Steam injection to displace DNAPLs from fractured media

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Abstract Steam was injected into laboratory scale cores of natural fractured permeable (sandstone) and impermeable (granite) rocks to evaluate tetrachloroethylene (PCE) removal efficiency. X-ray computer-assisted scanning was used to determine PCE saturations before, during and after application of steam, to determine removal efficiency and preferential pathways. Steam enters through the fracture displacing PCE and water, but rapidly condenses as the steam loses heat to the surrounding rock matrix. Steam continues to condense until the surrounding matrix is at least at the steam's temperature and pressure. Sharp steam fronts help ensure that all of the fracture and a significant fraction of the rock matrix is heated, reducing steam breakthrough. High DNAPL removal efficiencies were obtained, but with significantly different behavior for permeable and impermeable media, which must be incorporated into numerical models.

INTRODUCTION

The conceptual model of a typical contaminant spill into porous and fractured media has been put forward by Abriola (1989), Mercer & Cohen (1990), Kueper & McWhorter (1991) and Parker *et al.* (1994). In some cases, the contaminant is dissolved in water and thus travels in a fractured aquifer or aquitard as a solute. Fractures provide a fast channel for widely distributing the contaminant throughout the aquifer and also result in contaminant transport in somewhat unpredictable directions, depending on the fracture planes that are intersected (Hsieh *et al.*, 1985).

More typically a contaminant enters the subsurface as a liquid phase separate from the gaseous or aqueous phases present (Fig. 1). The NAPL may be leaking from a damaged or decaying storage vessel (e.g. in a gasoline station or a refinery) or a disposal pond, or may be spilt during transport and use in a manufacturing process (e.g. during degreasing of metal parts, in the electronics industry to clean semiconductors, or in an airfield for cleaning jet engines). The NAPL travels first through the unsaturated zone, under three-phase flow conditions, displacing air and water. The variations in matrix permeability, due to the heterogeneity of the porous medium, result in additional deviations from vertical flow. If the NAPL encounters layers of slightly less permeable materials (e.g. silt or clay lenses, or even tightly packed sand), or materials with smaller pores and thus a higher capillary entry pressure (e.g. NAPL entering a tight, water-filled porous medium), it will tend to flow mostly in the horizontal direction until it encounters a path of less resistance, either more permeable or

with larger pores. Microfractures in the matrix are also important in allowing the NAPL to flow through these low-permeability lenses.

If the NAPL is denser than water (e.g. chlorinated organic solvents, polychlorinated biphenyls, tars and creosotes), then once it reaches the water table it begins to form a mound and spread horizontally until either there is enough mass to overcome the capillary entry pressure or it finds a path of less resistance into the water-saturated matrix, either a fracture or a more porous/permeable region. Once in the saturated zone, the DNAPL travels downward until either it reaches a low enough saturation to become disconnected (forming drops or "ganglia") and immobile, or it finds a low-permeability layer. If the layer does not extend very far, the DNAPL will flow horizontally around it. In many cases, the DNAPL reaches bedrock or a tight clay layer. These layers usually contain fractures into which the DNAPL flows readily, displacing water. The capillary entry pressure into most fractures is quite low, on the order of a few centimetres of DNAPL head (Kueper & McWhorter, 1991). Flow into the fractures continues until either the fracture becomes highly DNAPL saturated, or the fracture is filled or closed below, or the DNAPL spreads thin enough to become disconnected. The DNAPL may flow into horizontal fractures within the fracture network.

In terms of remediation strategies, DNAPLs in fractured bedrock are probably one of the most intractable problems (National Research Council, 1994). They are a continuous source of dissolved contaminants for years or decades, making any pumping or active bioremediation alternative a very long term and costly proposition. Excavation down to the fractured bedrock is very expensive in most cases, and removal of the contaminated bedrock even more so. Potential remediation alternatives for consideration, include dewatering the contaminated zone via high-rate pumping and then applying Soil Vapour Extraction to remove volatile DNAPLs, or applying steam to mobilize and volatilize the DNAPL towards a collection well.

Steam injection has been proposed as a means of cleaning up underground contamination (EPA, 1995; Udell & Stewart, 1989), and is commonly used to enhance oil recovery. Several processes are at work during steam injection. The mobility of NAPL is increased by reducing its viscosity (Willman *et al.*, 1961) and in some cases the interfacial tensions decrease (Akatsuka *et al.*, 1995) as the temperature of the fluids rises. A hot water bank forms ahead of the steam front, which displaces NAPL ahead of it (Prats, 1986). NAPL can more easily volatilize into the gas phase, where it can then be removed in the outlet.

