JOURNAL OF
ENVIRONMENTAL HYDROLOGY

The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com

VOLUME 12 2004

A PROCEDURE FOR DELINEATION OF BEDROCK FRACTURE ZONES UNDER GLACIAL DRIFT FORMATIONS IN OHIO

Muhammad Asim
Carl Dokter
Chris Nitzsche
Ann Winegar
Yoram Eckstein

Department of Geology
Kent State University
Ohio, USA

In any aquifer the porosity can be either primary or secondary or a combination of the two, referred to as dual porosity. Primary porosity is the diffused, inter-granular porosity inherent to the rock, generated at the time of lithogenesis. Secondary porosity is the porosity created by post-genetic processes, e.g. fracturing or dissolution of the rock. Rates of groundwater production from bedrock sandstone units are commonly directly related to the presence and extent of secondary porosity. Bedrock fracturing can be product of tectonic stress or, in recently glaciated areas, unloading from the retreat of glaciers. The goals of our study were to test the hypothesis that the values of hydraulic conductivity, computed from the data stored in water well archives for single-home water wells penetrating bedrock sandstone formations may delineate mappable areas of high hydraulic conductivity, thus showing the distribution of fracture zones. We analyzed ninety-one well logs of private single-home water wells drilled through the glacial sediments into the sandstone bedrock formations in Geauga and Portage Counties of Northeastern Ohio. Aquifer thickness in each water well was determined from the lithological profiles, while the specific capacity data from production tests were used to estimate the values of the coefficient of transmissivity for each well. Combination of the two parameters yielded mappable values of hydraulic conductivity. The resulting values of hydraulic conductivity were characterized by a distinctly binary distribution, with low values apparently corresponding to massive un-fractured zones and high values corresponding to fractured zones with dual porosity. Once contoured on a map, these zones appeared clearly, with a transition between the areas of high and low hydraulic conductivity, i.e. high and low potential for groundwater production, respectively.

INTRODUCTION

In regions where a blanket of glacial drift covers bedrock formations, the productivity of water wells can depend strongly on the presence of fracture zones. This is particularly true when the bedrock formations immediately under the glacial drift consist of rock formations with low primary porosity, e.g. fine-grained clastics, siltstones, sandstones with clayey cement, or quartzitic sandstones, etc. Milici and de Witt (1988) for example characterized the bedrock sandstones that underlie the glacial sediments of the Appalachian Basin as “tight sandstones”. These “tight sandstones” typically have very low primary porosity, and water wells penetrating these formations produce little or no groundwater. There are areas in these sandstones however, that have significantly large secondary porosity. Primary porosity is the porosity inherent to a rock. It is “locked into” the rock at the time of lithification. Secondary porosity is developed in the rock at a time after deposition and lithification (Fetter, 2001). The secondary porosity of bedrock sandstones in glacial terrains is most likely brought on by the stress of glacial cover and subsequent unloading due to glacial retreat. The weight of the glaciers, as well as the scouring effect of the glaciers during retreat, led to the formation of fractures in the bedrock sandstones. These fractures significantly increase the porosity and allow for much greater water production than areas where primary porosity is the only porosity (Winslow and White, 1966).

With increasing urbanization of the world population, the demand for water supply is growing at a rapid pace. This is clearly exemplified by a gradual change of many rural communities in Northern Ohio into suburban “bedroom communities” with economic basis in a downtown metropolis such as Cleveland, Akron, or Toledo. It is therefore very important that water wells, especially those designed for the communal supply of groundwater, be capable of high production rates. To that end it is critical to be able to identify areas where one is likely to encounter conditions facilitating high production rates. In the case of “tight sandstones” or dense siltstones, favorable areas exist where the formations are fractured. In regions covered by the blanket of glacial drift the task is not simple. Most of the currently applied methods involve several variants of electric resistivity or electromagnetic conductivity surveys (e.g. Schlumberger or Wenner array, dipole-dipole, electromagnetic etc.) or seismic surveys. The methods are mostly somewhat helpful with identification of the subsurface lithology, stratification or determination of depth to the groundwater table. Their effectiveness in locating fractured zones beneath the blanket of glacial drift is at best very limited, and often questionable. Furthermore, the cost of such surveys, the presence of on-the-ground or under-the-ground structures often interfering with the interpretation of such surveys (e.g. metal pipelines, power lines, or even wire fences), and the problems with obtaining all the necessary right-of-way (e.g. when lines have to be spread beyond the property lines) reduce in most cases any rationale for using these methods.

