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A Biobarrier Concept for the Remediation of Groundwater in Fractured Rock

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A Biobarrier Concept for the Remediation of Groundwater in Fractured Rock

By Nathalie Ross, Ph.D.

Fractured rock aquifers are the most complex sites to remediate. To date, no known technologies have been proven to be successful in this setting. Complexity is attributable to the fracture framework, which governs groundwater flow, to the diffusion of contamination in the rock matrix, which is followed by a back diffusion that may last for decades, and to the challenge of delivering a remediation technology, which includes the cost of excavating. Recent work on a biobarrier concept showed potential for the control of contaminant transport in fractured environments.

The Concept: Biostimulation of Groundwater Microbes

The biobarrier concept is based on the stimulation of groundwater bacteria via the injection of nutrients in the fracture framework. This biostimulation promotes bacterial growth and production of extracellular polymeric substances (EPS). These secreted EPS form the skeleton of a biofilm that fills microfractures. Such a gelatinous matrix may act as a cut-off wall by decreasing the hydraulic conductivity or as a treatment wall by degrading the contaminants via embedded bacteria (Figure 1).

Biofilms are extensively studied in many disciplines, such as medicine (e.g. cystic fibrosis) and biotechnology (e.g. production of ethanol). Studies focus on avoiding detrimental biofilms (e.g. deterioration of metal and dental surfaces) or generating beneficial biofilms (e.g. biofilm reactors for wastewater treatment). In the environmental industry, biofilm applications range from water containment to pollutant degradation, including contaminant sorption and binding. Although investigations on the biobarrier concept has been reported for the control of groundwater in porous aquifer, limited information is available on a potential application in fractured media.

Promising Laboratory Studies

Studies conducted at laboratory scale have shown that groundwater bacteria, when biostimulated with molasses, may develop biofilms as thick as 1.1 mm on a rock surface. Biostimulated in a limestone fracture (having an aperture of 0.5 mm, a width of 5 mm, and a length of 50 cm), groundwater bacteria generated a bioclogging that led to a decrease of 4 orders of magnitude in groundwater velocity (initial velocity $\cong$ 2 $m \cdot min^{-1}$).

A closer look at the bacterial population revealed the presence of as much as 60 % of ultramicrobacteria (UMB), which are bacteria having a diameter ≤0.3 μm (Figure 2). These UMB are of interest in biobarrier formation because their low surface hydrophobicity facilitates their transport, and their size allows them to reach smaller fractures compared to "normal" size bacteria (typically 1 to 10 μm). This first experimental phase suggested the EPS-producer bacteria to be numerous enough in groundwater to sustain the development of a biobarrier providing the nutrient delivery is optimum.

Focus on a Fracture Plane at Field Scale

A well-characterized and non-contaminated site was selected in Southern Ontario with the goal of measuring the extent of bioclogging a fracture plane, the stability of the biobarrier over time, and the resistance of bacteria to starvation. Previous work at the site has identified two extensive horizontal fractures; the lowermost of these fractures (located at approximately 10.5 m below ground surface) was selected to evaluate the application of the biobarrier concept. The configuration includes 29 vertical boreholes that are 76 mm in diameter and are cased through the entire thickness of the overburden (Figure 3). The isolation of the fracture was obtained using a double-packer system, which was equipped with a variety of instrument combinations to monitor the development and effectiveness of a biobarrier in the fracture (Figure 4).

The effects of bioclogging on the environment were measured in terms of changes in the flow regime and changes in the physicochemical, microbiological, and ecotoxicological conditions. To measure changes in the flow pattern within the fracture, forced-gradient tracer experiments and the point dilution technique were used. Also, as required by environmental regulations, the biosafety of *in situ* bioremediation approaches needs to be addressed. As such, a battery of potential pathogen, as well as biotests for ecotoxicological changes, has been selected for analyses at different time interval during the biobarrier development.

