Characterization Methods for Fractured Glacial Tills[1]

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ABSTRACT. **This paper provides a literature review of methods successfully employed to characterize fine-grained and fractured or unfractured glacial deposits. Descriptions and examples are given for four major categories of characterization methods: physical, hydraulic, chemical, and indirect. Characterization methods have evolved significantly within the past ten years; however, there still exists uncertainty about the reliability of individual characterization methods applied to till deposits. Therefore, a combination of methods is best, the choice of which depends on the objectives of the work. Sampling methods, sampling scales, and reporting methods are extremely important and should be considered when interpreting and comparing results between sites. Recognition of these issues is necessary to ensure that decisions regarding the transport of fluids in fractured tills are not based on the assumption that poorly permeable tills are always an inhibitor of subsurface flow.**

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INTRODUCTION

Till-matrix materials composed of fine-grained silt and clay typically are of very low permeability; however, fractures within tills may significantly increase permeability. Transport of water and contaminants occurs in the matrix material (till) and in the fractures themselves. Fractures also enhance the amount of recharge that reaches the water table, and in some areas, flow within fractures may be the primary mechanism of recharge. Methods devised to determine hydraulic properties of fractured tills must be capable of distinguishing between transport within fractures and transport within the matrix. The composition of till and fracture-filling materials also causes fluids and contaminants to behave unexpectedly because of a wide range of influences, including mineralogy, environmental conditions (temperature, pH, reduction-oxidation potential, and so forth), organic carbon content, sorption, diffusion, and thermodynamically driven chemical reactions. For example, contaminants such as dense nonaqueous-phase liquids (DNAPLS) may move through fractures with little or no retardation (Kueper and McWhorter 1991), whereas other contaminants may be strongly sorbed onto fracture walls and enter matrix materials by diffusion.

The intent of this paper is to provide a review of characterization methods that have been used successfully in glacial till. Prior to 1990, few field studies were published on this topic but research regarding fractured tills has evolved rapidly since then. Many more references are available from the literature than can be provided in this review; however, a few selected reference citations are given for each application so that interested individuals have a starting place. Neither genesis of fractures in till nor the physics of flow through fractured media are discussed in this paper. Those issues are addressed elsewhere in this issue (Brockman and Szabo 2000; Fausey and others 2000) and in other texts. Several of the references given in this paper are from results of work on fractures in consolidated or crystalline bedrock and are specifically noted where present. Although results from, and concepts applied to, fractured rock may not be directly applicable to fractures in unconsolidated tills, many of the problems encountered in these environments are analogous. For the purposes of this paper, no distinction is drawn between fractures or other voids in tills, such as joints or biopores (root channels, wormholes, or burrows).

MATERIALS AND METHODS

The review is based on a compilation of literature and research regarding characterization of tills. The characterization methods described in this review include methods employed to describe the characteristics of and mass transport through matrix material and fractures. Many references were taken from conference proceeding abstracts given in *Mass Transport in Fractured Aquifers and Aquitards* (Jorgensen, Skjernaa, and others 1998). Some of these abstracts were expanded to extended papers and were published in a special issue of the journal *Nordic Hydrology* (for example Jensen and others 1999, Klint and Gravesen 1999, and McKay and others 1999). Additionally, references were obtained from the libraries of The Ohio State University and the US Geological Survey in Columbus, OH.

Because the perspective and experience of the author is from hydrogeology, the characterization methods and review materials discussed in this text necessarily reflect this discipline. Geotechnical engineering considerations are beyond the scope of this review; however, the reader is referred to Allred (2000) for more information. Additional information from the diverse fields of geology, soil science, chemistry, physics, and biology is needed for comprehension of the complexity of ground water flow and mass transport in this environment. Nevertheless, the following discussion, albeit from a hydrogeological perspective, should provide professionals in all fields with an appreciation for the varied tools we have at our disposal.

RESULTS

This section is organized into 4 subsections: physical methods, hydraulic methods, chemical methods, and

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indirect methods. These subsections include not only characterization methods of tills and the fractures found within them, but also tools for characterization of the flow of water and contaminants. Some overlap between subsections was unavoidable because certain tools can be characterized under more than one category (for example, chemical tracers such as tritium can be considered a hydraulic method and a chemical method). Cross-references between sections are supplied where appropriate.

Physical Methods

Physical methods are the most common and generally are the least expensive methods used to characterize fractures in till. The principal reasons for carrying out physical evaluations are: a) to determine the likely origin and age of the till deposits, which may influence the types, orientations, and degree of fracturing; b) to obtain direct measurements of fracture distribution, especially for fractures with visible oxidation, which may be indicative of rapid ground-water flow; and c) to identify other lithologic features such as sand layers or paleosols, which can act as conductive pathways for flow. Five general categories of physical characterization methods are described: mineralogic, fabric and structure, grain-size distribution, field mapping, and drilling and coring.

Many early studies determined the mineralogy and glacial genesis of tills by applying methods used in sedimentary geology and soil science to determine provenance and to correlate sedimentary units and soils over great distances. Hand identification of the mineralogy and lithology of pebbles and larger-sized clasts describe the underlying rocks scoured by the glacier. Statistical evaluation of pebble counts often shows that tills contain pebbles of mostly local origin but that larger erratics are often from distant source areas (for example, many larger glacial erratics in Ohio are of Canadian origin). Strobel and Faure (1987), for example, showed that the abundance of granitic and metamorphic clasts in till decrease exponentially with distance from the source area to a minimum of about 4% 800 km down-ice from the source area in southwestern Ontario, Ohio, and Indiana. Correlation and provenance studies, however, are made difficult because tills near preglacial lake settings or marine shorelines also may contain rainout pebbles or ice-rafted debris (Eyles, McCabe, and Bowen 1994).

X-ray diffraction, X-ray fluorescence, scanning electron microscopy, and analysis of thin sections provide chemical and structural information on the mineralogy of matrix and fracture-filling materials. Examination of hand samples or thin sections also allows for determination of the paragenetic sequence of fracture-filling sediments and precipitates. Staining and impregnation of till samples often reveals the interconnection and distribution of pores and fractures (Edwards, Shipitalo, and Norton 1988; Hatano and Booltink 1992). More information on these methods can be found in Amonette and Zelazny (1994) and Klute (1986).

