

USER'S GUIDE

Demonstration of a Fractured Rock Geophysical Toolbox (FRGT) for Characterization and Monitoring of DNAPL Biodegradation in Fractured Rock Aquifers

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14. ABSTRACT Our overarching goal is to advance the cost-effective, appropriate use of geophysical technology in fractured rock. Specifically, we envision the FRGT-MST (1) equipping remediation professionals with a tool to understand what is likely to be realistic and cost effective when contracting geophysical services, and (2) reducing misguided, money-wasting applications of geophysical methods at sites where those methods are doomed to failure.						
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INTRODUCTION

Geophysical technologies have the potential to improve site characterization and monitoring in fractured rock, but the appropriateness and effectiveness of geophysics at a particular site depends strongly on project goals (e.g., identifying discrete fracture zones, mapping hydraulic properties, tracking contamination or remediation efforts, etc.) and site characteristics (e.g., lithology, depth to bedrock, presence of infrastructure). No method works at every site or for every goal. New approaches are needed to identify the set of geophysical methods appropriate to project goals, their likely effectiveness given site conditions, and practical cost considerations given project budget constraints. To this end, we present the Excel-based Fractured-Rock Geophysical Toolbox Method Selection Tool (FRGT-MST). Our overarching goal is to advance the cost-effective, appropriate use of geophysical technology in fractured rock. Specifically, we envision the FRGT-MST (1) equipping remediation professionals with a tool to understand what is likely to be realistic and cost effective when contracting geophysical services, and (2) reducing misguided, money-wasting applications of geophysical methods at sites where those methods are doomed to failure.

APPROACH

The FRGT-MST is a user-friendly Excel-based software (**Figure 1**) for identification of the set of geophysical methods likely to be appropriate and effective for a given set of project goals based on site conditions. The ‘toolbox’ comprises 30 different geophysical methods divided into 4 categories: surface, cross-hole, borehole, and hydrologic. The user enters information in two tables (1) project and site parameters, including budget level; and (2) project goals (**Figure 2**). A third table is populated with indicators for whether each method could potentially support any of the specified goals, and whether each method is likely to work at the site described (**Figure 2**). The suite of potentially suitable methods is thus the intersection of the sets of appropriate and feasible methods.

Excel conditional formatting is used throughout the spreadsheet, coded based on simple rules of thumb and common-sense constraints for experiment design. For example:

- the feasibility of borehole optical televiewer requires that borehole fluids are not muddy/opaque;
- the feasibility of borehole radar requires that boreholes are open or PVC-cased; and
- the feasibility of crosshole methods with sufficient resolution generally requires well aperture (vertical:horizontal imaging area) >1.5.

Excel conditional formatting is also coded to identify which methods support specified project goals. For example,

- ERT is appropriate technology for time-lapse monitoring;
- surface seismic is appropriate technology for mapping depth to bedrock; and
- focused packer testing is appropriate technology for measuring small-scale hydraulic properties.

A series of 30 worksheet appendices are provided in the FRGT-MST, each with information on a different method from the toolbox (**Figure 3**). The appendices are hyperlinked from the table of methods in the FRGT MATRIX worksheet (**Figure 2**). Appendices provide basic information on the various

methods—a key reference and several graphics showing the instrumentation and (or) example results. The appendices are intended to provide overviews rather than in-depth information.

FRGT METHOD SELECTION TOOL

by F.D. Day-Lewis, C.D. Johnson, L.D. Slater, J.D. Robinson, D. Alarlagiannis, and C. L. Boyden

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<http://water.usgs.gov/logwbgas>

Last updated: 07/10/2015

This program was designed to run in Excel Microsoft Office 2010

SUMMARY
The Fractured Rock Geophysical Toolbox comprises a suite of geophysical methods for aquifer characterization and monitoring. This spreadsheet-based tool is designed to assist project managers and scientists in selecting tools that (1) satisfy study goals, and (2) are feasible for application at a given site, based on site characteristics as entered by the user.

INSTALLATION
Just use this spreadsheet. You may need to reset macro security to include the location of this file as a "trusted site." Go to "Excel Options" under the "Office Button." The spreadsheet is designed for use in Excel 2010 or later.

INPUT
The user must enter a site description and study goals using on the FRGT MATRIX worksheet using the numeric up-downs and menus provided.

OUTPUT
The spreadsheet will indicate the degree to which methods will be useful for satisfying project goals and which methods are likely feasible given the characteristics of the site.

