of boreholes) measurements minimize the disruption to the natural flow regime that can occur when wells are installed (e.g. short circuiting across aquitards); (2) the support volume of the geophysical survey can to some extent, dependent on the inherent limitations of any particular geophysical technique, be scaled through careful survey design; (3) geophysical measurements are relatively quick and inexpensive when compared to a pumping test or a slug test. Furthermore, three-dimensional (3D) realizations of the subsurface are now readily achievable using modern geophysical equipment and inversion algorithms. The basic conceptual analogy between the flow of electric current and groundwater has motivated many to pursue research towards the reliable prediction of K from geoelectrical measurements (here considered to include dc-resistivity, induced polarization (IP) and spectral induced polarization (SIP)). In fact, one could consider this objective a fundamental component of the relatively new, and expanding, field of ‘Hydrogeophysics’ (Rubin and Hubbard 2005). At first glance the approach seems viable using modeled electrical conductivity (σ), or resistivity ($\rho = 1/\sigma$)[1], as both electrical current and groundwater flow are channeled through the interconnected pore space and the parameters describing this transport, i.e. K for groundwater flow and σ for electrical current flow, are a function of parameters describing some measure of interconnected pore volumes, and/or interconnected pore surfaces (Schön 1996; Revil and Cathles 1999). However, the electrical estimation of K remains non-trivial for a number of reasons that include the limitations of petrophysical relationships, or more specifically, the uncertainty regarding how the effective properties controlling electrical current flow are related to the effective properties controlling fluid flow. This review takes a two-fold approach to examining the literature that has addressed geoelectrical characterization of hydraulic conductivity over the last thirty-five years. The

[1] From this point on, electrical conductivity, rather than resistivity, is used as it is more directly related to the charge conduction and storage processes occurring in porous media.

first part of the review deals with *petrophysical properties* and the relationships between these properties i.e. the linkages between geoelectrical properties and K. These linkages are summarized in Fig. 1. It is worth noting here that no direct relationship between an electrical measurement and K exists. Instead, these efforts have generally been based on the fact that a relationship between a geoelectrical measurement and K can be made based on the mutual dependence of both on another petrophysical property, for example porosity (ϕ) (Fig. 1). Thus this review also must consider such relationships. The relationship between dc electrical conductivity and K is first considered as this makes up the bulk of the pertinent literature published over the last 35 years (see left side of Fig. 1). The investigation of the petrophysical controls on the low frequency polarization (storage) measured with induced polarization is next reviewed in the context of significant advancements in the estimation of K that have resulted by utilizing geoelectrical parameters obtained from this method in conjunction with measures of electrical conduction (Fig. 1). In order to complete the petrophysical part of this review, the currently limited literature on spectral (frequency dependent) electrical measurements is covered (Fig. 1) as it suggests the enticing possibility of characterizing some measure of the 'hydraulic length scale' (Johnson et al. 1986; Katz and Thompson 1986) controlling groundwater flow, a property that is theoretically shown to control K.

In the interests of brevity, geophysical techniques other than resistivity, induced polarization and spectral induced polarization are excluded from the petrophysical part of this review. Seismic measurements may assist in the characterization of aquifer properties due to the dependence of seismic velocity on ϕ as first demonstrated by Gassman (1951).

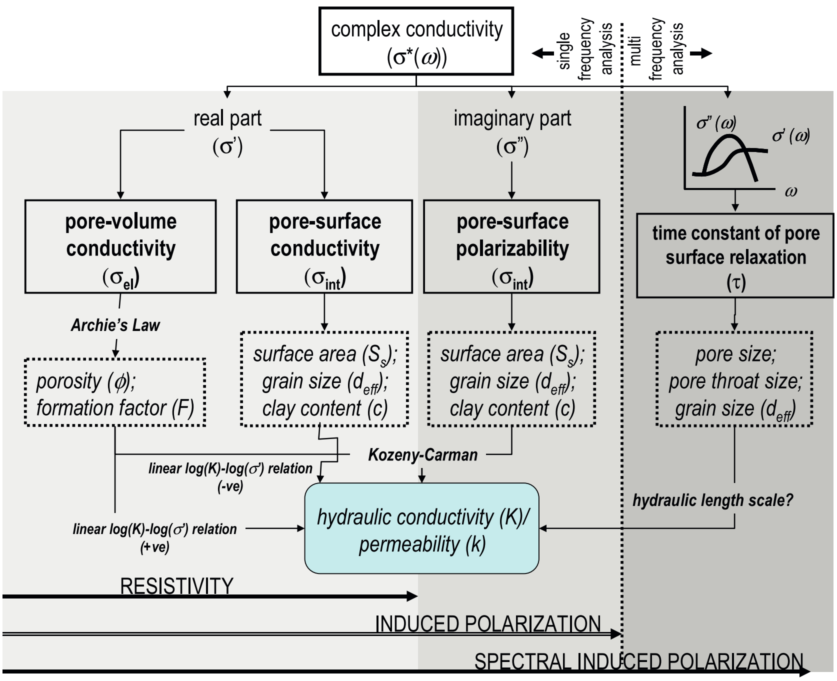

Fig. 1 Flowchart summarizing efforts to predict hydraulic conductivity (K) from petrophysical relationships established for electrical measurements

Reviews of the petrophysical basis for the estimation of aquifer properties are found in Schön (1996) and, recently, Pride (2005). However, Pride (2005) notes that the drained bulk modulus controlling compressional wave velocity is entirely independent of grain size and hence permeability. Similarly, the dielectric permittivity (ε) controlling EM wave velocity when conduction loss is negligible is a strong function of ϕ, which can be estimated from ground penetrating radar (GPR) data using mixing laws (e.g. Wharton et al. 1980). However, such relationships are again independent of grain size and hence permeability. Emerging geophysical technologies that may, in the future, offer unique opportunities to improve quantification of K include self potential (SP) and the nuclear magnetic resonance method (NMR). Self potential is a passive electrical method where natural currents are measured (see for review, Revil et al. 2006). One type of self potential, the streaming potential, is associated with the drag of ions in the electrical double layer in the direction of groundwater flow (Fournier 1989; Birch 1993). It may be possible to estimate seepage velocities from SP which could lead to estimates of K given measurements of porosity and hydraulic head field. The nuclear magnetic resonance (NMR) method, primarily a specialized laboratory geophysical technique, measures a pore-fluid magnetization relaxation caused by interactions with the grain surfaces in porous media (Korringa et al. 1962). The rate of relaxation scales linearly with the pore surface to volume ratio allowing the distribution of relaxation times to be related directly to the pore-size distribution (Straley et al. 1995). As the pore-size distribution is critical to determining K the NMR method may, in the future, significantly advance the science of estimating K from geophysical measurements. Yaramanci et al. (2005) review a field-based NMR technique, known as surface nuclear magnetic resonance imaging (SNMR) that may ultimately provide opportunities for K estimation from field measurement.

The second part of this review concerns characterization of spatial patterns of K variability in the field. There is a growing volume of hydrogeophysical literature that addresses the use of spatially extensive geophysical datasets for predicting distributions of K in-situ and at scales relevant to flow and transport in the subsurface. The current approaches, making use of modern instrumentation capable of rapidly collecting large datasets and data inversion procedures that can handle such data, are summarized in Fig. 2. The most frequently adopted approaches to this problem (left-hand side of Fig. 2) have been based on inversion of geoelectrical datasets for the distribution of subsurface geoelectrical properties followed by application of a petrophysical relationship to produce estimates of equivalent K distributions (as covered in the first part of this review). However, more recently joint/constrained inversion techniques, whereby geophysical and hydrological data are simultaneously inverted (perhaps conditioned on a limited dataset of directly measured K), have been proposed to overcome some of the recognized limitations of the aforementioned approach (Fig. 2). Such techniques offer the opportunity to constrain the geophysically determined K realizations to realistic values. Another recent hydrogeophysical development is the inversion of geophysical datasets for geostatistical parameters/functions describing the nature of the K structure without defining it explicitly. Although the majority of this work has applied seismic and/or high-frequency electromagnetic data (ground penetrating radar) it is reviewed herein as (1) the techniques are readily transferable to low-frequency electrical data, and (2) we will see that the merging of such inversion techniques with the strong petrophysical relationships linking K to low-frequency electrical properties presents an opportunity to obtain more meaningful estimates of K distribution and aquifer geometries than previously reported. Recommendations for future research in this exciting and challenging area of hydrogeophysics are also presented.

