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Biobarriers in Fractured Bedrock: From Laboratory Concept to Field Demonstration

By:

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BIOBARRIERS IN FRACTURED BEDROCK: FROM LABORATORY CONCEPT TO FIELD DEMONSTRATION

Nathalie Ross, Greg Bickerton, Suzanne Lesage, Louise Deschênes, Réjean Samson, and Kent Novakowski

ABSTRACT
The concept of biobarriers for the control of groundwater flow has been studied at laboratory-scale using a multidisciplinary approach and has been scaled up to a field demonstration undertaken in Mississauga (Ontario, Canada). In a limestone single fracture, the biostimulation led to a decrease of 99.2 % in the hydraulic conductivity after 22 days. The testing of monitoring tools, including the modeling of tracer experiments, showed the potential of the groundwater velocity, the planktonic bacteria, and the oxidation-reduction potential to provide an insight into the fracture bioclogging. These results suggest that the development of a persistent biofilm, having sufficient hydraulic impedance to significantly alter and diminish groundwater flow in natural fractures in a field setting, is indeed possible.

NWRI RESEARCH SUMMARY

Plain language title
Biobarriers in Fractured Bedrock: From Laboratory Concept to Field Demonstration

What is the problem and what do sicentists already know about it?
To control and limit groundwater movement in fractured rock aquifers, where the remediation options are limited, the use of a biological barrier has been suggested.

Why did NWRI do this study?
NWRI has the expertise relative to groundwater microbiology and fractured rock hydrogeology. The field site, well characterised by NWRI scientists, is available for site demonstration.

What were the results?
The concept of biobarriers for the control of groundwater flow has been studied at laboratory-scale using a multidisciplinary approach and has been scaled up to a field demonstration undertaken in Mississauga (Ontario, Canada). In a limestone single fracture, the biostimulation led to a significant decrease in the hydraulic conductivity after 22 days. The testing of monitoring tools showed the potential of the groundwater velocity, the planktonic bacteria, and the oxidation-reduction potential to provide an insight into the fracture bioclogging. These results suggest that the development of a persistent biofilm, having sufficient hydraulic impedance to significantly alter and diminish groundwater flow in natural fractures in a field setting, is indeed possible.

How will these results be used?
To prove the efficiency of the biobarrier concept and scale-up to a full scale application.

Who were our main partners in the study?
Queen's University, École Polytechnique de Montréal, and Petro-Canada

BARRIÈRES BIOLOGIQUES DANS LE SUBSTRATUM ROCHEUX FRACTURÉ : DU LABORATOIRE À LA DÉMONSTRATION SUR LE TERRAIN

Nathalie Ross, Greg Bickerton, Suzanne Lesage, Louise Deschênes, Réjean Samson et Kent Novakowski

RÉSUMÉ
Le concept de biobarrière comme moyen de maîtriser l'écoulement des eaux souterraines a été étudié en laboratoire selon une démarche multidisciplinaire, puis transposé à une échelle permettant une démonstration sur le terrain, qui a été entreprise à Mississauga (Ontario), au Canada. Au bout de 22 jours, la biostimulation avait mené, pour une fracture isolée dans du calcaire, à une diminution de 99,2 % de la conductivité hydraulique. La mise à l'épreuve des outils de surveillance, incluant la modélisation des essais avec traceurs, a montré que la vitesse des eaux souterraines, les bactéries planctoniques et le potentiel d'oxydo-réduction pouvaient constituer des indicateurs du biocolmatage de la fracture. Les résultats semblent indiquer que la formation d'un biofilm persistant, dont l'impédance hydraulique est suffisante pour modifier et réduire de manière significative l'écoulement des eaux souterraines par des fractures naturelles, sur le terrain, est effectivement possible.

Sommaire des recherches de l'INRE

Titre en langage clair
Barrières biologiques dans le substratum rocheux fracturé : du laboratoire à la démonstration sur le terrain

Quel est le problème et que savent les chercheurs à ce sujet?
On a proposé le recours aux biobarrières pour maîtriser et circonscrire les mouvements des eaux souterraines dans les aquifères de roc fracturé lorsque les mesures correctives envisageables sont limitées.

Pourquoi l'INRE a-t-il effectué cette étude?
À l'INRE, on possède les connaissances spécialisées en matière de microbiologie des eaux souterraines et d'hydrogéologie de la roche fracturée. Le site des essais sur le terrain, dont les caractéristiques sont bien connues des chercheurs de l'INRE, est disponible pour la démonstration.

