Trends, prospects and challenges in quantifying flow and transport through fractured rocks

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Abstract Among the current problems that hydrogeologists face, perhaps there is none as challenging as the characterization of fractured rock (Faybishenko and Benson 2000). This paper discusses issues associated with the quantification of flow and transport through fractured rocks on scales not exceeding those typically associated with single- and multi-well pressure (or flow) and tracer tests. As much of the corresponding literature has focused on fractured crystalline rocks and hard sedimentary rocks such as sandstones, limestones (karst is excluded) and chalk, so by default does this paper. Direct quantification of flow and transport in such rocks is commonly done on the basis of fracture geometric data coupled with pressure (or flow) and tracer tests, which therefore form the main focus. Geological, geophysical and geochemical (including isotope) data are critical for the qualitative conceptualization of flow and transport in fractured rocks, and are being gradually incorporated in quantitative flow and transport models, in ways that this paper unfortunately cannot describe but in passing. The hydrogeology of fractured aquifers and other earth science aspects of fractured rock hydrology merit separate treatments. All evidence suggests that rarely can one model flow and transport in a fractured rock consistently by treating it as a uniform or mildly nonuniform isotropic continuum. Instead, one must generally account for the highly erratic heterogeneity, directional dependence, dual or multicomponent nature and multiscale behavior of fractured rocks. One way is to depict the rock as a network of discrete fractures (with permeable or impermeable matrix blocks) and another as a nonuniform (single, dual or multiple) continuum. A third way is to combine these into a hybrid model of a nonuniform continuum containing a relatively small number of discrete dominant features. In either case the description can be deterministic or stochastic. The paper contains a brief assessment of these trends in light of recent experimental and theoretical findings, ending with a short list of prospects and challenges for the future.

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Résumé Parmis les problèmes aucquels font face les hydrogéologues, il y a celui de la caractérisation des roches fracturées (Faybishenko and Benson, 2000). Cet article discute des solutions associées aux quantifications des écoulements et des transports à travers les roches fracturées à l'échelles des essais de puits et des essais de traçage. Une part importante de la litérature traite des roches cristallines, des roches sédimentaires consolidées telles les grés, les calcaires (exeptés les karsts) et la craie. De fait, cet article traitera la même panoplie de roches. La quantification directe des écoulements et du transport dans de tels milieux est généralement abordée via la géométrie des fractures, les données de pression et de traçage, qui déslors sont les objets principaux de notre étude. La géologie, la géophysique et la géochimie (incluant la géochimie isotopique) sont criticables car elles donnent des informations qualitatives sur l'écoulement et le transport des aquifères fracturés, et son intégrées graduellement dans des modèles qualitatifs. La manière d'intégrer ces données dépasse malheureusement cet article. L'hydrogéologie des aquifères de fractures et les autres sciences de la terre s'intéressant aux roches fracturées méritent des traîtements différents. En toute évidence il est suggéré que rarement un modèle d'écoulement et de transport dans une roche fracturée puisse être traité comme un milieu isotropique continu, uniforme ou moyennement non-uniforme. Par ailleurs, il est admis la dépendance entre la forte hétérogénéité erratique et la variété de natures et de comportements des roches fracturées. Une manière de régler le problème est de considérer le milieu comme un réseau de fractures discrètes (avec une perméabilité de matrice ou de bloc). Une autre est de l'envisager comme un milieu non-uniforme (simple, double ou multiple) continu. Une troisième manière est de combiner ceci dans un modèle hybride d'un milieu non-uniforme, contenant un relativement petit nombre de fractures dominantes et discrètes. Dans d'auters cas la description peut être déterministe ou stochastique. L'article contient un brève apperçu de ces tendances à la lumière d'expériences récentes et de nouvelles théories, et

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se termine par une courte liste de «challenge» et de priorités pour le futur.

Resumen Entre los problemas actuales que enfrentan los hidrogeólogos, quizá no hay uno tan desafiante como la caracterización de roca fracturada (Faybishenko y Benson, 2000). Este artículo discute problemas asociados con la cuantificación de flujo y transporte a través de rocas fracturadas en escalas que no exceden las típicas asociadas con presión (o flujo) en un solo pozo o varios pozos y pruebas con trazadores. Debido a que mucha de la literatura del tema se ha enfocado en rocas cristalinas fracturadas y rocas sedimentarias duras tal como areniscas, calizas (excluyendo karst) y creta, también en contumacia lo hace este artículo. La cuantificación directa del flujo y transporte en tales rocas se hace comúnmente en base a datos geométricos de fracturas acoplados con pruebas de presión (o flujo) y trazadores, los cuales por lo tanto constituyen nuestra principal orientación. Datos geológicos, geofísicos y geoquímicos (incluyendo isótopos) son críticos para la conceptualización cuantitativa de flujo y transporte en rocas fracturadas, y se han estado incorporando gradualmente en modelos cuantitativos de flujo y transporte, en formas que desafortunadamente este artículo solo puede describir de paso. La hidrogeología de rocas fracturadas y otros aspectos de ciencia de la tierra de hidrología de rocas fracturadas amerita tratamientos separados. Toda la evidencia sugiere que uno raramente puede modelizar flujo y transporte en una roca consistentemente fracturada si la considera como una unidad continua isotrópica uniforme o poco uniforme. En vez de adoptar este enfoque, uno tiene generalmente que explicar la heterogeneidad altamente errática, dependencia direccional, naturaleza doble o multicomponente y comportamiento multiescalar de las rocas fracturadas. Una manera de lograr esto consiste en considerar que la roca contiene una red de fracturas discretas (con bloques de matriz permeable o impermeable) y otro modo en considerar la roca como una unidad continua no uniforme (sola, doble o múltiple). Un tercer procedimiento consiste en combinar las dos maneras anteriores en un modelo híbrido el cual consiste de un continuo no uniforme conteniendo un número relativamente pequeño de fracturas principalmente discretas. En ambos casos la descripción puede ser determinística o estocástica. El artículo contiene una evaluación breve de estas tendencias en base a descubrimientos recientes teóricos y experimentales, terminando con una lista corta de prospectos y desafíos para el futuro.

Keywords Fractured rocks · Discrete models · Continuum models · Flow · Transport

Introduction

All but unconsolidated subsurface materials are fractured to some degree. Natural fractures appear on a continuum of scales ranging from microcracks to crustal rifts (Bonnet et al. 2001). When containing material that is less permeable than the host rock, fractures may form barriers to flow. The literature on flow and transport through fractured rocks tends to focus primarily on discontinuities that are intrinsically more permeable than the surrounding parent rock. One reason is the role played by permeable discontinuities in the formation of ore deposits and the economic utilization of energy stored in petroleum, gas and geothermal reservoirs (Van Golf-Racht 1982). Another reason is the importance of fractured aquifers and fracture zones in bedrock terrains (including dikes and faults) as a source of groundwater to wells (Boehmer and Boonstra 1987; Lloyd 1999; Lachassagne et al. 2001). The development of elevated fluid pressures in permeable fractures having low shear strength and negligible tensile strength is a potential cause of rock deformation or failure in excavations and underground openings. This and the need to control seepage into mines and tunnels, and out of underground fluid storage caverns, render flow through permeable fractures of interest to mining and geotechnical engineers (Lee and Farmer 1993; Priest 1993; Guguen and Boutca 2004)). Low-permeability fractured rocks are of interest as potential barriers to fluid leakage out of natural and man-made storage reservoirs and to the subsurface migration of pollutants such as toxic and radioactive wastes (e.g. Neuman and Simpson 1985; Neuman and Neretnieks 1990). Recent books providing a broad perspective on the hydrogeology of fractured rocks include Singhal and Gupta (1999), Faybishenko et al. (2000), Evans et al. (2001) and the National Research Council (1996, 2001).

It would be difficult to review all aspects of fractured rock hydrology in a single paper. The present paper is therefore limited in scope largely (though not exclusively) to issues associated with the quantification of flow and transport through fractured rocks on scales not exceeding those typically associated with single- and multi-well pressure (or flow) and tracer tests. As much of the corresponding literature has focused on fractured crystalline rocks and hard sedimentary rocks such as sandstones, limestones (we exclude karst) and chalk, so by default does this paper. Direct quantification of flow and transport in such rocks is commonly done on the basis of fracture geometric data coupled with pressure (or flow) and tracer tests, which therefore form our main focus. Geological, geophysical and geochemical (including isotope) data are critical for the qualitative conceptualization of flow and transport in fractured rocks, and are being gradually incorporated in quantitative flow and transport models, in ways that this paper unfortunately cannot describe but in passing. The hydrogeology of fractured aquifers and other earth science aspects of fractured rock hydrology merit separate treatments.

Laboratory and field measurements of hydraulic and transport parameters (such as permeability; specific storage; constitutive relations between saturation, capillary pressure and relative permeability; advective porosity; dispersivity) in porous media represent averages over many pores. The same is true about state variables such as pressure, saturation, concentration, flux and velocity. As

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these bulk or macroscopic quantities are defined at each point in space, adopting them implies that one ignores the complexities of the pore structure, replacing it by a fictitious continuum. All that is required for such a continuum representation to be valid is that the quantities be measurable on a consistent "support" scale, which is large in comparison to a characteristic pore (or grain) scale and small in comparison to the flow or transport domain of interest. The support scale need *not* constitute a representative elementary volume (REV), defined by Bear (1972) as a volume large enough to eliminate erratic fluctuations in macroscopic medium properties. Such erratic fluctuations are known to exist at all scales (Neuman and Di Federico 2003) and are today treated quite successfully using geostatistical and stochastic methods (e.g. Kitanidis 1997; Dagan and Neuman 1997; Zhang 2001; Rubin 2003). They render the traditional REV concept inapplicable except in special cases (Zhang et al. 2000).

Though it is becoming increasingly feasible to characterize some highly fractured rock samples in the laboratory (e.g. Köhne et al. 2002; McDermott et al. 2003), in general fractured rocks must be characterized in situ. This is so because fracturing of hydrogeologic interest manifests itself on much larger than laboratory scales and fracture properties are strongly affected by in situ fluid distribution and stress conditions. The most elementary and prevalent method of characterizing fractured rocks hydraulically (or pneumatically, e.g. Chen et al. 2000) in situ is the single borehole packer test; increasingly, these are replaced or supplemented by sensitive high-resolution flow meters (e.g. Rouhiainen and Pöllänen 1999). Most commonly, one infers from packer tests hydraulic conductivities or permeabilities by treating the surrounding rock as a locally uniform (over the corresponding support volume) porous continuum (e.g. Illman and Neuman 2000). As the precise nature and size of a support volume associated with a packer test is difficult to ascertain (Beckie and Harvey 2002), it is common to quote results in terms of a nominal support scale equal to the length of the packed-off interval (this is valid at best for single-hole packer tests in which all measurements are confined to the fluid injection interval, not for fluid interference tests between boreholes or multiple test intervals within a single borehole as explained by Hyun et al. 2002, and Neuman and Di Federico 2003). Permeabilities obtained in this manner tend to be highly erratic and sensitive to the length of the test interval (e.g. Chen et al. 2000; Neuman and Di Federico 2003).