The sedimentary structure (as opposed to pedologic structure) or sedimentary fabric of glacial tills may be used in determining the genesis of the deposit; however, tills are typically massive and show few types of sedimentary structures. Tills may contain oriented pebbles that can be used to help define directions of ice movement during deposition. Lodgement tills may also contain subhorizontal and (or) conjugate sets of vertical fractures that were caused by forces exerted by ice movement. Clay-sized particles often have a preferred orientation, which results in anisotropy of the till matrix. The size of sediment grains may increase or decrease with depth due to changes in the energy regime during deposition.

One investigative method that can assist in correlation and age dating of till and till-related deposits is based on the detailed analysis of primary and secondary pollen assemblages (Carmichael, Mothersill, and Morris 1990; Dreimanis, Liivrand, and Raukas 1989). Age dating of wood fragments or other organic debris in till is also done by measurement of the abundance of the radioactive isotope carbon-14 (Flint 1957); however, the relatively rapid decay of carbon-14 ($t_{1/2}$ = 5,730 years) only permits age dating back approximately 35,000-40,000 years.

Grain-size distributions of till samples help describe the relative abundance of clay, silt, sand, and gravel, which may be related to occurrence of fractures (Tornes and others 2000). Although grain-size distribution analyses are sometimes used to estimate hydraulic conductivity, evidence indicates that values obtained by these methods may be inaccurate when compared with those obtained by other means (Bradbury and Muldoon 1990; Driscoll 1986). Grain-size analyses may provide relatively meaningless hydraulic conductivity values in systems dominated by structural macropores, which includes fractures.

Perhaps the earliest identification and differentiation of till features came from field mapping and examination of road cuts or other similar excavations. As of 2000, complex pit excavations, combined with sample collection and field mapping, have advanced to a high level of detail and relatively large scale (see for example, Christy, McFarland, and Carey 2000; McKay and Fredericia 1995). Although field mapping of tills can be done without the excavation of a pit, the structure of the till and orientation of fractures (if present) cannot be accomplished without a three-dimensional exposure.

Excavations provide a way to measure many aspects of fractures, including depth, intensity, trace frequency, aperture, spacing, orientation, and density. In the hopes of developing a standard measurement technique, Klint and Fredericia (1998) and Bosscher and Connell (1988) have prepared definitions and techniques for measuring the physical dimensions of fractures in till (Table 1). Care should be taken while making these types of measurements because exposures often only provide an apparent orientation of the fracture (similar to the problem of apparent dip in measuring the strike and dip of rocks). Fracture dimensions also can be used to determine the potential for fluid flow within the fractures. For example, a relation was established that, for a given water-level gradient, fracture flow velocity varies

TABLE 1

Measurable characteristics of fractures (modified from Klint and Fredericia, 1998 and Bosscher and Connell, 1988).

Characteristic	Description	Reporting units
Orientation	Strike and (or) dip direction of fracture.	Degrees
Spacing (S)	Mean perpendicular distance between adjacent fractures in an almost parallel fracture set.	Length (L)
Intensity (1/S)	Number of fractures per unit area.	Fractures per area (n/L^2)
Trace frequency	Number of fractures per unit length counted along a vertical and horizontal scanline.	Fractures per unit length (n/L)
Density	Cumulative fracture tracelength in a specified area.	Length of fractures per unit area (L/L^2)
Aperture	Width of fractures.	Length (L)

proportionally with the cube of the fracture aperture (Romm 1966; Snow 1969 *in* McKay, Cherry, and Gillham 1992). Harrison and others (1992) simulated fracture flow through a till and found that fractures with apertures as small as 10 μm are capable of transmitting significant amounts of contaminants to underlying aquifers.

Fractures often can be identified and mapped in the field by visual identification. They may be defined by cracks or voids in the till and commonly are filled with or surrounded by sediments or precipitates of varying color. An oxidized zone that is different in color than the surrounding unoxidized matrix may border fractures. It is important to note that physical methods are limited by the inability to distinguish between hydraulically active fractures and those that have been closed due to changing stress conditions or infilling with precipitates or sediments. Additionally, it may be difficult to distinguish unoxidized pre-existing fractures from fractures caused by excavation. McKay and Fredericia (1995) offer a protocol for fracture classification that addresses these issues.

An example of a fracture-mapping technique is given in Helmke, Simpkins, and Horton (1998), who mapped fractures using clear acetate and identified two genetically different fracture sets in Iowa tills. The first set of fractures was perpendicular to the dominant ice-flow direction and was deemed to be of glacial origin, whereas the second set of fractures was polygonal and due to desiccation. Klint and Gravesen (1999) dug trenches and mapped at least three different fracture sets that were interpreted to be the result of tectonic activity, desiccation, and freeze/thaw processes. Edwards, Norton, and Redmond (1988) photographed cleaned surfaces that were scanned and digitally processed to examine fracture distribution. Wet bulk density and macroporosity have been estimated by digital techniques that included scanning and digital analysis of core samples (Warner and others 1989). Mapping of rock fractures and measurement of flow velocities has also been done by use of nuclear magnetic resonance imaging (NMRI), (Dijk, Berkowitz, and Bendel 1999). Although a relatively new technique, NMRI eventually may be developed to permit the non-destructive, three-dimensional mapping of fractures and definition of primary flowpaths for water in glacial tills.

Drilling and coring methods have advanced significantly in the past decade. Conventional drilling methods, including auger or cable-tool drilling techniques, may disturb and homogenize core samples and make recognition of fractured intervals difficult. Split-spoon, Shelby-tube, or other core-barrel sampling devices may yield relatively intact samples. Alteration of the outer surface of the sample due to smearing, however, may mask visible fractures and cause bias in laboratory measurement of hydraulic properties from the core sample. Recently developed resonant sonic drill rigs that use energy waves to vibrate the drill stem through sediments are capable of obtaining core samples to depths up to about 170 m (US Department of Energy 1999). Drilling with the resonant sonic method has the advantages of almost 100% recovery of core and of greatly enhanced penetration rates that may be 2 to 4 times those of traditional drilling methods. Samples obtained by this method, however, may be subject to elevated temperatures, which may result in chemical or physical alteration.