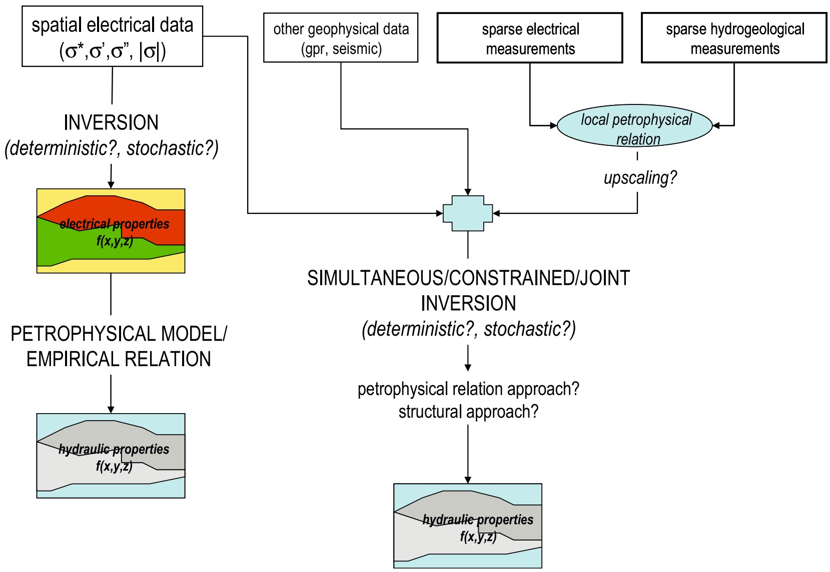

Fig. 2 Flowchart summarizing efforts to characterize aquifer geometries using geoelectrical measurements

2 Definition of Hydraulic and Electrical Properties

2.1 Hydraulic Properties

The saturated hydraulic conductivity (K) determines the rate at which fluids flow through a saturated porous medium for a given unit head gradient and can be defined for a homogeneous, isotropic material as,

$$K = k\frac{\rho_w g}{\mu}, \tag{1}$$

where k is the permeability, μ is fluid dynamic viscosity, ρ_w is fluid density and g is gravitational acceleration. The permeability is only a function of the physical properties of the medium (pore size distribution/surface area, pore connectivity, tortuosity) although it is well known that k (and σ,) are seldom isotropic. Here only isotropic, saturated k is considered as the effects of anisotropy on relationships between geoelectrical properties and k have yet to receive significant attention.

Much of the early work for predicting k of porous media is based on capillary tube models, the fundamental basis being the Kozeny–Carman equivalent channel equation (Carman 1939; Kozeny 1927). This model represents flow through a network of capillaries, each assumed to represent an independent flow path through the sample, with an effective path length (L_e) greater than the sample length (L). The permeability equation,

$$k = \frac{\phi(r^2)}{aT}, \tag{2}$$

is obtained, where ϕ is the porosity, T defines the pore capillary tortuosity ($T = [L_e/L]^2$), r is the hydraulic radius, being the ratio of pore volume to surface area and historically judged to be the only natural length scale of a porous medium (Thompson et al. 1987), and a is a shape factor (Scheidegger 1974). The inverse of the hydraulic radius is commonly represented by the measurable surface area per unit pore volume (S_{por}),

$$S_{por} = \frac{1}{r} = S_s \rho_s \frac{(1-\phi)}{\phi}, \tag{3}$$

where S_s is the specific surface area and ρ_s is the mineral density.

Capillary tube models are typically limited to plus or minus one order of magnitude accuracy (Thompson et al. 1987) but do yield values that, within a sedimentary unit, correlate well with k. Although capillary tube models are now recognized to be ultimately of limited value in k prediction, they are important in this review as much of the historical basis for applying electrical measurements to k estimation has been that theoretical geometric parameters in the Kozeny–Carman formulation (r and T) can be replaced with equivalent properties measurable with geophysics. Specifically, electrical measurements can be related to effective parameters of the pore space, being those controlling flow, rather than total volume parameters as appear in Eq. 2. As we shall review below, modified Kozeny–Carman equations that incorporate electrical measurements tend to yield improved estimates of permeability relative to Kozeny–Carman formulations in terms of total volume properties.

A significant advance in k prediction over capillary tube models came about following the application of percolation theory to transport in porous media (Katz and Thompson 1986; Thompson et al. 1987). This built upon work on modeling of electron hopping in semiconductors by Ambegaoker et al. (1971), who showed that transport in a random system with a broad distribution of conductances is dominated by those conductances that exceed some threshold value. This characteristic conductance is the largest conductance such that the set of conductances forms an infinite connected cluster (Thompson et al. 1987). Katz and Thompson (1986) adopted this percolation scheme for the prediction of permeability in porous rock whereby the threshold conductance is considered to define a characteristic length scale (l_c) in the porous rock (Thompson et al. 1987). This length scale has been estimated from a mercury-injection curve, whereby a distinct inflection point in the curve of mercury intruded (normalized by total pore volume) versus applied pressure is related, via the Washburn equation (Van Brakel et al. 1981), to a characteristic pore length (l_c) that allows the formation of a connected cluster spanning the porous medium. The resulting permeability equation is,

$$k = \frac{c l_c^2}{F}, \tag{4}$$

where F is the electrical formation factor (discussed below) and c = 1/226 (Katz and Thompson 1986). The equation has produced remarkably accurate predictions of k for sandstone samples, with agreement between measured and predicted k being stated as within experimental error (Thompson et al. 1987). We shall see that very recent work on electrical measurements conducted over a wide frequency range suggests that l_c, being the percolation threshold length-scale controlling fluid flow, might be related to electrical parameters defining the length-scale of electrical polarization of the interconnected pore surface.

2.2 Electrical Properties

The estimated geoelectrical properties of earth materials may be equally represented by a complex electrical conductivity (σ^*), a complex resistivity (ρ^*), or a complex permittivity (ε^*),

$$\sigma^* = \frac{1}{\rho^*} = i\omega\varepsilon^*, \tag{5}$$

where $i = \sqrt{-1}$.

Each of these parameters contains a total energy storage term (polarization) and a total energy loss term (conduction). In this review, the complex conductivity nomenclature is used as most interpretation of low frequency geoelectrical data relies on a basic premise that electrolytic and interfacial (surface) conduction act in parallel. This is most simply represented in conduction space where the two components are additive. The in-phase (real, σ') conductivity component is then a property defining the ability of the earth to transport charge via ohmic conduction currents (energy loss), as detected with dc-resistivity and EM induction methods. The out-of-phase (imaginary) conductivity (σ'') is a property defining the ability of the earth to transport charge via polarization (energy storage) as quantified with induced polarization techniques. These earth properties are normally estimated by measuring the magnitude ($|\sigma| = \sqrt{(\sigma')^2 + (\sigma'')^2}$) and phase ($\theta = \tan^{-1}(\sigma''/\sigma')$) of σ^*, most often by driving a sinusoidal voltage between two 'current injection' electrodes and measuring the sinusoidal voltage due to resulting current flow in the earth at two other potential electrodes. Conversion of the voltages and current actually recorded by the instrumentation to a complex electrical conductivity is achieved using the 'geometric factor' for the electrode arrangement (see for review, Binley and Kemna 2005). The real and imaginary components describing the conduction and polarization properties of the earth are then calculated using the relationships,

$$\begin{aligned} \sigma' &= |\sigma|\cos\theta \\ \sigma'' &= |\sigma|\sin\theta \end{aligned} \tag{6}$$

