Further Explorations into Ohio's Fractured Environment: Introduction to *The Ohio Journal of Science's* Second Special Issue on Fractures in Ohio's Glacial Tills[1]

Julie Weatherington-Rice, Ann D. Christy, and Michael P. Angle, Bennett and Williams Environmental Consultants Inc., Columbus, OH 43231; Department of Food, Agricultural, and Biological Engineering, The Ohio State University, Columbus, OH 43210; Ohio Department of Natural Resources, Division of Water, Columbus, OH 43224

Abstract. This paper summarizes the history of the Ohio Fracture Flow Working Group (OFFWG), describes their activities since the publication of the first special issue of *The Ohio Journal of Science* in 2000, and references selected recent publications by Ohio researchers, other researchers in the United States, and research efforts internationally. It also serves as an introduction to and overview of this second special issue of *The Ohio Journal of Science*.

Dedication. This special issue is dedicated to Jane L. Forsyth and Truman W. Bennett for their foundational contributions to glacial geology and hydrogeology, respectively, and their roles in understanding fractures in unconsolidated (glacial) materials.

OHIO J SCI 106 (2):4-8, 2006

INTRODUCTION

This second special issue on fractures of *The Ohio Journal of Science* comes to publication 13 years after the initial organization of the Ohio Fracture Flow Working Group (OFFWG) who gathered for the first time in March 1993 at The Ohio State University (OSU) to ask each other the fundamental questions *"Do you see cracks in the tills?"* and *"What do they mean?"* Functioning as an "ad hoc" research group under the umbrella of the Ohio Academy of Science, this working group was founded on the same basic principles as cooperative extension programs: simultaneous research, education, and outreach. The group has worked to solve and define the "*who, what, when, where, why, and how?"* of fracture formation and preservation in unconsolidated glacial materials. The solutions to those questions were presented in *The Ohio Journal of Science's* first special issue on fractures in Ohio's glacial tills (Weatherington-Rice and Christy 2000). This second special issue provides more research and documentation for the answers to these basic underlying questions and also takes these questions further to explore the "*how fast do fractures form, how long do fractures persist, and how we can plan land use in fractured terrain?"*

OFFWG Activities since the Last Special Issue in 2000

A rereading of the introduction to the first special issue on fractured tills (Weatherington-Rice and others 2000) notes planned OFFWG outreach efforts for 2000. In conjunction with the Water Management Association of Ohio, the OFFWG helped to organize a two-day conference and field trip on fractured glacial tills in May 2000 in Columbus, OH. Speakers from around the United States and Canada joined Ohio scientists and engineers in presentations and posters, and discussions at stops on the field trip. The abstracts and field guide for that conference are posted on the OFFWG web site at http://www.oardc.ohio-state.edu/fractures.

In March 2001, Peter Gravesen and Knud Erik Klint of the Geological Survey of Denmark and Greenland (http://www.geus.dk) came to Columbus for a one-day symposium and field trip of shared research with OFFWG members and colleagues. While the OFFWG continues to have contacts with researchers throughout the United States and Canada (the news group membership extends from Minnesota and Iowa to Washington, DC), the relationship with Denmark is particularly strong. The similarities between the bedrock and glacial geology of Denmark and that of western Ohio reinforce the shared experiences and challenges. Members of the OFFWG also participated in fracture and ground water conferences in Copenhagen, Denmark in 1998 and 2000.

During the summer and fall of 2001, the OFFWG coordinated the updating of the "OFFWG Fracture Bibliography" and the development of a bibliography addressing the issues of animal manure management as they affect surface and ground water sources. These bibliographies are posted on the OFFWG web site. In addition, Kathryn Clayton, the OFFWG intern for that summer, began compiling data that underlies the DRASTIC theory paper in this issue (Weatherington-Rice and others 2006a).

In October 2001, the OFFWG held a one-day symposium and field day in Defiance, OH, exploring fracture formation in the northwest Ohio Lake Plains. The paper by Weatherington-Rice and others (2006b) highlights one of the afternoon field stops along the Auglaize River. A similar one-day symposium and field day was held at OSU's Agricultural Technical Institute (ATI), Wooster, OH, in September 2003 to study fractures in the low-lime glacial tills of northeast Ohio. That experience explored the functions of fractures in fragipan

[1]Manuscript received 27 December 2005 and in revised form 18 January 2006 (#05-03F).

soils, including both a dyed pit study at ATI's Apple Creek farm and a fresh till cut at the Rupp Gravel Pit.