Quels sont les résultats?
Le concept de biobarrière comme moyen de maîtriser l'écoulement des eaux souterraines a été étudié en laboratoire selon une démarche multidisciplinaire, puis transposé à une échelle permettant une démonstration sur le terrain, qui a été entreprise à Mississauga (Ontario), au Canada. Au bout de 22 jours, la biostimulation avait mené, pour une fracture isolée dans du calcaire, à une diminution significative de la conductivité hydraulique. La mise à l'épreuve des outils de surveillance a montré que la vitesse des eaux souterraines, les bactéries planctoniques et le potentiel d'oxydo-réduction pouvaient constituer des indicateurs du biocolmatage de la fracture. Les résultats semblent indiquer que la formation d'un biofilm persistant, dont l'impédance hydraulique est suffisante pour modifier et réduire de manière significative l'écoulement des eaux souterraines par des fractures naturelles, sur le terrain, est effectivement possible.

Comment ces résultats seront-ils utilisés?
Prouver l'efficacité du concept de barrière biologique et le transposer à l'échelle réelle en vue d'applications.

Quels étaient nos principaux partenaires dans cette étude?
Université Queen's, École Polytechnique de Montréal, et Petro-Canada.

BIOBARRIERS IN FRACTURED BEDROCK: FROM LABORATORY CONCEPT TO FIELD DEMONSTRATION

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ABSTRACT

The concept of biobarriers for the control of groundwater flow has been studied at laboratory-scale using a multidisciplinary approach and has been scaled up to a field demonstration undertaken in Mississauga (Ontario, Canada). In a limestone single fracture, the biostimulation led to a decrease of 99.2 % in the hydraulic conductivity after 22 days. The testing of monitoring tools, including the modeling of tracer experiments, showed the potential of the groundwater velocity, the planktonic bacteria, and the oxidation-reduction potential to ~~get~~ provide an insight into the fracture bioclogging. These results suggest that the development of a persistent biofilm, having sufficient hydraulic impedance to significantly alter and diminish groundwater flow in natural fractures in a field setting, is indeed possible.

1. INTRODUCTION

To control and limit groundwater movement in fractured rock aquifers, where the remediation options are limited [1], the use of a biological barrier has been suggested [2]. Biological barriers consist of biofilms that develop after indigenous bacteria or injected bacteria are stimulated to grow, have attached on rock surfaces, and have secreted exopolymeric substances (EPS) [3].

A demonstration of the biobarrier concept, focusing on the biostimulation approach, i.e. the stimulation of the indigenous groundwater population with nutrients, was undertaken in Mississauga (Ontario, Canada) following a number of laboratory experiments in static microcosms [4, 5] and in flow-through apparatus [6]. This site, a flat-lying, thinly bedded shale (groundwater velocity of 5 m · day^{-1}), have been well characterized [7-10].

The study aimed at 1) measuring the efficiency of biostimulation to bioclog a planar fracture and at 2) testing the reliability of monitoring tools, such as point dilution tests as indicators of the biobarrier development. Results from the pre-bioclogging conditions, including tracer experiments in the plane fracture as well as the settings for the biostimulation are reported.

2. MATERIALS AND METHODS

2.1 Site description and instrumentation

The study site is located in Mississauga, Ontario, about 1.5 km north of Lake Ontario. The area is underlain by approximately 3 m of clayey-sand overburden and the upper 20 m of bedrock at the site consists of flat-lying, thinly-bedded shale which contains numerous limestone interbeds. Previous work [12] has identified two extensive horizontal fractures that are associated with the sharp contacts found between the limestone and shale. The fracture selected to evaluate the application of the biobarrier concept has also provided the setting for numerous studies investigating solute transport in fractured rock [7, 10, 12].

The current site configuration includes 29 vertical boreholes that provide access to the fracture in approximately a 25 m x 25 m area (Figure 1). Every borehole at the site was equipped with pneumatic packers to hydraulically isolate the fracture from other influences and to minimize well-bore storage effects. The packer systems were equipped with a variety of instrument combinations to monitor the development and effectiveness of a biobarrier in the fracture. A pressure transducer and thermistor were provided to measure changes in hydraulic head and temperature within the fracture. In addition twelve boreholes were also fitted with a mixing system and sampling lines. The mixing systems were required to conduct the various tests (i.e.

point dilution tests and tracer experiments) that were used to measure changes in the flow system as the biofilm developed. The sampling lines permitted groundwater samples to be collected from the fracture so that changes in microbial and physicochemical conditions could be monitored.

