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Are Visible Fractures Accurate Predictors of Flow and Mass Transport in Fractured Till?

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Article Impact Statement: This paper assesses whether the visible presence of fractures on the ends of till columns are indicative of fracture flow within the column.

Abstract

Tracer experiments conducted in the laboratory on undisturbed core samples (<7.3-cm-diameter) have been a standard method for estimating hydraulic and transport properties of fractured till since the 1980s. This study assesses the relationship between visible fractures on the top and bottom of core samples and the resulting hydraulic and mass transport properties of the core. We hypothesized that more visible fractures would indicate the presence of a well-connected fracture network, leading to greater hydraulic conductivity (K) values and earlier chemical breakthrough times. To test this hypothesis, water flow and bromide (Br-) tracer

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experiments were performed on ten, 16-cm diameter, 16-cm-tall samples of fractured Dows Formation till from central Iowa. Visually identifiable fractures were present on the top and bottom of every sample. Results indicate that the visual identification of fractures does not predict a connected fracture network, as some samples produced breakthrough curves showing rapid first arrival times and shapes characteristic of solute transport in a fractured medium, while others appeared similar to an unfractured medium. No correlation was found between the number of visible fractures and K (Pearson's r = 0.25), or Br- first arrival time (r = -0.33), but a strong negative correlation between K and first arrival time (r = -0.92). Results indicate that the sample volume was not large enough to reliably contain a connected fracture network. Thus, testing large volumes of till at the field scale coupled with fracture-flow modeling likely represents the best approach for estimating hydraulic and mass transport properties for fractured till.

Introduction

Fractured till comprises the predominant surficial material underlying agricultural fields in Iowa and much of the upper Midwestern United States (Prior et al. 1991; Rodvang and Simpkins 2001). Field and laboratory studies of fractured till, conducted in Iowa and elsewhere, have shown that till fractures can increase the bulk hydraulic conductivity (K) of a till formation by 1-4 orders of magnitude and provide pathways for the rapid movement of solutes (Grisak et al. 1980; McKay et al. 1993; Seo 1996; Jørgensen et al. 1998; Helmke et al. 2005a). Fractures therefore represent a potential mechanism for routing pesticides or agriculturally-derived nutrients into lakes, streams, and drinking water. Thus, determining the extent of fracture

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contribution to the groundwater flow system should be a routine component of site characterization in till-dominated regions. However, such determinations are rarely made, because measuring the hydraulic properties of fractured till is exceptionally difficult and presents a number of challenges at both the field and laboratory scale (McKay et al. 1993, Jørgensen et al. 1998, 2019; Helmke et al. 2005a).

The material properties of till and the heterogeneous nature of fracture networks complicate the measurement of fracture hydraulic properties in the field. Because most till contains a fine-grained matrix, installation of piezometers may inadvertently smear and close till fractures, resulting in K values that are lower than expected (D'Astous et al. 1989). Furthermore, even if borehole smearing is avoided, a given piezometer screen may not intersect any connected fractures, resulting in K values which resemble the unfractured till matrix (i.e., hydraulic isolation; Ruland et al. 1991). Although angled piezometers have been proposed as a means of avoiding hydraulic isolation, the few studies that have utilized them report similar K values to those obtained from vertical piezometers (D'Astous et al. 1989; Seo 1996). Finally, field studies such as pumping tests can provide information on fracture hydraulic properties, but they do not provide information on transport parameters.

Water flow and tracer experiments performed on core samples have been a standard method for determining hydraulic and mass transport parameters for fractured sediments, including till, since the 1980s (Grisak et al. 1980; Mackiewicz 1994; Jørgensen et al. 2004). Drill-core, Shelby tube, or Giddings probe samples (<7.62 cm diameter) are commonly used because they can be

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obtained through standard site sampling protocols (D'Astous et al. 1989; Mackiewicz 1994; Fausey et al. 2000; Timms et al. 2016). In the late 1990s and early 2000s, several studies performed flow and transport experiments on "large, undisturbed till cores (LUTC)" that were ~0.5 m in diameter and ~0.5 m tall. Large-volume cores were chosen because they were likely to contain enough connected fractures to be representative of in-situ flow and transport processes (Jørgensen et al. 1998; Helmke et al. 2005a).