In 2004, the OFFWG held a one-day indoor workshop at OSU in September. This workshop explored the field of natural resources applications in a Geographic Information Systems (GIS) format. Since much of the basic underlying documentation needed to predict and map fractures is now available in a GIS format, this emerging technology has become a critical tool for mapping soils and DRASTIC Ground Water Pollution Potential (Weatherington-Rice and others 2006a). It also became a critical local land-use and zoning tool for local governments planning surface and ground water protection efforts (Weatherington-Rice and others 2006c).

In addition to hosting scientific and outreach activities, group members have given numerous presentations at the annual meetings of the Ohio Academy of Science and the Midwest Ground Water Conferences. Papers from the last special issue of *The Ohio Journal of Science* have been introduced into legal briefings and presented as evidence in court hearings over the last several years, notably in front of the Ohio Environmental Review Appeals Commission (Ohio ERAC) administrative board, moving the concept of fracture flow out of the scientific and engineering realm into the legal realm. This shifting of the science to the legal world underscores Earl Finbar Murphy's adage that "The law always follows the science" (Weatherington-Rice and others 2006c) and documents the legal recognition of the scientific efforts of the OFFWG.

Overview of this Second Special Issue of *The Ohio Journal of Science*

As with the first special issue, this issue contains eight papers; including papers of scientific discovery, papers documenting additional data collection, and methods papers offering new approaches to viewing fractured fine-grained materials both spatially and statistically. The papers go further this time, however, and reach beyond the scientific/engineering applications to address land-use planning, public policy, and legal applications of fracture information. Now that scientists and engineers have defined the physical fracture formation process, can predict fracture occurrence, and have identified the potential for enhanced surface and ground water contamination through fractures, interweaving that understanding into local, regional, state, and Federal public policy becomes critical. It has been an underlying premise of the OFFWG that scientific discovery, by itself, is incomplete until its usefulness can be shared with the rest of humankind.

The first paper, by Bruno and others (2006), becomes a northeast Ohio companion paper to the central Ohio study site at Molly Caren Agricultural Center, location of the annual Farm Science Review, in the first special issue (Fausey and others 2000), and documents the detailed information that can be gained by site specific studies. The second paper by Szabo (2006) is a summation of decades' worth of field research and laboratory data analyses undertaken by the University of Akron's Department of Geology. This paper not only connects to the Brockman and Szabo (2000) paper in the first issue but also connects directly to the statistical analysis paper by Kim and Christy (2006), which gathers laboratory data from other locations. Kim and Christy (2006), for the first time, describe a statistical predictability to the presence of fractures in the natural "found" environment.

Beginning with the paper by Kim and Christy (2006), all of the other papers have been developed in central Ohio, linking connections between OSU's Department of Food, Agricultural, and Biological Engineering, the School of Environment and Natural Resources' Soil Science Program, and the Moritz College of Law to the Ohio Department of Natural Resources (ODNR)'s Division of Water. Additional supporting efforts were made by staff from the USDA Natural Resources Conservation Service's Ohio State Office, retired staff from the Ohio Environmental Protection Agency (Ohio EPA)'s Division of Surface Water Central Office, and staff from Bennett & Williams Environmental Consultants Inc.

The paper by Weatherington-Rice and Hall (2006) uses the information and concepts presented by Allred (2000) and links those concepts from the "cut" construction setting to the "fill" construction setting. In addition, this paper explores the *"how fast?"* of fracture formation and raises significant questions about the possibility that fractures are the underlying root cause of slope failure in "built" environments. Weatherington-Rice and Bigham's (2006) paper addresses the issue of *"how long?"* do fractures remain viable and begins to explore the conditions where matrix porosity may not be involved in contaminant storage and transport, even when the primary porosity of the matrix materials can be measured in the laboratory. This paper stretches Haefner's (2000) methods paper and raises significant questions about contaminant transport in the northwest Ohio Lake Plains and fine-grained glacial ground- and end-moraine settings. Verification, that in reduced iron matrix settings the matrix materials do not contribute to ground water flow, will necessitate changes in guidance documents and requirements measuring ground-water flow at potentially contaminating permitted land-use sites in Ohio.

To insure the inclusion of chosen subject matter for this special issue, the drafting of much more detailed versions of Weatherington-Rice and Bigham (2006), Weatherington-Rice and Hall (2006) and the two DRASTIC papers were assigned to co-author Weatherington-Rice as part of her dissertation at OSU. With the advent of web-based dissertation publication at OSU, the extended versions of these papers complete with additional graphics, data tables, and appendices are available to the interested reader without having to include all of the documentation in this special issue (Weatherington-Rice 2003).