A common way to characterize fractured rocks hydraulically (or pneumatically, e.g. Illman et al. 1998) *in situ* is through pressure interference tests between boreholes. Most commonly, one infers from such tests transmissivities or permeabilities as well as storativities or specific storage values (porosities in the case of pneumatic tests, Illman and Neuman 2001, Vesselinov et al. 2001b) by treating the surrounding rock as a uniform porous continuum. Treating the rock in this way often precludes one from inferring consistent parameters from all pressure data collected during a test. Instead, data collected in different monitoring intervals may yield different bulk rock properties unless the assumption of uniformity is relaxed (e.g. Vesselinov et al. 2001a, 2001b). Results obtained with and without explicit consideration of spatial variability may differ sharply, revealing a pronounced scale effect (Hyun et al. 2002; Neuman and Di Federico 2003).

Uniform equivalent permeabilities (Hsieh and Neuman 1985; Hsieh et al. 1985) and transmissivities (Gonzalez 1983; Neuman et al. 1984) derived from pressure interference tests in fractured rocks tend to be directional and may sometimes be represented by tensors. Hsieh and Neuman found the principal directions of a three-dimensional bulk permeability tensor of fractured rocks near Oracle, Arizona, to coincide with the major directions of fracture intersections. Theory (Romm and Pozinenko 1963; Snow 1969) suggests that, in general, the principal directions need not coincide with either fracture intersections or fracture planes.

Tracer tests are often conducted in conjunction with pressure interference tests. It is generally very difficult to interpret such tests consistently without accounting in one way or another for the nonuniform nature of the fractured rock (e.g. Tsang and Neuman 1995; Ando et al. 2003). Dispersivities derived from such tests by treating the medium as being uniform exhibit a scale effect consistent with that observed in porous media (Neuman 1990, 1991). In some such tests advective transport velocity appears to vary with direction (Jones et al. 1992; Meigs and Beauheim 2001). As pointed out by Neuman (2004), hydraulic anisotropy explains some but not all of the reported directional results. Neuman showed mathematically that directional variations in advective porosity may arise simply from incomplete mixing of an inert tracer between directional flow channels within a sampling (or support) volume of soil or rock that may be hydraulically isotropic or anisotropic. Situations were considered in which flow takes place preferentially through relatively conductive channels and/or fractures of variable orientation separated by material that forms a partial barrier to diffusive transport. It was found that in these situations the tracer center of mass is advected at a macroscopic velocity which is generally not collinear with the macroscopic Darcy flux and exceeds it in magnitude. These two vectors are related through a second-rank symmetric advective porosity tensor. If permeability is a symmetric positive-definite tensor, so is the advective porosity tensor. However, the principal directions and values of these two tensors are generally not the same; whereas those of permeability are a fixed property of the medium and the length-scale of the support volume, those of advective porosity depend additionally on the direction and magnitude of the applied hydraulic gradient. When the latter is large, diffusion has negligible effect on the advective porosity tensor and one may consider tracer mass to be distributed between channels in proportion to the magnitude of their Darcy flux. Neuman illustrated this on a simple example of an idealized fracture network.

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Responses to pressure interference and tracer tests in porous fractured rocks are at times amenable to interpretation based on a dual continuum model, in which the rock matrix forms one continuum and the fracture network another, overlapping continuum (Barenblatt et al. 1960; Warren and Root 1963). If one of these overlapping entities dominates all relevant aspects of flow and transport, the system acts as a single matrix- or fracture-dominated continuum. Otherwise, the model accounts for possible fluid and solute migration from one continuum to the other under a pressure and/or concentration differential between the two. If fluid and mass transfer between matrix and fractures is fast in comparison to flow and transport through the rock, one may consider the two continua to be at equilibrium and treat the rock as an equivalent or effective (single) matrix-fracture continuum (Peters and Klavetter 1988; Dykhuizen 1990; Pruess et al. 1990). In the absence of such equilibrium, it is common to adopt a dual porosity model (Bibby 1981; Moench 1984; Zimmerman et al. 1993; McKenna et al. 2001; Altman et al. 2002; Köhne et al. 2002; Reimus et al. 2003) in which the matrix acts as a non-conducting storage reservoir; the fractures form a conducting medium with negligible storage capacity; and the transfer of fluids (or solutes) between these two overlapping continua is linearly proportional to the pressure (or concentration) differential between them at each point in space-time. A more general version of the latter is a dual permeability model (Duguid and Lee 1977; Gerke and van Genuchten 1993a, 1993b; Wu et al. 2002) in which both the matrix and fracture continua conduct fluids and solute.

Models have also been proposed which account in various ways for internal gradients of pressure or concentration within matrix blocks (Kazemi 1969; Pruess and Narasimhan 1985; Berkowitz et al. 1988; Birkhölzer et al. 1993; Pan and Bodvarsson 2002). A seminal paper by Neretnieks (1980) cited experimental evidence for solute diffusion through the matrix of crystalline rocks. Guimerà and Carrera (2000) examined data from 90 tracer experiments in low-permeability fractured media on a wide range of distance (from 1 to 346 m) and peak arrival time (from 16 to 140,000 min) scales to find that apparent porosity grows as the square root of peak arrival time (from which the porosities are derived), attributing the phenomenon to matrix diffusion. Among many other examples, Meigs and Beauheim (2001) and McKenna et al. (2001) present evidence for matrix diffusion during tracer tests in the fractured Culebra Dolomite near Carlsbad, New Mexico. For a comprehensive qualitative and quantitative discussion of the matrix diffusion phenomenon the reader is referred to Carrera et al. (1998). In contrast, Shapiro (2001) modeled one-dimensional transport of tracers in fractured crystalline rock on the scale of kilometers by accounting explicitly for advection through high-permeability fractures, and simulating advective mass exchange between these and low-permeability fractures implicitly, as an equivalent diffusive process. The approach was based on the recognition that on this scale, diffusion in and out of the rock matrix is masked by advective mass exchange between high- and low-permeability fractures, and the finding that a classical matrix diffusion model (in which mass transfer is linearly proportional to a unique concentration differential between the two continua) would not reproduce the available data. The analysis yielded an effective matrix diffusion coefficient that is orders of magnitude larger than laboratory estimates of matrix diffusion in crystalline rock. Work by Becker and Shapiro (2003) suggests that the same may be true on scales much below those of kilometers.

Carrera et al. (1990) were able to successfully reproduce pumping tests in a fractured block of monzonitic gneiss by treating discrete fracture zones, and the rest of the fractured rock mass, as juxtaposed (non-overlapping) fracture-dominated (single) continua. A similar approach has been taken by Kimmeier et al. (1985) and Shapiro and Hsieh (1991).

All evidence thus suggests that rarely can one model flow and transport in a fractured rock consistently by treating it as a uniform or mildly nonuniform isotropic continuum. Instead, one must generally account for the highly erratic heterogeneity, directional dependence, dual or multicomponent nature and multiscale behavior of fractured rocks. One way is to depict the rock as a network of discrete fractures (with permeable or impermeable matrix blocks) and another as a stochastic (single, dual or multiple) continuum. A third way is to combine these into a hybrid model of a stochastic continuum containing a relatively small number of, or statistical information about, discrete features. The latter (e.g. Lee et al. 2001) can be thought of as a stochastic analogue of the deterministic juxtaposed-media model of Carrera et al. (1990). Carrera and Martinez-Landa (2000) have demonstrated on three case examples that, where flow is strongly controlled by a few dominant fractures or fracture zones, including these as discrete features in otherwise (in their case deterministic) continuum flow models of the rock mass had been both sufficient and helpful in calibrating and validating each model against recorded pressure interference test data collected in igneous and metamorphic rocks on a wide range of space-time scales.

The remainder of this paper is a brief assessment of current trends in the quantitative characterization and modeling of flow and transport in fractured rocks, ending with a short list of prospects and challenges for the future. Though the paper includes an extensive list of selected references, their purpose is merely to help the writer illustrate or support certain concepts and ideas, not to provide a comprehensive account of all relevant contributions to the area.

Conceptualization of Fracture Rocks as Discrete Networks

Trends in Discrete Network Modeling

In many fractured rock studies, especially those concerning the safety of geologic nuclear waste repositories or other presently or potentially contaminated sites, a

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declared goal is to delineate existing or potential avenues of groundwater flow and solute (e.g. radionuclide or other pollutant) migration. To do so, it may seem appropriate to map with as much detail as possible the geometry of fracture zones and individual fractures in order to generate information about the three-dimensional network they form in the rock. The idea is not to map only dominant discrete features as in the hybrid discrete-continuum models discussed in the Introduction, but to include in the model hundreds or thousands of fractures having a wide range of sizes. This necessitates the postulation of a theoretical or computational model to translate deterministic and/or statistical information about fracture geometry into terms that are useful for the analysis of groundwater flow and solute transport. The aim of most theoretical analyses of flow and transport in discrete fracture networks (DFNs) has been to derive bulk (equivalent) properties for generic networks. The motivation behind most real-world DFN applications has been to capture the intricacies of flow and transport in discrete fractures and/or channels in a way that is consistent with available site data.

A summary and critique of some early theoretical and real-world DFN applications was presented by Neuman (1987, 1988). More recent theoretical and computational approaches to flow and transport in DFNs are described in the books of Sahimi (1995), Adler and Thovert (1999) and Zhang and Sanderson (2002). Most state of the art theoretical studies consider random networks of interconnected line segments in two (Park et al. 2001a, 2001b; de Dreuzy et al. 2001a, 2001b, 2002, 2004; Liu and Bodvarsson 2001; Liu et al. 2002; Darcel et al. 2003; Benke and Painter 2003; Ji et al. 2004) or less commonly three dimensions (Margolin et al. 1998; Dershowitz and Fidelibus 1999; Cvetkovic et al. 2004), embedded in an impermeable matrix. Each line segment is ascribed a uniform transmissivity or width (aperture) to which the transmissivity is related through a power (usually cubic, sometimes quadratic as in Cvetkovic et al. 2004) relationship (law). For purposes of simulating unsaturated flow, each segment is assigned capillary constitutive relations and parameters similar to those of a uniform porous soil. An exception are the studies of Bogdanov et al. (2003a, 2003b) who use a three-dimensional model of permeable matrix blocks with planar fractures to investigate theoretically the impact of discontinuities on steady state and transient saturated flow regimes. In their model, each fracture is ascribed a uniform planar conductivity and a uniform transverse resistivity in either a deterministic or a random manner. A fully three-dimensional solution of the Stokes equation within pairs of intersecting smooth and rough-walled orthogonal fractures having impermeable walls, coupled with a random walk particle tracking method, has been used by Mourzenko et al. (2002) to investigate advective-diffusive transport at fracture intersections (see also Park et al. 2003).

