

Final copy as submitted to *Groundwater* for publication as:

Day-Lewis, F.D., Johnson, C.D., Slater, L.D., Robinson, J.L., Williams, J.H., Boyden, C.L., Werkema, D., and Lane, J.W., 2016, A Fractured Rock Geophysical Toolbox Method Selection Tool: *Groundwater*. doi:10.1111/gwat.12397

Title: A Fractured Rock Geophysical Toolbox Method Selection Tool

F.D. Day-Lewis (corresponding author), U.S. Geological Survey, 11 Sherman Place, Unit 5015, Storrs CT 06269, daylewis@usgs.gov

C.D. Johnson, U.S. Geological Survey, 11 Sherman Place, Unit 5015, Storrs CT 06269, cjohnson@usgs.gov

L.D. Slater, Department of Earth & Environmental Sciences, Rutgers University Newark, 101 Warren Street, Smith 135, Newark NJ 07102, lslater@andromeda.rutgers.edu

J.L. Robinson, Department of Earth & Environmental Sciences, Rutgers University Newark, 101 Warren Street, Smith 135, Newark NJ 07102, judyr@pegasus.rutgers.edu

J.H. Williams, U.S. Geological Survey, New York Water Science Center, 425 Jordan Rd., Troy, NY 12180, jhwillia@usgs.gov

C.L. Boyden, Former intern, U.S. Geological Survey, 11 Sherman Place, Unit 5015, Storrs CT 06269, clynetteboyden@gmail.com

D. Werkema, Environmental Sciences Division, Characterization and Monitoring Branch, U.S. Environmental Protection Agency, Office of Research and Development, 944 E. Harmon Ave., Las Vegas, NV 89119, werkema.d@epa.gov

J.W. Lane, Jr., U.S. Geological Survey, 11 Sherman Place, Unit 5015, Storrs CT 06269, jwlane@usgs.gov

Conflict of interest: None

Key words: geophysics, hydrogeophysics, fractured rock, field methods, characterization

Article impact statement: A spreadsheet-based software is presented to identify methods for use at fractured-rock sites, based on project goals and site description

Geophysical technologies have the potential to improve site characterization and monitoring in fractured rock, but the appropriate and effective application of geophysics at a particular site strongly depends on project goals (e.g., identifying discrete fractures) and site characteristics (e.g., lithology). No method works at every site or for every goal. New approaches are needed to identify a set of geophysical methods appropriate to specific project goals and site conditions while considering budget constraints. To

this end, we present the Excel-based Fractured-Rock Geophysical Toolbox Method Selection Tool (FRGT-MST). 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 applications of geophysics with unrealistic objectives or where methods are likely to fail.

The FRGT-MST is an Excel-based tool for identification of geophysical methods most likely to be appropriate for project goals and site conditions. The ‘toolbox’ comprises 30 surface, cross-hole, and borehole geophysical methods. Additionally, hydrologic tests appropriate to fractured rock are included. The user enters information in two tables for site parameters and project goals. Based on user entry, a third table is populated with indicators for which methods support specified goals and are feasible at the site. Worksheet appendices provide detailed information on various methods.

Conditional formatting is used throughout the spreadsheet, coded based on rules of thumb and common-sense constraints for experiment design. For example: (1) borehole optical televiewer requires that borehole fluids are not opaque; (2) borehole ground-penetrating radar (GPR) requires that boreholes are open or PVC-cased; and (3) cross-hole methods generally require well aspect ratio (vertical:horizontal imaging area) >1.5 for good resolution. Conditional formatting also indicates which methods support specified project goals.

As distributed, the FRGT-MST spreadsheet reflects application to the U.S. Geological Survey (USGS) research site at the Naval Air Warfare Center, West Trenton, New Jersey. The results of the FRGT-MST analysis correctly indicate that borehole and cross-hole radar methods are unlikely to work at the site, whereas borehole gamma and electromagnetic methods are likely to work and also support project goals. These recommendations are based on relatively simple site geologic information, in addition to the project goals.