The last three papers are process papers. The two DRASTIC papers (Weatherington-Rice and others 2006a; Weatherington-Rice and others 2006b) address the modifications that ODNR's Division of Water have made to the DRASTIC mapping process to factor in the effects of fracture flow as part of the contaminant transport

system here in Ohio. The final paper (Weatherington-Rice and others 2006c) puts the existence of fractures and their potential for rapid contaminant transport into the realm of land-use planning, public policy, and the law. It documents the need for incorporating fracture information into surface and ground water protection planning and policy, underscores the existing acceptance of DRASTIC mapping in both state and local planning applications, and begins to build a bridge to the legal community's acceptance of the importance of fractures for contaminant transport.

The list of authors for each paper fails to document the extensive contributions of other OFFWG members in their roles of internal and peer reviewers. All of these papers are stronger, easier to read, and more integrated because of their efforts. We acknowledge especially the following OFFWG members: Garry McKenzie, OSU Department of Geological Sciences; Norm Fausey, USDA Agricultural Research Service; Scott Brockman, ODNR Division of Geological Survey (retired); Annabelle Foos, University of Akron Department of Geology; Ralph Haefner, US Geological Survey; and Alan Kehew, Western Michigan University Department of GeoSciences. We also wish to acknowledge the contributions of Peter Precario, environmental attorney and former member of Ohio's ERAC, and Timothy DeWitt, formerly Planning Director for Delaware County, OH, and currently the Executive Director of the Bluegrass Conservancy. Special Issue Editors for this special issue are Ann Christy and Julie Weatherington-Rice (adjunct), co-coordinators of the OFFWG, OSU Department of Food, Agricultural, and Biological Engineering, and Mike Angle, ODNR Division of Water.

Special Issue Dedication

This second special issue is dedicated to two Fellows of the Ohio Academy of Science who have each been responsible for important foundational research in fracture formation both here in Ohio and well beyond. Jane L. Forsyth, affectionately known as the "Queen of the Pleistocene," is the living linkage between the work of George White and Richard P. Goldthwait and the activities of the OFFWG. Born in 1921, she worked closely with George White and Richard P. Goldthwait during her years at the Ohio Geological Survey and at OSU. The 1960s versions of the Glacial Map of Ohio (Goldthwait and others 1961) intertwine the glacial geomorphologic mapping research efforts by the three geologists, which still serves as a base to Ohio's glacial understanding.

Forsyth was still teaching at Bowling Green State University when the OFFWG convened for the first time in 1993. She quickly became a participant in fracture flow research and joined as a member of the "Fractured Till Army" (as she affectionately refers to the work group) attending workshops, symposiums, and giving her own lectures on Ohio's fractured glacial till. She co-authored the Introduction to the first special issue (Weatherington-Rice and others 2000) and continued to be an active participant at OFFWG and Ohio Academy of Science events for several more years. Ronald Stuckey (2003), OSU Department of Evolution, Ecology, and Organismal Biology, emeritus, collected all of Forsyth's papers and published them. Several of those papers serve as references to this special issue. The primary geological reference to the Auglaize River site in Defiance County is hers (Weatherington-Rice and others 2006b), and the research there and at the WillowCreek site in Portage County builds upon her earlier work.

Truman W. Bennett is often referred to as the "Father of DRASTIC." Born in 1932, he undertook PhD research in clay mineralogy at OSU in the 1950s before becoming one of the first practicing hydrogeologists in the United States. During his years at the Ranney Company, he perfected the construction techniques for Ranney collector wells and developed municipal and industrial well fields all over the United States and abroad. In his "retirement," he worked closely with staff at the National Ground Water Association to develop the concept of DRASTIC mapping for the US Environmental Protection Agency (US EPA), which was based on his extensive geological and hydrogeological experience (Aller and others 1987; Weatherington-Rice and others 2006a). He also founded the firm of Bennett & Williams Environmental Consultants Inc. in Columbus, OH, where he is still an active participant. It was his historic experience with Ohio's clay mineralogy and his repeated discovery of higher than predicted ground-water recharge volumes to Ohio's well fields that spurred the original organization of the OFFWG. The Ohio modifications to DRASTIC mapping conceptual understandings find their roots in his earlier work.