Cable-tool, "hydropunch," or direct push methods typically involve recording the number of blows or impacts required to push a drilling tool or probe through a given thickness of sediment. Drill stems fitted with a pressure sensor (penetrometer) measure the relative resistance of sediments to the force of downward pressure which, in turn, may be related to grain size and to the hydraulic properties of the till (see, for example, Strutynsky and Sainey 1990). Cone penetrometers equipped with electrical logging tools and pore-pressure-measuring devices provide additional downhole data. Klopp and Walker (1987) obtained electrical resistivity data by these methods to estimate clay content and water chemistry. Cone penetrometers have also been outfitted with lasers that cause hydrocarbons to fluoresce. This allows mapping of the distribution of hydrocarbons that may be present in fractures or matrix materials (Kenny and others 1999).

Although traditional coring techniques may allow characterization of tills in a vertical section, the orientation of fractures in tills often deviates from vertical. More importantly, a typical core sample may include few, if any, fractures within a given interval if the vertical-coring device was placed between fracture sets. To circumvent this problem, angled or horizontal drilling techniques may be used as demonstrated by Murdoch and others (1999) and Simpkins and Helmke (1998).

Because the sampling procedure may disturb the core sample, great care must be taken to obtain an intact and representative sample. Undisturbed coarse-grained, unconsolidated sediments in the unsaturated zone may be relatively easy to collect; however, saturated sediments are difficult to obtain through traditional methods because the sediment often shifts during sample collection. Large sample sizes (0.5 cubic meters or more), such as those collected by Foged and others (1998), Nilsson and Sidle (1998), and Hinsby and others (1996), may be required to retrieve adequate amounts of till and a representative set of fractures.

Correlation of lithology and fractures between core holes or wells is difficult in till because of heterogeneous characteristics inherent in most glacial sediments. For example, the continuity of lenticular sand and clay lenses often is interpreted from boreholes many tens of meters apart; however, Norris (1998) expressed concern that the data to support cross-hole correlation often are lacking. Similarly, fracture sets that have the same orientation or characteristics should not be assumed to be physically or hydraulically connected.

Hydraulic Methods

Most hydraulic methods used for the evaluation of the properties of fractured glacial tills were designed for granular porous media and have been adapted for use in fractured media. Geotechnical engineering properties of till will not be addressed in this paper: for more information on measuring engineering properties of tills, the reader is referred to Allred (2000).

Laboratory estimation of porosity of coarse-grained deposits such as gravel, sand, or coarse silt is done by comparison of unsaturated and saturated sample weights or impregnation under vacuum combined with microanalysis in thin section. Similar tests in fine-grained sediments such as clay are more problematic due to difficulty in removing the moisture from the sample and the resulting alteration of micropores during desiccation. Additionally, removal of ambient confining pressures present in the field may result in sample expansion. Laboratory tests for porosity in fine-grained sediments also are limited by the time required to fully saturate a sample. Bronswijk (1991) measured bulk density of small samples of till and calculated the dry weight of a known volume of till. All the pores were assumed to be filled with water, and simple subtraction yielded a porosity value for the samples. The Saran resin clod method described by Brasher and others (1966) also is commonly used for determining porosity on air-dried samples of fine-grained sediments. Some consolidation of the samples may occur during drying with this method, but, for most glacial tills, the change in porosity is likely to be very small. A summary of techniques used for determination of porosity and bulk density in soil samples is given in Blake and Hartge (1986).

Storage or specific yield can be estimated by saturation of a sample with a known volume of water, then desaturation under gravity flow or under an artificially induced pressure gradient. As is the case for measurements of porosity, saturation and desaturation of fine-grained materials may not be possible because of low permeability and extended time periods required for saturation and desaturation. Prill and others (1965) performed specific yield experiments on artificial samples of varying grain sizes. For fine-grained silt, specific yield values were approximately 6%. Two important conclusions came about as a result of Prill and others' work: first, the coarser the grain size of the sediment, the closer the specific yield will be to porosity, and second, it may take several months for fine-grained samples to reach equilibrium and provide accurate specific yield values. For fractured clay tills, the specific yield may be controlled by the fracture porosity, which is usually <1%, rather than the matrix porosity, which tends to remain saturated because of the capillary tension.

Measurement of hydraulic conductivity and transmissivity in the laboratory are most often done by permeameter, triaxial chamber, or consolidation (oedometer) tests. Undisturbed samples are subjected to a hydraulic gradient and measurements are made regarding the amount of water or other fluid that passes through a known area and length of sample during a measured time period. The Darcy equation is then used to calculate hydraulic conductivity. The sample also may be subjected to a confining pressure to simulate the weight of overlying sediments in the field. Careful consideration needs to be given to selection of realistic hydraulic-gradient values and confining pressures. Examples of these test methods are given in Desaulniers and others (1981), who document the use of consolidometers and triaxial methods to determine hydraulic properties of unfractured till, and Mishra, Parker, and Singhal (1989), who measured soil hydraulic properties and particle-size distributions to examine the uncertainty of measurement attributed to heterogeneity. Nimmo and Mello (1991) measured saturated hydraulic conductivity by forcing water through a sample in a centrifuge. Water-level declines between sample runs were reduced to a hydraulic conductivity value by means of a centrifugal analog of the gravitational falling-head formula.

Conventional laboratory tests for hydraulic conductivity and storage on small samples are usually indicative only of the matrix properties of the till. In a few studies, tests on large-diameter (0.5 m) samples of undisturbed till have succeeded in capturing enough of the fracture network to obtain hydraulic conductivity values that are similar to field-measured values (Hinsby and others 1996; Jorgensen, McKay, and Spliid 1998). There still remains a lot of uncertainty, however, about whether laboratory measurements are truly representative of large-scale field conditions at a scale appropriate for estimation of recharge or contaminant transport.

Extension of laboratory practices into the field involves larger sample sizes that likely include more fractures. Standard infiltration tests have been used to determine the rate at which water or other fluids infiltrate into till (Bohne and others 1993; Albrecht and Cartwright 1989; Booth and Price 1989). D'Astous and others (1989) and McKay, Cherry, and Gillham (1993) installed seepage collectors in trenches to evaluate the hydraulic conductivity of fractured tills. Nilsson and Sidle (1998) used large-scale infiltration tests within a 19.2 m^2 basin overlying fractured till. The researchers concluded that hydraulic conductivity was proportional to the volume of material sampled—as sample size decreases, hydraulic conductivity also decreases. Jorgensen (1998) used large flexible-wall permeameters (0.5-m diameter columns 0.5 m in height) and found that 96 to 99% of water flows through macropores, including fractures. Installation of soil-suction lysimeters or tensiometers may provide intervals for water sampling or measurement of other characteristics in till, such as soil-moisture tension, which can be related to degree of saturation and directions of water movement.