Electric conduction (as determined by σ') in non-metallic rocks is ionic, occurring through the pore-filling electrolyte and by ionic migration in the electrical double layer (EDL) forming at the grain-fluid interface. It is usually assumed that electrolytic conductivity (σ_{el}) and interfacial conductivity (σ'_{int}) add in parallel (Waxman and Smits 1968),

$$\sigma' = \sigma_{el} + \sigma'_{\text{int}} = \left({}^{1}\!/_{F}\right)\sigma_w + \sigma'_{\text{int}}, \tag{7}$$

where σ_w is the electrical conductivity of the pore-filling fluid and F is the electrical formation factor (Archie 1942). Polarization is associated with the accumulation of local charge gradients induced by the applied electric field. At the low-frequencies of complex conductivity methods (defined here as <1000 Hz) this charge accumulation is almost exclusively associated with the local redistribution of ionic charge in the EDL at the mineral-fluid interface. Other polarization mechanisms (e.g. the Maxwell–Wagner effect, molecular polarization) dominate at high frequencies outside the range of the complex conductivity method. It is therefore common to exclusively relate measured σ' to a mineral-fluid interfacial polarization (e.g., Börner et al. 1996; Vinegar and Waxman 1984),

$$\sigma'' = \sigma''_{\text{int}}. \tag{8}$$

3 Hydraulic Conductivity Estimation from Resistivity

The application of geophysical methods to estimate K is critically dependent upon the existence of a petrophysical relationship between geoelectrical properties and K. The fact that near surface geophysicists continue to intensively explore new approaches to K estimation both in the laboratory, and in the field, is testimony to the complexity of the linkages between geoelectrical properties and K. In this section, efforts to identify meaningful geophysical relationships between K and near-surface geoelectrical measurements are reviewed. Much of this work has used as a foundation the vast amount of research aimed at estimating the permeability of oil bearing sedimentary formations. Although an exhaustive review of the petroleum exploration literature is beyond the scope of this paper, pertinent work is covered in conjunction with the near surface geophysical literature.

Considering the basic parallel conduction model of Eq. 6, σ_{el} is the term that can be linked (via petrophysical models) to an interconnected pore volume, whereas σ'_{int} can be linked (via petrophysical models) to an interconnected surface area. A fundamental limitation of resistivity-based K estimation has therefore been that it is not possible to determine the relative importance of the controls of σ_{el} and σ'_{int} on the measured σ'. As a consequence, the relationship between σ' and K will depend on the physical and chemical properties of the minerals and pore fluids at a site i.e. they will dictate whether σ_{el} or σ'_{int} dominates measured σ'.

Empirical geoelectrical studies from different geological settings conducted during the 1970–1980's revealed a log–log linear relationship between K and $|\sigma| \cong \sigma'$ that is either positive or negative, depending on site mineralogy, grain size distribution and pore fluid chemistry (Huntley 1986). In the case of soils of relatively low S_s (gravels, sands and coarse silts) saturated with conductive groundwater, σ_{el} dominates and a positive linear log K-log σ' relationship results from the mutual increase of σ' and K with increasing porosity (ϕ) (Frohlich et al. 1996; Heigold et al. 1979; Mazac and Landa 1979; Purvance and Andricevic 2000a). A positive power law dependence of σ‘ on effective (interconnected) porosity (ϕ_{eff}) is empirically (Archie 1942) and theoretically (Sen et al. 1981), established in the absence of interface conduction,

$$\sigma' \approx \sigma_{el} = \frac{\sigma_w}{F} = \sigma_w \phi_{eff}^m, \tag{9}$$

where m is the Archie cementation factor. A positive power law dependence of k on ϕ is implicit in capillary tube models as shown, for example, in a theoretically derived equation for clean sandstone (Revil and Cathles 1999), applicable for consolidated sedimentrary rocks of low clay content, that is similar to a relationship presented by (Berg 1970),

$$k = \frac{d^2 \phi_{eff}^{5.1}}{24}, \tag{10}$$

where d is the grain diameter (m) and k is in m^2.

In the opposite case of soils with relatively high S_s (e.g. fine silts and clays), σ'_{int} can dominate measured σ' provided that σ_w is low. Indeed, a negative linear log K-log σ' relationship has been reported (Kelly 1977; Kelly and Reiter 1984; Kosinski and Kelly 1981; Ponzini et al. 1983; Purvance and Andricevic 2000a; Urish 1981). Such a negative relationship is expected given that (1) S_{por} shows an inverse square relation to K (Eqs. 2, 3), whereas σ'_{int} increases with an increase in S_s (i.e. increase of fine soil fraction). Understanding of the petrophysical relationship between σ'_{int} and structural properties is incomplete, although theory developed for quartz suggests a linear relationship between the dc interfacial conductivity ($\sigma_{int(dc)}$) and a weighted surface area to volume ratio S_0, (equivalent to S_{por})

$$\lim_{\omega \to 0} \sigma'_{\text{int}}(\omega) = \sigma_{\text{int}}(dc) = \frac{e\mu_s \Sigma_0 S_0}{f}, \tag{11}$$

where e is the electronic charge (a constant describing the charge carried by a single proton), μ_s is the effective surface ionic mobility, Σ_0 is the mineral surface charge density, ω is the angular frequency and f is a geometric factor characterizing the tortuosity of the grain-pore interface (Pride 1994; Revil and Glover 1998). In natural soils and rocks, power law relationships between σ'_{int} and S_{por} with exponents close to 1 (i.e. linear relationship) have been reported (Börner et al. 1996; Schön 1996).

Positive or negative linear log–log relationships between K and σ' (depending on the importance of σ_{el} relative to σ'_{int} as determined by the local geologic and geochemical environment) have recently been explained through theory (Purvance and Andricevic 2000b). These authors used a modification of a microscale network model for fluid and electrical charge transport (after Bernabe and Revil 1995) to show that the σ'-K relationship is indeed positive when interconnected pore volumes dominates electrical current flow and negative when the interconnected pore surface areas dominate electrical current flow. Purvance and Andricevic (2000b) then upscaled these microgeometrical relationships to arrive at power law relationships between σ' and ϕ (as per e.g. Eq. 8) and K and ϕ as per the Kozeny equation (Kozeny 1927). They found an additional upscaled power law relationship between σ' and specific surface area (S_s) that they stated was unreported: in fact this relationship, that results from the dependence of σ'_{int} on S_0 (Eq. 11), was empirically known (Börner et al. 1996; Schön 1996), if not theoretically derived. Using these theoretically derived relations, Purvance and Andricevic (2000b) derived the expected linear log–log empirical relations between σ' and K,

$$K = a(\sigma')^b, \tag{12}$$

where in the case of pore volume controlled conduction $\sigma' \approx \sigma_{el}$ and b is a ratio of the theoretically derived $\sigma' - \phi$ and $K - \phi$ power law exponents (both >0, thus b is positive). In the case of pore surface area controlled conduction $\sigma' \approx \sigma_{int}$ and b is now a ratio of the theoretically derived $\sigma' - S_s$ (being positive) and $K - S_s$ (being negative) power law exponents (b hence now negative). To apply Eq. 12 it woud be necessary to estimate a and b based on comparison of geoelectrical measurements with K values (e.g. from slug tests in the field or Darcy tests on samples in the laboratory).