The OFFWG are pleased to dedicate this second special issue of *The Ohio Journal of Science* to their lifetimes of geologic and hydrogeologic contributions to the science. We are also pleased to thank them while they are still able to accept our tributes.

Other Research Efforts in Ohio

Recently students at a number of Ohio universities have undertaken research relating to fracture formation and their relationship to the physical erosional process. Three such studies of note consider Lake Erie shoreline erosion conditions. These studies include Vagen's (2003) study in Lake County, Dawson's (1997) study at Painesville-on-the-Lake, and Highman's (1997) study of bluff erosion along the northeast shoreline.

Fisher (2002), in his published study of bulk density, Atterberg Limits, per cent natural moisture and permeability of 61 samples taken mostly in western Ohio, documents a database of information that should not be lost to fracture formation research. While Fisher does not link his study sites to a specific soil series that would support the work of Tornes and others (2000), he does list the locations by county, township, and section, as well as including soil origin and depth of the samples. If his data were linked with the ODNR Division of Geological Survey glacial till stack maps, it should be possible to incorporate his data into our understanding of matrix and combined matrix/fracture permeability for a number of sites across Ohio. That information could then be incorporated into the DRASTIC Ground

Water Pollution Potential mapping by ODNR. His paper provides a valuable starting point that needs to be explored by university research projects.

Malone and others (2003, 2004a,b) documents research undertaken at the USDA Agricultural Research Service's North Appalachian Experimental Watershed research station in Coshocton County, OH. Using data from natural Ohio soils and the USDA Root Zone Water Quality Model, the papers evaluate the effects of macroporosity on herbicide leaching and transport. The research, led by Malone (including a number of other OFFWG members), demonstrates that the presence of macropores, either naturally or biologically developed, preferentially enhance the movement of herbicides during rain-fall events. This basic research has direct application to surface and ground water contamination, Source Water Protection delineations, and the Total Maximum Daily Load (TMDL) assignments made by Ohio EPA staff to Ohio's watersheds (Weatherington-Rice and others 2006c).

Shipitalo and Gibbs continue their presentations at field days and conferences and writings on preferential flow of liquid manures in macropores and cracks in surface soil. Their most recent presentation and publication (Shipitalo and Gibbs 2005) was presented at the 2005 annual meeting of the American Society of Agricultural Engineers, and their paper was published in the proceedings for that conference. Presenting at the 2001 annual meeting of the American Society of Agricultural Engineers, Christy (2001) expanded on her earlier research on the ecosystems in subsurface fractures with McMahon (McMahon and Christy 2000).

Linking to Research Outside Ohio

Several papers of note documenting fracture research outside Ohio include the one by Helmke and others (2005a) documenting nitrate and Atrazine migration through four fractured glacial till units in Iowa. The recent fracture flow ground water modeling paper by Helmke and others (2005b) serves as a primer for those in Ohio and beyond who are struggling with the application of ground-water modeling to fractured till locations. McKay and others (2005) discuss ground-water flow through fractured saprolite in eastern Tennessee. The Midwest Geosciences Group, coordinated by Dan Kelleher and Tim Kemmis, based in Waverly, MN, publish field-ready logging guides for soils, glacial tills, and fractured bedrock which help to develop uniform field logging information. They are members of the OFFWG. Their web page is http://www.midwestgeo.com.

International research on fractures in unconsolidated materials also continues to be important. Weinberger's (2001) paper on stratified mud desiccation fractures has application well beyond Israel. The research being published from Denmark partners the work of the OFFWG. We have carefully modified our research projects so that we do not duplicate but rather complement their efforts. Of special note are the papers by Jorgensen and others (2003, 2004a,b,c) and the paper by Klint and others (2004). Among the topics covered are monitoring well interceptions of fractures, ground-water flow modeling, and pesticide transport. Because Denmark is predominately an agricultural country and they depend on ground water for most of their water supplies, they have actively been researching the issue of contaminant transport, especially pesticide transport. They are using DRASTIC as one of their screening tools and are developing a textural grain-size database for all of the soils in the country.

Future Planned OFFWG Efforts

The OFFWG has a number of research, education, and publication projects either active or planned for future completion. The North-central Geological Society of America (GSA) meeting, scheduled for April 2006 in Akron, OH, is hosted by the University of Akron. The OFFWG will convene a half-day symposium on Ohio Fracture research and will help to host a field day. That same weekend, several presentations are planned for the annual Ohio Academy of Science meeting in Dayton, OH. This issue will be published in time to be available for both meetings.

