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Spontaneous imbibition in porous basalt mediated by microbial perturbations

X. Xie *, S.L. Fox, G.A. Bala

P.O. Box 1625, Idaho National Laboratory, Idaho Falls, ID 83415-2110, USA

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Abstract

The fate and transport of organic contaminants in subsurface depend on complex interactions between several system components such as fluid chemistries, geochemistry, microbiology, geology, and physical parameters. This study describes imbibition studies to assess the incipient interaction between selected hydrocarbons and pertinent mineral surfaces as a function of aqueous phase chemistry and microbiological perturbation. Microbial perturbations may have significant impact with respect to monitoring the contaminants and finding better strategies for remediation. Basalt cores used in laboratory experiments were obtained at depths of 200 to 300 ft from a test well located at the Idaho National Laboratory (INL). Thin section analysis of core samples showed that the basalt was formed from feldspar and pyroxene crystals with most of the pore space occurring as vugs. Mercury injection tests indicated a wide range of pore throat sizes through which the vugs could be accessed. All of the vugs were connected by inter/intra crystalline pores that were less than about 0.5 μm in width. Although most pore space occurs as vugs, miscible displacement tracer tests did not reveal significant heterogeneity. Base-case spontaneous imbibition tests were conducted on cores that had been fully saturated with dodecane using synthetic groundwater as the invading phase. Imbibition tests were then performed against basalt with cell-free supernatants and sonicants (diluted by synthetic groundwater) of three indigenous microorganisms, *Acinetobacter genospecies*, *Arthrobacter globiformis* and *Bacillus atrophaeus* that had been isolated from the test well. Waterflooding was performed on each core after imbibition testing to obtain the Amott wettability index to water.

Imbibition tests show that, although the basalt/dodecane/synthetic groundwater system was strongly water-wetted, the scaled imbibition rate was much slower than previously observed for other core types such as sandstone and limestone. The production of organics obtained by waterflooding after spontaneous imbibition was close to zero, indicating that the basalt was strongly water-wet. At the same time, the water permeability by waterflooding was often extremely small at imbibition residual organic saturation. The distribution of trapped oil and its effect on relative permeability in the crystalline matrix may explain the relatively slow imbibition rates that were observed. The addition of microbial components in the invading aqueous phase resulted in higher imbibition rates and final recovery of organics than observed for synthetic groundwater.

Keywords: Basalt; Vugs; Spontaneous imbibition; NAPLs; Microorganisms

1. Introduction

The Snake River Plain Aquifer (SRPA) contains basaltic rocks and interbedded sedimentary deposits, with depth to water from about 196 ft to more than 900 ft

* Corresponding author. Tel.: +1 208 526 3537; fax: +1 208 526 9822.

E-mail address: xina.xie@inl.gov (X. Xie).

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below land surface at the INL site (Knobel et al., 2001). Past practices resulted in discharge of chemical wastes into infiltration ponds and disposal wells. Some of the waste constituents have percolated through the vadose zone and entered the Snake River Plain Aquifer (Pittman et al., 1988). The presence of non-aqueous phase liquids (NAPLs) may contaminate the underground water. Subsurface systems are considered by many to be strongly water-wet and most NAPLs are non-wetting phase with respect to groundwater in subsurface systems. However, polar components in the NAPLs may adsorb onto the rock surface and alter the wettability of the formation to other than strongly water-wet (Powers and Tamblin, 1995; Buckley, 1996). Other factors that mediate wettability changes are water soluble surface active constituents (Demond et al., 1994), mineralogy (Anderson, 1986) and microbial activities (Bala et al., 2002), etc. Alteration of wettability of solid surfaces changes the distribution of the fluids in the porous medium and has a profound impact on capillary pressure and relative permeability relationships. It affects the flow behavior and ultimate recovery of the non-aqueous phase during the clean up operations (Donaldson and Thomas, 1971; Anderson, 1987; Morrow, 1990).

Geohydrological studies indicated that fractures (produced by volcanic flow and cooling) and vesicles (vugs) of the basalt may be highly transmissive of groundwater (Ackerman, 1991; Smith, 2003). It is likely that NAPLs in the subsurface may also be able to move along with the groundwater. The ultimate fate and transport of NAPL contaminants are dominated by physical and chemical properties of solids and fluids and their interactions. Heterogeneity can affect the NAPL flow pattern in ways ranging from pore scale snap off and entrapment to large scale fingering (Chatzis et al., 1983; Wilson et al., 1990). In general, flow and transport of NAPLs in high transmissibility (fractured) media are dominated by viscous and gravity forces; in low permeability (matrix) systems they are dominated by capillary forces. For example, transport of organic contaminants in the subsurface may result from gravity segregation or spontaneous imbibition of aqueous liquid whereby NAPLs in the matrix are expelled into the fractures by the aqueous liquid and then being displaced from the fractures and recovered. The aqueous phase can be modified to enhance the imbibition processes.

Investigation of the effect of microbiological perturbations on the fate and transport of NAPLs is an ongoing study. The complex biological component can be viewed simplistically as the discrete presence of cells or biofilms, nutrient packages that may be introduced to support or suppress these organisms, and the end products resulting from metabolism and growth. Microbial activities capable of affecting surface or aqueous chemistries may result from 1) introduction of nutrients, 2) attachment, detachment, and film formation, 3) transformation of contaminants, 4) production of metabolites, and 5) cell death (Bala et al., 2002).

The effect of microbiological perturbations on the fate of NAPLs may be both positive and negative. If the system is driven to a less water-wet condition, the organic contaminants will have a tendency to spread across the surface of the solid media resulting in a larger bulk volume of contaminated solids. Conversely, this could be a positive outcome if the intention of the remediation technology is to improve the bioavailability of the contaminant and the appropriate organisms are present to transform or degrade the contamination.

This work, which is part of the Subsurface Science Initiative aimed at promoting more effective fate and transport modeling for risk analysis and remediation, reports the spontaneous imbibition of aqueous phase as a function of aqueous chemistry and microbiological perturbation. This information is essential to understanding how contaminant distribution and recovery may be influenced by microbiological systems.

2. Experimental

2.1. Material

2.1.1. Cores

Basalt cores, obtained from the INL core repository, were from well TAN33. The cores all originated from a formation depth of about 200 to 300 ft. The corresponding formation temperature was 13 °C. Core plugs with diameter of 1″ were cut from whole basalt core material, dried at 105 °C for 24 h and cooled in a desiccator. The liquid permeabilities ranged from 0.27 to 43 md and the porosities were about 10–13% (Table 1).

2.1.2. Oleic phase

Dodecane with 99% purity was used as the oil phase. It was degassed by vacuum before use. The viscosity and density of dodecane at ambient conditions were 1.383 cP and 0.748 g/ml respectively. The interfacial tension between dodecane and synthetic ground water, measured by Real-Time Video Imaging of Pendant Drops (Herd et al., 1992), was 49.61 dynes/cm.