Field-scale values of hydraulic conductivity in tills are often measured by single-well aquifer-test methods, which involve a withdrawal or addition of a known volume of water and measurement of the response of the water level in the well with respect to time. The time it takes for the well to return to the (pretest) static level is proportional to the hydraulic conductivity of the aquifer material. Single-well-volume displacement tests (slug tests) are employed in field applications primarily because of the low cost and simplicity of the technique; however, the volume of aquifer material tested is small as compared to multiple-well aquifer tests. Another form of slug testing involves pressurization of a well casing with air or other gases (such as nitrogen or carbon dioxide) to depress the water level so that measurement of recovery time and head can be made after the pressure is instantaneously released (see, for example, Strobel 1996). Measurements of water levels throughout the duration of the test are usually made with pressure transducers that are in the well. Prudic (1982) used slug tests to measure horizontal hydraulic conductivity in tills in western New York. The average value for 12 tests was 6×10^{-8} cm/sec, which was comparable to other measurement methods. Fausey and others (2000) measured vertical hydraulic conductivity in fractured till in Ohio using a method where the water level was held constant in the measuring device. The quantity of water required to maintain a constant water level was measured and used in calculations described in Amoozegar (1989). Results indicate that hydraulic conductivity of the matrix material was 4 times less than the hydraulic conductivity within fractures. Flowmeters or heat-pulse-flowmeter tests measure extremely small flow rates within a borehole or well that can be used to calculate hydraulic conductivity (Wolf and others 1991). Wang and others (1978) used a form of single-well-volume displacement testing in fractured media by pulse testing individual fracture apertures. Butler (1997) provides an in-depth review of the design and analysis of slug tests.

Smearing within the borehole has been shown to influence the results of downhole hydraulic tests (McKay, Cherry, and Gillham 1993; D'Astous and others 1989). Overcoring methods using Shelby tubes were used by these workers to reduce the effects of smearing on the borehole wall. Smearing is not a problem in all tills, and although there are some theories, it isn't exactly clear what factors control its occurrence. Various researchers have hypothesized that low-clay-content tills and highly overconsolidated tills are likely to be less susceptible to smearing, but no definitive studies of smearing have been conducted.

Larger-scale, multiple-well aquifer tests or pumping tests involve pumping water from a well and measuring water levels in adjacent monitoring wells. Step tests, in which the pumping rate is increased at regular intervals, provide important information regarding well yield and the specific capacity of the formation (Birsoy and Summers 1980). Step tests usually are done prior to a long-term aquifer test. For work in tills, low pumping rates (less than 1.0 liter per minute) may be required to prevent the water level from going below the screened interval. Because of heterogeneities in tills, wells that are screened over large intervals may require the use of inflatable straddle packers, which provide isolation from other zones of higher or lower hydraulic conductivity. Wells screened in till typically require a sand pack around the screen to prevent fine-grained materials from clogging the screen openings. Packer-test results may be influenced by flow of water through the sand pack instead of the till.

Strobel (1993) did aquifer tests in glacial deposits in three different settings in Ohio. Core samples of the deposits showed that end-moraine and ground-moraine deposits were fractured to depths of up to 5.0 m, whereas lacustrine deposits were unfractured. Strobel used a bladder pump with very low discharge rates to determine horizontal and vertical hydraulic conductivities. Hsieh and others (1985) injected fluid into a number of isolated zones in boreholes in fractured crystalline bedrock and measured the response in the same isolated zones in adjacent boreholes. The response was fitted to one of several possible analytical solutions to derive values of hydraulic conductivity. Long-term pumping tests from wells in overlying and underlying aquifers were used by van der Kamp, Maathius, and Menely (1986) to determine bulk hydraulic conductivity of a till. Jones, Lemar, and Tsai (1992) did two 24-hour aquifer tests: a constant-flow-rate and a constant-drawdown test where the head in the well was maintained by adjusting the pumping rate. They concluded that constant-drawdown tests work better because they are designed to decrease the rate of pump discharge with time, whereas a constant-flow-rate test may potentially dry up the well and exceed specific capacity. It should be noted that, in fine-grained deposits, 24-hour tests might not be long enough to attain equilibrium in water levels in observation wells. An excellent review of aquifer tests and their application to uniformly fractured aquifers and single vertical fractures is given in Kruseman and de Ridder (1991). Additionally, many hydrology textbooks, such as Domenico and Schwartz (1997) and Fetter (1994) offer chapters with discussions of aquifer-test methods and example problems.

Traditional aquifer-test methods are difficult in till and other low-permeability geologic materials for several reasons, including very long response times for water-levels to respond to the application or removal of stress, fracture flow (which causes difficulties in data interpretation), smearing along the borehole wall, storage in the sand pack around the well screen, and heterogeneities due to sand lenses and fractures. Before data collection begins, it should be realized that hydraulic conductivity might range over several orders of magnitude, depending on the degree of fracturing and grain-size distribution. Neuzil (1982) discusses many of the issues involved in doing such tests in low-permeability environments.

Clearly, data-collection efforts for aquifer tests in fractured tills have their difficulties. Analysis of the data to produce representative and reproducible results often is subjective. Discussion of the theory and procedures is beyond the scope of this paper; however, commonly used techniques include those of Hvorslev (1951); Cooper, Bredehoeft, and Papadoupulos (1967); and Bouwer and Rice (1976). Interpretation of multiple-well aquifer tests typically incorporates the methods outlined by Hsieh and others (1985) using the modified Hantush method (Hantush 1960, 1964). Neuman and Witherspoon (1969) developed a solution by modeling till as a leaky confining unit when overlying a productive aquifer. Keller and others (1989) used an analysis of the downward propagation of seasonal water-table fluctuations to determine vertical hydraulic conductivity in a thick clayey till. Results of Keller and others compared favorably to those from conventional smaller-scale field tests. Many of the data-analysis techniques listed above have been computerized in commercially available software packages. The software eliminates some of the subjectiveness of interpretations, but also may oversimplify complex hydrogeologic environments and allow the user to obtain results without completely understanding the method or its limitations.

