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A Field Demonstration of the development of a Biological Barrier in a Fractured Shale

By:
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A FIELD DEMONSTRATION OF THE DEVELOPMENT OF A BIOLOGICAL BARRIER IN A FRACTURED SHALE

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

ABSTRACT: To demonstrate the concept of the biological barrier at field scale, a fracture plane was isolated in shale (25 m × 25 m, average fracture aperture 165 μm) and 29 boreholes were equipped to monitor the fracture bioclogging. As a biostimulation approach, molasses and a source of nitrate are supplied under a forced-gradient flow on a 4-week cycle. This includes one week of starvation, which is used for tracer experiments. Background data revealed a relatively high groundwater salinity and a planktonic bacterial density of 5 log · mL^{-1}, which decreased to 4 log · mL^{-1} during the spring. Tracer experiments in pre-clogging conditions were necessary first to confirm the absence of a hydraulic connection between the control/source borehole and the monitoring boreholes, via point dilution tests under natural gradient. Second, after establishing the flow regime for the biobarrier development, tracer tests were conducted to determine initial groundwater velocities, which averaged 58.4 m · d^{-1} between the injection borehole and the withdrawal borehole. Winterization of the equipment was required before starting the biostimulation; an ongoing nutrients supply for the biobarrier development, which is monitored both *in situ* and via monthly groundwater sampling.

NWRI RESEARCH SUMMARY

Plain language title
A FIELD DEMONSTRATION OF THE DEVELOPMENTOF A BIOLOGICAL BARRIER IN A FRACTURED SHALE

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?
Background data suggested that the conditions for a biobarrier development are present, such as the bacterial density in groundwater varying from 10 000 to 100 000 bact. mL-1 over a year. To confirm the absence of a hydraulic connection between the control/source borehole and the monitoring boreholes, tracer experiments were conducted. Then the initial groundwater velocities were determined, which averaged 58.4 m . d-1 between the injection borehole and the withdrawal borehole. These results help designing the field demonstration of the biobarrier conpept in a fractured bedrock.

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

DÉMONSTRATION SUR LE TERRAIN DE LA FORMATION D'UNE BIOBARRIÈRE DANS UN SHALE FRACTURÉ

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

RÉSUMÉ : Pour démontrer sur le terrain le concept de barrière biologique, nous avons isolé un plan de fracture dans un shale (25 m × 25 m, ouverture moyenne de la fracture :165 µm) et 29 trous de sondage ont été équipés pour surveiller le biocolmatage de la fracture. La méthode de biostimulation a consisté à alimenter la zone étudiée en mélasse et en nitrate par écoulement suivant un gradient artificiel, selon un cycle de 4 semaines comprenant 1 semaine de privation d'aliments pour les besoins des essais avec traceurs. Les données de base ont révélé que la salinité des eaux souterraines était relativement élevée et que la densité des bactéries planctoniques de 5 log • mL^{-1} avait baissé à 4 log • mL^{-1} au cours du printemps. Des essais avec traceurs en conditions pré-colmatage ont été nécessaires d'abord pour confirmer, par des analyses de dilution ponctuelle le long du gradient naturel, que le trou de sondage témoin/source ne communiquait pas avec les trous destinés à la surveillance. Ensuite, après avoir établi le régime d'écoulement pour la formation de la biobarrière, des essais avec traceurs ont été effectués afin de déterminer les vitesses initiales des eaux souterraines, qui étaient en moyenne de 58,4 m/jour entre le trou d'injection et le trou de pompage. Il a fallu hivériser le matériel avant d'entreprendre la biostimulation, c'est-à-dire l'approvisionnement continu en nutriments en vue de la formation de la barrière biologique, dont la surveillance est effectuée à la fois *in situ* et par prélèvement mensuel d'échantillons.