With the critical importance of identifying fracture zones, there is a need to develop an inexpensive, easy and reliable method that will generate consistently reproducible results. In the following we are presenting a pilot study of a procedure that uses well-established and simple methods and allows for delineation of major fracture zones hidden under the blanket of glacial drift. The resulting data can be easily integrated into any mapping system (e.g. Geographic Information System).

THE DATA BASE

Ohio ranks among the top 10 states in number of private water wells. About 40% of Ohio’s homes, industries and farms obtain their water from private single-home water wells, according to Ohio

Department of Natural Resources (ODNR) records. Beginning in 1947, Ohio law required drillers to complete a well log and drilling report for each water well they drilled, and to submit the completed forms to ODNR. As a result, the ODNR has gathered information on thousands of private water wells distributed all over the State. Copies of these well logs filed with the agency are now easily accessible from the agency's online water well archive. A typical randomly chosen "Well Log and Driller's Report" is shown on Figure 1.

Keeping in mind that the records are based on driller's reporting, they are far from uniform and fully reliable. One driller's "dirt" may be another one's "top soil", or one's "heaving sand" may be another's "quicksand", etc. One driller may distinguish (and record) a foot-thick layer of gravel sandwiched between silt and clay, while for another it may be all "silty clay with some gravel" – hardly information useful for litho-stratigraphic correlations between nearby wells. Furthermore, often part of the information under the "Well Test Details" may be missing (e.g. rate of pumping or bailing, or the time duration of the test) or be uninformative, as on Figure 1, where the drawdown is shown as "total". A "total" drawdown would indicate the water table dropping to the pump intake, but there is no indication of the depth to the pump intake. Also, it is not clear whether the "total" drawdown occurred by the end of the test duration or much earlier - say - already during the first ten minutes into the pumping or bailing.

Yet, a complete data set from such a well test, conducted by a driller at completion of each private water well, can serve a valuable purpose of estimating the coefficient of transmissivity using the specific capacity method (Walton, 1970; Kasenow, 1996). Winslow and White (1966) observed that fracture zones in the sandstone are characterized by higher values of hydraulic conductivity and can support high production rates from water wells. The description of the lithological sequence

Water Well Log and Drilling Report
Ohio Department of Natural Resources
Division of Water
Phone: 614-265-6740
email: cleve.brown@dnr.state.oh.us
Water Home: http://www.dnr.state.oh.us/water

WELL LOG AND DRILLING REPORT

Well Log Number: 702648

ORIGINAL OWNER AND LOCATION

Original Owner Name: *PRIDEMARK DESIGN INC*	**Lot Number:**	
County: *GEAUGA*	**Township:** *BAINBRIDGE*	**Section Number:**
Address: *17310 BITTERSWEET TRAIL*		
City:	**State:** *OH*	**Zip Code:**
Location Number:	**Location Map Year:**	**Location Area:**

CONSTRUCTION DETAILS

Borehole Diameter:	**Total Depth:** *141 ft.*	**Depth to Bedrock:**
Casing Diameter: *6 in.*	**Casing Thickness:**	**Casing Length:** *42 ft.*
Well Use: *DOMESTIC*	**Screen Length:**	**Date of Completion:** *10/4/89*
Aquifer Type: *SHALE*	**Driller's Name:** *FREDEBAUGH WELL DRILLING*	

WELL TEST DETAILS

Static Water Level: *46 ft.*	**Test Rate:** *30 gpm*	**Associated Reports**
Drawdown: *Total*	**Test Duration:** *0.5 hrs.*	NONE

COMMENTS:

WELL LOG

Formations	From	To
TOP SOIL	0	1
BRN CLAY	1	10
BROKEN SANDSTONE	10	14
BRN SANDSTONE	14	94
CONGLOMERATE	94	122
SANDSTONE	122	122
GRY CONGLOMERATE	122	126
SANDSTONE	126	126
BLU SHALE	126	141

Figure 1. Example of a well log and driller's report downloaded from the ODNR website.

combined with the reported static water table can serve to determine the contributing aquifer thickness. Lastly, by combining the estimated coefficient of transmissivity with the aquifer thickness we can approximate the groundwater yielding formation's hydraulic conductivity.

STUDY AREA

A pilot study area was chosen in Northeastern Ohio to test the hypothesis that the values of hydraulic conductivity computed from the data stored in the ODNR water well archive for water wells penetrating bedrock sandstone formations may help to delineate mappable areas of high hydraulic conductivity, thus showing the distribution of fracture zones. The selected area covers Geauga and Portage counties (Figure 2). Figure 3 shows a detailed base topographic map of the study area. A great majority of homes in this area are supplied from private individual household water wells.