Preliminary Results Leading to Partnerships

The hydraulic approaches to estimating fracture permeability appear to provide reliable measurements with no detectable disruptions on the developing biofilm, despite their reliance on injecting pressurized water. After two weeks of biostimulation with molasses, measurements indicated a reduction of 70% to 90% in groundwater velocity and typical permeability reductions between 33% and 93% throughout the borehole grid (Figure 3). Ongoing testing aims at measuring the stability of this bioclogging several months after stopping the injection of nutrients. Ecotoxicological assessment revealed no adverse effects on a battery of organisms including local amphibians, used as potential wetland receptor of a bioremediated groundwater.

For the next development phase, the research team has built a partnership with the industry likely to apply the biobarrier at contaminated sites, namely Golder Associates Ltd. and Kinectrics Inc. Both laboratory and field scale work will be undertaken with the goal of investigating the fate of groundwater bacteria in a rock matrix, corroborating the matrix bio-sealing approach, and monitoring the bioclogging of a complex fracture framework. The proposed concept of biobarriers is attractive not only because of its expected low cost and maintenance, but also for its efficiency to contain the contamination while being environmentally sustainable (e.g. possibility to dismantle).

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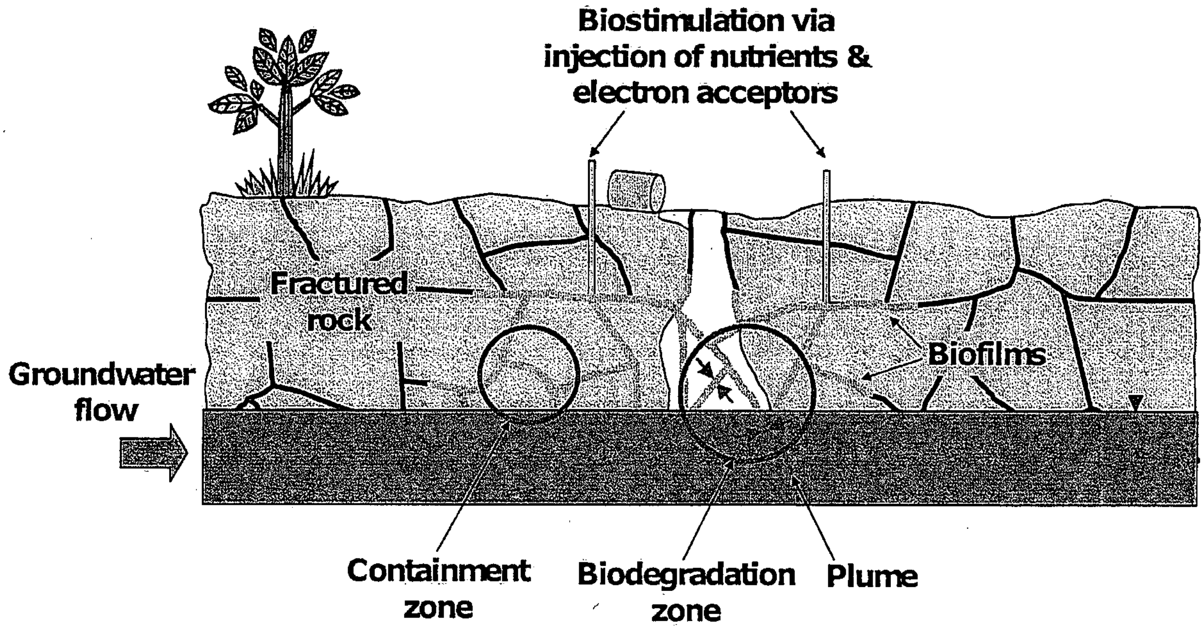
Figure Captions