4 Hydraulic Conductivity Estimation from Induced Polarization

After reviewing the $\sigma'-K$ literature presented above it is obvious that the prediction of K from electrical conductivity is fundamentally limited by the fact that although σ' is sensitive to the pore volume pathway (via σ_{el}) and pore surface area pathway (via σ_{int}), the electrical properties of only one of these can be inferred (by assuming that the other is relatively insignificant). This limitation can potentially be overcome with induced polarization, whereby both $|\sigma|$ and a measure of the charge storage associated with the interfacial polarization are recorded. The latter measurement is either (1) the phase lag (θ) between the voltage signal recorded on the soil and the transmitted current (frequency-domain measurement), or (2) the integral of voltage decay curve (m_t) recorded after an abrupt shut-off of the injected electrical current (time-domain measurement). Using θ in conjunction with $|\sigma|$ it is possible to compute the relative contributions of σ', i.e. charge loss (conduction), and σ'', i.e. charge storage (polarization), from Eq. 6. It is also possible to estimate the relative contributions of the conduction loss ($\approx|\sigma|$) and charge storage ($\approx|\sigma|$ x m_t) from the m_t and $|\sigma|$ obtained with time domain instruments, although the absolute values will be dependent upon how m_t is defined. Note that this approximation of the polarization magnitude from time domain measurements has been termed the normalized chargeability m_n (Lesmes and Frye 2001). Further information on the conversion of time domain IP parameters to estimates of the charge storage is omitted here for brevity but is available elsewhere (Lesmes and Frye 2001; Slater and Lesmes 2002b; Lesmes and Friedman 2005).

The value of IP measurements for the geoelectrical estimation of K results from the fact that σ'' is only a function of the interfacial properties ($\sigma'' \approx \sigma''_{int}$) i.e. the properties of the interconnected pore surface area alone. There now exists a substantial volume of literature demonstrating a power-law dependence of σ'' on S_{por} (Börner and Schön 1991; Börner et al. 1996; Knight and Nur 1987; Schön 1996; Slater and Lesmes 2002a; Slater et al. 2006) as shown in Fig. 3.

It is important to emphasize again that S_{por} is a commonly used measure of r ($S_{por} = r^{-1}$) in Kozeny–Carman type equations i.e.

$$k = \frac{\phi}{aS_{por}^2 T}. \tag{13}$$

However, a well recognized deficiency of Eq. 13 is that it is formulated in terms of total volume properties (ϕ, S_{por}) whereas the effective properties controlling fluid flow tend to be the pore throats (that contribute little to ϕ) (Katz and Thompson 1986). A considerable body of literature considers how the use of electrical properties can improve K prediction, for example recognizing that $F = T_{el}/\phi$ (assuming that electrical (T_{el}) and hydraulic tortuosity (T) are equal). Pape et al. (1982) derived the following Kozeny-type equation for sedimentary rocks,

$$K = \frac{0.00475}{FS_{por}^{3.1}}, \tag{14}$$

where K is in m/s and S_{por} in µm. Equation 14 was derived from a structural model of the interfacial rock geometry, accounting for the fractal character of the specific surface area of grains resulting from weathering and cementation (Katz and Thompson 1985), with S_s

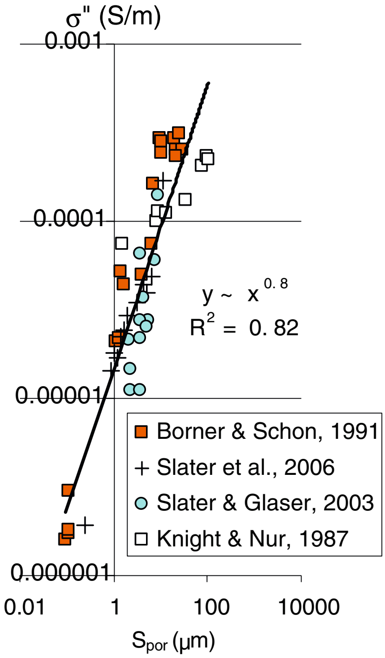

Fig. 3 Observed power-law relationship between σ'' and S_{por}. Data from Knight and Nur (1987) and Börner and Schön (1991) are sandstones, data from Slater and Glaser (2003) are alluvial unconsolidated sediments, data from Slater et al. (2006) are artificial kaolinite-sand mixtures. Linear correlation coefficient (R^2) shown

estimated from the nitrogen BET method (Brunauer et al. 1938) converted to an equivalent value consistent with Darcy flow.

A number of efforts have been made to utilize such an electrical formulation of the Kozeny–Carman equation to estimate K using the sensitivity of induced polarization data to S_{por} (Börner et al. 1996; de Lima and Niwas 2000; Slater and Lesmes 2002a; Sturrock et al. 1998, 1999). However, (Sturrock et al. 1998) cautioned that the fractal dimension (D) describing the mineral surface of the rock/soil under study may be different to that assumed in Eq. 14 (where $D = 2.36$).

Geoelectrical estimation of K is then based on the concept that the two unknowns in a modified Kozeny–Carman type equation (e.g. F and S_{por} in Eq. 13) can be extracted from the two measured electrical parameters i.e. the real (σ') and imaginary (σ'') parts of the complex conductivity. The imaginary conductivity is used to predict S_{por} based on a $\sigma''{-}S_{por}$ relationship such as shown in Fig. 3. Extracting F from σ' is possible if σ_w and σ'_{int} are known. Although an estimate of σ_w is often readily available, σ'_{int} cannot be measured directly and instead must be estimated from σ'' assuming a relationship between σ'_{int} and σ''_{int}. There is evidence to suggest that this relationship is approximately linear (de Lima and Niwas 2000; Schön 1996; Vinegar and Waxman 1984). A modified version of Eq. 14 formulated in terms of only electrical parameters, is

$$K = \frac{a}{F(\sigma'')^c}, \tag{15}$$

where *a* and *c* are constants, with *c* describing the power law dependence of the product of *K* and *F* on σ'' (Slater and Lesmes 2002a). The power law exponent *c* is a function of soil type with reported ranges from 2.8–4.6 for sandstone (Börner et al. 1996; Sturrock et al. 1998) and 0.9–1.6 for unconsolidated soils (Slater and Lesmes 2002a). de Lima and Niwas (2000) present a more complex Kozeny–Carman type formulation for shaly sandstones, based on self-similar clay coated models of sandstone (de Lima and Sharma 1990, 1992), that includes a 'lithoporosity factor', being a function of the shale porosity and the particle size distribution of the sands and clays. A summary of the basic approach common to all these efforts is given in Fig. 4.

This approach appears, at best, to yield approximately order of magnitude estimates of *K* when compared to Darcy-derived values (Börner et al. 1996; Slater and Glaser 2003; Slater and Lesmes 2002a; Weller and Börner 1996). This accuracy is consistent with that which can be expected from capillary tube models (Thompson et al. 1987). However, the more rigorous approach for shaly sandstones presented by de Lima and Niwas (2000) performed better than this when applied to experimental datasets (Vinegar and Waxman 1984). Slater and Lesmes (2002a) found that, for a wide range of unconsolidated soils, only S_{por}, and not ϕ, was strongly correlated with *K*. They attributed the lack of a significant $\phi - K$ relation to the relatively narrow range of ϕ in such soils. Based on this finding, (Slater and Lesmes 2002a) presented a simpler electrical model for *K* estimation based on an effective grain-size (Hazen 1911) approach that used a measure of σ'' only. They found that, for these soils, there was no significant difference in the *K* predicted versus *K* measured relation between the predictions based on the Kozeny–Carman formulation (Fig. 4) and that using only a single measure of σ''. However, in a recent field-scale study, this simpler model failed to predict the *K* distribution whereas satisfactory results were obtained using the approach described in Fig. 4 (Hördt et al. 2006).

Recent work suggests that the relationship between σ'' and S_{por} may not always be sufficiently strong to warrant this electrical approach to *K* estimation. Binley et al. (2005) examined weakly consolidated cores from a single site in a sandstone aquifer in the United Kingdom and found no evidence for a power law relation between σ'' and S_{por}. Describing results for sandstone cores from multiple sites within the UK, Scott and Barker (2005) also

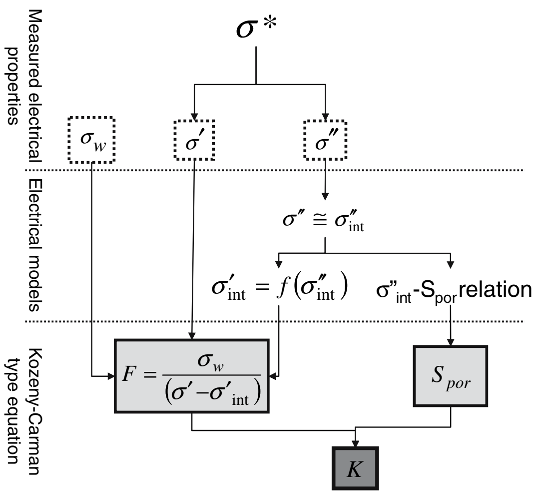

Fig. 4 Simplified overview of IP based estimation of *K* using a Kozeny Carman approach

obtained a relatively weak relationship between a measurement of polarization magnitude obtained from relaxation modeling of frequency dependent data and S_{por}. Whereas Binley et al. (2005) attributed this to the differences in the frequency dependence of σ^* between samples, Slater et al. (2006) suggested that this might reflect (1) the scale discrepancy between the nitrogen BET measurement of S_{por} and the corresponding electrical measurement on these cores, and (2) the relatively limited S_s range for these samples.