The presence or absence of connected fractures within a sample may result in estimates of K that over- or under-estimate the in-situ K value (Van der Kamp 2001; Young et al. 2019). Transport results may show similar variability, because sparse or discontinuous fracture networks within a sample will likely overestimate the influence of matrix diffusion (Grisak and Pickens 1980). While the visual identification of fractures is often used to determine whether fractures are present or absent in a given till unit and whether it is classified as fractured or unfractured (Corrigan et al. 2005; Manoli et al. 2012), it is difficult to determine the degree of connectivity within the fracture network prior to an actual laboratory experiment. This study attempted to assess the relationship between the visual presence of fractures on the top and bottom of multiple core samples and the resulting hydraulic and transport properties of the core. Visual identification of fractures was emphasized in this study – in contrast to fracture hydraulic properties – because such identification may occur in the field. We hypothesize that more visible fractures translate to greater K values and an earlier chemical breakthrough time.

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This paper presents the results of water flow and column tracer experiments performed on ten, 16-cm-diameter by 16-cm-tall core samples of fractured, Dows Formation till of the Des Moines lobe in central Iowa. The samples were intentionally larger than those used in a standard permeameter, in an effort to capture enough fractures to produce representative groundwater flow and mass transport behavior. The samples were removed from a 4.3-m vertical transect in trenches excavated during the construction of the Energy Transfer Partners, Dakota Access Pipeline (DAP) in Fall 2016. The K value of each sample was measured and bromide transport experiments were performed to demonstrate transport behavior.

Methods

Construction of the DAP began in Iowa in 2016 and cut a diagonal swath across prime farmland in the state (Fig. 1).

Because the pipeline track crossed onto Iowa State University (ISU) land and required a negotiated land-access agreement, the authors were allowed a three-week period during October 2016 to extract undisturbed till cores from three, 8-m-deep pipeline trenches just south of Ames, IA. The till unit sampled in this study was a loamy basal till of late Wisconsin age, part of the Alden Member of the Dows Formation. Mean textural composition for this till is 48 percent sand, 36 percent silt, and 16 percent clay (Kemmis et al. 1981; Helmke et al. 2005a). The Alden Member contains an oxidized zone in the upper 3-5 m and an unoxidized zone below that depth (Fig. 1) with a zone of partial oxidation in between (elsewhere known as the transition zone). It contains fractures that are clearly visible due to oxidized Fe-staining along fracture surfaces.

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These oxidation “halos” are common in the Dows Formation, including depths where the matrix unoxidized (Seo 1996, Eidem et al 1999; Helmke 2003). Ten till core samples were carved out of the sidewalls of Trench 2 (Fig. 1). Disturbed till samples were also obtained at the same depth interval in the trench and analyzed for sand, silt, and clay percentages using the method of Bouyoucos (1962).

To extract the till core, the sidewall of the trench was cut into a series of small benches down to a maximum depth of 4.3 m, and a 16-by-16-cm “square” subsample was carefully carved from the till. This procedure minimized the disturbance of the fractures and prevented additional fracturing. The samples were fitted into cylindrical PVC casings in the field and paraffin wax was poured between each sample and the casing to form a wax seal approximately 0.25-cm thick. This prevented sidewall flow during the column experiment (Grisak et al. 1980; Helmke 2003). Core ends were scraped with a hand trowel to reveal a fresh surface, and fractures (identified by the characteristic oxidation halos) on the newly-exposed surfaces were counted. Next, a 0.5-cm-thick layer of Ottawa sand was added to the top and bottom of each sample (see Helmke et al. 2005b), and a perforated polyethylene tube was threaded through the sand and attached to the inlet port to ensure uniform saturation of the core. The ends were capped with hard-rubber, Fernco® endcaps, which were stretched tightly before being ratcheted closed to prevent flexing under pressure. All contacts between the endcaps and the core casing were sealed with silicone caulk. In the lab, the till cores were inverted, saturated from the bottom up, and a constant unit hydraulic gradient was imposed across the sample using a Mariotte bottle filled

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with groundwater collected from a well located approximately 1 km southeast of where the cores were extracted (Seo 1996; Helmke 2003).

After steady flow through the columns was established, core effluent was collected for a fixed period of time, and hydraulic conductivity was then computed using the following form of Darcy's Law:

$$Q = KiA \quad [1]$$

Where Q is the volume of collected effluent per unit time (m^3/s), A is the entire cross-sectional area of the core through which flow occurs (m^2), and i is a unit hydraulic gradient (m/m).