Sommaire des recherches de l'INRE

Titre en langage clair
DÉMONSTRATION SUR LE TERRAIN DE LA FORMATION D'UNE BIOBARRIÈRE DANS UN SHALE FRACTURÉ

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 des 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?
Les données de base laissent supposer que les conditions propices à la formation d'une barrière biologique sont présentes, par exemple une densité bactérienne variant de 10 000 à 100 000 bactéries • mL^{-1} sur une année. Afin de confirmer que le trou de sondage témoin/source ne communiquait pas avec les trous destinés à la surveillance, on a procédé à des essais avec traceurs. Puis, on a déterminé les vitesses initiales des eaux souterraines, qui étaient en moyenne de 58,4 m/jour entre le trou d'injection et le trou de pompage.

Comment ces résultats seront-ils utilisés?
Ces résultats aident à concevoir la démonstration sur le terrain du concept de biobarrière dans un substratum rocheux fracturé.

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

A FIELD DEMONSTRATION OF THE DEVELOPMENT OF A BIOLOGICAL BARRIER IN A FRACTURED SHALE

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Kent Novakowski (Queen's University, Kingston, Ontario, Canada,)
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ABSTRACT: To demonstrate the concept of the biological barrier at field scale, a fracture plane was isolated in shale (25 m × 25 m, average fracture aperture 165 μm) and 29 boreholes were equipped to monitor the fracture bioclogging. As a biostimulation approach, molasses and a source of nitrate are supplied under a forced-gradient flow on a 4-week cycle. This includes one week of starvation, which is used for tracer experiments. Background data revealed a relatively high groundwater salinity and a planktonic bacterial density of $5 \log \cdot mL^{-1}$, which decreased to $4 \log \cdot mL^{-1}$ during the spring. Tracer experiments in pre-clogging conditions were necessary first to confirm the absence of a hydraulic connection between the control/source borehole and the monitoring boreholes, via point dilution tests under natural gradient. Second, after establishing the flow regime for the biobarrier development, tracer tests were conducted to determine initial groundwater velocities, which averaged $58.4 \ m \cdot d^{-1}$ between the injection borehole and the withdrawal borehole. Winterization of the equipment was required before starting the biostimulation; an ongoing nutrients supply for the biobarrier development, which is monitored both *in situ* and via monthly groundwater sampling.

INTRODUCTION

To control and limit groundwater movement in fractured rock aquifers, where the remediation options are limited (USEPA, 2001), the use of a biological barrier has been suggested (Ross and Bickerton, 2002). 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) (Bryers, 2000).

A demonstration of the biobarrier concept, focusing on the biostimulation approach, i.e. the stimulation of the indigenous groundwater population with nutrient, was undertaken in Mississauga (Ontario, Canada) following a number of laboratory experiments in static microcosms (Ross et al., 1998) (Ross et al., 2001a) and in flow-through apparatus (Ross et al., 2001b; Ross et al., 2002). This site, a flat-lying, thinly bedded shale (groundwater velocity of $5 \ m \cdot day^{-1}$), has been well characterized (Lapcevic et al., 1999; Novakowski, 1992; Novakowski and Lapcevic, 1994; Novakowski et al., 1995).

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 thermistors and tracer 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.

MATERIALS AND METHODS

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 (Lapcevic et al., 1990). Previous work (Novakowski, 1988) 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 (Lapcevic et al., 1999; Novakowski et al., 1995; Novakowski et al., 1998). Consequently, the properties of the fracture and the local flow system, prior to the development of a biobarrier, have been well characterized.

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 provides a schematic of the borehole layout and the fracture aperture measured at each location (Novakowski, 1988). 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. A more detailed description of the site, instrumentation and past work can be found in (Ross and Bickerton, 2002).