For steam injection into fractured rock, steam enters first through the fracture, but rapidly condenses as the steam loses heat to the surrounding rock matrix. Steam will continue to condense until the surrounding matrix is at least at the steam's temperature and pressure. This mechanism promotes sharp fronts which help ensure that all of the fracture and a significant fraction of the matrix is heated, rather than having steam travel very fast through the fracture to the outlet (or producing well).

OBJECTIVES

High resolution imaging techniques were applied to understand the flow of DNAPLs in fractures and to:

- remove the source of groundwater contamination,
- understand the physicochemical processes involved in steam injection, relevant to fracture flow,
- develop process to mobilize trapped residual DNAPL by altering environmental conditions,
- provide insights to interpret and improve numerical modeling of steam injection in fractures.

EXPERIMENTAL METHOD

CAT-scanning was used to image fractured rock cores, and to visualize the flow of single and multiple phases through the fracture, including:

(1) Fracture characterization: determine the fracture aperture distribution at very high resolution and non-destructively, to use in numerical modeling of the flow behaviour. The fracture aperture can be related to permeability or hydraulic conductivity through the "cubic law". Also used to map out the fracture network, connectivity and three-dimensional orientation.

(2) Single phase flow experiments: to characterize the overall absolute permeability and dispersivity of the fractures, and verify the numerical models.

(3) Two-phase flow experiments: to understand the contamination process, determine the relative permeabilities of water, air and NAPL in the fractures, and evaluate the role of viscous, capillary and gravity forces in two-phase flow.

(4) Three-phase flow experiments: conducted at room temperature and under steam injection conditions, to understand the role of the various forces and evaluate the effectiveness of steam injection in removing DNAPLs from fractured media.

Two different rock types were used in the experiments: impermeable granite and permeable sandstone. The porous rock matrix is expected to play very different roles in accumulating NAPL, water or energy during the flow experiments. The naturally fractured and unfractured rock cores were placed inside polycarbonate core holders, with an epoxy seal between the core holder and the rocks to avoid short-circuiting of fluids along the exterior of the rock cores. Thermocouples were placed along the length of the core to measure temperature rise during steam injection. The rock cores were typically 50 to 75 mm in diameter and 150 to 250 mm long.

RESULTS

A typical cross section of a fractured granite core is shown in Fig. 2. The core was scanned along its length, with over 140 scans collected to generate the fracture aperture distribution shown in Fig. 3. Details on the resolution of the scanning can be found in Keller (1997). Fracture apertures are on average around 0.45 mm for the granite cores and 0.2 mm for the sandstone cores, although some regions have apertures up to 4.5 mm.

Figure 4 presents the end of the PCE contamination of a granite fracture initially filled with water. The displacement is mostly through preferential paths, since the pressure required to move the DNAPL through the fracture is very low and it does not overcome the capillary forces trapping water in the small fracture apertures. In effect, DNAPL breaks into disaggregated ganglia rapidly within this fractured rock. DNAPL does not enter the granite matrix. In fact, experiments with water-saturated sandstone cores behave very similarly to the granite cores; DNAPL does not enter the matrix since the water is held tightly by the very small sandstone pores, and the DNAPL flow can easily be diverted through the fracture.

Figure 5 shows the final PCE saturation after steam injection. Very low residual NAPL is present. Considering that eight scans are required to generate each image of NAPL distribution after steam injection, the error bars on NAPL saturation are on the order of around ±15%, which indicates that the saturation may be essentially zero after steam injection. The mass balance results indicate that >95% of the PCE was recovered after steam injection from both granite and sandstone cores.

CONCLUSIONS

Removal efficiency in the fracture plane is high, typically greater than 99%. The steam front advances much faster in fractured sandstone than unfractured sandstone cores due to better heat transfer from the fracture to the matrix. The removal efficiency in sandstone matrix will depend strongly on fracture spacing, which controls the amount of heat that can be delivered. For granite cores, DNAPL removal is similar to simple water flooding, since the "sweep" efficiency through the fracture is almost the same; water flooding does not require the application of heat which reduces the cost significantly vs. steam injection. Fracture-matrix interactions play a major role in DNAPL removal efficiency using steam. Steam injection may result in very high DNAPL removal efficiency in fractured media due to sharp fronts and better heat transfer.