5 Hydraulic Conductivity Estimation from Spectral Induced Polarization

As previously discussed, the replacement of the total volumetric properties with effective properties based on electrical parameters is considered critical to improving the effectiveness of Kozeny–Carman type equations in K prediction (Revil and Cathles 1999). It is common to replace the total porosity term in the original Kozeny–Carman equation with electrical measurements that are related to the volume/connectivity of the pore space, such as $F = T_{\mathrm{el}}/\phi$ (Pape et al. 1982) and/or the Archie cementation factor, m ($1/F = \phi_{eff}^{m}$), resulting in weighted analogues of ϕ that controls fluid transport (Revil and Cathles 1999). However, defining the correct equivalent effective property to replace the hydraulic radius term of the Kozeny–Carman equation is not so simple. Note that S_{por} often used to characterize the inverse hydraulic radius (Fig. 1) is typically calculated using nitrogen BET surface area and ϕ measurements and is thus a total volume property. Johnson et al. (1986) introduced the Λ electrical geometrical parameter, which is a weighted pore volume to pore surface ratio with the weight favoring constricted regions of the pore space (i.e. the pore throats). Revil and Cathles (1999) showed that Λ represents a weighted analogue of $1/S_{por}$ defining the interconnected pore surface controlling fluid flow. Revil and Cathles (1999) noted that, although effective parameters for the hydraulic radius can be defined from electrical theory, such parameters are hard to measure. However, recent work suggests that this information may, possibly, be extractable from the additional information that is obtained by analyzing the frequency dependence of the complex conductivity $\sigma^*(\omega)$ i.e. the spectral induced polarization (SIP) method. Whereas single frequency IP measurements yield two electrical parameters (σ' and σ'' at the measurement frequency), additional electrical parameters are obtainable from the shape of the frequency dependence of $\sigma^*(\omega)$.

As theoretically based models for the frequency dependent electrical response of soils are lacking, phenomenological relaxation models are often adopted to describe $\sigma^*(\omega)$. The most commonly employed model is the four parameter Cole–Cole model (Cole and Cole 1941; Pelton et al. 1978),

$$\sigma^*(\omega) = \sigma_0\left[1 + m_g\left(\frac{(i\omega\tau)^c}{1 + (i\omega\tau)^c(1 - m_g)}\right)\right], \tag{16}$$

where σ_0 is the dc conductivity, τ is the mean relaxation time associated with the frequency dispersion, c is a shape exponent that typically ranges from 0.1–0.6 (for unconsolidated and consolidated sedimentary rocks) and m_g is the global chargeability (given by $m_g = 1-\sigma_0/\sigma_\infty$, where σ_∞ is the conductivity at high frequency). Parameter m_g, represents a global measure of the polarization associated with the interfacial charge storage.

There is a considerable volume of literature demonstrating that τ is related to the square of a characteristic pore or grain size that defines the length-scale over which ions in the electrical double layer diffuse during application of an electric current (Chelidze and Gueguen 1999; Olhoeft 1985). Considerable uncertainty exists regarding the petrophysical measure of this diffusion length-scale as evidenced by the recent discussion paper of Scott (2006). Multiple studies of mineralized rocks have equated the τ length scale with the diameter of the average grain size of the mineralized rock (Pelton et al. 1978; Wait 1982; Wong 1979). It has also been suggested that τ is related to the grain diameter (Klein and Sill 1982; Lesmes and Morgan 2001) of sedimentary rocks. However, more recent work has demonstrated a correlation between τ and the critical pore diameter or pore throat size determined from mercury porosimetry data (Binley et al. 2005; Scott and Barker 2003, 2005). Figure 5 shows τ as a function of the dominant pore throat size calculated from mercury intrusion measurements for sandstone samples from the United Kingdom as measured in two independent studies at different sites. The power law exponent of the best fit relation to both datasets is close to 2, being that expected from theory i.e. $\tau \propto R^2$ (Schwarz 1962), where R is the radial length of the polarization dispersion and often assumed equal to the median grain size. Models for the induced polarization effect in porous media invoke a dependence of τ on the square of either an effective pore radius (Hallbauer-Zadorozhnaya and Bessonov 2002) or a pore surface length scale determined by the distribution of wide or narrow pores (Titov et al. 2004, 2002).

The value of SIP for K prediction is currently uncertain and will ultimately depend on whether the diffusion length scale measured with SIP is closely related to the effective length scale of the surface controlling fluid flow e.g. l_c in Eq. 4. Kemna (2000) suggested that, due to the theoretical proportionality of both τ and K on the square of an effective length scale, a linear relationship between τ and K might be anticipated. He went on to propose an electrical equivalent of a grain characteristics model for K prediction presented for sedimentary rock by (Berg 1970), incorporating τ in place of an effective grain size and

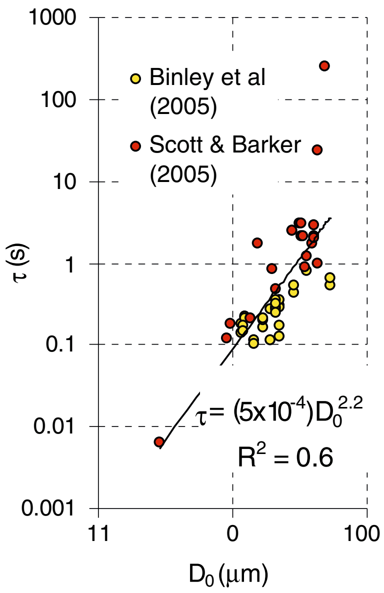

Fig. 5 Time constant (τ) from Cole–Cole relaxation modeling of SIP spectra versus dominant pore size (D_0) for UK sandstone samples from two independent studies

the Cole–Cole dispersion parameter c (Eq. 16) as a measure of the spread of the grain size distribution,

$$K \sim \frac{\tau}{F^u} e^{-1/c}, \quad (17)$$

where exponent u is a function of the fractal dimension and the Archie cementation exponent m. Essentially the same approach was presented by Sturrock et al. (1999) who estimated K for a suite of sandstone samples based on the grain size distribution inferred from broadband complex resistivity data.

Pape and Vogelsang (1996) derived a pigeon-hole model for the interpretation of time domain IP data obtained with a borehole logging tool. This model considered two modes of polarization (ion cloud expansion in a 'pigeon-hole' on the pore surface and ionic discharge within the electrolyte) occurring on a fractal surface. They concluded that the time constant of this model, being a length scale controlled by the fractal pore surface microstructure, is a measure of the permeability. Binley et al. (2005) presented results for weakly consolidated sandstones that provide evidence that τ and l_c may, indeed, be closely related. They found a power law relationship of the form $\tau \sim K^{0.26}$ (linear correlation coefficient $R^2 = 0.78$) measured at the same scale for 28 sandstone cores from three lithologic formations (Fig. 6). Kemna et al. (2005) also found a power law relationship of the form $\tau \sim K^{1.78}$ ($R^2 = 0.99$) for five pure sands of varying grain size saturated with the same electrolyte. Although these recent studies only provide empirical results, they indicate that SIP measurements of the time constant of the interfacial polarization (τ) may facilitate the geoelectrical estimation of the effective characteristic length scale controlling fluid flow as defined from application of percolation theory to porous media (Katz and Thompson 1986).