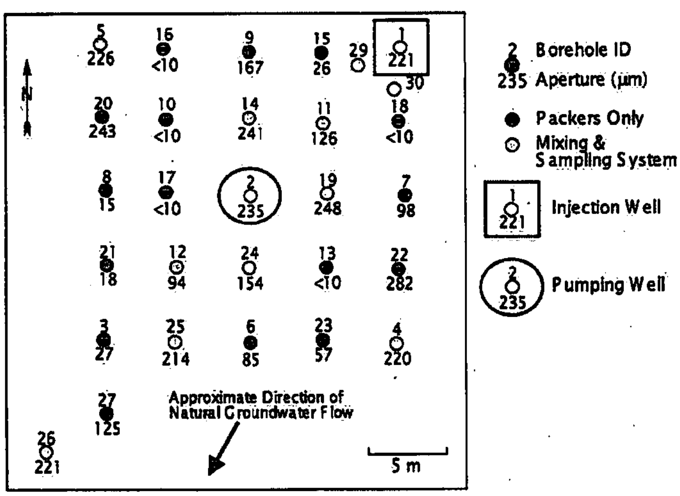

FIGURE 1. Schematic of field site and borehole layout.

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.

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. For this experiment, two independent methods were used to measure changes in the flow pattern within the fracture. Specifically, forced-gradient tracer experiments and the point dilution technique were used.

Point dilution tests (Drost et al., 1968) 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 were used in this experiment) 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.

Tracer experiments were also performed on a routine basis during the experiment and just prior to the injection of nutrients. The tests were conducted in an injection-withdrawal format (e.g. Novakowski et al. 1985) which involved injecting two tracers, bromide and Lissamine FF, into the injection well and monitoring their arrivals in the withdrawal wells and intermediate boreholes. The results were used mainly in a qualitative fashion to monitor changes in the average groundwater velocity between the two wells and to identify the presence of obstructions in the natural flow paths. The presence of biofilm in the fracture would be inferred based on significant changes in the pattern of successive breakthrough curves and retardation of the Lissamine FF relative to the bromide tracer. Previous tests in the fracture have shown both tracers to behave conservatively.

Biostimulation of the indigenous bacterial community. The biostimulation is conducted by injecting molasses (sol. 14 %) (Ross et al., 1998) and a nitrate source (sol. 500 mg · L^{-1}) in BH-1 at 5 mL · min^{-1} for 3 weeks pumped in 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 (Dubois et al., 1956).

RESULTS AND DISCUSSION

Acquisition of Groundwater Background Data. On average over one year, the groundwater showed a high salinity throughout the site (Figure 2-A) (Todd, 1980). 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 (Novakowski et al., 2003).

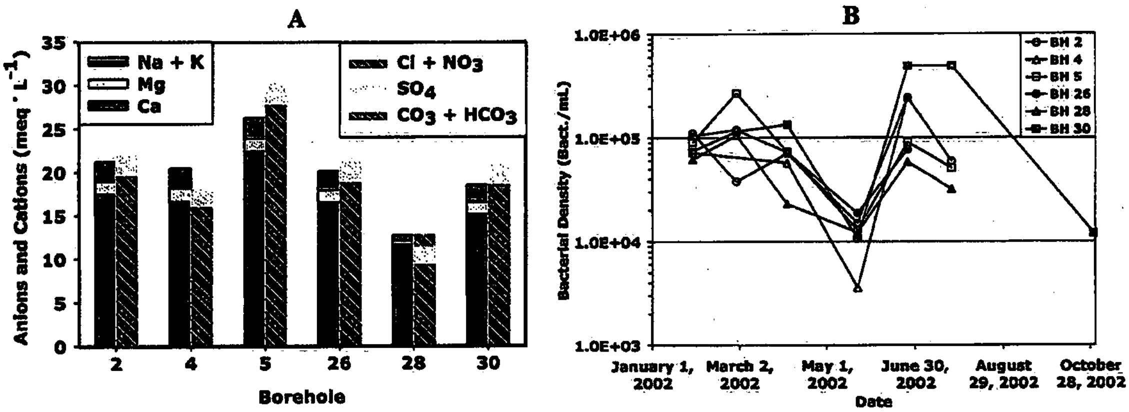

FIGURE 2. Groundwater chemical composition on average for a year (A) and changes in the bacterial density over a year (B) for 6 monitoring boreholes.