The study area is characterized by glacial sediments unconformably overlying bedrock composed of the Pennsylvanian age sandstones of Sharon Conglomerate Member (SCM) of the Pennsylvanian System Pottsville Formation. The SCM is laying unconformably on Cuyahoga Shale and Berea Sandstone of the Mississippian-Devonian age. Table 1 shows a schematic stratigraphic column of the study area.

A large majority of the water wells in the study area were drilled into the SCM. The unit consists mostly of quartzitic sandstone, grading to pebbly to conglomeratic in its lower portion. It ranges

Figure 2. Location of the study area.

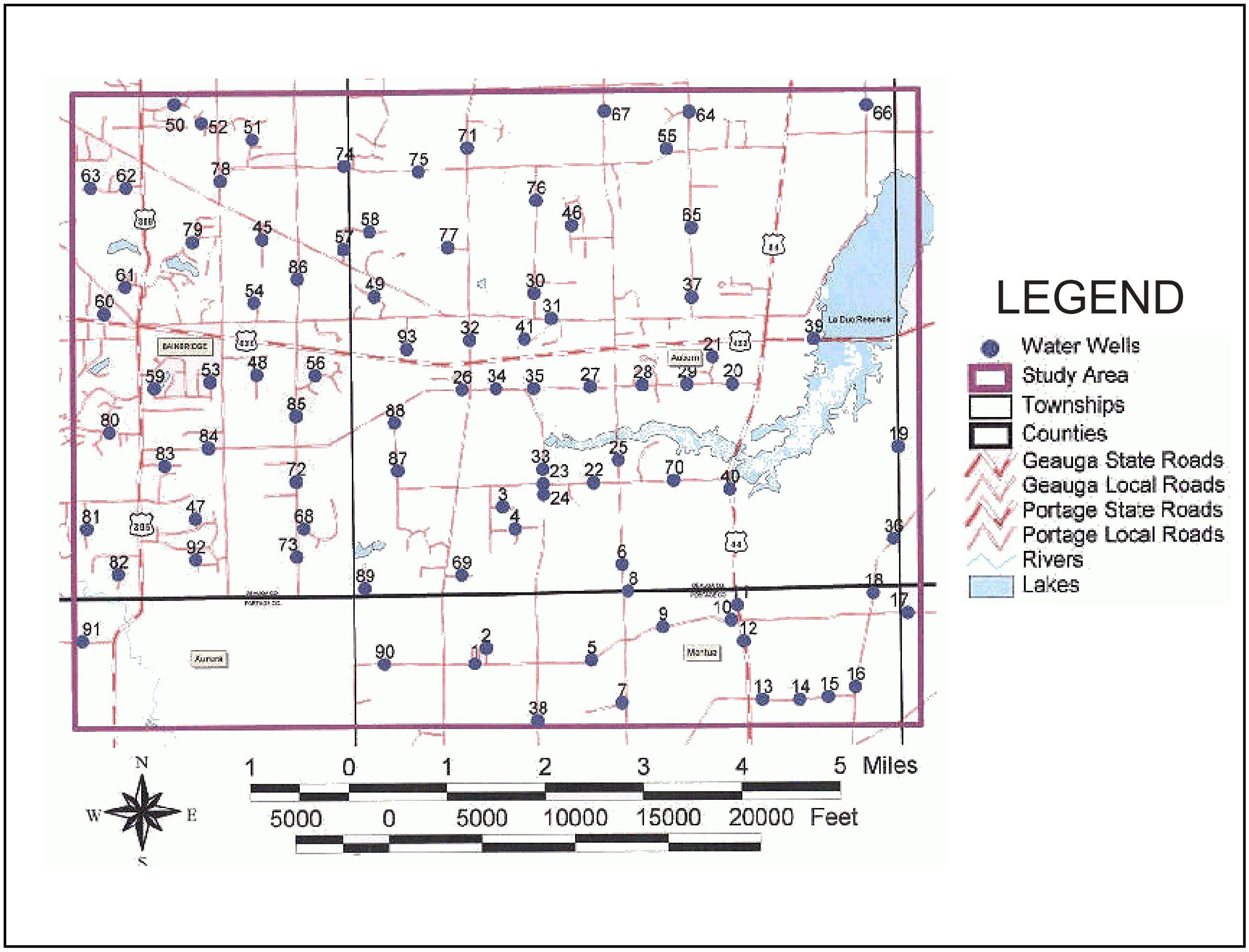

Figure 3. Base map of the study area with network of the water wells used in our study.

within the study area from about 25 m to more than 35 m (or approximately 80 to 120 feet) in thickness. The formation is often found with remnants of a bedrock shale unit and/or glacial till above it, creating confined to semi-confined conditions. The aquifer is recharged by rainfall seeping locally through the glacial drift and entering the sandstone directly at the surface where it outcrops up-dip, only a short distance to the north-northwest of the study area.