DISCLAIMER
In our experience no one tool or single method achieves all goals when working in fractured-rock aquifers. We encourage a multi-disciplined approach that uses methods that measure different subsurface properties, thereby improving the detection, characterization, and interpretation of the aquifer. This FRGT utility is intended to help select methods and to assess their appropriateness and the potential for success given the goals of your investigation.

Results at any one site may vary depending on the actual tools and acquisition settings used. We recommend that when making tool selections you read the manuals or consult the vendors for the range of operation for each tool. The tools shown in the appendix are for descriptive purposes only and do not constitute an endorsement of any particular brand or tool.

ACKNOWLEDGMENTS
Development of this tool was supported by the Environmental Security Technology Certification Program through grant ER-201118 and by the US Geological Survey Toxic Substances Hydrology Program.

INTRODUCTION FRGT MATRIX M1 M2 M3 M4 M5 M6 M7 M8 M9 M10 M11 M12 M13 M14 M15 M16 M17

Figure 1. FRGT INTRODUCTION worksheet which provides background information and instructions for the use of the FRGT-MST.

FRGT METHOD SELECTION TOOL											USGS science for a changing world		RUTGERS Environmental Social Technology Center						
Fill in cells shaded aqua-blue (in column D). All other cells will be automatically updated. ☒ Indicates method is potentially suitable ☐ Indicates method is likely not suitable ☒ Indicates method is likely appropriate/effective ☐ Indicates method is not likely appropriate/effective 																			
Project and site parameters 1. What is the depth to bedrock (m)? 15 2. What is the electrical resistivity of bedrock (ohm-m)? 500 3. What is the minimum spacing between wells (m)? 4 4. What is the well casing? Open 5. What is the vertical extent of open holes (m)? 50 6. Is borehole fluid turbid/muddy (opaque)? Yes 7. Borehole diameter (inches) 6 8. Cultural EM interference? (utilities, pipes, etc.) Yes 9. Is it possible to disturb the ground for electrodes or geodes? Yes 10. What is native groundwater conductivity (micro-S/cm)? 150 11. What is the project cost threshold for a given method? Medium				Methods Appropriate for goals Effectiveness at site Relative cost Method contributes to goal: Made infeasible by site parameter:				Method contributes to goal: Made infeasible by site parameter:											
Goals A. Identify discrete fracture network characteristics No B. Identify lithologic contacts No C. Map depth to bedrock No D. Understand large-scale anisotropy, average fracture cov. No E. Estimate discrete fracture hydraulic properties Yes F. Estimate small-scale effective hydraulic properties Yes G. Estimate large-scale hydraulic properties Yes H. Identify interval hydraulic connections Yes I. Time-lapse snapshots of amendment delivery Yes J. Continuous monitoring of degradation No K. Screening for iron minerals No				Surface methods 1. EM terrain conductivity (induction) ☒ ☒ Low 2. ERT ☒ ☒ Low 3. GPR ☒ ☒ Low 4. Resistivity - azimuthal ☒ ☒ Low 5. SP - azimuthal ☒ ☒ Low 6. Seismic refraction ☒ ☒ Low 7. Seismic reflection ☒ ☒ Medium 8. Time-domain EM ☒ ☒ Low				Cross-hole methods 9. ERT ☒ ☒ Medium 10. GPR ☒ ☒ High 11. IP ☒ ☒ Medium 12. Seismic ☒ ☒ High				Borehole methods 13. ATV ☒ ☒ Low 14. Caliper ☒ ☒ Low 15. EM induction ☒ ☒ Low 16. Flowmeter (single hole) ☒ ☒ Low 17. Flowmeter (cross-hole) ☒ ☒ Low 18. Damu ☒ ☒ Low 19. IP and Normal Resistivity ☒ ☒ Low 20. Magnetic susceptibility ☒ ☒ Medium 21. NMR ☒ ☒ Low 22. OTV ☒ ☒ Low 23. Radar (borehole GPR) ☒ ☒ Medium 24. Video camera ☒ ☒ Low				Hydrologic tests 25. Dilution/Fluid replacement ☒ ☒ High 26. Focused packer testing ☒ ☒ High 27. Fluid resistivity & temperature ☒ ☒ Low 28. High resolution temperature ☒ ☒ High 29. Open-hole hydraulic tests ☒ ☒ Medium 30. Tracer tests ☒ ☒ High			
Assumptions - Wells are partially or completely fluid filled				This FRGT utility is intended to help select methods and to assess their appropriateness and the potential for success given the goals of your investigation. Actual performance of the geophysical and hydraulic tools may vary depending on the specific tool used and acquisition settings.															
Comments																			

Figure 2. FRGT MATRIX worksheet, where the user enters project/site parameters and goals and the output table is generated showing which methods are likely feasible for the site and appropriate to specified goals. Method satisfying both feasibility and appropriateness conditions are indicated by 'green lights' in column F, whereas methods that are infeasible or inappropriate are indicated by 'red lights.'