After measuring the hydraulic conductivity, a 0.5 mMol (40 ppm) solution of a potassium bromide (KBr) was slowly injected into the bottom of the core. The Br- in the core effluent was captured using a fraction collector, and concentrations were analyzed by using an Orion Br-specific electrode (linear detection limit = 0.4 ppm; Thermo Scientific 2008). The ambient concentration of Br- in the in-situ groundwater was approximately 0.12 ppm. Because the concentration was below the electrode's linear detection limit, Br- first-arrival times were determined by identifying the first sample in the fracture collector in which concentrations were higher than 0.4 ppm. For the three cores with the lowest K values, Br- concentrations were measured every 96 hrs over the period of one month. For these samples, calibration curves were computed before each measurement in order to correct for instrument drift during the time interval between measurements.

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Results and Discussion

Values of K for the ten cores were within the range of the K values reported for the Dows Formation (3.0 x 10^{-5} to 8.0 x 10^{-9} m/s; Seo 1996); however, the values showed great variability over small depth intervals (Fig. 2). Values of K for the 1-2 m and 2-3 m interval were about one order of magnitude lower than those determined for the large, undisturbed core experiments of Helmke et al. (2005a), (Fig 2). Furthermore, the interval between 3.1-3.5 m described in Helmke et al. (2005a) had a K value of 6.8 x 10^{-8} m/s, but the three till cores within that same interval in this study had K values that were 13% and 88% lower, and 1250% higher, respectively (Table 1). Particle-size data showed little variability with depth, however the sand fraction percentage was an average of 10% higher than values reported by other studies (Fig 2. panel 2; Kemmis et al. 1981; Helmke et al. 2005b). We observed no discernable relationship between particle size, K, and the first arrival time of the Br- tracer.

Table 1. Bulk K values for cores between 3.1-3.5 m depth compared to the K in Helmke et al. (2005b).

Depth (m)/Parameter	**3.2-3.4**	**3.4-3.6**	**3.6-3.8**
Bulk K (m/s)	6.3 x 10^{-8}	7.9 x 10^{-9}	1.0 x 10^{-6}
Change relative to 6.8 x 10^{-8} m/s value presented in Helmke et al. (2005b) (%)	-13%	-88%	1250%

Tracer experiments were performed on all ten samples; however, data for three of the experiments were lost due to a hard drive failure. Experiments were not able to be re-run on these three cores due to the presence of residual concentrations of the Br- tracer. After the

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completion of the tracer experiments, theoretical first arrival times were computed by dividing the length of the core (16 cm) by the average linear velocity of groundwater. This velocity is defined as (Freeze and Cherry 1979):

$$v = \frac{Ki}{n} \quad [2]$$

Where v is the average linear velocity of groundwater (m/s), K is the measured bulk hydraulic conductivity (i.e., Figure 2, column 3), i is the unit hydraulic gradient (m/m), and n is porosity (m^3/m^3). Two hypothetical cases were then considered: one where flow occurred exclusively in the fractures (v_f), and another where flow occurred exclusively in the matrix (v_m) To compute v_f, the fracture porosity was used for *n* Equation 2, while v_m was calculated using the bulk porosity values. Fracture porosity and bulk porosity values are from Helmke (2003) and Helmke et al. (2005a). The parameters used to compute v_f and v_m are shown in Table 2.

Table 2: Theoretical and measured breakthrough times, as well as parameters used to calculate average linear velocity assuming groundwater flow occurs either exclusively in the fractures (v_f) or the matrix (v_m). Values of n and n_f are from Helmke (2003) and Helmke et al. (2005a). Pore volume was computed by multiplying the volume of the sample by the value of porosity. An asterisk indicates a depth where velocities were computed, but transport experiments were not performed.

Depth (m)	Fracture-only first arrival (min)	Matrix-only first arrival (min)	Measured first arrival (min)	v_f (m/s)	v_m (m/s)	Measured bulk K (m/s)	n_f (m^3/m^3)	n (m^3/m^3)	Pore Volume (m^3)
1.7	3	722	9	7.9×10^{-4}	3.7×10^{-6}	1.1×10^{-6}	0.0014	0.298	9.6×10^{-4}
2.3	10	2085	30	2.8×10^{-4}	1.3×10^{-6}	3.9×10^{-7}	0.0014	0.305	9.8×10^{-4}
2.4	10	2259	12	2.6×10^{-4}	1.2×10^{-6}	3.6×10^{-7}	0.0014	0.305	9.8×10^{-4}
2.6	3	739	15	7.9×10^{-4}	3.6×10^{-6}	1.1×10^{-6}	0.0014	0.305	9.8×10^{-4}

