Hydrogeol J (2017) 25:2221–2224
DOI 10.1007/s10040-017-1663-4

ESSAY

Crustal permeability

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Received: 16 May 2017 / Accepted: 15 August 2017 / Published online: 2 September 2017

Abstract Permeability is the dominant parameter in most hydrogeologic studies. There is abundant evidence for dynamic variations in permeability in time as well as space, and throughout the crust. Whether this dynamic behavior should be included in quantitative models depends on the problem at hand.

Keywords Permeability · Brittle-ductile transition · Crystalline rocks · Fault zones

Introduction

A physicist colleague once remarked that the entire field of groundwater hydrology seems to consist of pursuit of a single parameter—permeability (k). He further noted that permeability is an awkward parameter, defined indirectly based on Darcy's law, and is scale dependent and difficult to measure. Most hydrogeologists would concede that these claims contain an element of truth, but nearly all of us agree that characterization of permeability is essential to quantify the flow of fluids through the Earth's crust, which impacts crustal rheology and deformation as well as the transfer of matter and energy.

There is a longstanding gulf between the hydrogeologic perspective of permeability as an essentially static material property that exerts control on fluid flow and the perspective of economic geologists, crustal petrologists, and others who recognize permeability as a dynamic parameter that changes in response to tectonism, fluid production, and geochemical reactions. Consider for instance the credibility gap between a geologist who, based on careful study of outcrops, recognizes the signature of many cycles of permeability creation and decay (e.g. Cann et al. 2016; Micklethwaite et al. 2016) and a hydrogeologist who might tend to simulate the same flow system using constant hydraulic properties. Issues associated with hydraulic fracturing, enhanced geothermal systems, and geologic carbon sequestration have begun to promote a constructive dialog between the 'static' and 'dynamic' views of permeability, helping to bridge this historical dichotomy. Additionally, although the very term 'intrinsic permeability' seems to imply an immutable property, there is abundant evidence that permeability varies in time as well as space. Temporal variability in permeability is particularly pronounced in environments characterized by high strain rates and/or strong chemical and thermal disequilibrium.

The journey from deep crust to the uppermost crust

Below the brittle-ductile transition

Most of the Earth's crust lies below the brittle-ductile transition (BDT), where hydrogeologists rarely venture. The continental crust is typically 25–70 km thick, the geothermal gradient is roughly 25 °C/km, and the BDT occurs at a temperature of roughly 350–400 °C (depending on rock type and strain rate), thus at a typical crustal depth of only 10–15 km (Fig. 1). In areas with adequate seismic data such as southern California (USA) (Nazareth and Hauksson 2004) and Japan (Tanaka and Ishikawa 2005), the BDT can be mapped as the base of the seismogenic crust.

Available data continue to support a general distinction between the hydrodynamics of the brittle upper crust, where topography and magmatic heat sources dominate patterns of flow and externally derived (meteoric) fluids are common,

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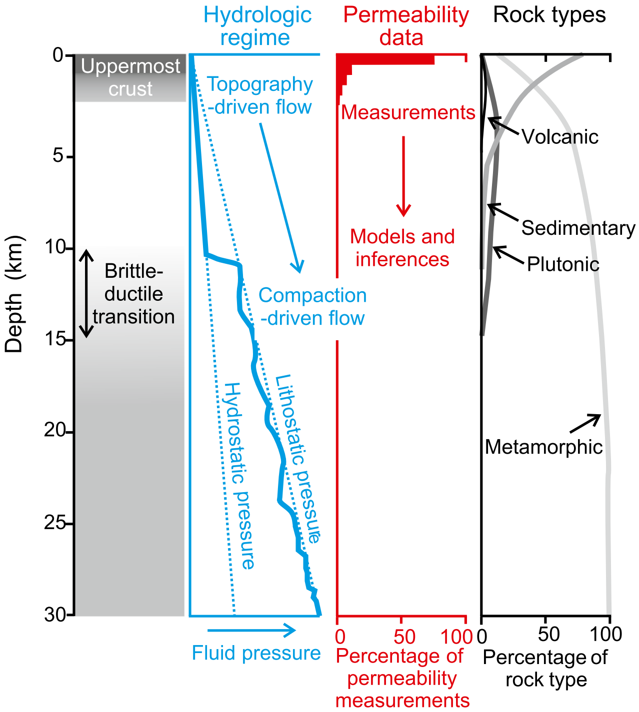

Fig. 1 Hydrologic regimes, permeability data, and rock types from 0 to 30 km depth in the continental crust (modified from Wilkinson et al. 2009; Connolly and Podladchikov 2016; and Ranjram et al. 2016)

and those of the ductile lower crust, dominated by (de)volatilization reactions and internally derived fluids (Ingebritsen and Manning 1999). The apparent absence of a permeability discontinuity or barrier at the transition implies that fluids produced in the middle and lower crust during metamorphism can be transmitted to the upper crust.