Bogdanov et al. (2003b) list a number of three-dimensional computer codes based on the DFN concept. The application of such DFN models to specific sites has followed one of two approaches. One approach has been to generate numerous random DFNs, each including hundreds or thousands (8,500 in Fig. 1, Herbert et al. 1991) of fractures, for the purpose of ascribing random effective parameters to subdomains of the rock mass being analyzed, which would then be treated as a randomly heterogeneous (stochastic) continuum (e.g. Cacas et al. 1990a; Herbert and Splawski 1990). As the subdomains are usually much larger than the average spacing between fractures, such stochastic continuum models have a much lower spatial resolution than does the underlying DFN. Another approach has been to simulate flow (e.g. Dershowitz et al. 1991) or transport (e.g. Cacas et al. 1990b) across the entire rock mass using high-resolution DFNs with thousands or tens of thousands of fractures (20,000 in the case of Cvetkovic et al. 2004). The international Stripa project has shown (SKB 1993) that whereas it has been possible to construct both types of fracture network models for a large (125×150×50 m) undisturbed block of crystalline rock (the so-called Site Characterization and Validation block) and to calibrate them against observed hydraulic and tracer data, these models have generally not performed better than much simpler and more parsimonious continuum or hybrid discrete-continuum models incorporating at most a few dominant discontinuities. Tsang and Neuman (1995) concluded based on experience gained from the international INTRAVAL project that several field hydraulic and tracer experiments have proven equally amenable to analysis by discrete and continuum models. Ando et al. (2003) found that a high-resolution stochastic continuum model of flow and transport in fractured crystalline rocks at Fanay-Augères

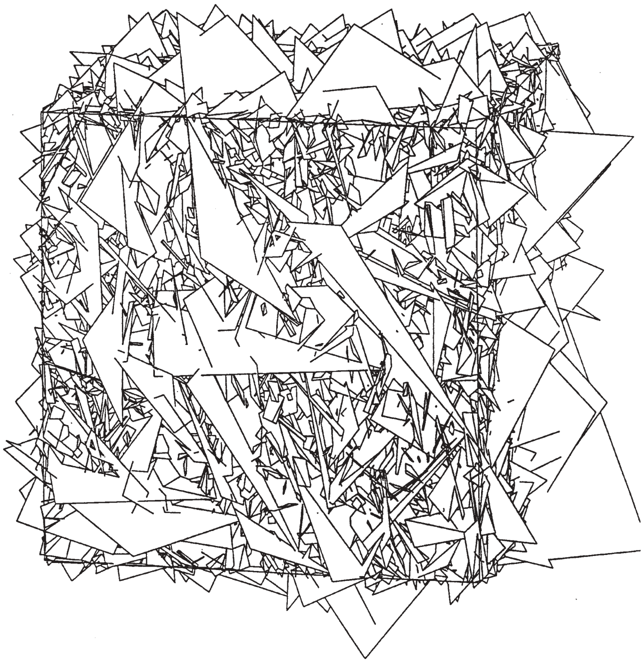

Fig. 1 Realization of a 12.5-m-sided cube generated by Herbert et al. (1991) to compute equivalent hydraulically conductivity tensor for "averagely fractured" crystalline rock at the Stripa Mine in Sweden

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performed as well, and in some important ways better, than the DFN-based models of Cacas et al. (1990a, 1990b). At the Äspö Hard Rock Laboratory in Sweden (SKB 2003a, 2003b; Rhén and Smellie 2003; Marschall and Elert 2003; Winberg et al. 2003), a wide range of discrete and continuum models appear to have been capable of capturing key aspects of flow and transport in a fractured crystalline rock mass, including relatively simple models described by Dverstorp et al. (1996). Since DFN models incorporate many more details, and data, than do typical (deterministic or stochastic) continuum or hybrid discrete-continuum models, it may seem puzzling that they do not outperform the latter models. In the writer's opinion, there are a number of issues that must be resolved to render DFN models more competitive.

Issues with Delineation of Discontinuities

A major issue to overcome is that of data limitation: the ability to map discontinuities in the rock with available geological and geophysical tools tends to decrease as the scale of the discontinuity goes down. Major fracture zones (in comparison to the rock volume being investigated) can generally be delineated on maps and cross sections with sufficient accuracy and detail to justify treating them as deterministic discrete entities in flow and transport models. However, the detection and delineation of smaller zones may require greater effort coupled with the use of specialized geophysical tools such as electromagnetic reflectometry or radar and seismic tomography. Individual fractures may not register at all in such geophysical surveys but reveal themselves primarily as linear traces on outcrops or local features in cores and borehole geophysical logs (such as acoustic TV). Experience shows that (e.g. Ahlbom et al. 1983a, 1983b, 1983c, 1983d; Carlsson and Gidlund 1983) the density of fractures registered on surface outcrops is often significantly smaller than that found in boreholes immediately below the surface, implying that information collected along surface outcrops may not be representative of conditions inside the rock mass. Attempts to correlate discontinuities between boreholes have shown that this is difficult to do for all but major planar features (on scales not much smaller than the area being investigated). Consequently, both surface and subsurface data are limited in that they provide much less information about fracture shapes and sizes than about densities and orientations, though all four parameters are equally important for the construction of realistic fracture network models. The most important difficulty, however, is that geology and geophysics alone do not provide any quantitative information about fracture apertures of the kind required to assess fracture flow and transport parameters purely on the basis of fracture-geometric data. Hence there is no escaping from the need to measure these parameters in situ by means of hydraulic (or pneumatic) and tracer tests. To the extent that such measurements are translated into apertures (a common practice in the earlier days of DFN modeling which some still follow), the latter are equivalent values (not actual apertures, which tend to be highly variable in the interior of each fracture) that may or may not correspond to actual geometric apertures, as pointed out below.

Issues with Characterization of Discontinuities

Another major issue to overcome is that of characterizing the flow and transport properties of individual fractures other than geometrically well defined major discontinuities. A growing tendency in DFN modeling is to characterize fractures in terms of equivalent flow and transport parameters (such as transmissivity, porosity and dispersivity) derived from *in situ* pressure (or flow) and tracer tests; some DFN models require instead (or in addition) information about equivalent fracture apertures derived (as just noted) indirectly from such tests. To characterize individual fractures, pressure (or flow) and tracer tests are typically conducted in isolated intervals of selected boreholes (as already mentioned, an alternative is to log the borehole using sensitive high-resolution flow meters such as the Posiva difference meter employed by Rouhiainen and Pöllänen 1999). Even in rare situations where the test interval is known to intersect a single fracture, or where a sensitive high-resolution flow meter is used, one seldom knows how far this fracture extends from the borehole and what other fractures it may intersect. One may therefore not be sure that fracture characteristics identified from such tests are representative of the entire fracture and of only one fracture. One way to tell whether the pressure response during a single-hole packer test is representative of planar flow through one or several subparallel fractures, or a three-dimensional network of interconnected fractures, is to identify the dimensionality of the surrounding flow regime in the manner of Illman and Neuman (2000). Alternatively, one may identify a (typically fractional) "flow dimension" using a method proposed by Barker (1988) as done recently by Kuusela-Lahtinen et al. (2003); more on this later. Only if such methods indicate that flow is two dimensional, and dominated by a single fracture, may one perhaps be justified in ascribing the inferred flow parameters to one fracture. The author is not aware of any way to identify in situ the transverse hydraulic resistance of a fracture as required for the DFN model of Bogdanov et al. (2003a, 2003b). It thus appears that evaluating in situ the flow and transport characteristics of individual fractures, with the possible exception of some clearly defined dominant features, remains an open challenge.

To quantify fracture aperture on the basis of hydraulic or tracer tests (as required by some DFN models), one must invoke theoretical models which correctly and consistently relate the former to the latter. Developing such a theoretical model remains a challenge for future research. The simplest and most commonly used model is one that assigns an "effective hydraulic aperture" to each fracture in proportion to the cube root of planar flow rate within it, based on the classical "cubic law" (e.g. Folger et al. 1999). Interpreting tracer test results in a manner consistent with the cubic law yields an "effective transport aperture" which is typically larger than the hydraulic aperture (Nowakowski et al. 1985; Shapiro and Nicholas

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1989; Silliman 1989; Tsang 1992; Cady et al. 1993; Lapcevic et al. 1999; Zimmerman and Yeo 2000). For reactive tracers, Cvetkovic et al. (2004) introduce yet another "effective retention aperture." The failure of the cubic law to explain many laboratory and field observations of flow and transport in natural rock fractures has been amply documented by Neuman (1987). Among early laboratory examples of such failure one may cite the work of Gale et al. (1985; see also Gale 1990), which shows strong evidence that significant deviations from the cubic law occur at elevated normal stresses, and the experiments of Makurat (1985), which demonstrate even greater deviations under the application of cyclic shear stresses. The former authors conclude that the cubic law, with appropriate corrections for fracture wall roughness, holds only for fractures whose adjoining surfaces are not in contact. "For fractures that are in intimate contact, corrections for roughness alone do not appear to be adequate to completely define the flow properties and tortuous flow paths of single fractures." Various modifications to the cubic law have been proposed (most recently by Basha and El-Asmar 2003) which however have been shown to offer only a partial resolution of the dilemma (Konzuk and Kueper 2004; for the case of non-Newtonian fluids consult Di Federico 2001). For the cubic law to work with acceptable accuracy, it may need to be applied locally by allowing the hydraulic aperture to vary spatially within a fracture (Brush and Thomson 2003; Cheng and Cvetkovic 2003; Inoue and Sugita 2003; Lee et al. 2003); however, characterizing such spatial variations in situ on field scales below the surface remains a challenge.

Characterizing a fracture in terms of its aperture(s) is not appropriate when it contains or is partially coated with porous material, possibly including microcracks, which may exert partial or complete control on its hydraulic and transport properties (Bossart and Mazurek 1991; Sharp et al. 1996; Robinson et al. 1998; Weisbrod et al. 2000; Tsang and Doughty 2003; Auradou et al. 2003). In fractures with unstable surface characteristics, apertures may vary (sometimes quite rapidly) with time due to deposition on (Thoma et al. 1992; Chekuri et al. 1995; Soll and Birdsell 1998) or erosion of (Weisbrod et al. 1998, 1999) the fracture walls.