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2.8*	13	2805	N/A	2.1×10^{-4}	9.5×10^{-7}	2.9×10^{-7}	0.0014	0.305	9.8×10^{-4}
3.0	17	13379	6120	1.6×10^{-4}	2.0×10^{-7}	5.9×10^{-8}	0.00038	0.296	9.5×10^{-4}
3.4	122	95100	6120	2.2×10^{-5}	2.8×10^{-7}	8.3×10^{-9}	0.00038	0.296	9.5×10^{-4}
3.8*	3	1973	N/A	1.1×10^{-3}	1.4×10^{-6}	4.0×10^{-7}	0.00038	0.296	9.5×10^{-4}
4.1	31	23919	6120	8.7×10^{-5}	1.1×10^{-7}	3.3×10^{-8}	0.00038	0.296	9.5×10^{-4}
4.4*	19	14893	N/A	1.4×10^{-4}	1.8×10^{-7}	5.3×10^{-8}	0.00038	0.296	9.5×10^{-4}

The results of the remaining seven cores formed two distinct groups: those characterized by rapid Br- transport and those characterized by slow transport. Results from the “rapid” cores showed nearly 100% Br- recovery within 15 hours of injection with a mean early arrival time of the tracer of 16.5 minutes (Fig. 3).

First arrival times for the rapid cores nearly matched the theoretical first-arrival times (in minutes) computed using only groundwater velocities in the fractures (Fig. 2, panel 4). Breakthrough, defined as the time required to reach a relative concentration of 0.5, occurred between 1.5-4.2 hrs from the start of the experiment, and required only 0.04-0.35 pore volumes of effluent. As a result the rapid cores showed the characteristic shape of the breakthrough curve for solute transport in a fractured medium; i.e., early first arrival times and a rapid rise in effluent Br- concentration (Fig. 3; Grisak et al. 1980; Helmke et al. 2005a,b).

In contrast, Br- in column effluent from the slow cores was monitored for about 30 days with a mean tracer recovery of 75% and a mean first arrival time of 102 hours (Fig. 4). The tracer experiments were terminated at about 30 days. For cores obtained at depths of 3.2 m and 4 m, the

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slow first arrival times approximated the first arrival times predicted by the average linear velocity equation in a porous medium (Freeze and Cherry, 1979; Fig. 2, panel 4). The gradual slopes of the "slow core" breakthrough curves suggested that matrix diffusion and mechanical dispersion were important in these samples (Fig. 4) and that bulk water flow through the till matrix dominated over flow through connected fractures (Freeze and Cherry 1979; Grisak et al. 1980).

Although the first arrival times were much slower than those observed in "rapid" cores, the 3.36-m-depth core showed a first arrival time that is 1400 hours faster than the predicted first arrival time for soil without fractures. Furthermore, the fraction of pore volume at breakthrough (0.34) was within the range of those observed in the "rapid" cores (Fig. 2, panels 3 & 4). We hypothesized initially that the stark contrast in tracer behavior between the rapid and slow cores could be predicted from observation of fractures at the top or bottom of the till core; however, we observed no correlation between the number visible fractures and K (Pearson's r = 0.25) or the number of visible fractures and Br- first arrival time (r = -0.33; Helsel and Hirsch, 2002). There was, however, a strong negative correlation between K and Br- first-arrival time (r = -0.92). These results demonstrate the importance of fracture connectivity; i.e., samples with well-connected fractures are more likely to have higher K values and exhibit more rapid transport. However, the lack of a relationship between the number of visible fractures and either K or Br- first arrival indicates that it is difficult to assess whether the fractures are connected prior to laboratory investigation.

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The lack of a relationship suggests that fractures observed in the 2-D plane at the bottom of a core cannot predict 3-D connectivity, particularly if the mean fracture length in the Dows Formation, 7.9 cm, is less than the length of the 16-cm till core (Helmke et al. 2005b). Long et al. (1982) reasoned that smaller samples in fractured rock were more likely than larger samples to have one or two well-connected fractures which spanned the entire length of the sample, resulting in rapid transport of solutes during tracer experiments. The results of the "rapid" core (Fig. 3) may support this idea. The "slow" cores, however, showed the opposite phenomena; i.e., when well-connected fractures were absent, flow and transport results resembled those produced by a homogenous, unfractured media.