6 Spatial Patterns of K Variability

The first part of this review has considered the petrophysical basis of K estimation from geoelectrical methods and summarized the findings of laboratory studies. In the second part

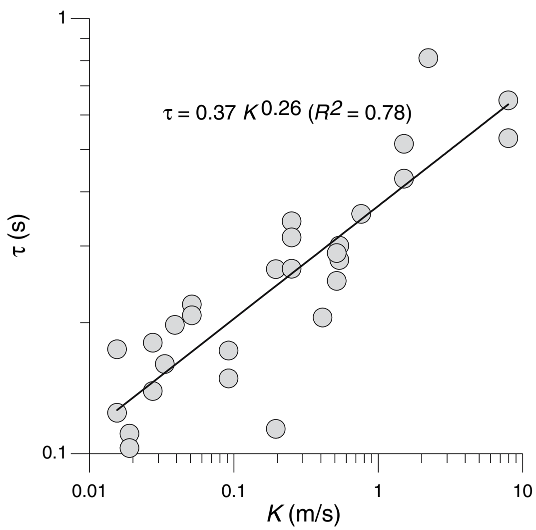

Fig. 6 Observed relationship between Cole–Cole time constant (τ) and vertical hydraulic conductivity (K) for 28 weakly consolidated sandstone cores (from Binley et al. 2005)

of this review, we turn our attention to the field-scale and consider the geoelectrical estimation of spatial patterns of *K* variability. Here we consider how the geophysical inversion of spatially extensive electrical measurements made in the field (either at the surface or in boreholes) can yield estimates of the spatial distributions of the electrical properties of the subsurface (we consider both the conduction (σ') and polarization (σ'') properties of the earth). Within the context of this review, inversion of geophysical datasets has most commonly focused on defining the spatial distribution of the magnitude of an aquifer property such as *K*. The images can then be used to define estimated zones of low or high *K*. However, it has also been suggested that the spatial continuity afforded by tomographic geophysical data is amenable to providing geostatistical descriptors of the hydraulic property of interest e.g. spatial correlation statistics describing the *K* structure (Hubbard et al. 1999; Linde et al. 2006b). One example is the hydrogeophysical characterization study at the U.S. Department of Energy (DOE) South Oyster Bacterial Transport Site (Chen et al. 2001; Hubbard et al. 2001). Here a Bayesian framework, allowing for complex petrophysical relationships between the geophysical parameters and *K*, was used to condition *K* estimates from a combination of direct flowmeter hydraulic measurements combined with both tomographic GPR and seismic data. Figure 7 illustrates how estimates of the spatial distribution of *K* obtained using geostatistical mapping techniques differ when the geophysical datasets are included in the estimation. The incorporation of the geophysical datasets appears to allow the spatial variability in estimated *K* to be mapped in regions remote from the flowmeter wells. However, others have questioned the value of geophysical tomograms for inferring geostatistics as tomographic resolution, and hence image structure, is dependent on geophysical data acquisition, regularization, data error and the physics of the underlying measurements (Day-Lewis and Lane 2004). A thorough treatment of the role of geophysical images in defining geostatistics is beyond the scope of this review but is found in the recent review by Linde et al. (2006a).

6.1 Direct Mapping of Geophysical Images to Aquifer Properties Using Petrophysical Relations

A common approach to geoelectrical imaging of aquifer properties is a procedure whereby geoelectrical data are inverted for images of the variation in electrical properties that are later converted to images of the distribution of a hydrological parameter based on a petrophysical relationship, possibly established with direct hydrological measurements at the same site. Such a procedure is actually possible using any physical property (e.g. other geophysical properties) that exhibits a correlation with *K*. This conversion may be obtained via direct mapping, geostatistical or Bayesian techniques (Chen et al. 2001; Linde et al. 2006a).

Such an approach has been applied to obtain estimates of the 2D distribution of *K* from induced polarization data using the electrical form of the Kozeny–Carman equation presented in Eq. 13 (Hördt et al. 2006; Kemna et al. 2004; Slater and Glaser 2003). In the study of Kemna et al. (2004) a modified form of Eq. 13 was used to account for the effect of variable saturation on the electrical measurements. Figure 8 shows some of the results obtained from this study, whereby the electrical-derived *k* distribution is compared with the lithologic sequence known at the site. The geophysical image predicts a *k* structure showing some consistency with the lithologic sequence, including a horizontal band of low *k* coinciding with the thin clayey–silt layer. Although the predicted *k* values are within a range expected of the sediments at this site, no direct measurements of *k* were made to

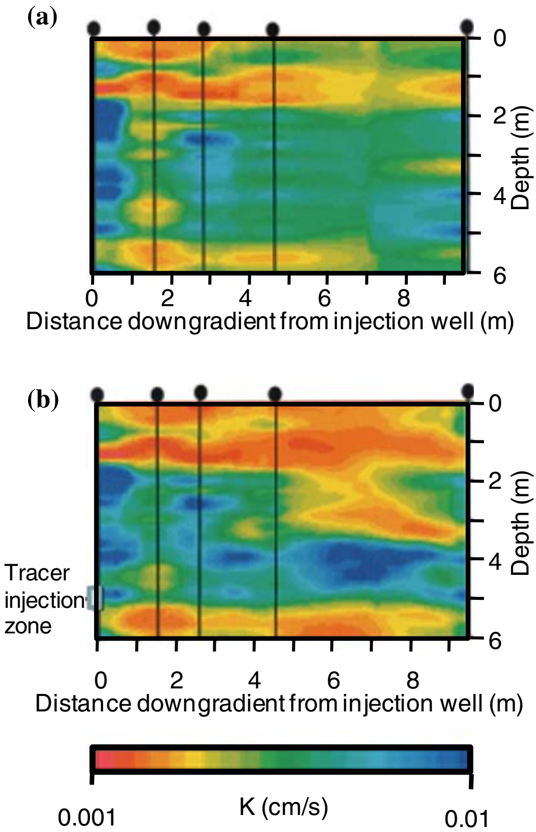

Fig. 7 Comparison of *K* structure estimated at the DOE South Oyster Bacterial Transport Site using (**a**) borehole flowmeter data; (**b**) both flowmeter data and geophysical tomography data following injection of a tracer (tracer location shown). Black circles denote wells with flowmeter data (after Hubbard et al. 2001)

evaluate the predictive accuracy of the model. In the study of Hördt et al. (2006) surface resistivity and induced polarization data were inverted for *K* estimates using Eq. 15 and the model parameters given by Börner et al. (1996). The results of this study demonstrated that order of magnitude K estimates are obtainable from such electrical geophysics-based versions of the Kozeny–Carman equation.

Other efforts to determine *K* distributions using such an approach have utilized geophysical techniques other than resistivity and IP. Chen et al. (2001) describe the use of a Bayesian framework to improve estimates of *K* distribution relative to those obtained from hydrologic methods alone, using a correlation between dielectric permittivity (ε) derived from GPR data and ϕ. They showed that, despite the small variation in log-*K* and ε across the site, the geophysical data improved the estimation of *K*, particularly where data coverage of the hydrologic measurements is low.