SELECTION AND LOCATION OF THE WATER WELLS

The large number of single-home water wells distributed throughout the study area allowed for careful selection of water wells that would provide, according to our best judgment, the most accurate information. The most difficult aspect was selecting water wells that could be accurately located on a map. Unlike the oil and gas industry in Ohio, there is no legal requirement for private water wells to be surveyed. They are filed either with an address, or under the last name of the person who owned the property at the time the well was drilled. This significantly narrowed the field of potentially useful data sets. The pool of wells was reduced to those for which there was an exact address.

Once a set of water wells with known addresses was established, the task of spotting the wells on the map began. This was accomplished by using a set of base-maps developed by the Ohio Department of Transportation (ODOT). These base-maps were in the form ArcView® Shapefiles. Using ArcView®3.2a software, the names and locations of the roads within the study area were identified. Then, using plat books and Microsoft® Streets and Trips 2002® software, the locations

Table 1. Stratigraphic Column in the Study Area

AGE (mya)	SYSTEM	SERIES	GROUP	ROCK UNIT
320	PENNSYLVANIAN	MORROWAN	POTTSVILLE	Sharon Shale Sharon Sandstone Sharon Conglomerate
320 360	MISSISSIPPIAN	KINDERHOOKIAN	CHATAQUAN	Cuyahoga Shale Berea Sandstone Bedford Shale
375	DEVONIAN	SENECAN		Ohio Shale

of those addressed were established and spotted on the base-map in ArcView® as points, with a point attribute table attached to store the data. In the end, 91 water wells were selected to create as even a distribution of data points as possible throughout the study area (Figure 3).

COMPUTATIONAL METHODOLOGY

The data set available from the "well tests" conducted at completion of a private single-home water well consist of the following parameters:

1. static water level (or depth from the well-head to the water level in the well)
2. rate of pumping (or bailing)
3. time duration of pumping (or bailing)
4. water level or drawdown at the end of pumping

Additionally, the Well Log and Driller's Report list the lithological sequence encountered during drilling, thus providing information on the thickness of the groundwater yielding formations.

Assuming Cooper and Jacob (1946) and Jacob's (1950) approximation valid, the Theis solution for transient radial flow to a well can be simplified to:

$$T = \frac{2.306Q}{4\pi(h_o - h)} \log\left(\frac{2.25Tt}{r^2 S}\right) \qquad (1)$$

where:

T is the coefficient of transmissivity (L^2/t)

Q is the pumping rate (L^3/t)

S is the coefficient of storage (dimensionless)

r is the radial distance from the observation point to the center of the well (L)

t is the time from the beginning of the pumping

h_o is the static water level (L)

h is the water level at any time during the pumping (L)

Considering that the water level observations are made within the pumping well, the value of r becomes r_w, i.e. the well radius (L). Thus, the relationship between specific capacity of the tested well and the coefficients of transmissivity and storage of the aquifer can be expressed as:

$$\frac{Q}{h_o - h} = \frac{4\pi T}{2.306 \log\left(\dfrac{2.25Tt}{2.693{}_{w}^{2} S}\right)} \qquad (2)$$

The assumptions inherent in this equation are:

1. the well penetrates and is uncased through the entire thickness of the aquifer
2. well loss is negligible
3. the effective radius of the well has not been affected by the drilling and development operations, and is equal to the nominal radius of drilling

Equation (2) has two unknown aquifer parameters, *T* and *S*. Furthermore, as *T* appears in both arithmetic and the logarithmic portions of the equation, it can be solved for the value of *T* only through an iterative process, combined with an assumed value of *S*. In addition, the value of S is strongly dependent on the degree of confinement, i.e. whether the aquifer is confined, "leaky" or entirely unconfined. However, Walton (1970) demonstrated that, since the specific capacity in that equation is a function of the logarithm of (1/*S*), large errors in estimated value of S result in comparatively small errors in the resulting value of *T*. Over or underestimating *S* by as much as two orders of magnitude yields roughly 10% to 20% error in the resulting value of *T* (Walton, 1970). Thus, although not precise, an adequate approximation of the value of *S* can be usually derived from examination of the relationship between the lithological well sequence and the reported static water level.