Research by Eun Kyoung Kim continues as she develops a series of processes to determine if sand and clay percentages of fractured laboratory samples (identified in the paper published here, Kim and Christy 2006) extrapolate to the natural. She is working with high-lime, low-lime, and leached fine-grained Ohio materials. She also will be running samples supplied by other OFFWG members from other locations in the United States and Denmark to determine the geographic limits of the Ohio research. Other combined research publications are planned with fellow scientists from Denmark. Finally, work continues of the fractures in fragipan soils from northeast Ohio. The low-lime, high-silica content glacial tills and soils represent a significantly different parent material than those tills found in western Ohio, but they still fracture. That research, when completed, will build upon Szabo's (2006) published research in this issue, since most of his data sources are from northeast Ohio where fragipans are common.

Membership in OFFWG and/or the news group is open to anyone interested in this vital field of research. Current membership is diverse and inclusive of many disciplines. Our unique diversity is one of the major underlying foundations of our research successes. Please contact weatheringtn-rice.1@osu.edu for more information.

LITERATURE CITED

Aller L, Bennett T, Lehr J, Petty R, Hackett G. 1987. DRASTIC: a standardized system for evaluating ground water pollution using hydrogeologic settings. Washington (DC): US Environmental Protection Agency. EPA/600/2-87/035. 455 p.

Allred BJ. 2000. Survey of fractured glacial till geotechnical characteristics: hydraulic conductivity, consolidation, and shear strength. Ohio J Sci 100(3/4):63-72.

Brockman CS, Szabo JP. 2000. Fractures and their distribution in the tills of Ohio. Ohio J Sci 100(3/4):39-55.

Bruno PW, Szabo JP, Foos A. 2006. Mineralogy of weathered Wisconsinan till along a fracture in the root zone. Ohio J Sci 106(2):17-21.

Christy AD. 2001. Ecosystems in subsurface fractures: roots, earthworms, and calcite-forming microorganisms. ASAE Annual Meeting Paper 01-7023. 10 p.

Dawson SA. 1997. A lithologic study of glacial till bluffs at Painesville-on-the-Lake to determine possible geologic cause of erosion problems in the area [thesis]. Bowling Green (OH): Bowling Green State Univ. 182 p.

Fausey NR, Hall GF, Bigham JM, Allred BJ, Christy JM. 2000. Properties of the fractured glacial till at the Madison County, Ohio, Field workshop pit site. Ohio J Sci 100(3/4):107-12.

Fisher HH. 2002. Hydraulic conductivity of Ohio's glaciated soil, its implications, and suggestions for further studies. Ohio J Sci 102 (5):106-9.

Goldthwait RP, White GW, Forsyth JL. 1961. Glacial map of Ohio. Ohio Div of Geological Surv Miscellaneous Geologic Investigations Map I-316. Map with text.

Haefner RJ. 2000. Characterization methods for fractured glacial tills. Ohio J Sci 100(3/4):73-87.

Helmke MF, Simpkins WW, Horton R. 2005a. Fracture-controlled nitrate and atrazine transport in four Iowa till units. J Environ Qual 34:227-36.

Helmke MF, Simpkins WW, Horton R. 2005b. Simulating conservative tracers in fractured till under realistic timescales. Ground Water 43(6):877-89

Highman TA. 1997. A study of soil joints in relation to bluff erosion along the Lake Erie shoreline, northeast Ohio [thesis]. Kent (OH): Kent State Univ. 162 p.

Jorgensen PR, Helstrup T, Urup J, Seifert D. 2004a. Modeling of nonreactive solute transport in fractured clayey till during variable flow rate and time. J Contam Hydrol 68:193-216.

Jorgensen PR, Klint KES, Kistrup JP. 2003. Monitoring well interception with fractures in clayey till. Ground Water 41(6):772-9.

Jorgensen PR, McKay LD, Kistrup JP. 2004c. Aquifer vulnerability to pesticide migration through till aquitards. Ground Water 42(6): 841-55.

Jorgensen PR, Urup J, Helstrup T, Jensen MB, Eiland F, Vinther FP. 2004b. Transport and reduction of nitrate in clayey till underneath forest and arable land. J Contam Hydrol 73:207-26.

Kim EK, Christy AD. 2006. Use of soil texture analysis to predict subsurface fracturing in glacial tills and other unconsolidated materials. Ohio J Sci 106(2):22-26.