To analyze multiphase or unsaturated flow in fractured rocks (as done for example in the context of potential radioactive waste disposal at Yucca Mountain in Nevada, natural recharge through fractured chalk in southern England, and migration of contaminants through fractured chalk in the Negev desert of Israel), it is necessary to possess information about capillary variables (e.g. residual and existing saturation) and properties (constitutive relations between saturation, capillary pressure and relative permeability, and associated parameters) of the rock. DFN models such as that of Liu and Bodvarsson (2001) and Liu et al. (2002) require such information for individual fractures. This is an open challenge considering that (see Introduction to National Research Council 2001) unsaturated flow in fractures may interact strongly with the surrounding matrix, exhibit intermittent behavior and be controlled at low saturations by film flow. Factors that may create significant fracture-matrix interaction include high matrix suction, large contact area between water and fracture wall, and absence of fracture coating that would impede matrix imbibition (e.g. Thoma et al. 1992; Ho 1997). Isolated fractures that are not connected to a network, and therefore ignored in most (though not all) DFN models, may act to accelerate flow in porous fractured rock under unsaturated (Su et al. 2003) as well as saturated (Berkowitz and Scher 1996) conditions. During inflow into a dry fracture broad, pulsating, water-filled blobs or "capillary islands" may form that are connected by thin "rivulets" which snap and reform in an intermittent manner (Su et al. 1999, 2001). Intermittent flow through partially saturated fractures has been observed in the field (e.g. Dahan et al. 1999; Faybishenko 1999; Weisbrod et al. 2002), exhibiting unpredictable nonlinear dynamic (chaotic) behavior (Faybishenko 1999). Film flow may occur in fractures having either small or large hydraulic apertures; is not directly controlled by this aperture; does not require that the water form a contiguous phase; is strongly enhanced by fracture roughness; may exceed mean saturated velocities by orders of magnitude (Tokunaga and Wan 1997, 2001; Or and Tuller 2000); and may (at least in theory) travel in the form of solitary waves exhibiting chaotic behavior (Dragila and Wheatcraft 2001). As explained in a relatively recent overview by Chen et al. (1995), instability and fingering may cause water to propagate through fractures much faster than would be the case under stable conditions; more recent studies on fingering in fractures and fractured rocks include Glass and Nichol (1996), Neuman and Chen (1996), Birkhölzer and Tsang (1997), Pruess (1999), and Glass et al. (2000). Fracture intersections may potentially contribute to intermittency and instability of flow by acting as switches to alter capillary droplet into film flow, create blockages and capillary bridges, induce changes in local flow pattern, and influence the formation of fingers (Dahan et al. 2000; Faybishenko et al. 2000; Glass et al. 2002a, 2002b, 2003; Salve et al. 2002; Dragila and Weisbrod 2004).

Dynamic Nature of Flow Channels

The notion of plane flow through an effectively uniform fracture plane does not account directly for the complex nature of flow and transport through an intricate network of preferred paths or "channels" within the fracture plane and/or along fracture intersections (Tsang and Neretnieks 1998). It remains to be demonstrated that the effect of such tortuous channels on flow, solute advection and dispersion can be captured indirectly by means of effective fracture apertures or dispersivity (Bodin et al. 2003a). That preferred flow paths must indeed exist is strongly supported by direct and increasingly sophisticated measurements of asperity and aperture variations in laboratory samples of natural fractures and faults (Brown and Scholz 1985; Gentier 1986; Gale et al. 1987; Power et al. 1987; Vickers et al. 1992; Hakami and Larssen 1996; Renshaw et al. 2000; Isakov et al. 2001; Loggia et al. 2004). Such

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measurements show that asperities and apertures may vary by orders of magnitude over distances of less than a millimeter. As such, they are best described as spatially correlated random fields defined at all (a continuum of) points in the plane of a fracture or fault. Fracture and fault asperities (Brown 1995; Power and Tullis 1995) as well as fracture apertures (Brown et al. 1986; Cox and Wang 1993) appear to delineate random fractals whose variance and spatial correlation scale increase with fracture size. As such, the random fractals form nonstationary (statistically nonhomogeneous) random fields with (possibly) stationary increments. It follows that any effective flow or transport properties, which depend on the spatial distribution of asperities and apertures, must vary with the size of a fracture or a fault (Bodin et al. 2003a; Neuman and Di Federico 2003).

Laboratory studies (e.g. Neretnieks et al. 1982; Haldeman et al. 1991; Brown et al. 1998), field experiments (Neretnieks 1993; Abelin et al. 1994; Lapcevic et al. 1999) and numerical simulations (e.g. Tsang 1984; Tsang and Tsang 1987, 1989; Moreno et al. 1988; Johns and Roberts 1991; Moreno and Tsang 1991; Tsang et al. 1991; Moreno and Neretnieks 1993; Amadei et al. 1994; Zimmerman and Bodvarsson 1996; Park et al. 1997; Plouraboué et al. 1998; Roux et al. 1998; Vandersteen et al. 2003) suggest collectively (Tsang and Neretnieks 1998) that flow and transport in rough-walled fractures tends to occur in highly variable and tortuous channels forming a braided pattern. The channels are dynamic in that their spatial distribution varies with the externally imposed flow regime. To map out such flow channels by tracer tests or other means would therefore not yield information about the intrinsic flow properties of the medium. The alternative, to characterize aperture or local effective parameter variations in more than one or perhaps a few major fractures or faults (or other discontinuities such as dikes) in the field, does not appear to be practical.

Field evidence suggests the existence of preferred pathways or channels on scales larger than an individual fracture. Hsieh et al. (1985) used cross-hole hydraulic tests to evaluate the hydraulic conductivity of fractured granites near Oracle, Arizona, on scales of several tens of meters. They found that this hydraulic conductivity can be represented by a three-dimensional ellipsoid the major axes of which are subparallel to the intersections of the three dominant (and orthogonal) fracture sets at the site. This suggests (though does not prove) that fracture intersections may sometimes exert a greater influence on the overall hydraulic conductivity than do the fracture planes, possibly due to enhanced weathering along the fracture intersections. The notion is further supported by the work of Abelin and Birgersson (1987) and Abelin et al. (1987a, 1987b) in connection with the 3-D migration experiment at Stripa. In measuring water inflows into 2×1 m isolated sections of a 75-m-long tunnel with two side arms 12.5 m in length, the authors found a poor visual correlation between the spatial distribution of these inflow rates and fracture density along the tunnel wall. The correlation improved dramatically when fracture density was replaced by the density of fracture intersections, suggesting that these intersections convey more water to the tunnel than do the fracture planes. One of 11 tracers injected in separate intervals in three boreholes drilled into the roof of the experimental tunnel was not recovered below but only in another drift approximately 150 m away, by accident. This shows that preferred pathways may exist on scales much larger than those of individual fractures and their intersections.

Poor correlations were found between hydraulic conductivities from single-hole packer tests and the number of open natural fractures intersected by the test intervals in saturated crystalline rock (Jones et al. 1985; Ahlbom et al. 1983a, 1983b, 1983c, 1983d; Gale et al. 1987; Olsson et al. 1989, Figs. 3.9–3.13; Ando et al. 2003) and slightly welded unsaturated tuff (Chen et al. 2000). This is yet another reason to ask (Neuman 1987) what precisely is the relationship between fracturing and measurable rock flow and transport properties in situ? Further research appears to be needed to help address this fundamental question.

Implications vis-à-vis Conceptualization of Fractured Rocks as Discrete Networks

A major motivation for the construction of DFN models with hundreds or thousands of fractures is the view that a detailed description and integration of the rock's smallest components amenable to field mapping and characterization (considered by most to be individual fractures and by some to include channels) would provide a valid description of rock behavior on larger scales. This reductionist philosophy, that summing a system's parts yields a valid description of the system as a whole, is challenged by modern complex system theory according to which the whole is often not merely the sum total of its parts (for an easy and delightful description of this concept by a Nobel Laureate in physics the author recommends Murray Gell-Man's (1994) The Quark and the Jaguar). There is a good reason to suspect that this challenge applies to fractured rocks. Laboratory and field research during the past three decades, and especially in recent years, has led to fundamental advances in the understanding of how flow and transport take place within and between individual fractures and matrix blocks. In situ experiments have yielded valuable information about flow and transport phenomenology of fractured rock masses on field scales. To date, integrative models have not proven capable of predicting observed field-scale phenomenology without calibration against such observations; when calibrated, such models have not proven to be superior to simpler models constructed primarily on the basis of larger-scale phenomenological data. This undoubtedly stems in part from complexities discussed earlier some of which may be resolved through future research and model development. On a more fundamental level the difficulty may stem from the well-established principle that open complex systems, such as fractured rock environments tend to be, cannot be described uniquely on the basis of sparse data

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and need not be described in great detail to capture their salient phenomenological behavior by a model (Ando et al. 2003).

Field-scale phenomenology of flow and transport in fractured rock masses reveals itself most directly in field observations and measurements of phenomenological quantities such as pressure or hydraulic head, solute concentration, and fluid or solute mass flux. For this and the former reasons, it has long been the opinion of this writer (Neuman 1987, 1988) that site-specific hydrogeologic models of flow and transport in fractured rocks are most robust when based on directly measurable rock flow and transport properties, rather than on properties derived indirectly from fracture geometric models. Many authors share the philosophy that, in practice, it may be feasible to delineate the geometry and evaluate the bulk flow and/or transport properties of a limited number of site-scale features such as major fracture zones, dikes or faults. It may likewise be advisable to incorporate such features explicitly in a hydrogeologic site model as discrete entities. Yet it often is neither necessary nor advisable to do the same with smaller features except a relatively small number that have direct impact on flow and transport in the near field of a (existing or potential) fluid (e.g. unlined tunnel or fluid storage cavern) or solute (e.g. geologic waste repository) source. These features, and the surrounding rock, would then need to be characterized in situ using hydraulic and tracer techniques that typically yield bulk medium parameters such as hydraulic conductivity, specific storage, advective porosity, and dispersivity. In some cases, the tests may reveal dual continuum type responses from which one may infer bulk mass transfer coefficients between the continua. In either case, these measurable bulk properties would then be taken as a matter of course to represent the rock as a single or multiple (e.g. Jardine et al. 2001; Meigs and Beauheim 2001) continuum. Site-scale heterogeneity would manifest itself in distinct differences between the bulk properties of the host rock and embedded discrete features (e.g. Carrera et al. 1990; Martinez-Landa et al. (2000); Flint et al. 2001).

Conceptualization of Fracture Rocks as Nonuniform Continua

The philosophy of basing models on phenomenological flow and transport variables, which are directly measurable on field scales of relevance to hydrogeologic analysis, suggests a focus on bulk rock properties rather than on the properties of numerous individual fractures or rock matrix blocks. Experience shows that such bulk properties tend to exhibit pronounced spatial variability due to the intensely heterogeneous nature of fracture rocks. Ascribing separate bulk properties to dominant features and the remainder of the fractured rock mass (or segments thereof) deterministically while ignoring spatial variability within these features, mass or segments may sometimes work for flow (as in the case of Carrera et al. 1990) but has seldom proven to work for transport. For this reason, Neuman (1987, 1988) proposed (and this paper continues to advocate) representing the interior bulk flow and transport properties of dominant fractured rock features, and the remaining rock mass, as separate correlated random functions of space (random fields). The rest of the paper is devoted to an exploration of this idea.