A relationship between solute transport behavior and the degree of oxidation of the till could be hypothesized from the depths of the rapid and slow cores (Fig. 5). The rapid cores were obtained from the oxidized upper 3 m, while the cores that exhibited slower first arrival times were either from the unoxidized zone or the small partially-oxidized (transition) zone that existed between them. Field data indicated that the fracture density and fracture aperture in the Dows Formation were smaller in the cores located in the partially oxidized (i.e., transition), and at greater depths (Helmke 2003, Helmke et al. 2005a,b). Thus, although fractures did not appear to cease below the zone of oxidation, cores taken from depths below 3 m at this site were more likely to contain fewer connected fractures and they did not exhibit rapid transport behavior.

Although the relationship between K and first arrival time in a core might predict "rapid" or "slow" transport behavior, the morphology of the breakthrough curves show that there was still

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considerable variability within two groups (Fig. 3). For instance, the till core from the depth interval 2.40-2.56 m (blue circles, Fig. 3) showed the lowest K value of the four cores presented, but it was the first to exhibit breakthrough (C/C_o value of 0.5) at 1.5 hrs. Breakthrough occurred for the three other depth intervals of 1.70-1.86 m, 2.60-2.76 m, and 2.76-2.92 m at 2.7, 0.5 and 2.25 hours after interval 2.4-2.56, respectively. This variability in breakthrough time occurred even though the hydraulic gradient was the same and two of samples showed the same measured bulk K value of 1.1 x 10^{-6} m/s. Although the K value for each of the slow cores (Fig. 4) was lower than values reported in previous studies (Seo 1996; Helmke et al. 2005a,b), the core with the lowest K value showed the best evidence of fracture-controlled transport of Br-. This variability is somewhat expected, because fracture-enhanced transport is governed by groundwater velocities in the fractures, which are not well described by bulk K values. Thus, while bulk K values can provide broad insight into the transport behavior of a group of core samples, the behavior of individual samples will be highly dependent upon the specific fracture network contained therein.

Summary and Conclusions

Water flow and tracer experiments were performed on ten cores extracted from a 4.3-m profile of fractured, Dows Formation till from a trench excavated for the Dakota Access Pipeline in central Iowa. The results indicated that there was no relationship between the number of fractures on the top and bottom of the core, K, and the first arrival time of bromide, a non-sorbing, conservative tracer. Results did show a strong negative correlation between K and Br- first-arrival time (r = -0.92), indicating that samples with higher K values are likely to contain

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well-connected fractures and therefore exhibit more rapid transport. Although K could be used to predict “rapid” or “slow” transport behavior, individual breakthrough curves within these groups showed a high degree of variability. For instance, the ± 540% range of tracer breakthrough times in two cores with roughly identical K values demonstrated that even when K data indicated that well-connected fractures were present, the effect of the fracture network on transport behavior was unpredictable.

Although the volume of the till core used in this study was larger than that used in a standard permeameter, the core was likely still too small to ensure that there were connected fractures in each sample. This finding was consistent with studies in fractured rock, which indicated that highly-variable flow and transport behavior was likely for experiments conducted on samples smaller than the representative elementary volume (REV; Wang et al. 2002; Min et al. 2004). For the till of the Dows Formation, that minimum volume (the REV) has been estimated to be about 4 m^3 (Young et al. 2019). Although previous studies on “large, undisturbed till columns” in this unit did not sample this volume either, the LUTC were sufficiently large that each contained a connected fracture network. (Helmke et al. 2005a,b). Yet, because they are below the REV, the networks tested were likely not representative of the in-situ fracture network. Furthermore, given the difficulty associated with collecting (excavating) and working with large, undisturbed till columns, that approach will be untenable for most site characterization studies. For fractured till of the Dows Formation, testing large volumes of till at the field scale (e.g., McKay et al. 1993;

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Seo 1996) coupled with fracture-flow modeling likely represents the best approach for estimating hydraulic and mass transport parameters in fractured till.

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Figure Captions

Figure 1. Photo of Trench 2 showing the 4.3 m sampling transect (blue vertical line) and geologic boundaries in the till (left). Materials in the upper meter included modern soil, sand, and a plow layer. The transition zone is not marked. Trench 2 is located within the Walnut Creek watershed immediately south of Ames, IA along the trend of the pipeline (right image).

Figure 2. Geology, particle size distribution, Log K, and Br- first arrival log times for the seven core tracer experiments. Values of K were determined for samples at depths of 3, 3.5 and 4.3 m without accompanying tracer experiments. The absence of a blue dot in Column 4 indicates that no transport experiment was performed. Values of K and first arrival times are provided in Table 2.