We encourage users to examine the spreadsheet’s equations to gain insight into experiment design. We stress that the FRGT-MST is meant to be a simple tool. Like any tool, its capabilities are limited. The

results of the FRGT-MST are not the official recommendations of USGS, Rutgers, or EPA. The USGS, Rutgers University, and EPA 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 software, there could be undetected errors. Users who find errors are asked to report them to the first author. The spreadsheet is available from <http://water.usgs.gov/ogw/bgas/frgt>.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

[Appendix A. Supporting Information: Explanation and examples from the FRGT-MST spreadsheet](#)

Please note: "Supporting Information" is generally not peer reviewed. Wiley-Blackwell is not responsible for the content or functionality of any supporting information supplied by the authors. Any queries (other than missing materials) should be directed to the corresponding author.

Acknowledgment

This work was supported by ESTCP grant ER-201118, the U.S. Geological Survey (USGS) Toxic Substances Hydrology Program, USGS Office of Groundwater, and the U.S. Environmental Protection Agency (EPA) through its Office of Research and Development via agreement DW-14-92381701 to the USGS. This software tool has been subjected to USGS and EPA review and approved for publication. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Appendix A. Supporting Information

The FRGT-MST comprises Excel worksheets including (1) an introduction worksheet (**Figure S1**), (2) the FRGT MATRIX worksheet, where users input site and project information and results are generated (**Figure S2**), and (3) 30 worksheet appendices (**Figure S3**), which are hyperlinked from the FRGT MATRIX and provide information on the methods comprising the fractured rock geophysical toolbox. The FRGT-MST spreadsheet can be downloaded from <http://water.usgs.gov/ogw/bgas/frgt/>.

The screenshot shows the 'FRGT METHOD SELECTION TOOL' Excel spreadsheet. The title bar at the top reads 'FRGT METHOD SELECTION TOOL' in large blue letters. Below the title, there are logos for the U.S. Environmental Protection Agency, USGS (with the tagline 'science for a changing world'), and Rutgers University. The authors are listed as 'By F.R. Day-Lewis, C.D. Johnson, L.D. Slater, J.L. Robinson, John H. Williams, C. L. Boyden, D. Verheem, and J.W. Lane, et al.'. The contact info is 'http://water.usgs.gov/ogw/bgas/frgt'. The last updated date is '11/6/2015'. A note states 'This program was designed to run in Excel - Microsoft Office 2010'. The spreadsheet is divided into sections: SUMMARY, INSTALLATION, INPUT, OUTPUT, DISCLAIMER, and ACKNOWLEDGMENTS. A photograph on the right side shows a green tent set up outdoors near a building and a vehicle. The spreadsheet interface includes row numbers (1-42) and column letters (A-J).

Figure S1. FRGT INTRODUCTION worksheet which provides background information and instructions for the use of the FRGT-MST.