As all the water wells included in our study penetrated the sandstone bedrock under semi-confined conditions, with the glacial till as the "leaky-confining" layer, the value of *S* was assumed to be 0.001 for all the computations. The equation (2) was thus run for each well data set, with successive iterations to converge on the value of *T* using Microsoft® Excel® spreadsheet. The values of *T* were then divided by the aquifer thickness to obtain the hydraulic conductivity of the aquifer rock formation. The entire data base and computation results are shown in Table 2.

The values of hydraulic conductivity were used to populate the point attribute table created in ArcView® for the water wells. Then the ArcView~3D Analyst® program was used to generate a map of the hydraulic conductivity values. The values were contoured using a spline method of gridding and contouring. Each data point was assigned a weight of 1 and used 12 data points for the interpolation using a tension algorithm (ESRI, 200). This created a contour map showing the distribution of the values of hydraulic conductivity in the aquifer (Figure 4).

DATA ANALYSIS AND INTERPRETATION

The histogram of the values of hydraulic conductivity for the study area clearly shows a bimodal nature of the values of hydraulic conductivity (Figure 5). There are two clear sets of hydraulic conductivity values present, with somewhat of a transition zone between them. The majority of the hydraulic conductivity values tend to fall in the range of 7 to 14 m/day (23 to 46 ft/day). The smaller cluster of higher values set tends to fall in the range of 48 to 55 m/day (158 to 180 ft/day). To truly understand the significance of the bimodal distribution, it is necessary to turn to the contour map of the hydraulic conductivity (Figure 4). Examination of the map shows that the values of higher hydraulic conductivity are spatially distributed in zones. These zones tend to occur in lineaments, trending southwest to northeast. The distinctly linear anisotropy for the values of hydraulic

Table 2. Data Base and Results

WELL ID	**ODNR WELL ID**	**GLACIAL THICKNESS (ft)**	**BEDROCK ELEVATION (ft)**	**SURFACE ELEVATION (ft)**	**TRANSMISSIVITY (ft^2/day)**	**AQUIFER THICKNESS (ft)**	**HYDRAULIC CONDUCTIVITY (ft/day)**
1	867490	98	1092	1190	3126	61	51
2	714799	70	1110	1180	2014	46	44
3	809314	94	1066	1160	387	39	10
4	853393	81	1079	1160	1417	40	35
5	662597	78	1092	1170	1752	52	34
6	554320	87	1063	1150	1989	52	38
7	258591	58	1092	1150	10897	62	176
8	633686	50	1104	1154	2299	38	61
9	904571	44	1106	1150	15413	91	169
10	501326	14	1146	1160	1666	67	25
11	899531	15	1135	1150	1528	40	38
12	637589	20	1170	1190	902	60	15
13	931291	36	1154	1190	1311	87	15
14	915089	47	1123	1170	1238	59	21
15	718657	23	1167	1190	1794	31	58
16	485558	52	1098	1150	7070	38	186
17	408506	34	1116	1150	5179	26	200
18	666442	42	1078	1120	1732	72	24
19	662589	44	1106	1150	836	46	18
20	849335	40	1190	1230	2426	18	135
21	932749	52	1198	1250	362	72	5
22	868979	81	1079	1160	1457	20	73
23	809285	79	1091	1170	3158	38	84
24	768353	84	1116	1200	1457	16	91
25	554320	87	1063	1150	1999	32	62
26	740832	27	1153	1180	295	98	3
27	904506	67	1153	1220	807	90	9
28	518879	70	1170	1240	116	58	2
29	853169	39	1171	1210	204	68	3
30	616118	40	1150	1190	1937	45	43
31	602154	28	1162	1190	7070	47	150
32	806397	112	1068	1180	455	5	91
33	732603	41	1119	1160	4329	30	144
34	849335	40	1130	1170	2426	18	135
35	740804	90	1060	1150	753	30	25
36	778685	48	1092	1140	4248	24	177
37	508393	35	1185	1220	761	85	9
38	554301	111	1099	1210	2671	64	42
39	742658	37	1083	1120	649	22	30
40	567824	43	1097	1140	914	33	28
41	833165	0	1160	1160	3500	25	140
45	702648	10	1190	1200	416	80	5
46	625700	25	1215	1240	389	71	5