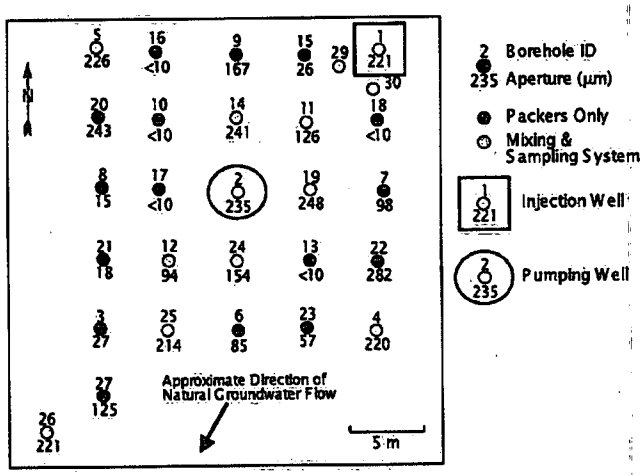

FIGURE 1. Schematic of field site and borehole layout.

During the experiment, groundwater was obtained from a well BH28 (not shown) located approximately 100 m up-gradient of the study area. The water was pumped from a deeper section of the bedrock which had been shown to be hydraulically unconnected to the study fracture. This groundwater was then combined with the nutrient mixture and injected into the fracture at BH1 (Figure 1). To better control the distribution of the nutrients, a withdrawal well (BH2) was included approximately 15 m down-gradient of the injection well. The flow rate at both the injection and withdrawal well was established at approximately 250 ml/minute.

2.2 Measurement of changes in groundwater flow system

During the development of a biofilm in a bedrock fracture, corresponding changes in the flow system are also expected to occur. Any non-seasonal variations in the groundwater flow system may provide indirect evidence of the extent, and perhaps location, of bioclogging in the fracture. Point dilution tests [13] provide a direct method for measuring the groundwater velocity (but not direction) and were used to monitor changes in the magnitude and distribution of velocity in the fracture. The approach involves injecting a pulse of conservative tracer (KBr and the fluorescent dye Lissamine FF) into an isolated section of a borehole and monitoring the decrease in concentration as the groundwater flow gradually removes the tracer.

The rate at which the concentration decreases can be related to the groundwater velocity in the fracture. These tests were performed simultaneously in the twelve boreholes locations with mixing systems and were repeated at routine intervals during the experiment. To obtain the background condition (i.e. prior to biofilm development) the test were also performed just prior to the injection of nutrients. Numerous tests were also performed prior to the experiment (and the associated pumping activity) to evaluate natural variations in groundwater velocity and the precision of the equipment. The up-gradient well (BH28) was one of the twelve boreholes used for point dilution testing. The study fracture in BH28 was isolated from the lower feature used to supply water to BH1 using a packer. The velocity measurements obtained from this well were not influenced but the pumping activities in the study area and provided an indication if any natural variations in velocity occurred during the experiment.

2.3 Biostimulation of the indigenous bacterial community

The biostimulation is conducted by injecting molasses (sol. 14 %) [4] and a nitrate source (sol. 500 mg $\cdot$ L^{-1}) in BH-1 at 5 mL $\cdot$ min^{-1} for 3 weeks pumped from BH-2. The biostimulation is then stopped for a week for tracer experiments, and the injection of nutrients continues for three more weeks. The concentration of molasses is measured by the phenol-sulfuric acid method [14].

3. RESULTS AND DISCUSSION

3.1 Acquisition of groundwater background data

On average over one year, the groundwater showed a high salinity throughout the site (Figure 2-A) [15]. BH 28, located 100 m outside the monitoring grid, had significantly lower anions and cations concentrations, a sign that this well might have more connections with surface water. On the contrary, BH 5 had a significantly higher ions concentrations, which could be explained its location in a tighter area thus reducing the dilution with surface water [16].