Trends in Stochastic Continuum Modeling

The stochastic continuum concept, originally developed for randomly heterogeneous porous media (e.g. Dagan and Neuman 1997), was first applied to fractured rocks by Neuman and Depner (1988) and Tsang et al. (1996). A rational for such application was offered by Neuman (1987, 1988). It was based on the recognition that detailed field measurements of permeability (and other parameters) in fractured rocks represent volumes which are often intersected by only one or a few fractures. As pointed out by Shapiro and Hsieh (1998) and Chen et al. (2000), and implied by the previous discussion, it is often not feasible to interpret such tests using geometric fracture models. Instead, the tests are more commonly interpreted by treating the rock as a locally uniform continuum. Such interpretation yields bulk permeabilities (and perhaps other parameters) that vary sharply from one test interval to another in a seemingly erratic manner. Ideally, testing should be done at as high a spatial resolution as is deemed technically and economically feasible. At the same time, testing resolution should be coarse enough and the instrumentation sensitive enough that a statistically significant number of permeabilities (or other parameters) above the equipment detection limit be available for analysis. Experience shows that, with present-day equipment, a spatial resolution on the order of 1 – 2 m may yield permeabilities amenable to treatment by the stochastic continuum approach in saturated crystalline rocks (Winberg 1991; Ando et al. 2003); permeabilities measured at a finer resolution of 50 cm have proven amenable to such analysis in unsaturated tuff (Chen et al. 2000). Longer intervals may be required or the stochastic approach may not apply in some sparsely fractured rocks with low-permeability matrix such as granite interlaced with schist at the Mirror Lake site (e.g. Shapiro and Hsieh 1998, Figs. 2, 3).

it was mentioned earlier that the precise nature and size of a support volume associated with a single-hole packer test is difficult to ascertain (Beckie and Harvey 2002). It is therefore common to associate such measurements with a nominal support scale equal to the length of the test interval. Even if the nominal support scale is kept constant, the number and orientation of fractures intersecting the interval and the effective radius of the actual support volume vary from one interval to another. It has been shown by Braester and Thunvik (1984) that these variations have only a marginal effect on the estimation of permeabilities by standard (continuum) formulae, which generally yield a directional value more or less normal to the borehole. This leads to a directional bias which, however, can be minimized by working with

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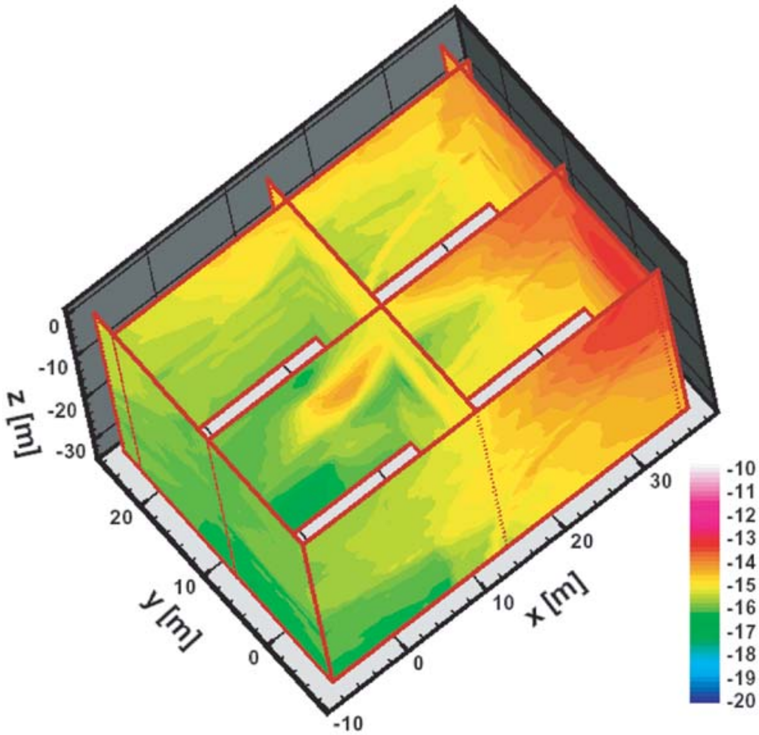

Fig. 2 Three-dimensional representation of kriged log air permeability estimates (measured in m^2) in unsaturated fractured tuff at the Apache Leap Research Site near Superior, Arizona, based on single-hole packer test results (after Vesselinov et al. 2001b; see also Chen et al. 2000)

data from boreholes drilled at various angles (e.g. Winberg 1991; Chen et al. 2000; Ando et al. 2003). The residual local effects (of varying fracture number, orientation, effective radius, interpretative error) may often be sufficiently random to justify lumping them with measurement errors and treating both as random noise having zero mean and spatial autocorrelation. Such "white" noise manifests itself as a jump or "nugget effect" at the origin (zero lag) of a (semi)variogram, which is easily quantified using standard geostatistical methods. Directional effects generally reappear on scales larger than the individual straddle interval in the form of an anisotropic covariance structure.

It is important to note that neither the nominal nor the (unknown) actual support scale associated with the in situ measurement of permeability (or any other bulk parameter) have much to do with a traditional Representative Elementary Volume (REV; e.g. Bear 1972). For this concept to apply, a measured parameter would have to be independent of support scale when the latter exceeds that of an REV. To the writer's knowledge, no such scale invariance has ever been observed within a fractured rock mass. Quite the contrary: available field evidence suggests (Neuman and Di Federico 2003) that permeability in fractured rocks generally varies with support scale; apparent dispersivity varies with the scale of observation (mean travel time or distance of a dispersing plume); spatial correlation (structural coherence) varies with the scale of the sampling window (domain of investigation); and permeability, porosity as well as dispersivity vary with the scales of spatial resolution (descriptive detail). Moreover, these scale variations are virtually indistinguishable from those observed in porous media, and both can be explained qualitatively and quantitatively using a single unified theoretical framework. The framework is that of a multiscale stochastic continuum (more on this later).

High-Resolution Imaging and Connectivity of Fractured Rocks

Single-hole pressure test results obtained at a given nominal support scale may be amenable to geostatistical projection onto the surrounding rock to obtain stochastic images of rock heterogeneity at a spatial resolution as fine as the support scale. Figure 2 (Chen et al. 2000; Vesselinov et al. 2001b) is a three-dimensional representation of log air permeability (measured in m^2) at a resolution (pixel size) of 1 m, estimated by kriging (Deutsch and Journel 1998) on the basis of 1-m scale packer tests in six vertical and inclined boreholes drilled into unsaturated fractured tuff at the Apache Leap Research Site (ALRS) near Superior, Arizona. It is important to recall that kriging also yields the associated estimation error variance and, if needed, covariance. Figure 3 shows, at a resolution of 2 m, the spatial distribution of probabilities that hydraulic conductivity of fractured granite in a plane normal to a drift at the abandoned Fanay-Augères mine in France exceeds a particular value (4×10^{-7} m/s). The probabilities were estimated by Ando et al. (2003) by means of indicator kriging (Deutsch and Journel 1998) on the basis of 2.5-m-scale single-hole packer tests in several boreholes drilled from the drift in various radial directions. One can use such results to map out estimates of the conditional (on measured values) mean conductivity or

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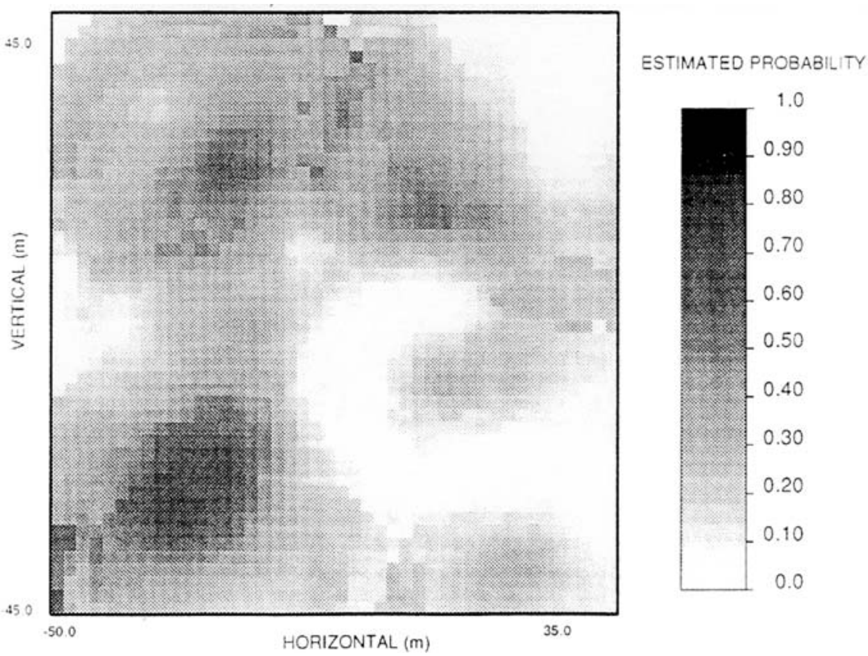

Fig. 3 Kriged estimate of probability that the hydraulic conductivity of fractured crystalline rock in a plane normal to the test drift at Fanay-Augères in France exceeds 4×10^{-7} m/s (after Ando et al. 2003)

other statistical moments such as median or mode. One can also generate random conditional realizations of hydraulic conductivity two of which are depicted at a spatial resolution of 2.5 m in Fig. 4 (Ando et al. 2003).

It has often been stated that DFN models provide information about hydraulic "connectivity" throughout a fractured rock mass, though the term has never been defined precisely. One unambiguous definition of hydraulic connectivity (perhaps continuity or persistence might be better terms) is the joint probability that hydraulic conductivities at any two points, separated by a given lag vector (directional distance), fall above some relatively high value; correspondingly, lack of connectivity is the joint probability that these conductivities fall below some relatively low value. Defined in this manner, hydraulic connectivity is easily evaluated on a continuum using methods of indicator geostatistics: Fig. 5 is a map of joint probabilities that hydraulic conductivities at any two points in the plane of Fig. 3, separated by any lag vector measured from the center of the map, fall (top) below detection limit (8×10^{-10} m/s) or (bottom) above 4×10^{-7} m/s (after Kostner 1993). The maps are based on 2.5-m-scale single-hole packer tests in boreholes at the Fanay-Augères site.

Another way to obtain high-resolution images of bulk fractured rock hydraulic properties is through geostatistical inversion of cross-hole pressure interference tests. At the ALRS, numerous cross-hole pneumatic interference tests have been conducted (Illman et al. 1998) by injecting air into one isolated borehole interval while monitoring pressure simultaneously in numerous other such intervals within this and surrounding boreholes. The injection and monitoring wells occupied a rock volume spanning several tens of meters. The tests were interpreted numerically by Vesselinov et al. (2001b) using a geostatistical inversion technique, yielding three-dimensional "tomographic" images of rock heterogeneity at a spatial resolution of 1 m. Figure 6 depicts one such high-resolution image of log air permeabilities (measured in m^2) based on the simultaneous inversion of three cross-hole tests, and Fig 7 shows a corresponding image of log air-filled porosities. The inverse solution yields an estimation covariance matrix for each tomographic image, which in turn can be used to generate random realizations of log permeability and porosity conditioned on the cross-hole pressure data.

Lavenue and de Marsily (2001) used successfully a geostatistical inverse approach to generate 100 random estimates of spatial hydraulic conductivity distributions in fractured and unfractured portions of the Culebra Dolomite near Carlsbad, New Mexico, conditioned jointly on hydraulic data from several three-dimensional pumping tests, by assigning different geostatistical properties to conductivities in fractured and unfractured rock types.

Meier et al. (2001) interpreted cross-hole pumping tests within a sub-vertical shear zone in granite using geostatistical inversion with the aim of identifying flow channels controlling the migration of tracers. As the spatial correlation of transmissivity (T) was unknown the authors adopted a variety of geostatistical hypotheses to estimate 40 T fields honoring all available hydraulic data. All these T fields revealed channels having similar topologies with a preferred horizontal orientation, of which only a few were supported by tracer test data. This is a classical example of how a detailed description of heterogeneity supported by hydraulic data may be insufficient to predict solute migration without further conditioning on tracer test data.