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 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).

Point dilution and tracer 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., 1995; Novakowski et al., 2003). Notice in Figure 2 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.

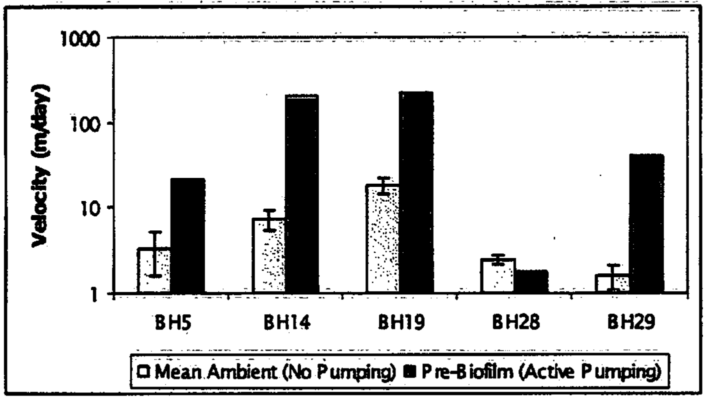

FIGURE 3. Groundwater velocities from selected boreholes under ambient and active pumping conditions (pre-biofilm development). Error bars describing the variability in ambient velocities is indicated by +/- 1 standard deviation.

The tracer experiment was conducted only under active pumping conditions. The test was initiated by injecting 50 ml of the mixture of 1 g/L Lissamine FF and 30 g/L of KBr into BH1 followed by 25 ml of deionized water to clear the sample lines. The movement of the tracer was monitored primarily in the withdrawal well BH2 but also in intermediate boreholes equipped with sample lines. During the experiment, the pumping rate varied between 214 and 298 ml/minute in the injection well and between 228 and 300 ml/minute in the withdrawal well. The Lissamine FF results of the pre-biofilm test are presented in FIGURE 4 for the withdrawal well BH2. The peak of the break-through curve suggests an average linear velocity of 58.4 m/day between BH1 and BH2. This result is consistent with the point dilution results presented in Figure 3. The proximity of BH14, BH19 and BH29 to active pumping wells would be expected to produce groundwater velocities greater than the integrated average found between BH1 and BH2. Although not shown, the break-through of the tracer in BH11, BH14, BH19, BH29 and BH30 also suggested that transport between BH1 and BH2 occurred preferentially to the east of the centre line joining the two wells.

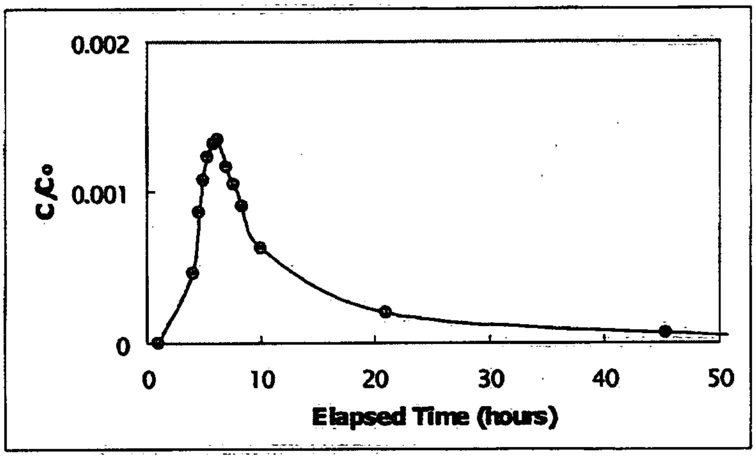

FIGURE 4. Lissamine FF results of the pre-biofilm tracer experiment for the withdrawal well BH2.

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.

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