Acknowledgements The work was carried out in collaboration with Dr. Martin Blunt (Petroleum Eng. Stanford University) and Dr. Paul Roberts (Civil Eng., Stanford University) and was partially funded by Project SU-95-4 from the US EPA and the DoD through the Western Region Hazardous Substance

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FIGURE 1. Typical DNAPL spill scenario.

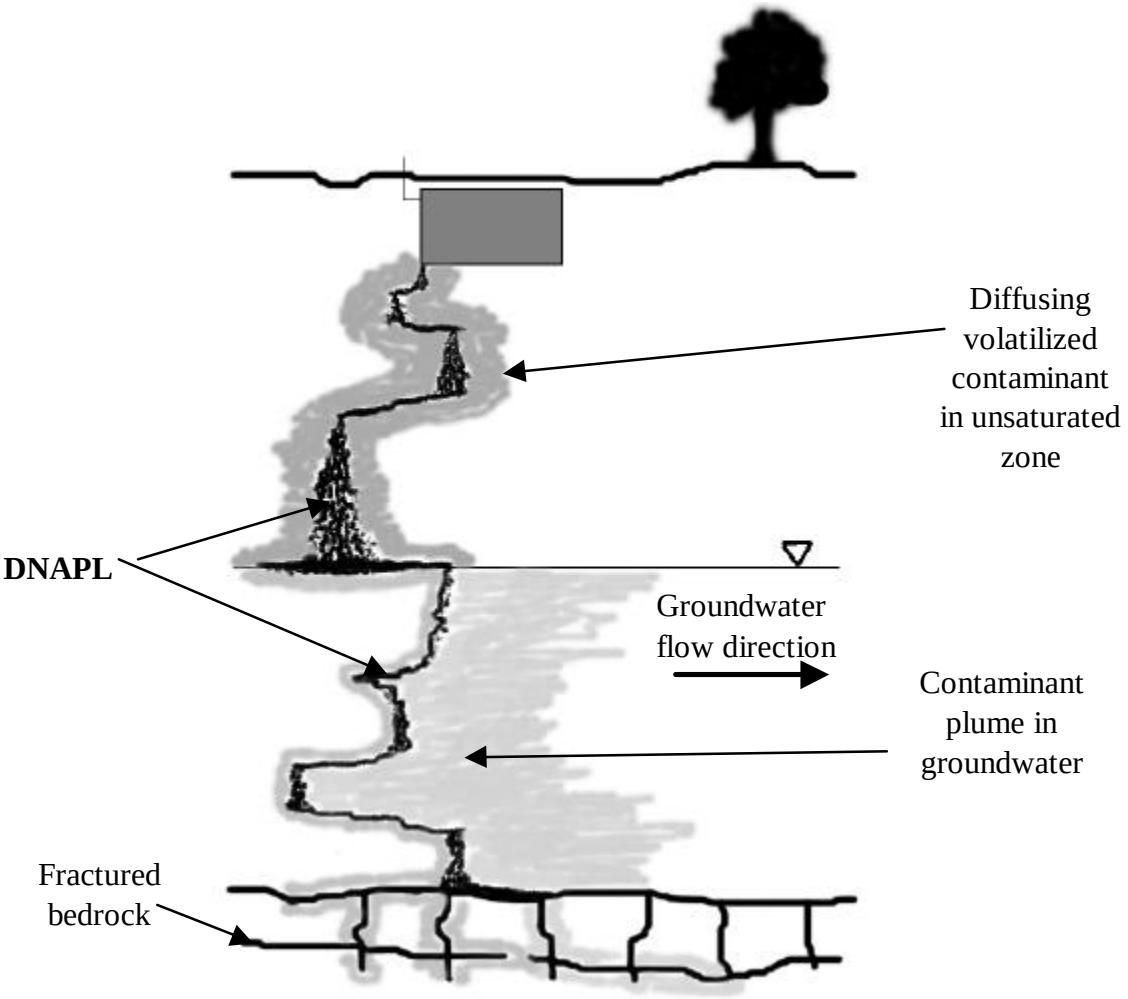

FIGURE 2. Typical CAT-scan of a fractured granite core.