Beyond data collection and interpretation, there are numerous other difficulties in hydraulic characterization of fractured tills:

- Because tills are anisotropic and heterogeneous, results from measurement methods for infiltration rate, hydraulic conductivity, and other hydraulic properties change with different orientations and sampling methods. Several workers, including Schulze-Makuch and others (1999), Banton (1993), and Keller and others (1989), used various techniques and scales of study to confirm that measurement method and scale influence hydraulic conductivity measurements in heterogeneous materials.
- Smearing by drilling or coring may cause significant disturbance within a borehole. This causes biased values of measured hydraulic properties.
- Some clearly visible fractures may not be hydraulically conductive, as found by Baumann and Foged (1998). Therefore, even though fractures may be observed in the field, they are not necessarily part of the active flow system. A sample population of fractures in one locality may include both active fractures and isolated, inactive fractures.
- Many other variables are involved in the way water moves through fractured porous media, including temperature (Giakoumakis and Tsakiris 1991), rainfall intensity prior to measurement, which may cause sedimentation in fractures (Gimenez and others 1992), and reduction of water movement into the matrix (that is, "healing") due to fracture coatings (Thoma, Gallegos, and Smith 1992).

Although the problems in measuring hydraulic parameters of fractured tills seem numerous, data collection and interpretation techniques continue to advance. Hsieh (1998) summarizes three critical advances towards our understanding of the hydraulics of flow in fractured media: analysis of aquifer-test data by numerical models, combining aquifer tests with geophysical exploration, and three-dimensional visualization. In addition, as the scientific community recognizes the significance of ground water recharge and transport of contaminants through fractured tills, more emphasis will be placed on developing and perfecting hydraulic characterization methods.

Chemical Methods

Chemical methods to evaluate till properties include two general categories: those that determine the solid-phase chemical composition of till and fracture-filling or fracture-lining material, and those that determine the chemistry of pore waters. Solid-phase analyses of till often help constrain the types and magnitude of water-sediment interactions. Water chemistry within pore spaces provides important information regarding till genesis, recharge, and contaminant transport.

Chemical analyses of the solid-phase materials that comprise tills are similar to analysis of other types of geologic materials except that determination of clay mineralogy offers some unique challenges not typically encountered in coarser-grained sediments. Properties such as cation exchange capacity, charge characteristics, and surface area are important in understanding clay-mineral interactions with solutes. Methods to determine these properties are quite complex and are beyond the scope of this review. The reader is referred to Sparks and others (1996), Amonette and Zelezny (1994), Dixon and Weed (1992), and Klute (1986) for more information.

Two different approaches are utilized for chemical analysis of clay samples from till; selective dissolution and total chemical analysis. For selective dissolution, specific elements or compounds are removed and quantified without regard to the rest of the sample. The sample may be first evaluated for its organic material content, and the organics are then removed through an oxidation process or other treatment. Carbonate content (specifically the minerals calcite and dolomite) may be assessed by acidification. After removal of organic material and carbonate minerals, the remaining residue may undergo selective dissolution for elements such as manganese (Chao 1972), iron (Mehra and Jackson 1960), and aluminum (McKeague, Brydon, and Miles 1971). Total chemical analysis involves digestion of the entire sample in a strong acid. The resultant solution is subjected to elemental analysis using standard wet chemistry techniques. The results of total chemical analyses are usually reported as a weight percent of the element in an oxide form. Analysis methods for many inorganic substances in sediments are described in Fishman and Friedman (1989). Jackson (1975) probably offers the most complete methodology available for chemical analyses of clay minerals.

Transport of dissolved contaminants in fractured tills can be strongly influenced by a variety of processes including sorption to solids on fracture faces or within the matrix, diffusion into the relatively immobile pore water in the matrix, and chemical or biochemical transformations (for example biodegradation of dissolved hydrocarbons). Sorption processes include electrostatic attraction to charged mineral surfaces, which strongly effect many cations, acids, and some polar organic molecules, and hydrophobic attraction to solid organic matter, which tends to effect weakly polar molecules, such a trichloroethylene. Sorption processes are often modeled as a simple linear or non-linear relationship that require experimentally derived distribution coefficients (K_d) values. In homogeneous materials, (K_d) values can be used to calculate a retardation coefficient (r_f) which is the ratio of the velocity of a sorbing contaminant to the velocity of the water, as explained in Fetter (1999). Distribution coefficients for many types of contaminants can be measured in tests in the laboratory (see, for example, Fetter 1999), and are widely used in granular deposits. However, this simple approach is less successful in fractured glacial tills, because the contaminant is often not uniformly distributed through the material.

In fractured clays, contaminants tend to be transported by flowing ground water through the fractures, but they can also diffuse into the relatively immobile pore water in the fine-grained matrix between fractures. This process is referred to as matrix diffusion (Grisak and Pickens 1980), and it can greatly retard the migration of both sorbing and non-sorbing contaminants. Field-scale experiments in fractured tills in Canada (McKay, Gillham, and Cherry 1993) and Denmark (McKay and others 1999) compared migration rates for non-reactive dissolved tracers (chloride and bromide) to colloidal tracers (bacteriophages), which were expected to diffuse very slowly, and observed that the dissolved tracers were retarded by factors of 10-100. Recent field experiments in fractured residual clays show that matrix diffusion can retard solute migration by factors of up to 500 (McKay and others 2000). For contaminants influenced by sorption, the differences may be even greater, because once the contaminants migrate into the matrix, they are more likely to sorb to clay surfaces. Description of methods for evaluating or numerically modeling the influence of matrix diffusion is beyond the scope of this paper; however, one critical parameter that is needed for such evaluation is the *effective* diffusion coefficient. The effective diffusion coefficient is a function of the characteristics of the compound, the geologic material, and the chemistry of the pore water. A variety of methods of measuring diffusion coefficients in glacial clays or other fine-grained materials have been developed. The methods usually involve placing a soil sample in contact with a reservoir containing the contaminant and then measuring the concentration changes in the reservoir due to diffusive losses into the soil sample. These methods are described in detail by Shackleford and Daniel (1991), Novakowski and van der Kamp (1996), and van Rees and others (1991).

Chemical and biochemical transformations are even more complex than sorption and matrix diffusion, and there have been very few studies of these processes in fractured clay tills. Hence, they are not discussed further in this paper.