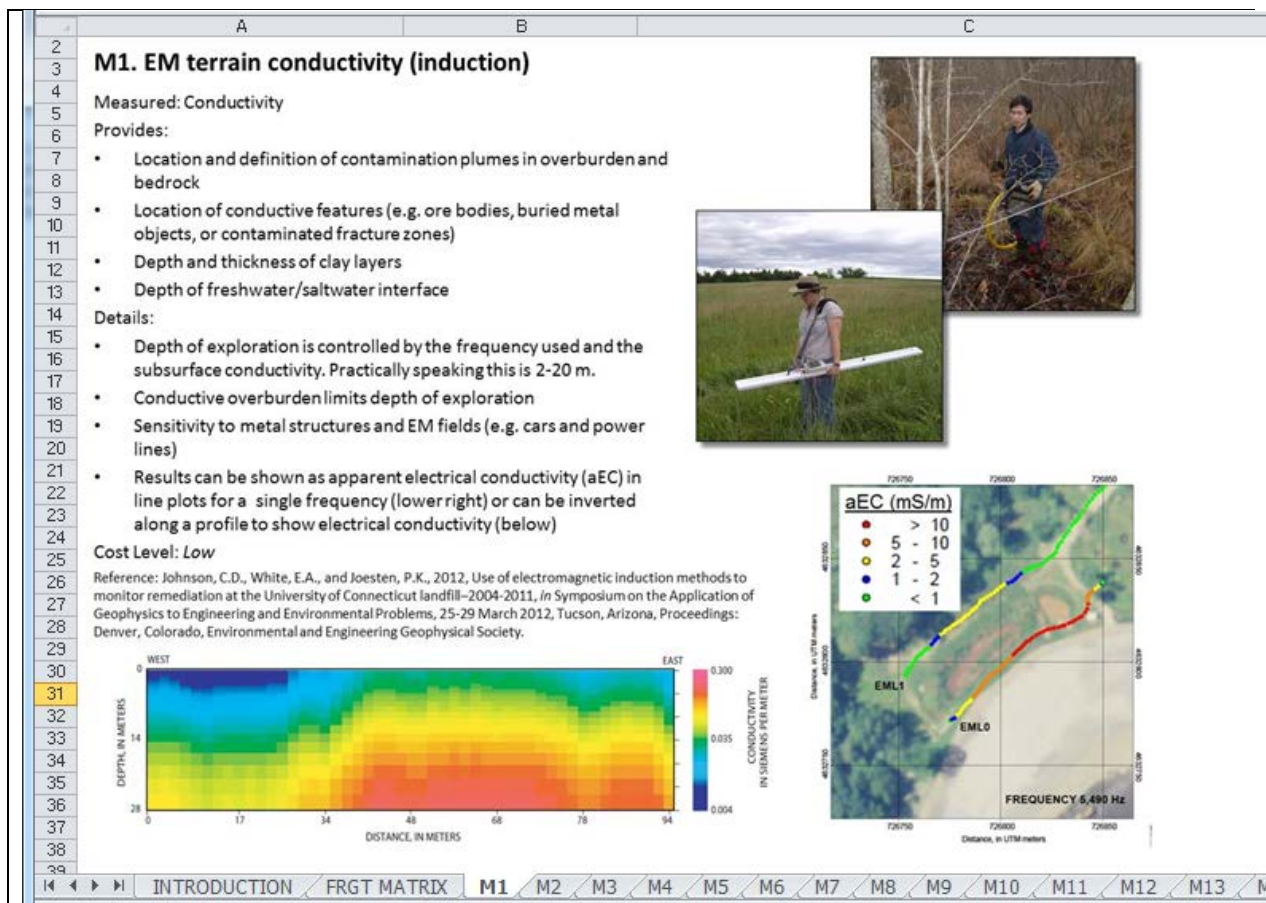


Figure 3. Worksheet appendix M1, providing an overview of surface-based electromagnetic terrain conductivity.