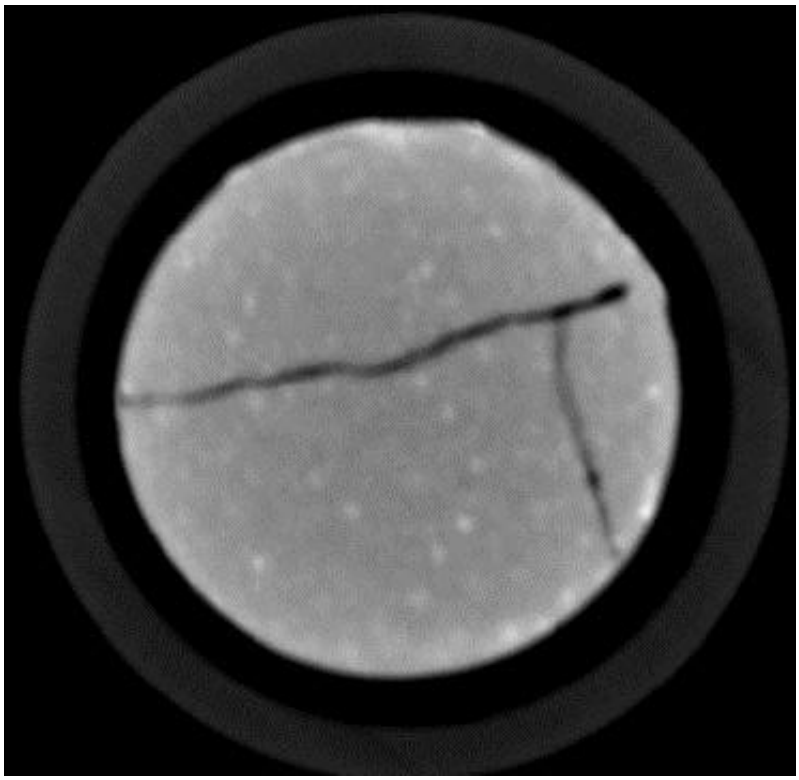

FIGURE 3. Fracture aperture distribution of a granite core.

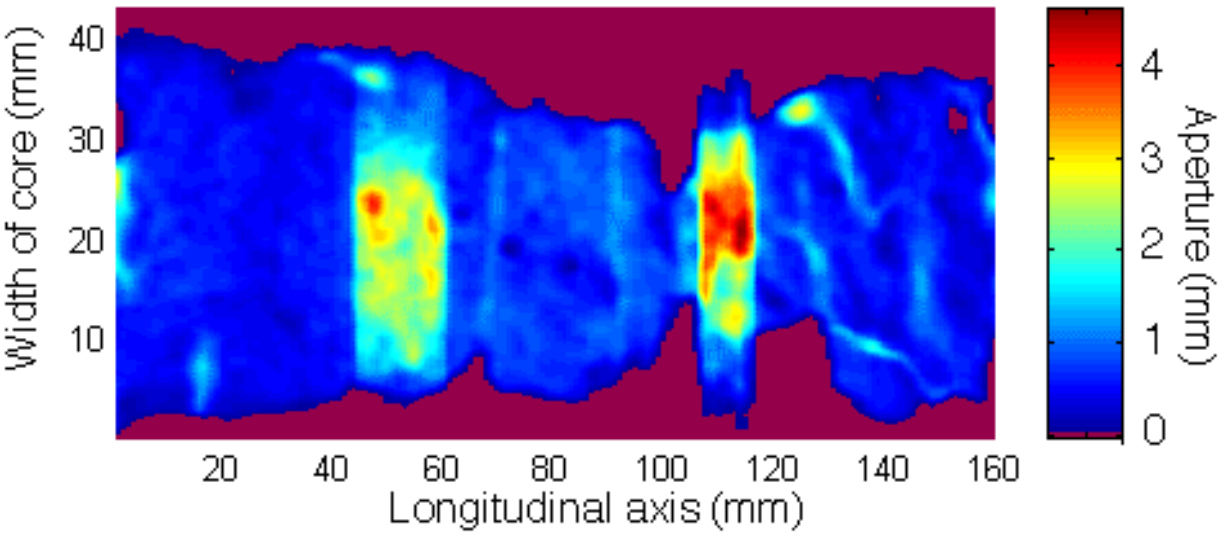

FIGURE 4. End of PCE contamination of fractured granite core.