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Figure 3. Br- breakthrough curves for the four “rapid” cores of fractured till of the Dows Formation.

Figure 4. Br- breakthrough curves for the three “slow” cores of fractured till of the Dows Formation.

Figure 5: Fracture tracings and degree of till oxidation for the “rapid” and “slow” cores. While the length, connectivity, and number of fractures observed on the surfaces of each core could not be used to predict transport behavior, there appears to be a relationship between the degree of oxidation and transport velocity.

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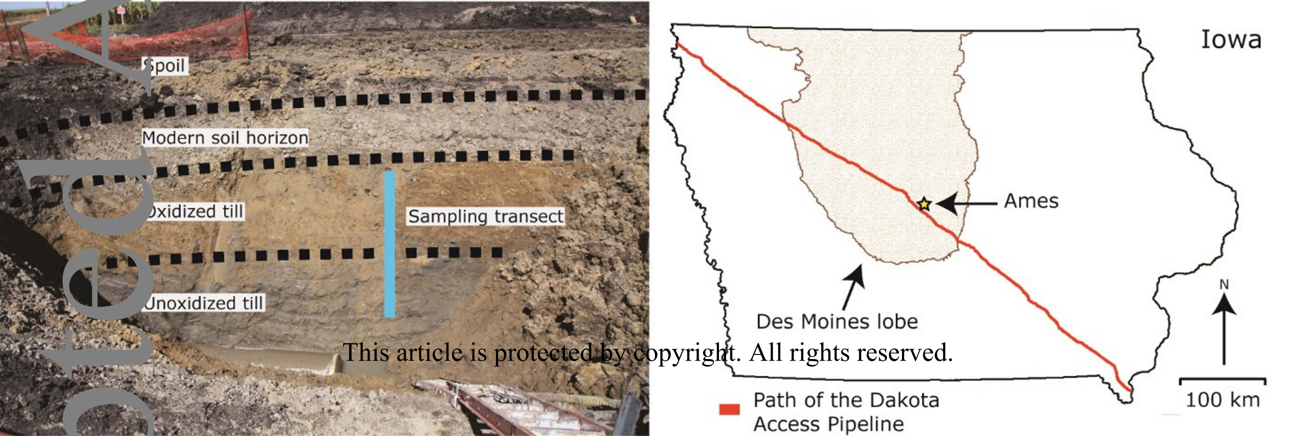

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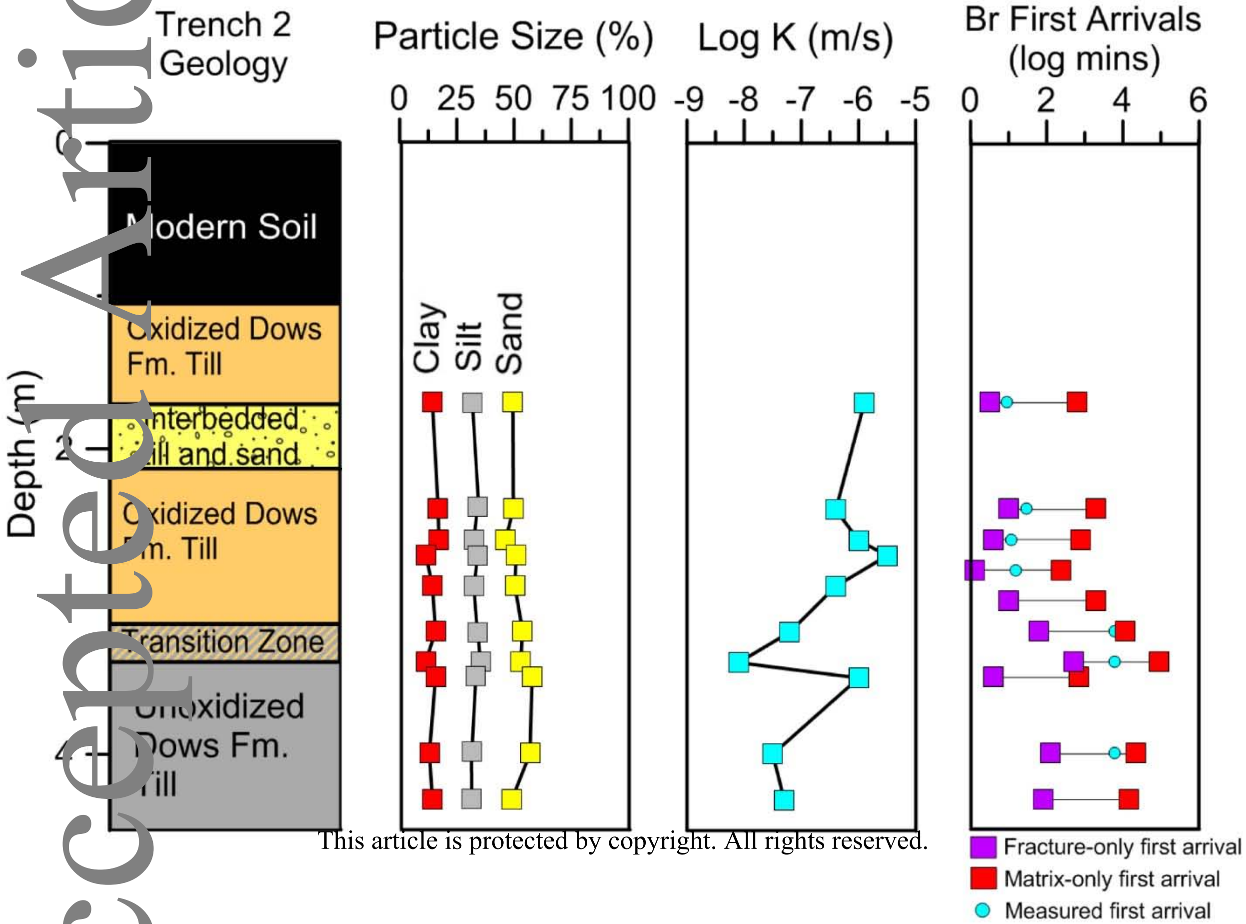

