ARTICLE IN PRESS

Journal of Contaminant Hydrology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Contaminant Hydrology

journal homepage: www.elsevier.com/locate/jconhyd

Insights about transport mechanisms and fracture flow channeling from multi-scale observations of tracer dispersion in shallow fractured crystalline rock

N. Guihéneuf[a,b,*,1], O. Bour[b], A. Boisson[a,2], T. Le Borgne[b], M.W. Becker[c], B. Nigon[a,3], M. Wajiduddin[d], S. Ahmed[e], J.-C. Maréchal[f]

[a] BRGM, D3E, NRE, Indo-French Center for Groundwater Research, Uppal Road, 500007 Hyderabad, India
[b] OSUR, Géosciences Rennes, UMR6118 CNRS – Université de Rennes 1, Campus de Beaulieu, 35042 Rennes Cedex, France
[c] Department of Geological Sciences, California State University Long Beach, Long Beach, California, 90840, United States
[d] Indo-French Center for Groundwater Research, Uppal Road, 500007 Hyderabad, India
[e] National Geophysical Research Institute, Indo-French Center for Groundwater Research, Uppal Road, 500007 Hyderabad, India
[f] BRGM, D3E, NRE, 1039 rue de Pinville, 34000 Montpellier, France

ARTICLE INFO

Keywords:
Cross-hole tracer tests
Single-well injection-withdrawal tracer test
Solute transport
Flow channeling
Non-Fickian dispersion
Fractured rock

ABSTRACT

In fractured media, solute transport is controlled by advection in open and connected fractures and by matrix diffusion that may be enhanced by chemical weathering of the fracture walls. These phenomena may lead to non-Fickian dispersion characterized by early tracer arrival time, late-time tailing on the breakthrough curves and potential scale effect on transport processes. Here we investigate the scale dependency of these processes by analyzing a series of convergent and push-pull tracer experiments with distance of investigation ranging from 4 m to 41 m in shallow fractured granite. The small and intermediate distances convergent experiments display a non-Fickian tailing, characterized by a –2 power law slope. However, the largest distance experiment does not display a clear power law behavior and indicates possibly two main pathways. The push-pull experiments show breakthrough curve tailing decreases as the volume of investigation increases, with a power law slope ranging from − 3 to − 2.3 from the smallest to the largest volume. The multipath model developed by Becker and Shapiro (2003) is used here to evaluate the hypothesis of the independence of flow pathways. The multipath model is found to explain the convergent data, when increasing local dispersivity and reducing the number of pathways with distance which suggest a transition from non-Fickian to Fickian transport at fracture scale. However, this model predicts an increase of tailing with push-pull distance, while the experiments show the opposite trend. This inconsistency may suggest the activation of cross channel mass transfer at larger volume of investigation, which leads to non-reversible heterogeneous advection with scale. This transition from independent channels to connected channels when the volume of investigation increases suggest that both convergent and push-pull breakthrough curves can inform the existence of characteristic length scales.

1. Introduction

Groundwater flow in fractured bedrock occurs in preferential flow paths that occupy a small fraction of the rock volume (National Research Council, 1996) and may transport contaminant very quickly from point to point (Tsang and Neretnieks, 1998). The complexity of fracture geometry and fracture network connectivity lead to the interaction of high-permeability domains dominated by advection with low-permeability domains characterized by diffusion (National Research Council, 1996). Excluding chemical reactions and sorption, mass-exchange processes in fractured formations can be conceptualized as (1) hydrodynamic dispersion that describes mass spreading related to local mixing, (2) heterogeneous advection that describes mass spreading related to separation of advective pathways, and (3) matrix diffusion related to mass exchange between mobile and immobile zones (Becker and Shapiro, 2003, Bodin et al., 2003). Identifying the respective roles

* Corresponding author.
E-mail address: nicolas.guiheneuf@g360group.org (N. Guihéneuf).
[1] Present address: G360 Institute for Groundwater Research, University of Guelph, N1G 2W1, Ontario, Canada
[2] Present address: BRGM, DAT, Direction régionale Bretagne, 2 rue Claude Jouanet, 35700 Rennes, France
[3] Present address: International Geothermal Center Bochum, Bochum, Germany

http://dx.doi.org/10.1016/j.jconhyd.2017.09.003
Received 24 May 2017; Received in revised form 6 September 2017; Accepted 11 September 2017
0169-7722/