Although documented examples of direct mapping approaches exist, it is recognized that errors in geophysical data acquisition/inversion, combined with errors associated with the adopted petrophysical relationships can limit the value of the geophysical realizations of hydraulic properties so acquired (Kowalsky et al. 2006; Linde et al. 2006a). Hydrogeophysical research is thus increasingly turning to joint inversion strategies whereby multiple geophysical datasets, and/or hydrological datasets, are processed simultaneously to produce more realistic estimates of hydraulic parameters that satisfy all the available

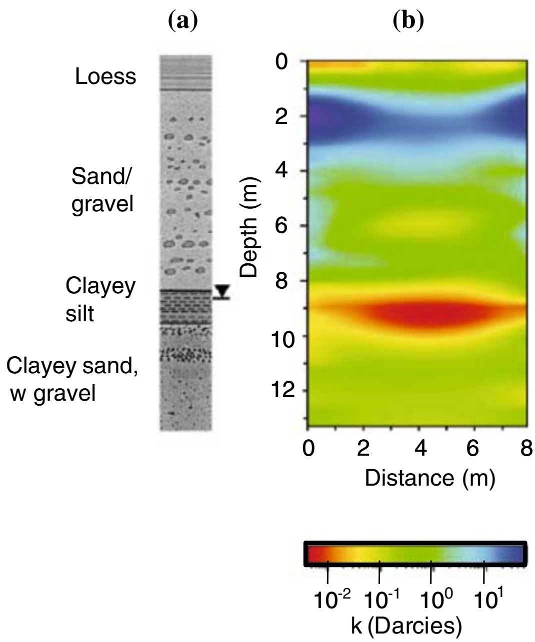

Fig. 8 Comparison of (**a**) lithologic log with (**b**) 2D *k* distribution estimated using a Kozeny–Carman approach applied to resistivity and induced polarization data (modified from Kemna et al. (2004)

datasets. The inclusion of hydrological data obviously has the potential to better constrain *K* estimates from geophysical inversion. Although, to date, such strategies have not primarily been applied to low-frequency electrical datasets, it is prudent to briefly review them here as (1) they can be readily applied to resistivity and induced polarization data, and (2) they have considerable potential to improve the characterization of aquifer geometries at the field scale. Given the petrophysical basis for estimating effective parameters controlling fluid flow from electrical measurements as described in the first part of this review, it appears only a matter of time before such measurements will be coupled in joint inversion frameworks for the prediction of field scale realizations of *K*.

6.2 Simultaneous/Joint/Constrained Inversion

Joint inversion methods, either (1) coupled inversion of geophysical and hydrological data or (2) coupled inversion of multiple geophysical data, have recently been adopted to overcome some of the limitations of the conversion of inverted geophysical images to aquifer properties based on petrophysical relationships described in the previous section. It is intuitive to expect that inversion of geophysical data for aquifer properties will benefit from hydrogeological constraints; however, the approach is somewhat in its infancy, presumably due to a lack of effective methods for joint inversion. When two datasets are both sensitive to the same physical property then simultaneous inversion is achieved by finding a physical model minimizing the misfit of both datasets (Lines et al. 1988; Vozoff and Jupp 1975). However, in hydrogeophysical problems the datasets are more, often than not, sensitive to different physical quantities.

Pioneering work in this field was conducted by researchers at Stanford University and focused on the use of seismic geophysical datasets, combined with petrophysical relationships between seismic data and *k*, to constrain the inversion for *k* distributions using hydrological datasets (Copty et al. 1993; Hyndman and Gorelick 1996; Hyndman et al. 1994, 2000; Rubin et al. 1992). A notable advancement in the approach was the 'split-inversion method' whereby seismic geophysical data were used to extract the lithologic zonation that matches both geophysical data and tracer concentration data (Hyndman and Gorelick 1996; Hyndman et al. 1994, 2000). A similar approach was adopted in a synthetic study by Linde et al. (2006c), who illustrated that tomographic GPR could be used to obtain such lithologic zonation (assuming a relationship between ε and *K*) that could then be applied to improve the hydraulic conductivity models obtained from inversion of tracer test data. The primary limitation of such approaches has been the questionable validity of assumed petrophysical relationships at the field scale. In order to address this, efforts have been made to determine how to upscale petrophysical relationships identified at the core-scale to petrophysical relations that are statistically meaningful at the scale of a tomographic survey (Day-Lewis et al. 2005; Moysey et al. 2005).

A more recent joint inversion approach, that excludes the requirement of the existence of a specific site petrophysical relationship, is the 'structural approach', which assumes that changes in different physical properties occur in the same direction for a given position (Gallardo and Meju 2003; Gallardo and Meju 2004; Haber and Oldenburg 1997). This approach is appealing as it recognizes that different geophysical properties of the subsurface depend on the same minerals and fluids without specifying an assumed petrophysical relationship. Gallardo and Meju (2003) describe an interesting application of the structural approach to jointly invert electrical resistivity and seismic refraction data for lithological zonation of near-surface unconsolidated sediments. Although the interpretation of the zones in terms of physical properties (e.g. *K*) was beyond the scope of the paper, the potential application of such novel joint-inversion strategies is nicely demonstrated in this paper. Figure 9a shows a cross-plot of the resistivity and seismic velocity for all points in the model domain and illustrates the existence of distinct relationships between the two properties. The authors classify nine resistivity–velocity curves which, when assigned and mapped into the model space, yields a single consistent structural image of the near-surface (Fig. 9b). A very recent extension of this structural approach is described in Linde et al. (2006c) who used GPR and dc resistivity data to define the 3D zonation of a sandstone aquifer and estimated the effective petrophysical properties of each zone. Characterizing the *K* distribution of the subsurface using such an approach would require that the *K* structure is controlled by the identified zonation. This situation was assumed in a very recent paper (Paasche et al. 2006) whereby fuzzy *c*-means cluster analysis was used to define a subsurface zonation that again assumes the existence of petrophysical relationships within the zones without defining them. The method was applied to crosshole GPR and crosshole seismic, constrained by limited gamma log and slug test data, to generate plausible *K* realizations.

7 Discussion—Future Directions

Given the review of the literature presented herein, three areas of research are recommended in order to improve the likelihood of meaningful geoelectrical characterization of *K* at the field scale.

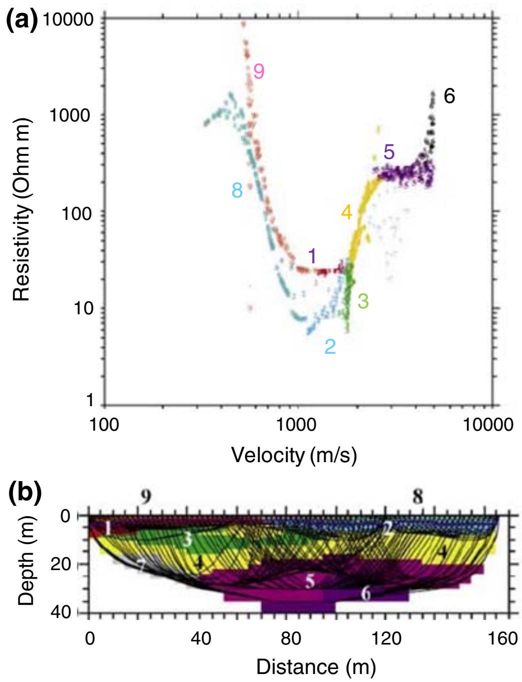

Fig. 9 The structural joint-inversion approach applied to near surface resistivity and refraction seismic data after Gallardo and Meju (2003) (**a**) resistivity–seismic velocity relationships identified in the jointly inverted data; (**b**) structural mapping of these relationships into subsurface zones

7.1 Petrophysical Research on Effective Electrical Properties

Whereas parameters representing the effective interconnected pore volumes are readily obtainable for geoelectrical measurements (e.g. *F*), parameters required to define the effective interconnected pore surface area are not so easily obtained from geoelectrics. Although induced polarization measurements have often been shown as sensitive to S_{por}, this is well recognized not to be a good measure of the effective length scale controlling fluid flow. Recent work has demonstrated that the characteristic time constant describing the relaxation spectrum observed in SIP datasets is well correlated with the pore throat size or pore size. It is such parameters that provide a better estimate of the length scale controlling fluid flow (Thompson et al. 1987).