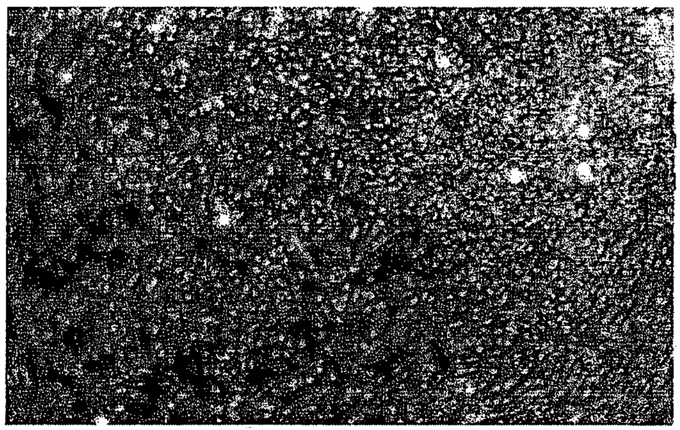
Figure 1. Schematic of the biobarrier concept showing a containment zone and a biotreatment zone

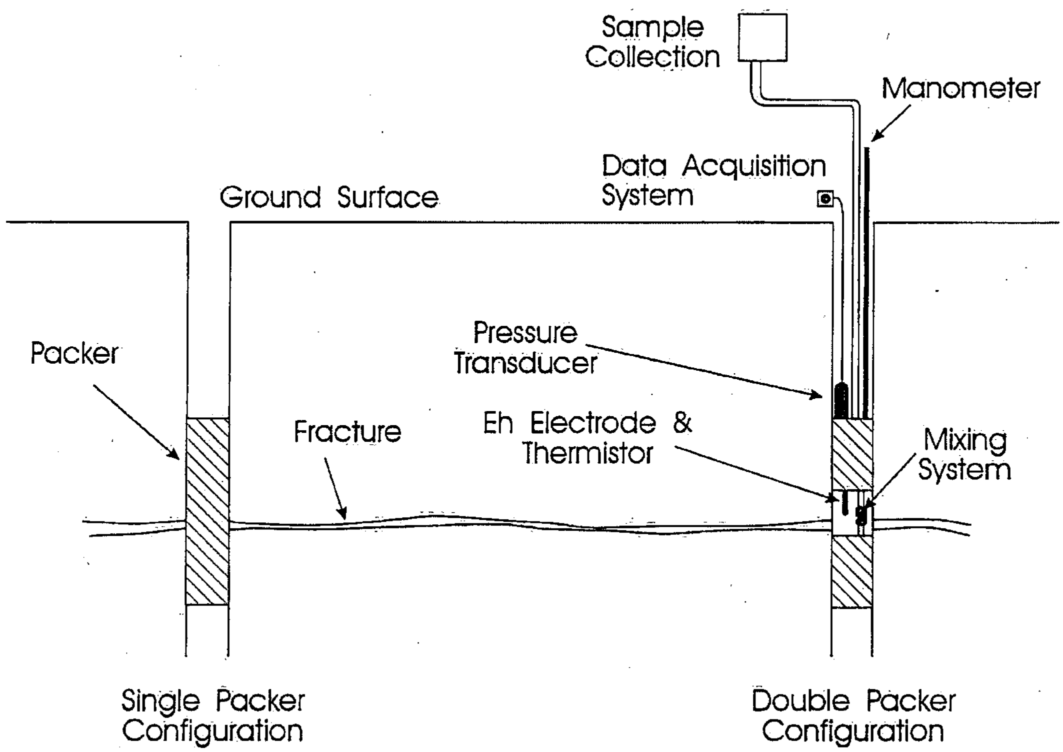
Figure 2. Groundwater bacteria stained with LIVE/DEAD® BacLight™ epifluorescence kit. Bacteria are mainly cocci as a result of starvation conditions; the green cells are viable, and the red cells have damaged membranes.

Figure 3. Field setting showing the boreholes grid

Figure 4. Schematic of the packer configuration


Biostimulation via injection of nutrients & electron acceptors
Fractured rock
Groundwater flow
Biofilms
Containment zone
Biodegradation zone
Plume

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