Table. 2. Data

WELL ID	ODNR WELL ID	GLACIAL THICKNESS (ft)	BEDROCK ELEVATION (ft)	SURFACE ELEVATION (ft)	TRANSMISSIVITY (ft^2/day)	AQUIFER THICKNESS (ft)	HYDRAULIC CONDUCTIVITY (ft/day)
49	529518	0	1200	1200	113	73	2
50	646371	24	1196	1220	451	76	6
51	764600	18	1222	1240	308	90	3
52	646391	39	1201	1240	409	79	5
53	507141	22	1198	1220	416	70	6
54	922974	29	1081	1110	46	46	1
55	782780	48	1152	1200	1036	57	18
56	828949	108	1042	1150	35	35	1
57	899599	0	1250	1250	1214	15	81
58	893044	28	1202	1230	662	21	32
59	700604	18	1152	1170	413	39	11
60	675494	18	1132	1150	1226	26	47
61	256285	14	1176	1190	967	26	37
62	722139	26	1174	1200	1771	28	63
63	922807	19	1101	1120	2274	62	37
64	764267	14	1206	1220	511	50	10
65	623926	55	1195	1250	240	86	3
66	914809	25	1135	1160	339	80	4
67	907071	82	1128	1210	641	21	31
68	903133	80	1020	1100	605	26	23
69	806359	42	1108	1150	1790	41	44
70	768404	76	1084	1160	324	49	7
71	702608	69	1181	1250	555	41	14
72	802248	12	1138	1150	1241	37	34
73	801923	65	1025	1090	437	89	5
74	904177	18	1252	1270	438	70	6
75	505254	28	1172	1200	990	51	19
76	530621	12	1218	1230	335	76	4
77	856198	10	1210	1220	1994	74	27
78	630140	25	1215	1240	308	72	4
79	611713	24	1096	1120	1415	20	71
80	840701	1	1049	1050	2611	86	30
81	932837	8	1142	1150	1170	48	24
82	633346	31	1059	1090	6667	36	185
83	861000	56	1044	1100	72	72	1
84	597195	15	1155	1170	418	57	7
85	508357	15	1125	1140	761	64	12
86	630117	5	1195	1200	11981	59	203
87	725337	105	1025	1130	171	60	3
88	539061	49	1101	1150	6667	33	202
89	675870	27	1123	1150	1457	45	32
90	505964	40	1110	1150	9137	45	203
91	592627	2	1078	1080	989	59	17