For many crustal-scale hydrogeologic problems, the BDT may reasonably be considered the lower boundary of the domain of interest. However, the underlying ductile regime can be an important fluid source to the brittle regime, affecting the cycling of certain elements and perhaps even balancing the global water cycle over geologic time. Consider for instance that the time-integrated metamorphic fluid flux from a Himalayan-scale orogeny represents a water volume 10× greater than the total amount in Earth's rivers and lakes (Jay Ague, Yale University, unpublished data, 2012).

Yardley (2016) posits a fundamental difference between regions where the continental crust is being thickened and/or heated (prograde metamorphism, less common) and where the crust is stable and/or cooling (retrograde metamorphism, more common). In regions of prograde metamorphism, porosity waves may expel fluids from ductile rocks below the BDT. Connolly and Podladchikov (2016) present a general, analytical steady-state solution to predict the dynamic variations in fluid pressure and permeability necessary to accommodate fluid production. Weis (2016) considers magmatic-hydrothermal systems, where igneous intrusion causes the BDT to be unusually shallow, and where transport of heat and matter spanning the BDT is essential to create economically useful metal deposits. Weis adopts a dynamic-permeability model in which permeability generally follows a power-law depth-dependent relation but can increase with pressure above the BDT and both decrease with temperature and increase with pressure below the BDT. This $k(z, T, P)$ model reflects current understanding of the mechanics of rock failure. Recent empirical data appear to support the persistence of permeability (Watanabe et al. 2017), and thus potentially exploitable geothermal resources, below the BDT.

Between the brittle-ductile transition and the 'uppermost crust'

The depth range between the BDT and roughly 2-km depth is still largely *terra incognito* from a hydrogeologic perspective, but fundamentally important from the standpoint of energy resources (oil, gas, geothermal), geologic carbon sequestration, certain options for nuclear waste disposal, induced seismicity (and tectonism in general), ore deposits, global biogeochemical cycles, and life in the deep biosphere.

As is the case below the BDT, rocks in this depth range are most likely metamorphic (Fig. 1; Wilkinson et al. 2009). Metamorphic rocks constitute about 90% of the continental crust by volume, though only 11% of surface exposures. In contrast, sedimentary rocks, the focus of most hydrogeologic research, constitute only a few percent of crustal volume, despite ~73% of surface exposures.

In considering permeability (and hydrogeologic conditions in general) between the BDT and the uppermost crust, it is of interest to note that enhanced geothermal systems, geologic carbon sequestration (Lucier and Zoback 2008), and deep injection of waste fluid (Hsieh and Bredehoeft 1981; Weingarten et al. 2015) all entail similar stimuli, namely fluid-injection rates on the order of 10s of kg/s, as do simulations of ore-forming systems (e.g. Weis 2016). In North America, fluid-injection practices have caused a recent and dramatic increase in $M_w > 3$ seismic events (e.g. Ellsworth 2013). An unintended consequence of this ongoing injection experiment is the opportunity to explore and assess dynamic crustal permeability to depths of perhaps 10 km.

The uppermost crust (0–2 km depth)

Direct permeability measurements are abundant only in the uppermost crust, roughly 0–2 km depth, and even here the availability of data diminishes greatly below about 0.5 km depth (Fig. 1; Ranjram et al. 2016; Achtziger-Zupancic et al. 2017). The permeability structure of the uppermost crust is highly heterogeneous and, whereas a wide variety of k–z relations have been suggested, it is risky to extrapolate crustal-scale k–z relations to the uppermost crust, or perhaps even to define such relations (e.g. Ranjram et al. 2016; Burns et al. 2016). The permeability of clastic sediments in the cool shallow crust is often well-predicted as a function of mechanical compaction and consequent porosity-permeability relations (e.g. Luijendijk and Gleeson 2016; Daigle and Screaton 2016). However, this predictability diminishes at depths where diagenetic processes become important; similarly, hydrothermal alteration of volcanic rocks tends to cause significant reduction of permeability at temperatures in excess of approximately 40–50 °C (Burns et al. 2016).