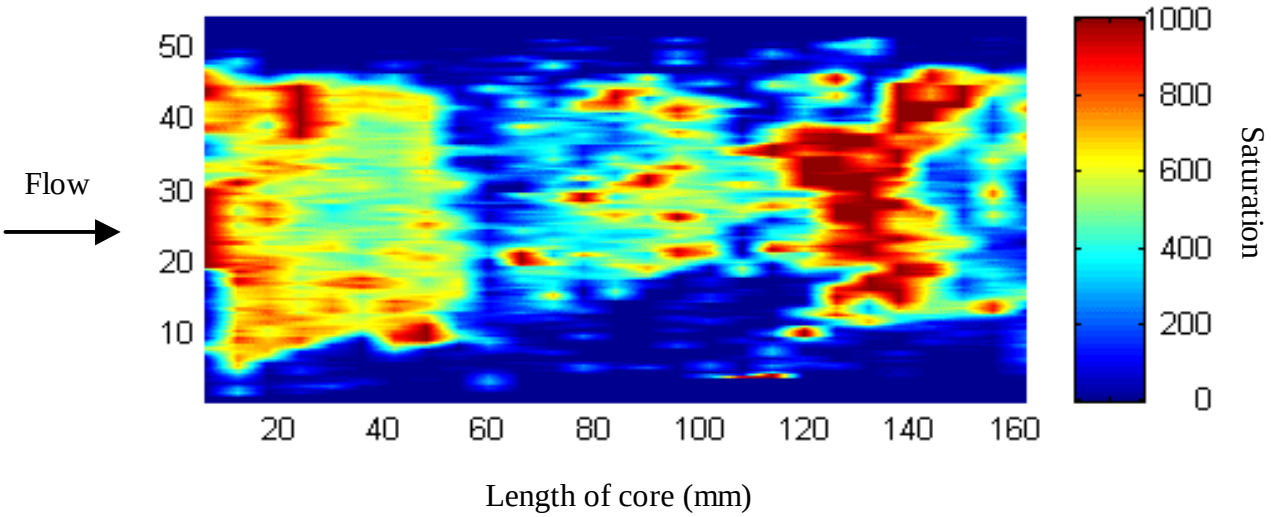
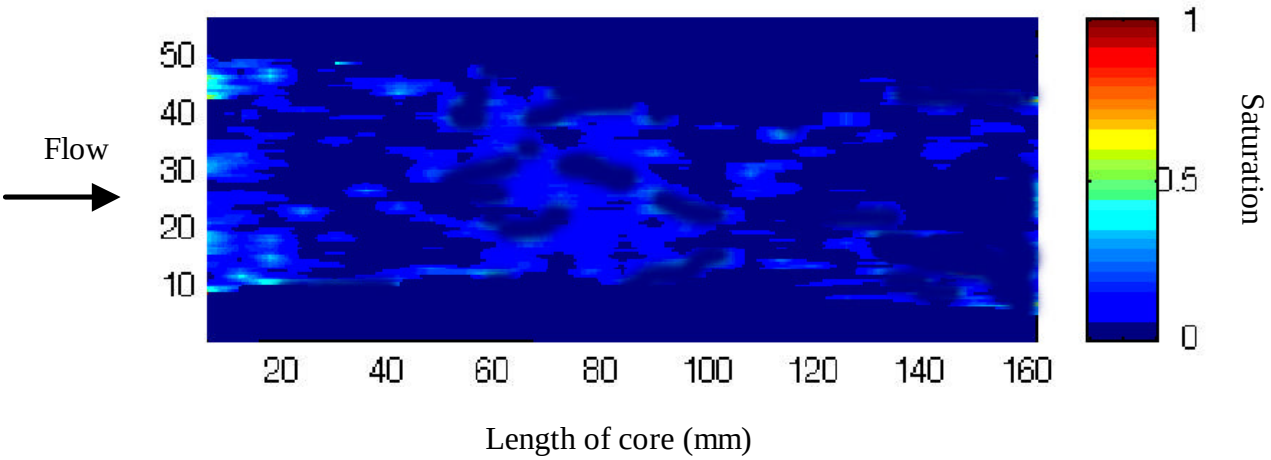
FIGURE 5. Residual PCE contamination after steam injection in granite.