7.2 Improving Accuracy of Field Geophysical Instrumentation

Although frequency dependent electrical measurements are relatively straightforward to obtain in the laboratory, an accurate field measurement of the phase angle (θ) required to compute σ'' and τ can prove problematic. First, the signal to noise ratio for the θ is often small, particularly when the ground is conductive (e.g. where the groundwater is more saline). Second, the effects of electromagnetic and/or capacitive coupling between potential measurement and current injection wiring, as well as electromagnetic coupling between wiring and the conductive earth, can result in θ artifacts that rapidly swamp the IP signal of interest. These artifacts increase with frequency. Furthermore, the measurements at the lowest frequencies tend to be very time consuming, making high-resolution surveys impractical. Therefore, whereas single-frequency measurements of σ'' are relatively easily obtained in the field if the ground is resistive enough to provide a measurable θ, obtaining θ measurements over a sufficiently broad frequency range to permit relaxation modeling and τ estimation is extremely difficult. Improvements in instrumentation to better suppress coupling effects, and/or data processing to model and thus remove these artifacts from the measured data, will likely accelerate implementation of IP/SIP at the field scale.

7.3 Application of Joint/Constrained Inversion Methodologies to Geoelectrical Data

Joint inversion procedures, whereby the sensitivity of multiple geophysical/hydrological datasets to K is utilized in a synergistic fashion, currently offer the most promising approach to predicting meaningful estimates of K structure in situ. The state-of-the-art joint/constrained inversion methodologies briefly reviewed herein have to date primarily been applied to geophysical measurements that are sensitive to total volume properties rather than effective properties controlling fluid flow. Most of the efforts with joint/constrained inversion have focused on the use of seismic or GPR datasets. However, both ε and seismic velocity are related to the total porosity of soil/rock and not the effective porosity (ϕ_{eff}) required in K prediction. Furthermore, they contain no information on the tortuosity of the interconnected pore volumes. The geophysical realizations of K obviously depend on the quality of the petrophysical relationship between K and the geophysical measurement obtained. This review has discussed how the electrical methods (resistivity, IP and SIP) are related to the effective properties required for K prediction i.e. effective measures of the interconnected pore volume and interconnected pore surfaces. Joint inversion of resistivity and induced polarization data, constrained with σ_w measurements (and perhaps local direct measures of K) would allow the methodology shown in Fig. 4 to be applied at the field-scale. Field inversion of SIP data is still in its infancy and restricted by the logistical difficulties (primarily EM coupling) of obtaining the shape of the frequency dispersion over a sufficiently wide range of frequencies at the field-scale.

7.4 Inversion Using Time-lapse Tomographic Data

An alternative approach to the use of geophysics in the field-scale characterization of K is to jointly utilize time-lapse geophysical and hydrological data to calibrate flow and transport models. Changes in geophysical datasets (e.g. as a result of solute transport or moisture change) responsive to volume properties can be expected to depend only on the active volume influenced by fluid flow. For example, although ε distributions obtained from GPR tomography will reflect the distribution of total porosity, changes in ε as a result of moisture content change will presumably reflect only the active porosity i.e. ϕ_{eff}. Such concepts have encouraged efforts to use time-lapse geophysical datasets to monitor changes in moisture in the vadose zone (Binley et al. 2001; Daily et al. 1992) and changes in solute concentration in the saturated zone (Day-Lewis et al. 2003; Kemna et al. 2002; Singha and Gorelick 2005; Slater et al. 2000). Temporal changes in geophysical (combined with available hydrological datasets) resulting from solute transport or moisture variations can potentially be used to calibrate solute transport models and thus predict K distributions. In a synthetic study Kowalsky et al. (2004) utilized an assumed petrophysical ($\varepsilon-\phi-K$) relation to generate multiple parameter distributions that reproduced point measurements of K, contained pre-specified patterns of spatial correlation, and were consistent with the synthetic neutron probe and GPR travel time datasets. Kowalsky et al. (2006) illustrated

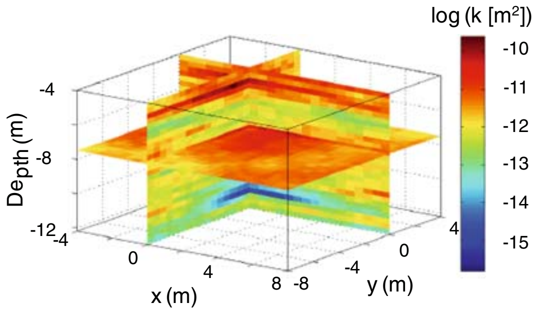

Fig. 10 Log permeability of the 200 East Area of the U.S. Department of Energy Hanford site obtained from joint inversion of time-lapse ground penetrating radar and neutron probe datasets (after Kowalsky et al. 2006)

how this approach could be used to generate realizations of log-*k* at the DOE Hanford site through joint inversion of available neutron probe and GPR datasets (Fig. 10). Binley et al. (2002), in a field study of saline tracer transport through an unsaturated sandstone aquifer, compared estimates of tracer first and second spatial moments obtained through modeling the Richard's equation (and constrained by petrophysical estimates of unsaturated properties) with the moments calculated from the changes in moisture content due to the tracer injection inferred from tomographic borehole resistivity and between borehole GPR. Although, they admitted significant uncertainty in the approach, they were able to calculate a value for the vertical saturated hydraulic conductivity at the scale of tracer transport that was found consistent with in situ values obtained from hydraulic tests on the saturated zone.

Although not a joint inversion-based approach, Vanderborght et al. (2005) describe a novel synthetic study whereby cross-borehole electrical imaging data were used to visualize tracer transport. They modeled the spatially averaged tracer breakthrough obtained from the electrical images with an equivalent advection dispersion equation and compared the results with modeling of local breakthrough curves using a stream tube model. They showed that the spatial correlation of the stream tube velocity in the horizontal direction could be quantified from time-lapse electrical images and, as the spatial correlations of the stream tube velocity and *K* were closely related, also the correlation scale of *K* in the same direction. Although only a synthetic study, this work is a nice illustration of how time-lapse electrical data could potentially be used to statistically characterize the spatial *K* structure of the earth.

Without doubt the rapidly growing research focusing on joint inversion strategies will ultimately lead to improved methods of *K* characterization in the field. Advances in addition to those discussed above will likely include (1) incorporation of multiple sets of geophysical and hydrological data; (2) accounting for spatial variability in petrophysical functions applied; (3) using joint inversion to predict spatial correlation functions.

8 Conclusions

This paper has reviewed the petrophysical basis for estimating hydraulic conductivity from low frequency electrical measurements (resistivity, induced polarization and spectral induced polarization). The fundamental reason for pursuing hydrogeophysical application of these geophysical methods is that the electrical properties sensed are related to petrophysical parameters controlling the effective transport (rather than total volume) properties of soils and rocks. Decades of research aimed at geophysical estimation of *K* have attempted to exploit correlations between electrical resistivity and (1) effective pore volume/formation factor based on Archie's Law, and (2) pore surface area/clay content when interfacial electrical conduction is present. More recently, petrophysical research on the induced polarization method has shown that the interfacial polarization measured with IP displays a power law dependence on the specific surface to pore volume (quantifying the interconnected pore surface area), a parameter that has traditionally been used to represent the inverse hydraulic radius measurement required to predict K from popular Kozeny–Carman type equations. In the last few years, new research on spectral induced polarization suggests that better estimates of the effective length scale of the interconnected surface area controlling fluid flow may be obtainable from the shape of the polarization relaxation.

The upscaling of these petrophysical properties to field-scale estimation of aquifer geometries remains a formidable task. Joint inversion strategies, whereby multiple geophysical and/or hydrological datasets are inverted simultaneously, are increasingly being preferred over inversion strategies based on the conversion of an image of a geophysical property to an equivalent hydraulic property from a petrophysical relationship. However, most joint inversion strategies have employed seismic or ground penetrating radar datasets, techniques that are primarily sensitive to total volume properties (e.g. total porosity) rather than effective properties more closely related to fluid flow, although Linde et al. (2006c) describe a joint inversion strategy using dc-resistivity and ground penetrating radar. The opportunity, therefore, exists to link, (1) the petrophysics relating low frequency electrical measurements to effective hydraulic properties, with (2) the joint inversion strategies developed in recent years, to obtain meaningful estimates of K distribution and aquifer geometries at the field scale. Such an approach may ultimately lead to accurate non-invasive quantification of hydraulic conductivity from geophysical methods.

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