Klint KES, Gravesen P, Rosenbom A, Laroche C, Trenty L, Lethiez P, Sanchez F, Molinelli L, Tsakiroglou CD. 2004. Mulit-scale characterization of fractured rocks used as a means for the realistic simulation of pollutant migration pathways in contaminated sites: a case study. Water, Air, and Soil Pollution: Focus 4:201-14.

Malone RW, Logsdon S, Shipitalo MJ, Weatherington-Rice J, Ahuja L, Ma L. 2003. Tillage effect on macroporosity and herbicide transport in percolate. Geoderma 116:191-215.

Malone RW, Shipitalo MJ, Meek DW. 2004a. Relationship between herbicide concentration in percolate, percolate breakthrough time, and number of active macropores. Trans ASAE 47(5):1453-6.

Malone RW, Weatherington-Rice J, Shipitalo MJ, Fausey N, Ma L, Ahuja LR, Wauchope RD, Ma Q. 2004b. Herbicide leaching as affected by macropore flow and within-storm rainfall intensity variation: a RZWQM simulation. Pest Manag Sci 60:277-85.

McKay LD, Driese SG, Smith KH, Vepraskas MJ. 2005. Hydrogeology and pedology of saprolite formed from sedimentary rock, eastern Tennessee, USA. Geoderma 126:27-45.

McMahon MJ, Christy AD. 2000. Root growth, calcite precipitation, and gas and water movement in fractures and macropores: a review with field observations. Ohio J Sci 100 (3/4):88-93.

Shipitalo MJ, Gibbs F. 2005. Preferential flow of liquid manure in macropores and cracks. ASAE Annual Meeting Paper 05-2063. 9 p.

Stuckey RL, editor. 2003. Linking Ohio Geology and Botany: Papers by Jane L. Forsyth. Compiled by Ronald L. Stuckey. Columbus (OH): RLS Creations. xiv, 338 p, 6 colored maps.

Szabo JP. 2006. Textural and mineralogical characteristics of tills of northeastern and north-central Ohio. Ohio J Sci 106(2):9-16.

Tornes LA, Miller KE, Gerken JC, Smeck NE. 2000. Distribution of soils in Ohio that are described with fractured substratums in unconsolidated materials. Ohio J Sci 100(3/4):56-62.

Vagen J. 2003. The influence of groundwater on bluff erosion at Bill Stanton Community Park, Lake County, OH [thesis]. Toledo (OH): Univ of Toledo. 97p.

Weatherington-Rice J. 2003. Fracture occurrence and ground water pollution potential in Ohio's glacial and lacustrine deposits: a soils, geologic, and educational perspective [DPhil dissertation]. Columbus (OH): The Ohio State Univ. 400 p.

Weatherington-Rice J, Bigham JM. 2006. Buried Pre-Illinoian-Age lacustrine deposits with "green rust" colors in Clermont County, Ohio. Ohio J Sci 106(2):35-44.

Weatherington-Rice J, Christy AD, editors. 2000. Fractures in Ohio's glacial tills. Ohio J Sci 100(3/4):36-112.

Weatherington-Rice J, Christy AD, Angle MP, Aller L. 2006a. DRASTIC hydrogeologic settings modified for fractured till: Part 1. Theory. Ohio J Sci 106(2):45-50.

Weatherington-Rice J, Christy AD, Angle MP, Gehring R, Aller L. 2006b. DRASTIC hydrogeologic settings modified for fractured till: Part 2. Field observations. Ohio J Sci 106(2):51-63.

Weatherington-Rice J, Christy AD, Forsyth JL. 2000. Ohio's fractured environment: introduction to The Ohio Journal of Science's special Issue on fractures in Ohio's glacial tills. Ohio J Sci 100(3/4):36-8.

Weatherington-Rice J, Hall GF. 2006. Fracture and gully formation in glacial fill: field observations at the WillowCreek Landfill, Portage County, Ohio, with implications to historic earthen dam failure sites in the US. Ohio J Sci 106(2):27-34.

Weatherington-Rice J, Hottman A, Murphy EF, Christy AD, Angle M. 2006c. Fractured tills, Ohio's ground water resources, and public policy considerations addressed by DRASTIC maps. Ohio J Sci 106(2):-64-73.

Weinberger R. 2001. Evolution of polygonal patterns in stratified mud during desiccation: the role of flaw distribution and layer boundaries. GSA Bulletin 113(1):20-31.