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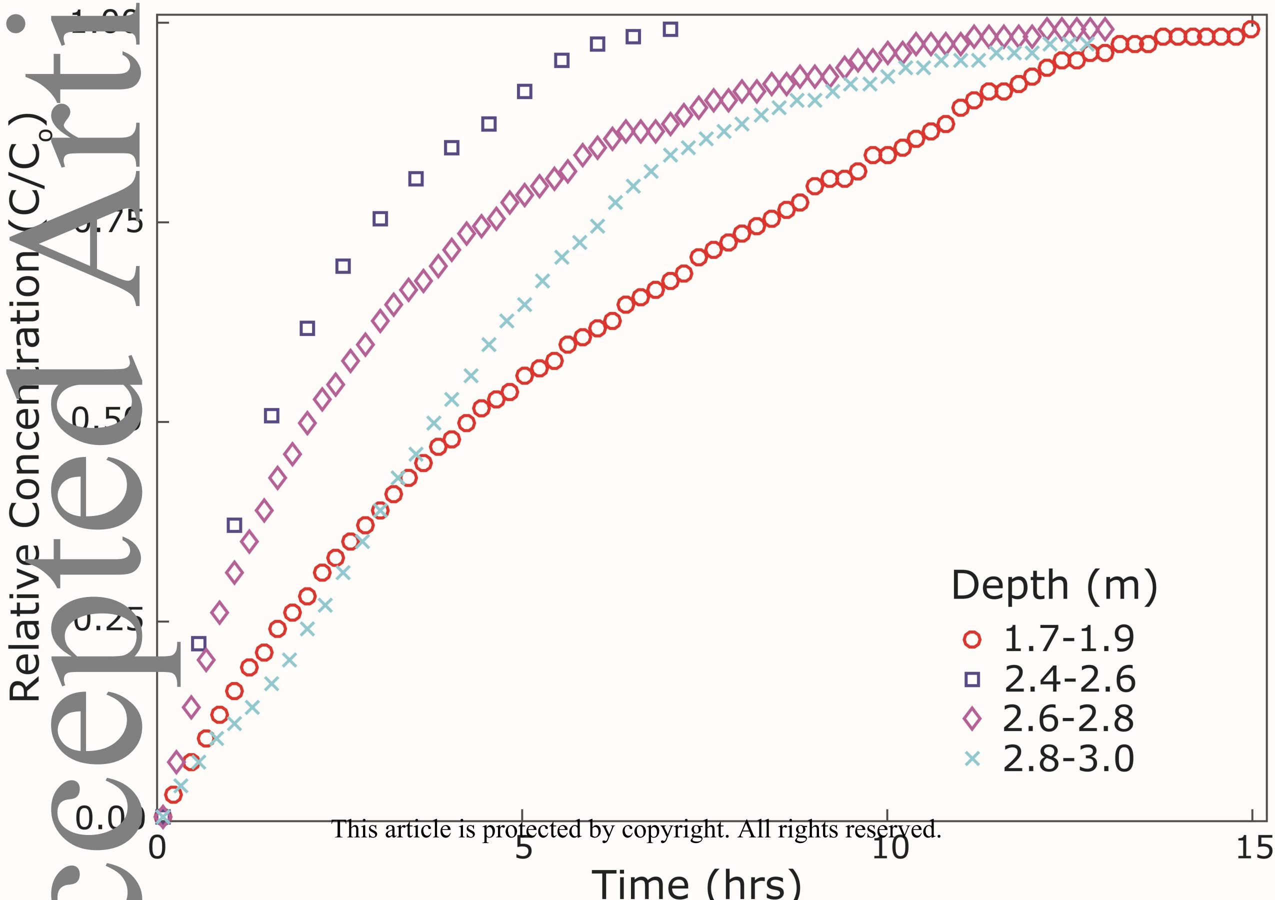