Because tills and the clay they contain are poorly permeable and severely limit the migration of fluids with respect to time, information regarding till genesis can be obtained from water chemistry. Thus the pore spaces between clay-sized particles may still contain connate water that was present when the clay was deposited. Hendry and Wassenaar (1999) used environmental isotopes (δD and ^{18}O) in tills to estimate ages of glacial deposits in Saskatchewan, Canada. They used the isotopic data to show that the till under question was actually younger than previously believed. Simpkins and Bradbury (1992) used water chemistry in tills to determine the rates of flow, velocity, and the age of ground waters in southeastern Wisconsin.

Water chemistry also can provide abundant information concerning the characteristics of the recharge area. For example, land use practices have been statistically related to ground water chemistry (Squillace and others 1999; Eckhardt and Stackelberg 1995). Alternatively, many constituents are derived from dissolution of components of the tills themselves. For example, the occurrence of sulfate in tills was described by Hendry, Cherry, and Wallick (1986), and Keller and van der Kamp (1988). Both papers concluded that sulfate was derived from dissolution of sulfate-rich bedrock fragments.

Widespread anthropogenic tracers such as tritium (^3H), ^3He, and chlorofluorocarbons have been used to date waters through measurement of tracer concentration or analysis of the ratio of parent to daughter material and a known decay rate (Reilly and others 1994). The mere presence or absence of such constituents can set bounding limits on the age of water. If these or other anthropogenic constituents are present at depths greater than predicted by advection or diffusion through the matrix, then they may be indicative of fracture flow. Water chemistry also can provide information on longer-term natural recharge rates (Hendry and Wassenaar 1999) and help to identify recharge areas based on major-ion evolution (Desaulniers and others 1981; Keller and others 1991).

Absolute dates and calculated recharge rates can be determined by age-dating water samples; however, care must be taken to define water from within fractures (which might yield a young age) as opposed to water with the matrix (which might yield a much older age). Similarly, relatively young waters may have ample time to mix or equilibrate with components of the older till, resulting in ages that might be misleadingly old. For example, Keller (1991), Murphy and others (1992), and Bacon and Keller (1998) discuss some of the issues and problems related to carbon-14 dating of ground waters that have been in contact with older carbon from calcite and (or) organic matter.

Tracer tests on fractured tills can be used to determine the connection of the sampled interval to other intervals and predict contaminant transport rates. In most tracer studies, an inert tracer such as chloride, bromide, or dye is injected into a till sample and data are collected regarding the concentration of the tracer at a specific point with respect to time. The resultant breakthrough curve (a plot of concentration as a function of time) defines the velocity of the tracer and helps describe the degree of dispersion. If less mass leaves the system than was introduced, then sorption, diffusion, or chemical transformation probably occurred. Some of the tracers used in till and selected references that document their use are listed in Table 2. These experiments, when done in controlled environments, increase our understanding

TABLE 2

Selected chemical tracers used to characterize mass transport in fine-grained sediments.

Tracer	Reference
Contaminants and pesticides	
Atrazine	Shipitalo and others (1990)
DNAPL Creosote	Hinsby and others (1996)
EDTA[1]	Jardine and others (1998)
Mecocrop (MCPP) and metsulfuron	Hoffman and others (1998)
Mecocrop (MCPP) and simazine	Jorgensen and others (1998)
Nitrate (NO_3^-)	Helstrup and others (1998)
	Jorgensen (1998)
Orthophosphate (PO_4^{-3})	Jensen and others (1998)
Inert tracers	
Bromide (Br)	Hoffman and others (1998), Jardine and others (1998), McKay, Gillham, and Cherry(1993)
Colloids	Harvey and others (1989), McKay, Gillham, and Cherry (1993)
Dye	Hoffman and others (1998), Shnegg and Kennedy (1998)
Helium (He)	Jardine and others (1998)
Iodide (I)	Espeby (1990), van Ommen and others (1989)
Neon (Ne)	Jardine and others (1998)
Potassium bromide (KBr)	Foged and others (1998)
Calcium chloride ($CaCl_2$)	Jorgensen, McKay, and Spliid (1998)
Sodium chloride (NaCl)	Hartelius and Larsen (1998)
	Sidle and others (1998)
Strontium bromide (SrBr)	Shipitalo and others (1990)
Stable and radiogenic isotopes	
Carbon (^{14}C)	Simpkins and Bradbury (1992)
Carbon ($\delta^{13}C$ in DOC)	Murphy and others (1989)
Dueterium (^{2}H)	Simpkins and Bradbury (1992)
	Hendry and Wassenaar (1999)
Oxygen (^{18}O)	McKay, Cherry, Bales, and others (1993), Simpkins and Bradbury (1992)
	Espeby (1990)
Phosphorus (^{32}P)	Jensen and others (1999)
Tritium (^{3}H)	Simpkins and Bradbury (1992), Bradbury (1991)
	Daniels, Fritz, and Leap (1991), McKay and Fredericia (1995)
	Solomon and Sudicky (1991)
Microbiological	
Colloid-sized PRD-1[2] and MS-2[2]	Hinsby and others (1996), McKay, Cherry, Bales, and others (1993)

1. EDTA was tagged with ^{57}Co, ^{51}Cr, and ^{109}Cd

2. Bacteriophage

of contaminant migration and remediation techniques; however, transferability of results between sites may be limited because each fractured till site has unique characteristics.

Indirect Methods

Measurement of characteristics of tills by indirect methods is generally noninvasive and does not specifically require sample collection. This section includes brief descriptions of remote sensing, geophysical techniques, and computer simulations.

Remote sensing of the Earth's surface from satellites or aircraft can provide information regarding moisture content, vegetation types, soil types, ground water recharge and discharge areas, and surface expression of large-scale fractures (Jiren and others 1997; Schultz 1997; Mattikalli and Engman 1997). Remote-sensing platforms obtain reflectance and radiance values of the Earth's surface, which can be separated into discrete wavelength bands and then calibrated to ground-truth data. Because the spectral response of wet soil is different from that of dry soil, remote sensing has been shown to provide estimates of soil moisture in the top 5.0 cm of soil and can be used to estimate other soil properties such as saturated hydraulic conductivity (Engman 1997; Engman and Chauhan 1995). Large-scale fractures and faults that appear as linear features (lineaments) have been mapped successfully by use of aerial photography. Although remote-sensing techniques may be quite useful in large-scale applications, the resolution of the data is on the order of meters to tens of meters, whereas fractures in till exposed on the surface may be less than a meter in length and considerably narrower. The usefulness of remote-sensing platforms to locate and map fractures exposed at the surface is minimal with 2000 technology available to the general public; however, rapid advances in the resolution of data provided by remote-sensing platforms may provide sufficient data for analysis of smaller-scale fractures in the near future.