EXAMPLE

The distributed FRGT-MST Excel file reflects project parameters/goals and site characteristics for the U.S. Geological Survey research site at the Naval Air Warfare Center (**Figure 4**). The results of the spreadsheet analysis correctly indicate that (1) borehole and cross-hole radar methods are unlikely to work at the site, and (2) borehole gamma and electromagnetic methods are likely to work and also support project goals. In this case, these recommendations are based on relatively simple site geological information, in addition to the project goals, provided by the user.

FRGT METHOD SELECTION TOOL											USGS science for a changing world		RUTGERS Environmental Science Technology Center Program	
Fill in cells shaded aqua-blue (in column D). All other cells will be automatically updated. ● indicates method is potentially suitable ○ indicates method is likely not suitable ● indicates method is likely appropriate/effective ○ indicates method is not likely appropriate/effective 														
Project and site parameters 1. What is the depth to bedrock (m)? 15 2. What is the electrical resistivity of bedrock (ohm-m)? 100 3. What is the minimum spacing between wells (m)? 4 4. What is the well casing? Open 5. What is the vertical extent of open holes (m)? 20 6. Is borehole fluid turbid/muddy (opaque)? No 7. Borehole diameter (inches) 6 8. Cultural EM interference? (utilities, pipes, etc.) Yes 9. Is it possible to disturb the ground for electrodes or geodes? Yes 10. What is native groundwater conductivity (micro-S/cm)? 150 11. What is the project cost threshold for a given method? High				Methods Surface methods 1. EM terrain conductivity (induction) ● ● ● Low 2. ERT ● ● ● Low 3. GPR ● ● ● Low 4. Resistivity - azimuthal ● ● ● Low 5. SP - azimuthal ● ● ● Low 6. Seismic refraction ● ● ● Medium 7. Seismic reflection ● ● ● Low 8. Time domain EM ● ● ● Low Cross-hole methods 9. ERT ● ● ● Medium 10. GPR ● ● ● High 11. IP ● ● ● Medium 12. Seismic ● ● ● High Borehole methods 13. ATV ● ● ● Low 14. Caliper ● ● ● Low 15. EM induction ● ● ● Low 16. Flowmeter (single hole) ● ● ● Low 17. Flowmeter (cross-hole) ● ● ● Low 18. Gamma ● ● ● Low 19. IP and Normal Resistivity ● ● ● Low 20. Magnetic susceptibility ● ● ● Low 21. NMR ● ● ● Medium 22. OTV ● ● ● Low 23. Badger (borehole GPR) ● ● ● Medium 24. Video camera ● ● ● Low Hydrologic tests 25. Dilution/fluid replacement ● ● ● High 26. Focused packer testing ● ● ● High 27. Fluid resistivity & temperature ● ● ● Low 28. High resolution temperatures ● ● ● High 29. Open-hole hydraulic tests ● ● ● Medium 30. Tracer tests ● ● ● High				Method contributes to goal: A B C D E F G H I J K		Made infeasible by site parameter: 1 2 3 4 5 6 7 8 9 10 11				
Goals A. Identify discrete fracture network characteristics Yes B. Identify lithologic contacts Yes C. Map depth to bedrock No D. Understand large-scale anisotropy, average fracture orientation No E. Estimate discrete fracture hydraulic properties Yes F. Estimate small-scale effective hydraulic properties Yes G. Estimate large-scale hydraulic properties No H. Identify interval hydraulic connections Yes I. Time-lapse snapshots of amendment delivery Yes J. Continuous monitoring of degradation No K. Screening for iron minerals No														
Assumptions - Walls are partially or completely fluid filled														
Comments - May require the use of a borehole liner.														
This FRGT utility is intended to help select methods and to assess their appropriateness and the potential for success given the goals of your investigation. Actual performance of the geophysical and hydrologic tools may vary depending on the specific tool used and acquisition settings.														

Figure 4. FRGT Matrix with inputs and output for the U.S. Geological Survey research site at the Naval Air Warfare Center in West Trenton, NJ.

DISCUSSION AND LIMITATIONS

We encourage users to look at the equations used throughout the spreadsheet to gain insight into experiment-design parameters and the potential uses of various methods. We stress that the FRGT-MST is, necessarily, a simple tool and like any tool, its capabilities are limited. The results of the spreadsheet analyses are not the official recommendations of USGS or Rutgers. The USGS and Rutgers provide no warranty, expressed or implied, as to the correctness of the furnished software or the suitability for any purpose. The software has been tested, but as with any complex software, there could be undetected errors. Users who find errors are requested to report them to the Dr. Frederick Day-Lewis (USGS) at daylewis@usgs.gov.

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