A deterministic tomography approach based on travel-time analysis was recently used by Brauchler et al. (2003; see also Brauchler 2004) to reconstruct the three-dimensional distribution of bulk pneumatic diffusivities in a cylindrical laboratory sample of unsaturated fractured sandstone.

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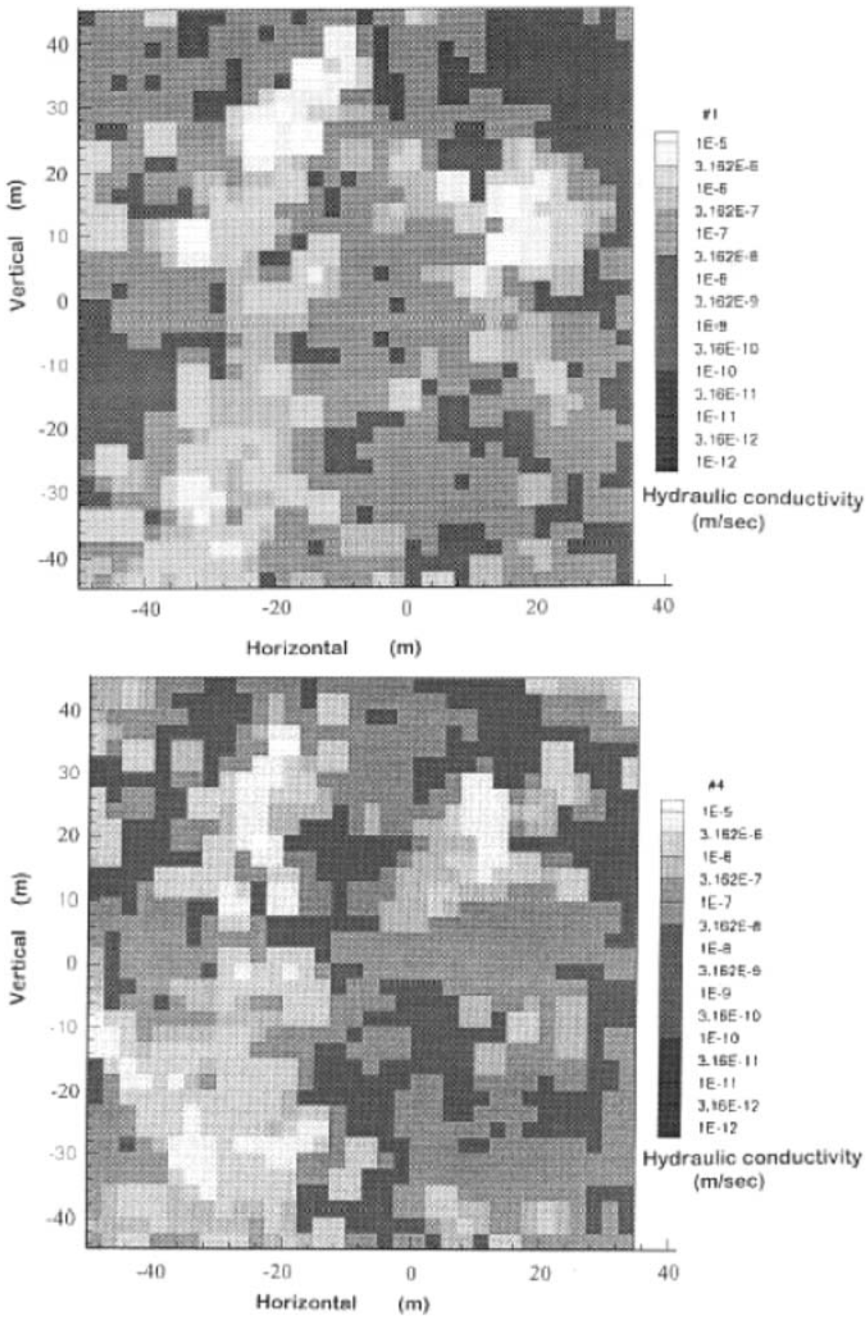

Fig. 4 Two random realizations of hydraulic conductivity in the plane of Fig. 2 honoring available packer test data (after Ando et al. 2003)

Stochastic Continuum Representation of Channeled Flow on the Field Scale

Groundwater flow and transport equations associated with random permeability and porosity fields are stochastic. Since the random parameters fields are defined over a continuum, so are the solutions to these stochastic equations. Hence such solutions can be obtained using standard numerical methods at a spatial resolution as high as that of the underlying random parameter fields. In parameter fields that are spatially correlated over scales significantly larger than the scale of model resolution (e.g. the random fractal transmissivity field in Fig. 8 (left), generated by Grindrod and Impey (1993) on a 128×128 grid conditional on 35 data points) the stochastic solutions may reveal the presence of channels (e.g. as revealed in Fig. 8 (right) by spatial variations in steady state Darcy velocity, computed by Grindrod and Impey on a grid of 128×128 cells by superimposing a mean-uniform hydraulic gradient on the same transmissivity field) through which much of the flow and transport take place. It is clear that the channels in Fig. 8 do not reflect directly the spatial variability of the underlying transmissivity field. Instead, the channels are oriented preferentially along the mean hydraulic gradient, indicating that they are dynamic and nonunique. It therefore makes little sense to construct rigid network models of discrete flow channels; in the opinion of the writer, the correct approach is to model spatial variations in intrinsic medium properties

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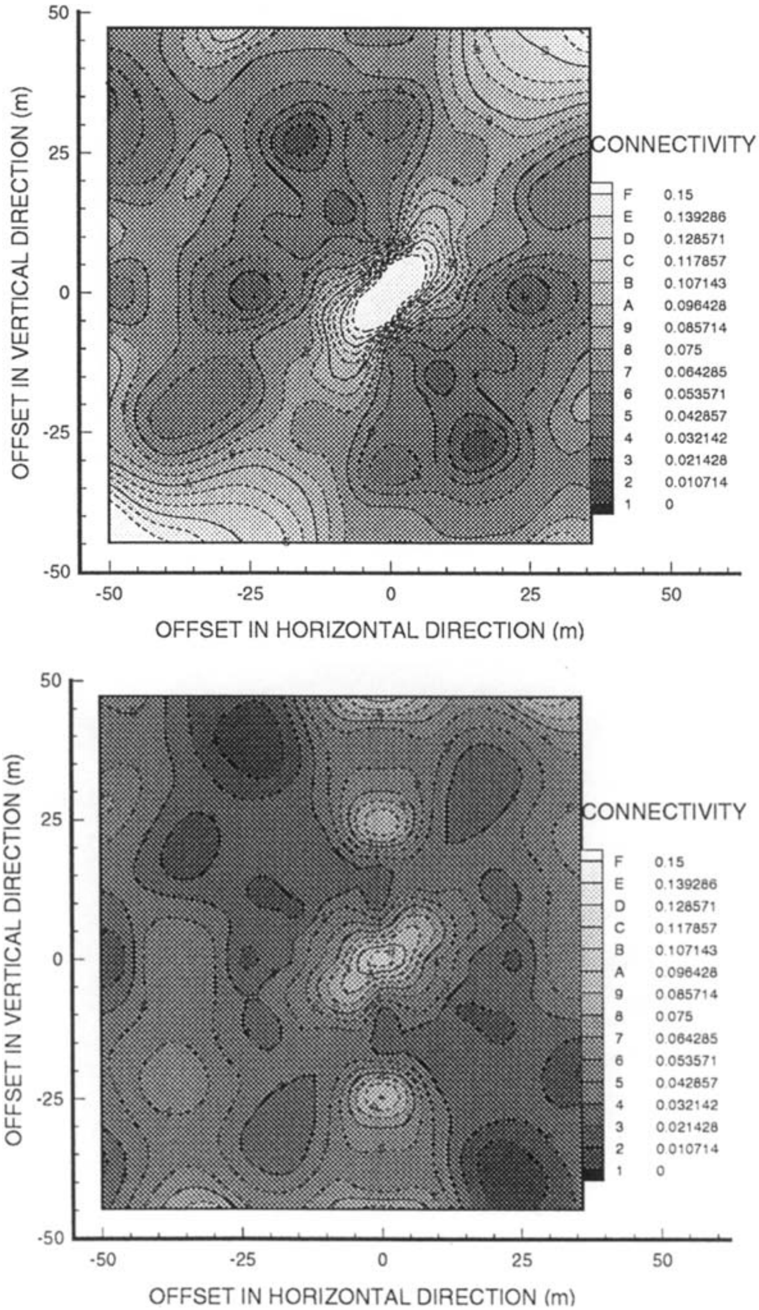

Fig. 5 Map of joint probabilities that hydraulic conductivities at any two points in the plane of Fig. 3, separated by a given lag vector (directional distance, measured from the center of the map), fall (*top*) below detection limit (8×10^{-10} m/s) and (*bottom*) above 4×10^{-7} m/s (after Kostner 1993)

(such as permeability and porosity) throughout the domain of interest, and delineate channels by solving the corresponding stochastic flow and transport equations under specific conditions (initial, boundary, source terms) of relevance to the problem(s) being analyzed (e.g. Bodvarsson et al. 2003).

Equivalent Parameters, Spatial Variability and Scale

In some locally uniform fractured rock masses it is sometimes possible to interpret pressure and/or tracer breakthrough signals from several boreholes simultaneously in a way that yields consistent equivalent hydraulic and/or transport parameter values for the rock mass. Methods of interpreting pumping tests in terms of equivalent medium properties include those described by Gringarten (1982, 1984, 1987a, 1987b), Moench (1984), Boehmer and Boonstra (1987), and Barker (1988). The method of Barker (for a recent application see Kuusela-Lahtinen et al. 2003) invokes a fractional flow dimension parameter which however is defined only in terms of radial distance from the pumping well; as such, it is not an intrinsic (equivalent) medium property but a fitting parameter applying at best to radially converging/diverging flows. Neuman et al. (1984) were able to associate an equivalent transmissivity tensor with a portion of the fractured Culebra dolomite near Carlsbad, New Mexico, based on multiple pumping test data from three wells

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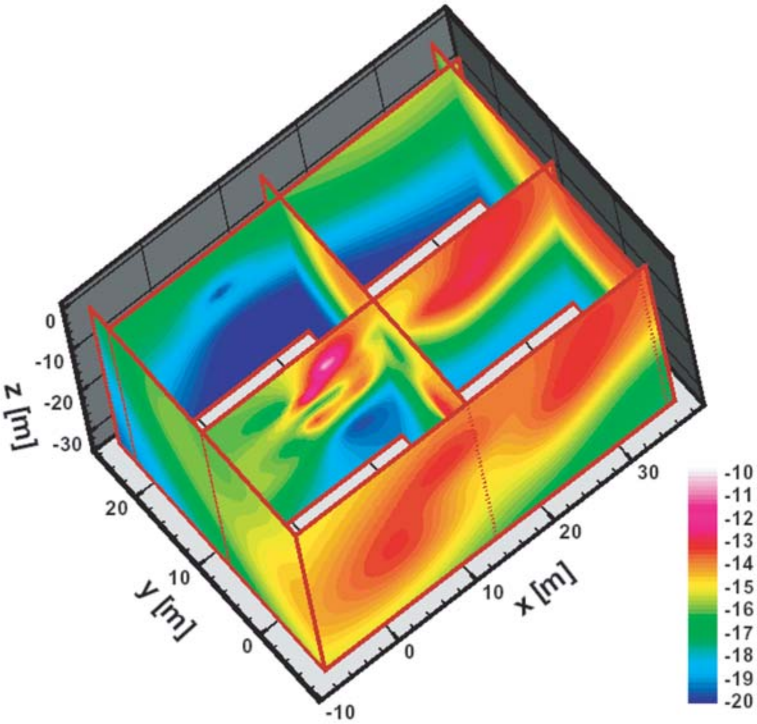