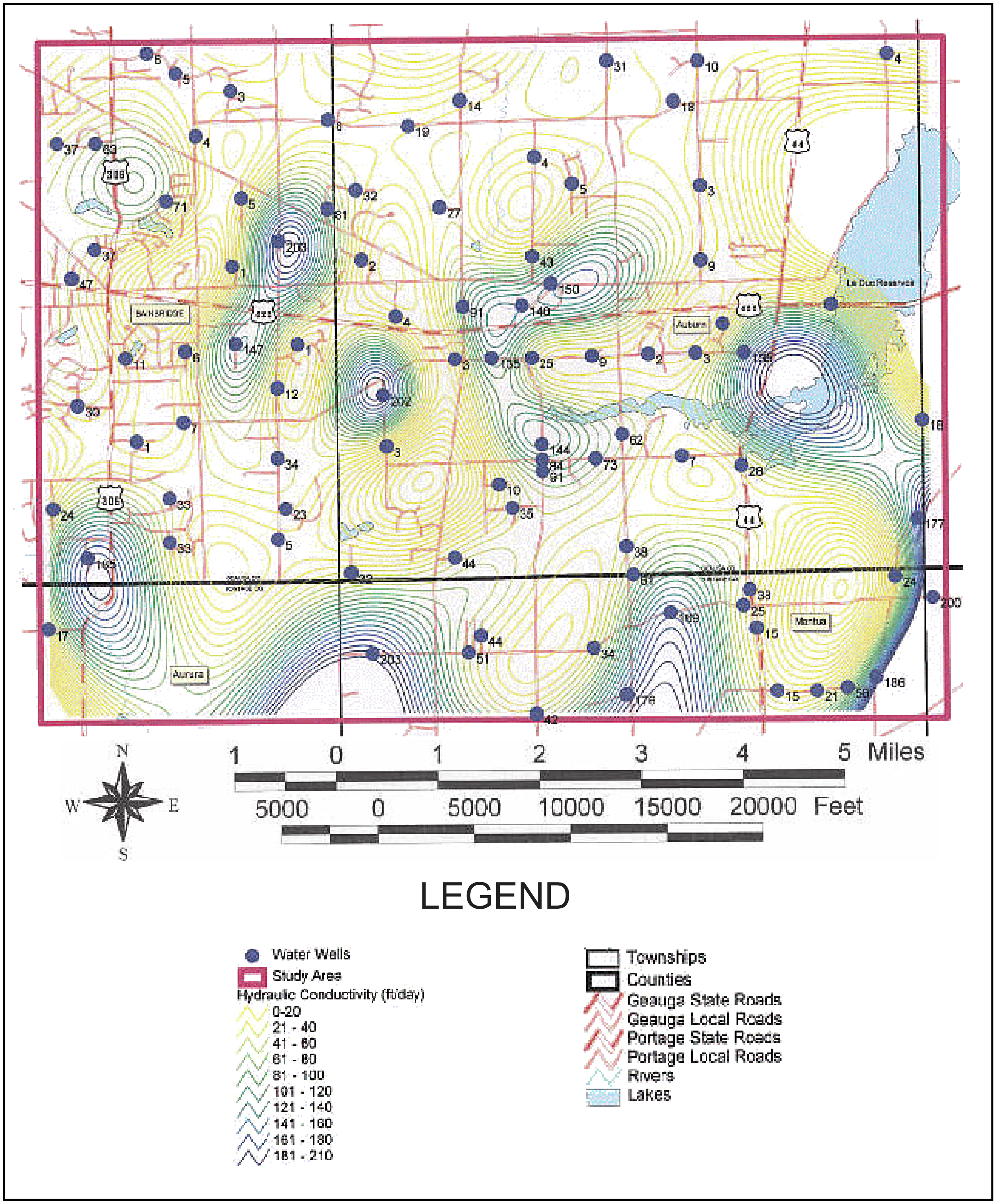

Figure 4. Contour map showing the distribution of the values of hydraulic conductivity in the aquifer.

conductivity is ascribed to superposition of the fracture system on the sandstone primary porosity (Winslow and White, 1996). Furthermore, the southwest to northeast trend corresponds to the direction of glacial advance and retreat. Figure 6 shows a map of the extent of Quaternary glaciation and direction of glacial movement in Ohio. Such correspondence may suggest that the fractures originated as a result of the stress loading and subsequent unloading of glacial advance and retreat.

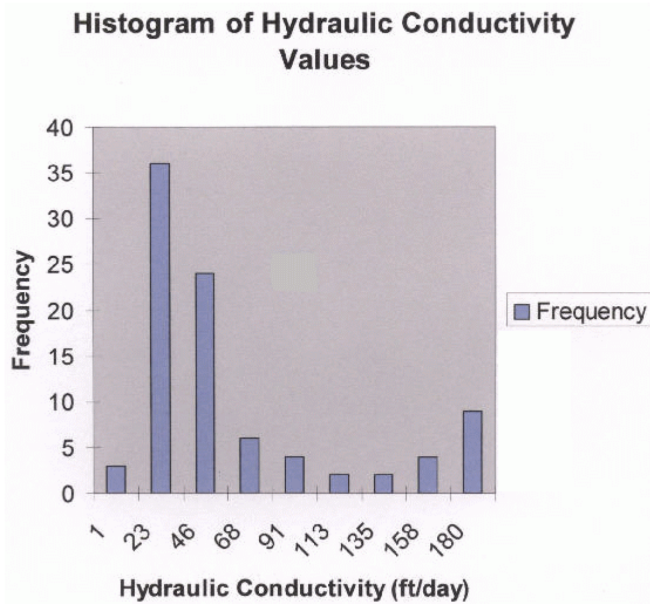

Figure 5. Histogram of the values of hydraulic conductivity for the study area.