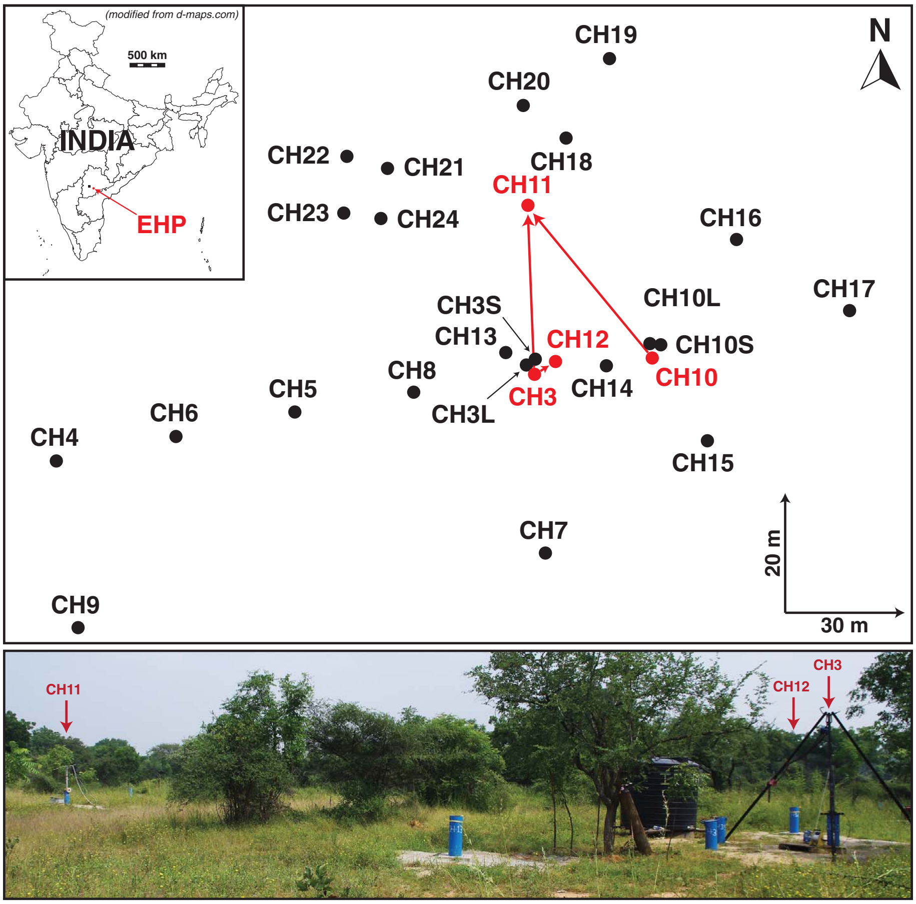

Fig. 1. Location of the Experimental Hydrogeological Park (EHP) in the Telangana state of Southern India (Latitude: 17°17′47″N; Longitude: 78°55′12″E). Zoom on the borehole location is provided with, in red, the boreholes used for tracer experiments (i.e. convergent and push-pull tracer experiments). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of these different processes is challenging since they may have similar signatures in tracer breakthrough curves. This identification is nevertheless critical as it may lead to different conceptual models of transport.

Tracer experiments conducted in fractured media often display behavior that cannot be properly interpreted with classical solutions of the advection dispersion equation (ADE) (Bodin et al., 2003). The apparent scale-dependent dispersion (Gelhar et al., 1992; Berkowitz, 2002; Zhou et al., 2007; Zech et al., 2015) and the long tailings of breakthrough curves are signatures of anomalous transport, also called non-Fickian transport (e.g., Carrera, 1993; Haggerty et al., 2000; Berkowitz, 2002; Willmann et al., 2008; Kang et al., 2015). While the asymmetric shape of breakthrough curves clearly indicates transport that does not follow the ADE, many processes have been proposed to explain this anomalous behavior (e.g., Haggerty et al., 2000, 2001; Becker and Shapiro, 2000, 2003; Reimus et al., 2003; Willmann et al., 2008; Pedretti et al., 2013; Babey et al., 2015; Kang et al., 2015).

Several authors have explained the long breakthrough curve tailing in fractured formations with the matrix diffusion process (e.g., Neretnieks et al., 1982; Maloszewski and Zuber, 1990, 1993; Moench, 1995; Haggerty et al., 2000; Meigs and Beauheim, 2001; Reimus et al., 2003; Zhou et al., 2007). Matrix diffusion occurs due to mass exchange between mobile zones where water flows in the fractures or channels and immobile zones in which water is stagnant in the porous rock matrix or in the fracture (Rasmuson and Neretnieks, 1986). For instance, Hadermann and Heer (1996) carried out forced-gradient tracer experiments with various conservative tracers in the Grimsel granite and have highlighted the impact of matrix diffusion. In particular, most of tracer tests displayed a breakthrough curve with a power law slope of -1.5, which is characteristic of matrix diffusion (e.g., Hadermann and Heer, 1996; Haggerty et al., 2000; Shapiro et al., 2008). Using numerous conservative tracers with different diffusion coefficients during the same experiment (i.e. under forced or natural gradient experiments) is one of the approaches to highlight the evidence of matrix diffusion (e.g., Garnier et al., 1985; Jardine et al., 1999; Callahan et al., 2000; Shapiro, 2001; Meigs and Beauheim, 2001; Cvetkovic and Cheng, 2011) or alternatively to exclude its impact (Becker and Shapiro, 2000).

Channeling of fluid flow is also known to strongly impact solute transport in fractured formations as it produces heterogeneous pathways of different velocities, called hereafter “heterogeneous advection” (Tsang and Neretnieks, 1998; Becker and Shapiro, 2003). At the fracture scale, because of rough wall surfaces and tight fractures, paths of least resistance can be formed that conduct water preferentially (Neretnieks et al., 1982; Bourke, 1987; Pyrak-Nolte et al., 1987; Hakami and Larsson, 1996). In some cases, it has been shown that less than half of the fracture plane may participate in the overall flow (Bourke, 1987; Abelin et al., 1994, Becker and Tsoflias, 2010). Channeling effects may also have an important impact on solute transport at the network scale and for large distances (Abelin et al., 1991; Tsang et al., 1991, de Dreuzy et al., 2012). Heterogeneous advection induced by fluid flow channeling was found to be the main solute transport process under forced-gradient tracer experiments in fractured crystalline rocks in New Hampshire (Becker and Shapiro, 2000, 2003). In particular, convergent (i.e. cross-borehole tracer test) and weak dipole experiments were performed at the Mirror Lake site using different conservative tracers. All breakthrough curves displayed similar late time behavior characterized by a tailing with a power law slope of -2 (Becker and Shapiro, 2000, 2003).

The joint use of different flow configurations, such as push-pull and convergent tracer tests, is a way to reduce both the conceptual model and parameter uncertainty (Tsang, 1995; Meigs and Beauheim, 2001; Becker and Shapiro, 2003; Nordqvist et al., 2012). In particular, push-