Static or dynamic permeability?

Temporal changes in permeability can be gradual or abrupt. Streamflow responses to earthquakes demonstrate that dynamic stresses can instantaneously change permeability on a regional scale (e.g. Rojstaczer et al. 1995); large (1 mm) fractures can be sealed by silica precipitation within 10 years (Lowell et al. 1993); and calcite dissolution in coastal carbonate aquifers causes significant changes in porosity and permeability over timescales of 10^4–10^5 years (Sanford and Konikow 1989). At the other end of the spectrum, the reduction of pore volume during sediment burial modifies permeability very slowly. For example, shale permeabilities from the US Gulf Coast vary from about 10^{-18} m^2 near the surface to about 10^{-20} m^2 at 5 km depth (Neglia 1979), and the natural subsidence rate is 0.1–10 mm $year^{-1}$ (Sharp and Domenico 1976), so one can infer that it takes perhaps 10^7 years for the permeability of a subsiding package of shale to decrease by a factor of 10. Even in the uppermost crust, crustal-scale permeability is a dynamically self-adjusting property, reflecting a competition between permeability destruction by processes such as compaction and permeability creation by processes such as fluid sourcing (e.g. Connolly and Podladchikov 2016; Okada et al. 2016; Miller 2016; Taron et al. 2016; Weis 2016) and tectonically driven fracturing and faulting.

Nonetheless, permeability can reasonably be treated as a static parameter for a wide range of applications in the uppermost crust—for example, for typical low-temperature hydrogeologic investigations with timescales of days to decades, permeability may be considered static in the absence of seismicity. Similarly, if it takes perhaps 10^7 years for the permeability of a subsiding package of shale to decrease by a factor of 10, permeability in sedimentary basins may be considered static for investigations on much shorter timescales. Whether the dynamic variation of permeability is important to include in analyses depends upon how quickly, and how much, permeability is changing relative to the requirements of the problem at hand.

Recent research on enhanced geothermal reservoirs (Preisig et al. 2016; Miller 2016; Taron et al. 2016), ore-forming systems (Micklethwaite et al. 2016; Weis 2016), and the hydrologic effects of earthquakes (e.g. Okada et al. 2016) yields broadly consistent results regarding permeability enhancement by dynamic stresses. Shear dislocation caused by tectonic forcing or fluid injection can increase near- to intermediate-field permeability by factors of 100 to 1000. Dynamic stresses (shaking) in the intermediate- to far-field corresponding to seismic energy densities >0.01 J/m^3 also increase permeability, albeit often by <<10 and at most by a factor of approximately 20 (e.g. Wang and Manga 2010; Manga et al. 2012). These permeability increases are transient, tending to return to preseismic values over timescales on the order of months to decades (e.g. Elkhoury et al. 2006; Kitagawa et al. 2007). There is reasonable agreement between the magnitude of near- to intermediate-field permeability increases (10^2–10^3 fold) directly measured at enhanced geothermal sites (e.g. Haring et al. 2008), inferred from field evidence (e.g. Saffer 2016; Howald et al. 2016), invoked in simulations of transient hydrothermal circulation (e.g. Howald et al. 2016; Taron et al. 2016; Weis 2016), and inferred from seismic and metamorphic data (Ingebritsen and Manning 2010).

New resources for crustal permeability data

Most of the foregoing material is discussed in much greater detail in a recent book titled *Crustal Permeability* that draws on the work of 123 contributors (Gleeson and Ingebritsen 2016). Additional resources have emerged in this era of exploding information technology and accessibility. Fan et al. (2016) outline a vision for the "DigitalCrust": a community-governed, four-dimensional data system emphasizing permeability and porosity. The Crustal Permeability data portal (University of Victoria 2017) is a complementary effort intended to unearth and share permeability data. In contrast to DigitalCrust, the Crustal Permeability data portal will not host data, and data do not have to be spatially located. Data requirements are simply that the data be: peer-reviewed (published in a peer-reviewed journal, book or report); include permeability or other related fluid-flow and transport parameters; and be hosted and publicly available on an online data repository such as figshare or institutional webpages such as those of the US Geological Survey. These new resources should be useful contributions to the understanding of fluid flow in our complex, heterogeneous, fascinating planet.

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