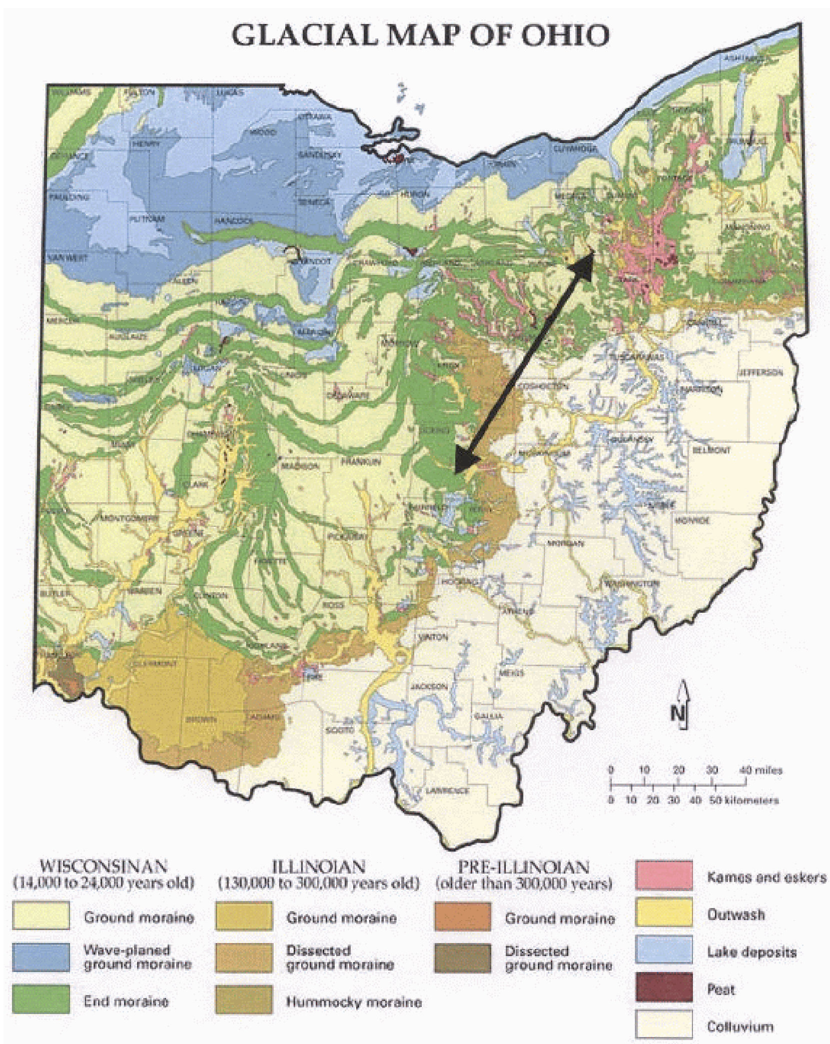

Figure 6. The extent of Quaternary glaciation and direction of glacial movement in Ohio.

CONCLUSIONS

The method presented in the paper is an inexpensive and reliable alternative to geophysical methods of locating areas in which bedrock fracturing has occurred. Although the assumptions inherent in the Theis' method and in the equation (2) are seldom fulfilled, the method should never be considered as a tool to compute the actual hydraulic conductivities of the aquifer material. Nevertheless the method is robust enough to allow for the identification of fracture enhanced porosity zones over large areas. The advantages of this method are found not only in the monetary savings, but first and foremost in the ability to map areas in which fracture enhanced porosity occurs using data that is readily available. The major drawback of this method is that it requires a relatively extensive amount of pre-existing water wells to exist in the area. It also requires that water wells have been logged, to include lithologic logging and pumping, or production (bailing) tests. From this perspective, the method lends itself to refining and better managing areas of existing groundwater production, not to the exploration of new aquifers.

ACKNOWLEDGMENT

We would like to acknowledge very helpful comments and suggestions provided by Dr. Thomas Berg, Chief, Ohio Geological Survey and his staff. This paper is based on a class research project conducted by the four first authors under the guidance of the last author.

REFERENCES

Fetter, C.; (2001). *Applied Hydrogeology* - Fourth Edition; Prentice Hall, Upper Saddle River, New Jersey; 598 pp.

GIS Data Depot; (2000). www.gisdatadepot.com,

Kasenow, M.; (1996). *Production Well Analysis;* Water Resources Publications, Colorado, p. 22

Milici, R. and W. de Witt; (1988). The Appalachian Basin, Geological Society of America, in: The Geology of North America - Sedimentary Cover - North American Craton, Geological Society of America, Virginia, pp 427-469.

Ohio Department of Natural Resources; (2002). http://www.dnr.state.oh.us.

Ohio Department of Transportation; (2001). ESRI Shapefile CD dataset.

Ohio GIS data; (2002). ftp.geodata.gis.state.oh.us/neodata/.

Ormsby, T. and J. Alvi; (1999). Extending ArcView® GIS, ESRI Press, California, 525p.

Winslow, J.D. and G.W. White; (1966). Geology and Ground-Water Resources of Portage County, Ohio, United States Geological Survey, Washington, D.C., 80 pp.

ADDRESS FOR CORRESPONDENCE
Yoram Eckstein
Department of Geology
Kent State University
Kent, OH 44242
USA

E-mail: yeckste1@kent.edu