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Two-dimensional distribution of microbial activity and flow patterns within naturally fractured chalk

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Abstract

The two-dimensional distribution of flow patterns and their dynamic change due to microbial activity were investigated in naturally fractured chalk cores. Long-term biodegradation experiments were conducted in two cores (~20 cm diameter, 31 and 44 cm long), intersected by a natural fracture. 2,4,6-tribromophenol (TBP) was used as a model contaminant and as the sole carbon source for aerobic microbial activity. The transmissivity of the fractures was continuously reduced due to biomass accumulation in the fracture concurrent with TBP biodegradation. From multi-tracer experiments conducted prior to and following the microbial activity, it was found that biomass accumulation causes redistribution of the preferential flow channels. Zones of slow flow near the fracture inlet were clogged, thus further diverting the flow through zones of fast flow, which were also partially clogged. Quantitative evaluation of biodegradation and bacterial counts supported the results of the multi-tracer tests, indicating that most of the bacterial activity occurs close to the inlet. The changing flow patterns, which control the nutrient supply, resulted in variations in the

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concentrations of the chemical constituents (TBP, bromide and oxygen), used as indicators of biodegradation.

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1. Introduction

Fractured rocks are considered the most difficult type of geological setting for groundwater cleanup by pump-and-treat technologies (Macdonald and Kavanaugh, 1994). Common alternatives are natural attenuation and in situ bioremediation. Relying on these alternatives requires an understanding of the effects of microbial activity on the dynamics of flow in fractured rocks.

Most of the flow in heterogeneous media takes place in specific regions, usually referred to as preferential flow paths or channeling (Tsang and Tsang, 1987). Preferential flow paths in fractures have been reported to range from a centimeter to tens of meters in length (Abelin et al., 1994; Park et al., 1997; Dahan et al., 1999; Dijk et al., 1999; Keller et al., 1999; Wendland and Himmelsbach, 2002), and occur either because of the irregular shape of the fracture void or due to different fracture characteristics within fracture networks. Understanding the flow patterns in low-permeability fractured porous rocks, such as chalk, glacial tills or shales, is extremely important since the fractures are considered to be fast conduits for contaminant distribution, whereas the large volume of porous matrix provides extensive storage capacity, which is responsible for contaminant retardation (Nativ et al., 1999).

The roughness of natural fracture surfaces generates a variable aperture distribution, which plays a major role in flow patterns and transport within fractured rocks (Tsang and Tsang, 1987; Thompson and Brown, 1991). The geometric structure of the fracture voids can change as a result of physical, chemical and biological processes (Weisbrod et al., 1999; Dijk and Berkowitz, 2000; Hill and Sleep, 2002), thus affecting flow and transport processes. Recently, the development of new techniques has provided new insight into flow processes within fractures. For example, Dijk et al. (1999) used nuclear magnetic resonance imaging (NMRI) to measure three-dimensional void geometry and water velocities in a natural fracture. These velocity images supported earlier studies that had, on theoretical grounds, implied the occurrence of both main flow channels and stagnant water regions within the individual fractures. In addition, they concluded that the main flow region occupies only approximately 25% of the fracture volume. A similar estimate was provided by Dahan et al. (2000) following a multi-tracer experiment.

The activity of microorganisms in groundwater is usually enhanced when associated with organic contamination, especially when the microorganisms are artificially stimulated to consume contaminants as a carbon source. However, such beneficial activity may affect the saturated hydraulic conductivity (K_s) and flow patterns in the aquifer (Oberdorfer and Peterson, 1985; Ralph and Stevenson, 1995; Baveye et al., 1998). Indeed, reductions in the K_s of geological materials due to biomass accumulation have been examined both in the