Fig. 6 Three-dimensional representation of kriged log air permeability estimates (measured in m^2) obtained by simultaneous inversion of three cross-hole pneumatic injection tests in unsaturated fractured tuff at the Apache Leap Research Site near Superior, Arizona (after Vesselinov et al. 2001b)

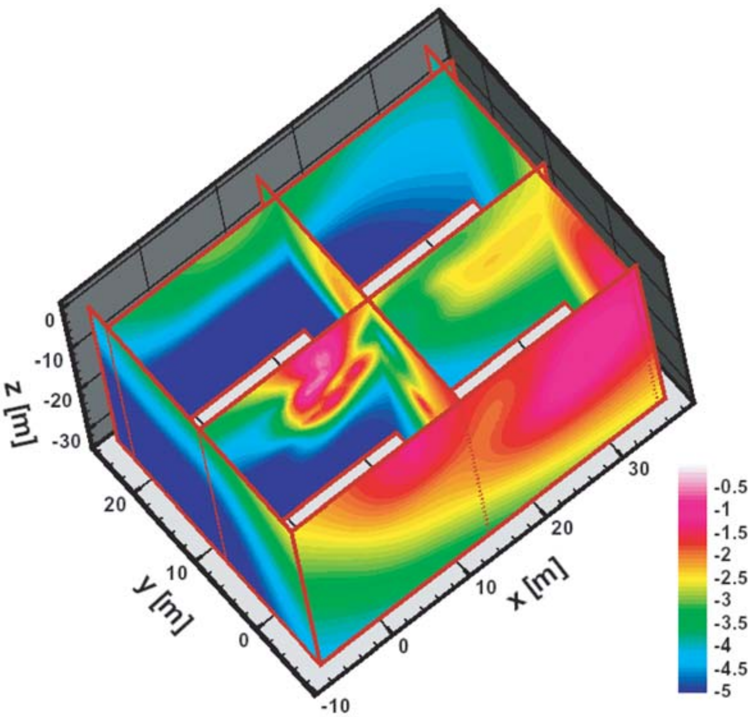

Fig. 7 Three-dimensional representation of kriged log air-filled porosity estimates obtained by simultaneous inversion of three cross-hole pneumatic injection tests in unsaturated fractured tuff at the Apache Leap Research Site near Superior, Arizona (after Vesselinov et al. 2001b)

spaced about 33 m from each other. Similarly, Hsieh et al. (1985) succeeded in associating a three-dimensional equivalent hydraulic conductivity tensor with a 25-m-deep volume of fractured crystalline rock near Oracle, Arizona, on the basis of cross-hole pressure data from three wells spaced 5–10 m apart. Examples of multi-well tracer tests interpreted with reasonable consistency in terms of equivalent transport parameters include those described by Jones et al. (1992), Moench (1995), McKenna et al. (2001), and Meigs and Beauheim (2001).

In many cases it is not possible to interpret pressure and/or tracer breakthrough signals from several boreholes simultaneously in a way that would yield consistent equivalent hydraulic and/or transport parameter values for

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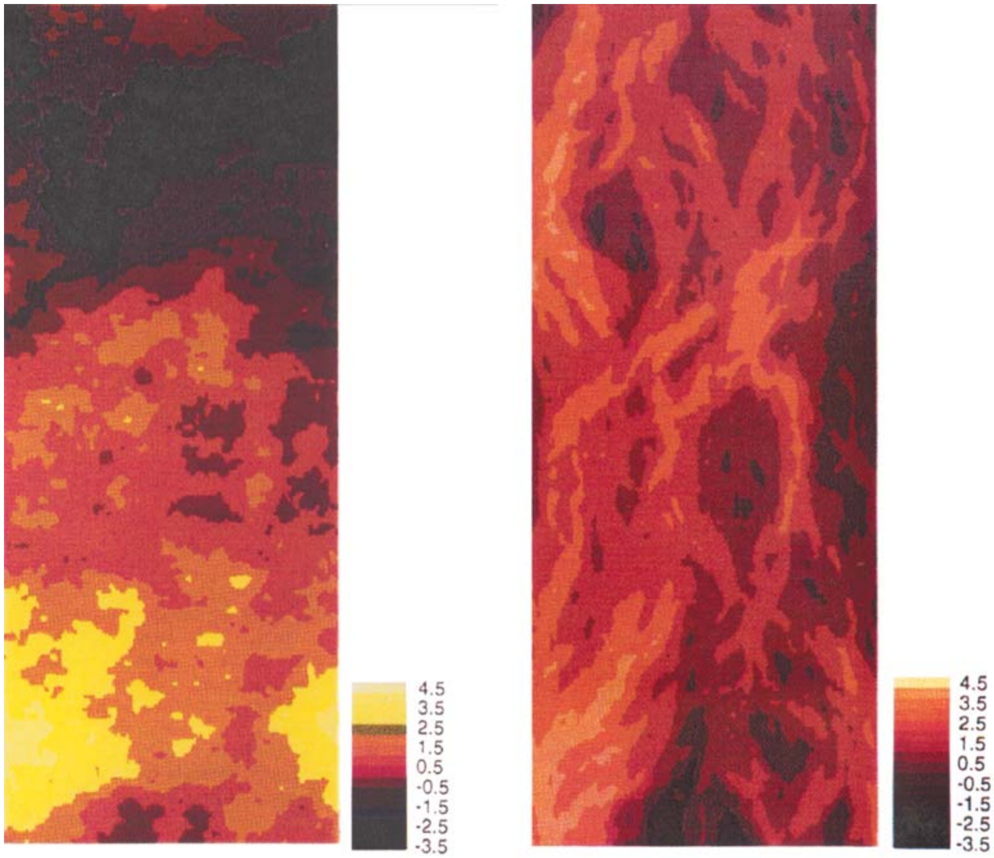

Fig. 8 Random fractal transmissivity field generated on a 128×128 pixel map conditional on 35 data points (*left*); Spatial variations in steady state Darcy velocity, computed on a grid of 128×128 cells by superimposing a mean-uniform hydraulic gradient on the same transmissivity field (*right*) (after Grindrod and Impey 1993)

the rock mass. This is so because the hydraulic and transport properties of fractured rocks tend to vary spatially at a very wide range of frequencies and amplitudes. For example, it was found by Illman and Neuman (2001) and Vesselinov et al. (2001b) that to interpret cross-hole pneumatic pressure tests in unsaturated fractured tuff at the ALRS in terms of equivalent (uniform) medium properties (air permeability and air-filled porosity) on the scale of these tests (several tens of meters), it was necessary to analyze the transient pressure record from each monitoring interval independently of all other such records, yielding a large number of disparate "equivalent" parameter values, one for each record. Only by allowing air permeability and air-filled porosity to vary spatially in three dimensions on a scale much smaller than that of the cross-hole tests, over 1-m grid cells as in Figs. 6 and 7, were Vesselinov et al. (2001b) able to reproduce simultaneously pressure records from multiple cross-hole tests and pressure intervals.

It was found by Illman and Neuman (2001) and Vesselinov et al. (2001b) that treating the rock as being uniform on the scale of cross-hole tests at the ALRS yields higher (by 1–2 orders of magnitude) mean estimates of air permeability (and air-filled porosity) than are obtained upon either resolving or directly measuring smaller-scale spatial variations in these bulk fracture properties. A similar permeability scale effect was reported by Martínez-Landa et al. (2000) in the context of cross-hole tests in saturated fractured granites at the Grimsel site in Switzerland, interpreted by means of a numerical inverse model. Both findings are in line with an earlier conclusion by Neuman (1990, 1994) that the scale effect diminishes as one improves the degree to which spatial variability is explicitly resolved by the model that one uses to estimate these parameters.

The permeability scale effect observed at the ALRS is unrelated to the method of testing: there is consistency between single-hole and cross-hole test results corresponding to a wide range of injection rates and to steady state as well as transient flow regimes. The scale effect is likewise unrelated to the method of test interpretation: there is consistency between results obtained by means of steady state analytical formulae from single-hole test data (Guzman et al. 1996), which are shown elsewhere to compare well with transient type-curve (Illman and Neuman 2000) and inverse (Vesselinov and Neuman 2001) analyses of the same data, and steady state (Illman and Neuman 2003) as well as transient type-curve (Illman and Neuman 2001) and numerical inverse (Vesselinov et al. 2001b) interpretations of cross-hole test data. Contrary to a suggestion in the literature (Butler and Healey 1998a, 1998b), the observed scaling behavior is not an artifact of rock conditions around the injection borehole: neither the single-hole (Illman and Neuman 2000) nor the cross-hole (Illman and Neuman 2001) test results have been affected by any skin effect of consequence (though skin effects are well known to impact single-hole measurements at many other sites, and need to be properly assessed). The pro-