Geophysical methods respond to physical property contrasts of materials in the subsurface. Many geophysical methods are available for work in unconsolidated sediments, including electrical methods, seismic, gamma, neutron activation, magnetics, and ground-penetrating radar. Most geophysical methods provide the necessary information for determining lithology and thickness; however, identification of fractures has proven more difficult.

Because clays and other fine-grained sediments typical of tills have distinctively low resistivity (high electrical conductivity) and are stacked vertically, borehole electrical methods are straightforward. Surface electrical methods to distinguish depth and layering of tills are more difficult. Thin layers of coarser-grained materials within flat-lying tills are difficult to discern. Electrical methods also are made difficult by interference introduced from other electromagnetic fields. For example, Hartelius and Larsen (1998) used a saline infiltration experiment and a resistivity pole-dipole array. The results generally were poor because of heterogeneities in the till. McKay, Balfour, and Cherry (1998) used surface electrical conductivity to map the edge of a landfill in a fractured till, but this method was not effective in delineating the lateral extent of a downgradient chloride plume. Azimuthal resistivity involves taking a series of oriented measurements along diagonal lines of a circle. This method allows for determination of a preferred orientation of higher or lower resistivity. Penttinen, Sutinen, and Honninen (1999) used azimuthal resistivity and conductivity to determine depositional anisotropy. Azimuthal resistivity may have application in tills with fractures due to ice shove or ice shear (for example, basal lodgement tills). Because fractures commonly are filled with air or with other fluids of high resistivity, a direction of higher resistivity may be detected if fractures lie along a preferred orientation. Taylor and Fleming (1988) determined strike and porosity of fractures in till using azimuthal resistivity. This method cannot be used for polygonal desiccation or other randomly oriented fractures because in those situations there is no preferred direction of fracture orientation.

Seismic methods involve sending a pulse of energy (usually in the form of a hammer strike on the surface) into sediments. The reflection or refraction of the energy waves from bedding contacts or other structures sends a portion of the energy back to the surface where an array of geophones measure the response. Seismic methods are ideal for determination of thickness or depth to bedrock, bulk modulus, and other engineering properties.

Natural-gamma techniques can be used to differentiate fine-grained sediments, such as clay, from coarser sand or gravel lenses. Gamma radiation is released from radioactive decay of uranium, potassium, and thorium. These elements commonly are adsorbed on the surfaces of clay particles, but generally not on coarser-grained sands and silts (Keys 1990). Natural gamma borehole logging defines the thickness and depth of clay or sand lenses in till. Gamma logging can be done in open or cased boreholes and by airborne methods.

Other geophysical methods also may be used in clay-rich sediments. Jarvis and Leeds-Harrison (1990) used a neutron probe to determine moisture content of sediments. Schwarz (1990) used magnetics to differentiate alluvial and glacial sediments, which may be quite difficult to do from surface exposures alone. Ground-penetrating radar has been used with great success to locate buried underground objects; however, depth penetration is usually limited in clay-rich tills. Hsieh (1998) described the use of cross-well geophysical methods with seismic or electromagnetic waves to examine wave velocity and attenuation between boreholes in fractured crystalline bedrock; these attributes then were related to fracture density. Burke, Schmidt, and Campbell (1969) used a cross-plotting method and combined data from gamma-gamma, neutron, and acoustic logs to determine the amount of secondary porosity in carbonate-rock aquifers. This method also may be applicable in fractured-till settings; however, no examples of such applications have yet been documented.

The advance of digital computers to solve complex mathematical problems has provided researchers with powerful tools to perform numerical simulations. Although the computer models are simulations of the real world that, by necessity, must include many simplifying assumptions, the results often provide insight into how a hydrologic system operates. The first step in understanding the sources and sinks of water to a hydrogeologic system is to develop a conceptual model. A simple water balance can be constructed to qualitatively identify key features that control the gain or loss of water. For example, Sophocleous (1991) used a soil-water balance and water-level fluctuation in piezometers to estimate storage and recharge in a semi-arid environment. This approach also might be suitable for glacial sediments where the water table is close to the surface. The conceptual model also may help to determine which data need to be collected for construction and calibration of the numerical model.

By constructing a model to fit observed conditions using realistic input parameters and application of accepted principals and equations, valuable information can be gained about the hydrologic system, including rough estimates of hydraulic properties and details of transport of contaminants. Similar to the problems mentioned in the discussion on hydraulic methods, simulation of porous media with dual porosity within the matrix and the fractures is difficult. Commonly, porous media are assumed to be homogeneous with a higher simulated hydraulic conductivity because of the fractures (also known as the equivalent porous media, or EPM, approach). Alternatively, models that simulate each fracture (discrete fracture models) are limited because of the lack of field data to corroborate the extent and location of each fracture. Sidle and others (1998) modeled chloride transport in a fractured 4.0 by 4.48 m block of till and used both EPM and discrete-fracture models. They found that the EPM model fit the breakthrough curves well for the shallow and early stages of the simulation (less than 2.5 m and 1 day of simulated time), whereas the discrete fracture model fit the solute breakthrough curves better at depths of 4.0 m and times greater than 3 days. Thus, fracture and matrix flows were significant at shallow depths but fracture flow dominated at greater depths.

Numerical simulation techniques applied to mass transport in fractured tills are highly varied. Grisak and Pickens (1980), Tang and others (1981), and Sudicky and Frind (1982) provide some of the earliest solute-transport theory regarding mass transport and discrete fracture models. Simulations conducted by Neretnieks (1985) indicated that mass moves predominantly along networks of irregularly shaped pathways in the plane of the fracture and that most of the flow occurs in only a few fractures. Neretnieks also determined that channels within the fractures were so poorly interconnected that there may not be any interaction between adjacent fractures. Jourde, Bidaux, and Pistre (1998) simulated flow through fractured tills, and incorporated a parameter for fracture density. They also provided a detailed sensitivity analysis of the influence of fractures. Kueper and McWhorter (1991) modeled the flow of DNAPLs in fractures and found that they moved through fractures relatively quickly with little attenuation. Harrison and others (1992) simulated solute transport through a fractured till using a two-dimensional Laplace transform Galerkin finite element model. The modeling results indicated that even small hydraulically active fractures that are difficult to detect or identify are capable of transmitting contaminants to underlying aquifers.