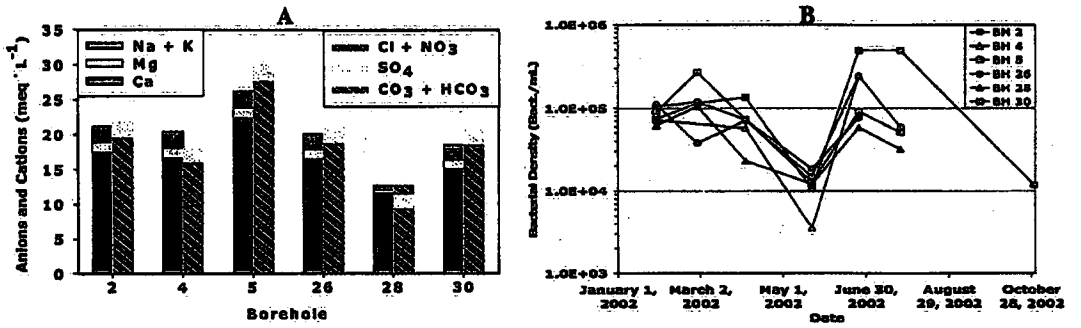

FIGURE 2. Groundwater chemical composition on average for a year (A) and changes in the bacterial density over a year (B) for 6 monitoring boreholes.

The groundwater bacterial density was maintained in the 5 log · mL^{-1} except for the spring months, reaching 4 log · mL^{-1}, which might be the result of dilution by the rain and snow melt events (Figure 2-B). Additional assessment of the groundwater bacteria will give insights into the changes in the diversity and the partioning from groundwater (planktonic) to the rock surface (sessile).

3.2 Point dilution experiment

The point dilution tests were initiated by injecting a tracer composed of 700 µL of a mixture of 1 g/L Lissamine FF and 30 g/L of KBr and 3 mL of deionized water. The tracer was then followed by an injection of 25 ml of deionized water to clear the sample lines of tracer. The duration of the point dilution tests averaged 3 days for tests performed without active pumping (i.e. ambient groundwater conditions) and varied between 6 hours and 3 days with active pumping conditions (but prior to the biofilm development). Each borehole was sampled between eight and fifteen times during the test. The results of the point dilution tests for selected boreholes are presented in Figure 3. A more complete description of the ambient groundwater velocities at the site can be found in Novakowski *et al.* (2003) [16]. Notice in Figure 3 that, as expected, all the boreholes except BH28 showed a pronounced increase in groundwater velocity during active pumping. The injection rate during the point dilution tests varied between 272 and 330 ml/minute and the withdrawal rate between 281 and 332 ml/minute. No change in the up-gradient borehole (BH28) was detected indicating that BH28 could effectively be used to monitor natural changes in the ambient flow. Conducting point dilution tests in BH28 was intended to avoid falsely attributing natural or seasonal changes in velocity to bioclogging in the fracture.

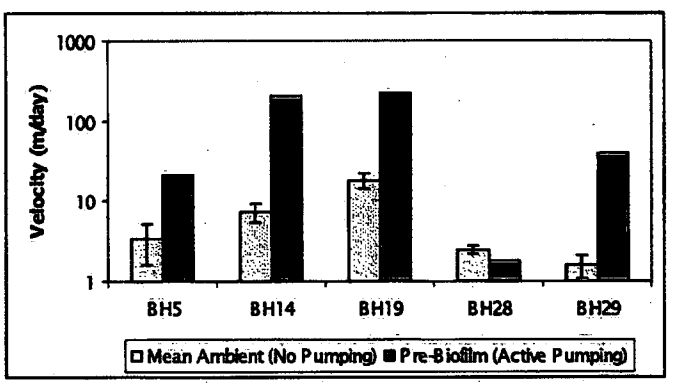

FIGURE 3. Groundwater velocities from selected boreholes under ambient and active pumping conditions (pre-biofilm development). Error bars describing the variability in ambient velocities is indicated by +/- 1 standard deviation.

4. CONCLUSIONS

The promising results obtained in the laboratory showing the potential of bioclogging a fracture media for the control of groundwater were scaled-up for a field demonstration in Mississauga, Ontario. After instrumenting 29 boreholes, which isolate a shale fracture of 165 µm on average, background data and pre-clogging conditions were measured for comparison with the bioclogging conditions. Biostimulation with molasses and a nitrate source was initiated on a 3-week injection and 1-week starvation cycle. *In situ* monitoring and monthly groundwater sampling are ongoing to document the efficiency of the biobarrier development.

5. ACKNOWLEDGEMENTS

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