FRGT METHOD SELECTION TOOL																												
<p>Fill in cells shaded aqua-blue (in column C). All other cells will be automatically updated.</p> <p> <input checked="" type="checkbox"/> indicates method is potentially suitable <input type="checkbox"/> indicates method is likely not suitable <input checked="" type="checkbox"/> indicates method is likely appropriate/effective <input type="checkbox"/> indicates method is not likely appropriate/effective </p>																												
Project and site parameters		Methods	Appropriate for goals	Effectiveness at site	Relative cost	Method contributes to goal:											Made infeasible by site parameter:											
						A	B	C	D	E	F	G	H	I	J	K	1	2	3	4	5	6	7	8	9	10	11	
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)? 40 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 geophones? Yes 10 What is native groundwater conductivity (micro-S/cm)? 150 11 What is the project cost threshold for a given method? High		Surface methods																										
		1. EM terrain conductivity (induction)	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		2. ERT	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		3. GPR	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		4. Resistivity - azimuthal	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		5. SP - azimuthal	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		6. Seismic refraction	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		7. Seismic reflection	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Medium																							
		8. Time domain EM	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		Cross-hole methods																										
		9. ERT	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Medium																							
		10. GPR	<input checked="" type="checkbox"/>	<input type="checkbox"/>	High																							
		11. IP	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Medium																							
		12. Seismic	<input checked="" type="checkbox"/>	<input type="checkbox"/>	High																							
		Borehole methods																										
		13. ATV	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		14. Logplot	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		15. EM induction	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		16. Flowmeter (single hole)	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		17. Flowmeter (cross-hole)	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		18. Gamma	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		19. P and Normal Resistivity	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		20. Magnetic susceptibility	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		21. NMB	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Medium																							
		22. DTN	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		23. Badu (borehole GPR)	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Medium																							
		24. Video camera	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		Hydrologic tests																										
		25. Dilution/fluid replacement	<input checked="" type="checkbox"/>	<input type="checkbox"/>	High																							
		26. Focused pulsed current	<input checked="" type="checkbox"/>	<input type="checkbox"/>	High																							
		27. Fluid resistivity & temperature	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Low																							
		28. High resolution temperature	<input checked="" type="checkbox"/>	<input type="checkbox"/>	High																							
		29. Open-hole hydraulic tests	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Medium																							
		30. Tracer tests	<input checked="" type="checkbox"/>	<input type="checkbox"/>	High																							
		<p>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.</p>																										

Figure S2. 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. Methods 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.’

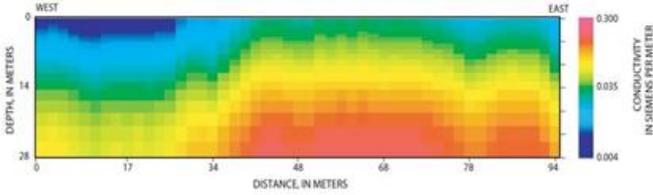
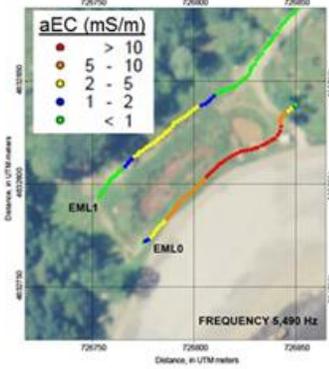
	A	B	C
2	M1. EM terrain conductivity (induction)		
3	Measured: Conductivity		
4	Provides:		
5	<ul style="list-style-type: none"> • Location and definition of contamination plumes in overburden and bedrock • Location of conductive features (e.g. ore bodies, buried metal objects, or contaminated fracture zones) • Depth and thickness of clay layers • Depth of freshwater/saltwater interface 		
6	Details:		
7	<ul style="list-style-type: none"> • Depth of exploration is controlled by the frequency used and the subsurface conductivity. Practically speaking this is 2-20 m. • Conductive overburden limits depth of exploration • Sensitivity to metal structures and EM fields (e.g. cars and power lines) • Results can be shown as apparent electrical conductivity (aEC) in line plots for a single frequency (lower right) or can be inverted along a profile to show electrical conductivity (below) 		
8	 		
9	Cost Level: Low		
10	Reference: Johnson, C.D., White, E.A., and Joesten, P.K., 2012. Use of electromagnetic induction methods to monitor remediation at the University of Connecticut landfill-2004-2011, in Symposium on the Application of Geophysics to Engineering and Environmental Problems, 25-29 March 2012, Tucson, Arizona, Proceedings: Denver, Colorado, Environmental and Engineering Geophysical Society.		
11	 		
12	<p>INTRODUCTION FRGT MATRIX M1 M2 M3 M4 M5 M6 M7 M8 M9 M10 M11 M12 M13 M14</p>		

Figure S3. Example FRGT worksheet appendix, M1, providing an overview of surface-based electromagnetic terrain conductivity.