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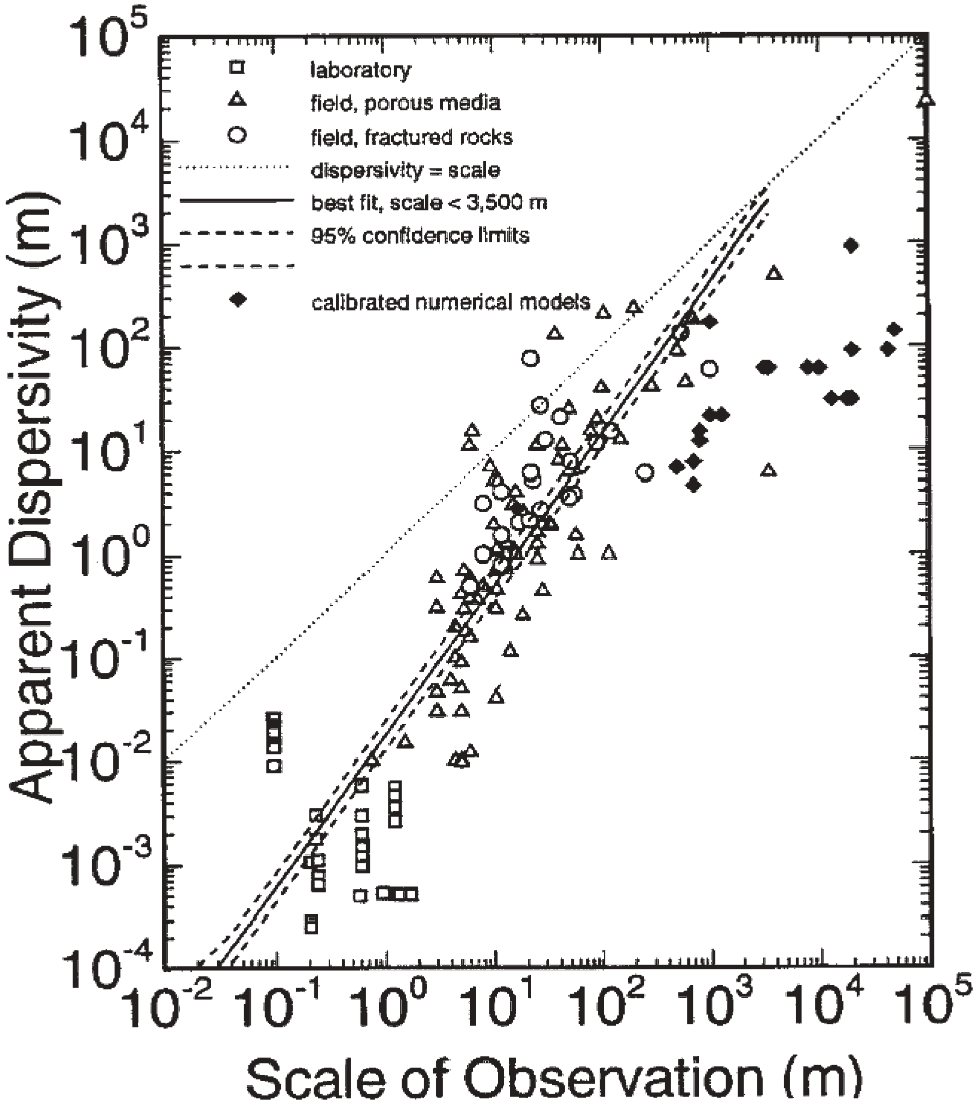

Fig. 9 Apparent longitudinal dispersivities versus scale of observation worldwide (after Neuman 1995)

nounced permeability scale effect observed at the ALRS appears to be real.

Estimates of air-filled porosity obtained at the ALRS by numerical inversion of transient pressure data from five cross-hole tests upon treating the rock as being uniform exceeded the mean of tomographic inverse estimates from three of these tests by a factor of over 20 (Vesselinov et al. 2001b). There are no reliable measurements of porosity on a support scale of 1 m, only tomographic estimates based on much larger-scale cross-hole tests.

Another manifestation of scaling is revealed when one considers the spread of solute plumes as a function of travel time or average travel distance. Apparent longitudinal dispersivities from a variety of laboratory and field tracer studies world-wide, represented by open symbols in Fig. 9 (Neuman 1995), increase with the scale of observation at a rate that is faster than linear (slope larger than 1:1 on logarithmic paper). In fact, a regression line fitted to the open symbols exhibits a logarithmic slope of 1.5:1. The dispersivity is termed apparent because it is determined on the basis of traditional Fickian advection-dispersion models of solute transport which treat it as a constant. Dispersivities designated by open symbols are additionally derived on the assumption that the medium in each case has uniform permeability and advective porosity. As Fig. 9 clearly shows, the apparent longitudinal dispersivity is not constant but tends to increase at a supralinear rate with the scale of observation. The manner in which dispersivity increases with scale appears to be similar in porous media (triangles) and fractured rocks (circles) outside the laboratory. The solid diamonds in Fig. 9 exhibit a slower rate of increase which, contrary to some persistent claims in the literature (e.g. Bodin et al. 2003b), is not inconsistent with the faster rate exhibited by open symbols (Neuman and Di Federico 2003): whereas the latter derive from models that treat the medium as if it was uniform, the former derive from models calibrated against head data which thus account explicitly for some degree of spatial variability in the underlying permeability or transmissivity field.

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Overlapping and Juxtaposed Multiscale Continua

The above scale-dependencies can be interpreted consistently by viewing log permeability as a random fractal defined on a continuum and characterized by a power variogram (Neuman and Di Federico 2003). The interpretation is based on the recognition (Neuman 1990; Di Federico and Neuman 1997; Di Federico et al. 1999) that such a random fractal field is equivalent to an overlapping hierarchy of statistically homogeneous random fields (modes) with variance that increases as a power of spatial correlation scale. A theoretical interpretation of the observed permeability scale effect at the ALRS, consistent with this view, has recently been published by Hyun et al. (2002); a corresponding interpretation of the dispersivity scale effect in Fig. 9 has been offered by Neuman (1990, 1991) and Di Federico and Neuman (1998).

Neuman (2003a) has demonstrated mathematically that the multiscale mode-superposition model of Di Federico and Neuman (1997) and Di Federico et al. (1999) is consistent with a representation of multimodal spatial variability in which space is filled by a discrete number of juxtaposed (mutually exclusive) materials or categories (including discontinuity and host rock types, e.g. Lavenue and de Marsily 2001; McKenna et al. 2003), each having its own architecture (spatial topology and geometry) and attributes (e.g. permeability or porosity). In this representation, the spatial distribution of categories is characterized by indicator random variables I_i $(\boldsymbol{x})$ and their attributes by random fields y_i $(\boldsymbol{x})$, i =1,..., M. A given attribute y $(\boldsymbol{x})$, is expressed as $y(\mathbf{x}) = \sum_{i=1}^{M} I_i(\mathbf{x})y_i(\mathbf{x})$ where I_i $(\boldsymbol{x})$ = 1 if category I occurs at point $\boldsymbol{x}$, $I_i(\boldsymbol{x})$ = 0 otherwise $\sum_{i=1}^{M} I_i(\mathbf{x}) = 1$. The probability of attribute i is p_i $(\boldsymbol{x})$=Pr$\{I_i(\boldsymbol{x})$=1$\}$ = $E\{I_i(\boldsymbol{x})\}$, $\sum_{i=1}^{M} p_i(\mathbf{x}) = 1$, and the joint probability of attributes i and j is p_{ij} $(\boldsymbol{x}, \chi)$=Pr$\{I_i(\boldsymbol{x})$=1, $I_j(\chi)$= 1$\}$= E $\{I_i(\boldsymbol{x})I_j(\chi)\}$. In general, the indicator variables and their attributes are auto- and cross-correlated within and between categories. Neuman (2003a) has demonstrated mathematically that when (a) $I_i(\boldsymbol{x})$ and $y_i(\boldsymbol{x})$ are statistically homogeneous and anisotropic with identical directions and ratios of principal integral scales, and (b) the categories overlap in a way which preserves their local architecture, $p_i(\boldsymbol{x})$=p_i becomes a constant representing the volumetric proportion of the i^{th} category in space and $\gamma_y(s) = \sum_{i=1}^{M} p_i\gamma_{yii}(s)$. This states that the variogram $\gamma_y(s)$ of an attribute, sampled jointly over overlapping statistically homogeneous and anisotropic categories, is the sum of the variograms γ_{yii} (s) of statistically homogeneous and anisotropic components of this attribute sampled over individual categories, weighted by their volumetric proportions. Hence the spatial increments of attributes associated with overlapping categories are mutually uncorrelated. The latter is a key premise underlying the multiscale mode superposition theory of Di Federico and Neuman (1997) and Di Federico et al. (1999), which is thus seen to be consistent with the multimodal spatial variability representation $y(\mathbf{x}) = \sum_{i=1}^{M} I_i(\mathbf{x})y_i(\mathbf{x})$.

Prospects and Challenges for the Future

The future promises to continue revealing many fascinating details about flow and transport phenomena in naturally fractured rocks on the laboratory and local field scales, primarily through nondestructive imaging methods such as X-ray tomography (Polak et al. 2003a, 2003b, 2003c, 2004) and positron emission projection (Loggia et al. 2004). Translating such detailed understanding into phenomenological terms suitable for the characterization and analysis of fractured rock flow and transport behavior on hydrogeologic field scales will remain a long-term challenge.

A major challenge facing the further development of high-resolution network models with hundreds or thousands of fractures will be to overcome two major challenges. One major challenge stems from complexities of flow and transport in fracture and matrix block interiors and at their intersections, which may be gradually resolved through future research and model development. A more fundamental challenge stems from the well-established principle that open complex systems, such as fractured rock environments tend to be, cannot be described uniquely on the basis of sparse data and need not be described in great detail to capture their salient phenomenological behavior by a model. This notwithstanding, it is important to insure that conceptual models of flow and transport in fractured rocks are consistent with current geologic knowledge about rock type and factors influencing the formation and alteration of fracture networks in the field.

Field-scale phenomenology of flow and transport in fractured rock masses reveals itself most directly in field observations and measurements of quantities such as pressure or hydraulic head, solute concentration, and fluid or solute mass flux. For this and the former reasons, it remains the opinion of this writer that site-specific hydrogeologic models of flow and transport in fractured rocks are most robust when based on directly measurable rock flow and transport properties, and less so when based on properties derived indirectly from fracture geometric models. This suggests a focus on bulk rock properties rather than on the properties of numerous individual fractures or rock matrix blocks. Major challenges entail improving our ability to measure the bulk flow and transport properties of fractured rocks under both saturated and unsaturated (as well as other multiphase) conditions on a range of practical scales, develop more robust methods of describing their spatial variability, improve our understanding of how they scale, improve our ability to deal with sparsely fractured rocks in which bulk properties are difficult to define or measure, and assess the effect on large-scale flow and transport of unresolved phenomena occurring on scales smaller than the support of bulk measurements (i.e., on and below the scales of individual fractures or matrix blocks).

A major challenge for the future is to develop methods that combine flow, transport and/or geophysical tomography (e.g. Day-Lewis et al. 2003) to image remotely the

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structure and makeup of fractured rocks, as well as flow and transport through them, at relatively high levels of spatial and temporal resolution.

Yet another major challenge for the future is to include in every descriptive and/or predictive analysis of flow and transport through fractured rocks a quantitative assessment of uncertainty arising from the underlying conceptual-mathematical framework, corresponding parameter estimates, and scenarios under which a system is assumed to operate. The open and complex nature of fractured hydrogeologic environments precludes describing them uniquely on the basis of sparse data. Describing fractured rocks on the basis of a single conceptual model is prone to statistical bias and underestimation of uncertainty (Neuman 2003b). The bias and uncertainty may be reduced by postulating, exploring and utilizing several alternative models for a given site and purpose. A comprehensive strategy for constructing alternative conceptual-mathematical models, selecting the best among them, and using them jointly to render optimum predictions under uncertainty has recently been proposed by Neuman and Wierenga (2003; available at http://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6805/ or by request from the author). A key formal element of this strategy is Maximum Likelihood Bayesian Model Averaging (MLBMA, Neuman 2003b), the utility of which vis-à-vis air permeability data from unsaturated fractured tuff at the ALRS has been recently demonstrated by Ye et al. (2004). Whereas conceptual uncertainty cannot be assessed in an absolute sense, MLBMA is able to do so in a relative sense conditional on a given set of alternative conceptual-mathematical models and associated data. This or other similar methods of uncertainty assessment should, in the writer's view, become an integral part of hydrogeologic fractured rocks analyses in the future.

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