DISCUSSION

The preceding text provides a brief introduction to the many tools available for characterization of fractured tills. The following section discusses how a combination of these techniques may provide more insight into the nature of fractured tills. The issues of scale, with specific regard to sample size and measurement scale, are discussed in addition to a short description of how reporting methods may assist in the clear and concise dissemination of results.

Each of the tools described above has advantages and disadvantages; however, experience in the field and in the laboratory dictates that a combination of methods usually is best. Many studies have documented how different measurement methods for hydraulic conductivity yield different results. For example, Wolf, Celia, and Hess (1991) measured hydraulic conductivity with grain-size distribution analyses, multiport permeameters, and borehole flowmeter tests and found that laboratory tests underestimated hydraulic conductivity as compared to field measurements. Taylor and others (1990) evaluated six methods of measuring the vertical distribution of hydraulic conductivity: straddle-packer tests, grain-size analyses, electrical conductivity logging, natural flow through the borehole, Stoneley wave attenuation, and a single-well electrical tracer test. All tests were found to have their applications and limitations, but no single test was definitive in all hydrologic situations. Fredericia and others (1998) used trenches, drilling of horizontal holes with multiport samplers and packers, ring infiltrometers, pond infiltration tests, and a microbial tracer (PRD1) to determine hydraulic conductivity of fractured tills; results indicate significant variability between each of these measurement methods. Healy (1989) collected data from tensiometers, moisture probes, and meteorological instruments to estimate seepage using four analysis methods: the Darcy equation, zero-flux plane, surface-based water budget, and ground-water-based water budget. Again, limitations were noted for each of the four techniques. Simpkins and Helmke (1998) evaluated tills in Iowa using Shelby tube core samples, angled and vertical wells, slug tests, and low rate (less than 1.0 L/min) pumping tests. They evaluated flow considering both dual-porosity conditions and Darcian flow and concluded that multiple methods are necessary to characterize all aspects of flow. Connell (1984) used measurements of fracture orientation, length, and spacing combined with grain-size analysis, clay mineralogy, carbonate content, and microstructural analysis to determine that all fractures at a study site in Wisconsin were related to ice shear. To characterize a site in Canada, van der Kamp (1994) mapped fractures in excavations, did geophysical surveys, measured bulk permeability, did slug tests and multiple-well aquifer tests, and measured seasonal changes in pore pressure and settlement due to surface loading. Foged and others (1998) describe various methods used to evaluate fractured tills in Denmark using thin sections, large block samples (0.5 by 0.5 m) in a triaxial chamber, and potassium-bromide tracer tests.

Knowing the type of information and the level of accuracy required for site characterization is important before proposing any work. Time, cost, equipment, and expertise often limit the selection of characterization tools. Although most work related to fractured tills is directed towards remediation of contaminant spills, research into the use of multiple techniques often can be quite expensive and afforded only by large research grants (see, for example D'Astous and others 1989; Jones, Lemar, and Tsai 1992; Jones 1993).

Many reports touch on the problem of scale and the effects of the sample size with regard to identifying the characteristics of fractured till (see, for example, McKay, Cherry, and Gillham 1993; Keller and others 1989). Fractures in tills may occur at many different scales: from microscopic preferential pathways that may be a millimeter or less in width, to extensive fracture systems that may extend tens of meters into the subsurface. Core samples may intersect a fracture plane; however, unfractured samples often are preferentially chosen for analysis because of the belief that the sample was fractured during drilling or after collection. We must continuously ask ourselves whether a given sample is representative of field conditions and will our results answer questions about recharge rates, flow of water, and flow of contaminants in the subsurface.

The relation between scale and dispersivity of contaminants has been examined by several workers (Gelhar, Gutjarh, and Naff 1979; Sudicky and others 1983; Van Wesenbeeck and Kachanoski 1991). They all came to similar conclusions and found that the degree of dispersivity was related to the size of the sample or scale of the test. A similar relation between scale of measurement and hydraulic conductivity was reported by Schulz-Makuch and others (1999). They found that hydraulic conductivity increased with the scale of measurement in heterogeneous sediments.

The concept of a representative elementary volume (REV) describes the minimum volume of material beyond which the effects of heterogeneity are minimized. It is important to be able to distinguish the differences in behavior of contaminant transport due to fractures as opposed to behavior due to heterogeneity. To address problems of scale, scaling factors have been proposed. As stated by Ahuja and Williams (1991) "...scaling is a means to relate soil properties of different soil types or spatial locations by use of simple conversion factors, called the scaling factors." Vogel and Cislerova (1993) used a scaling-based inverse problem to obtain values of field-scale saturated hydraulic conductivity and moisture capacity. Based on these studies, it appears that a variety of methods *at different scales* are necessary to ensure that fractures are considered in a site evaluation of fractured, heterogeneous materials.

Finally, many reporting methods and statistical measures have been used to present data regarding fractured tills. As shown on the cover of this issue, a photograph may often be a very convincing means of argument. Data types and definitions listed in Table 1 help to define the characteristics of fractured tills so that consistency is maintained and comparisons between sites can be made. Rose diagrams and projected stereonets are used to display the orientations of fractures and faults. These methods may demonstrate a preferred orientation (if present) of fractures in till. Statistical measures of heterogeneity (including descriptive statistics regarding hydraulic conductivity and spacing or density of fractures) include autocovariance and autocorrelation functions (Freeze and others 1990) and fractal dimensions of permeability of stratified soils (Kemblowski and Wen 1993). Unlu and others (1990) describe several statistical methods for characterizing the spatial variability of hydraulic properties in soil. Graphs that present data on the distribution of fracture characteristics with depth also can be used very effectively (for example, McKay, Cherry, and Gillham 1993).

Fractures in tills have caused many difficulties for workers interested in site characterization and the fate and transport of contaminants in the subsurface. As reported by Ruland, Cherry, and Feenstra (1991), active ground water flow in fractures varies widely, ranging in depth from 5.0 m to more than 10.0 m at 12 different sites in southwestern Ontario. Some hydrogeologists would argue that fractures in tills are unimportant for mass transport because they are not connected to the local and (or) regional flow system. Others state that fractures in tills are the cause of unexplained contaminant migration. Yet, unless specific tests are done to conclusively evaluate the contributions of fractures to the flow system, these assumptions may not be valid.

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