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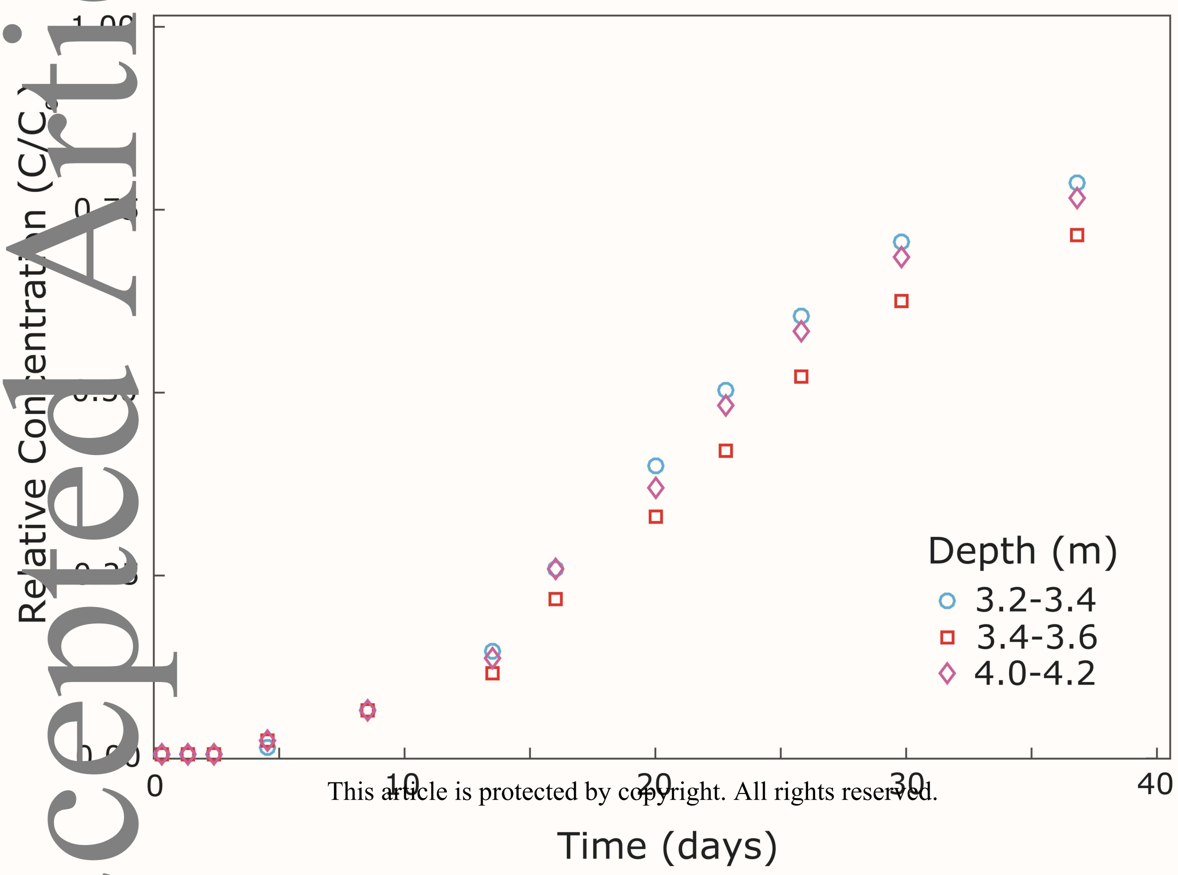

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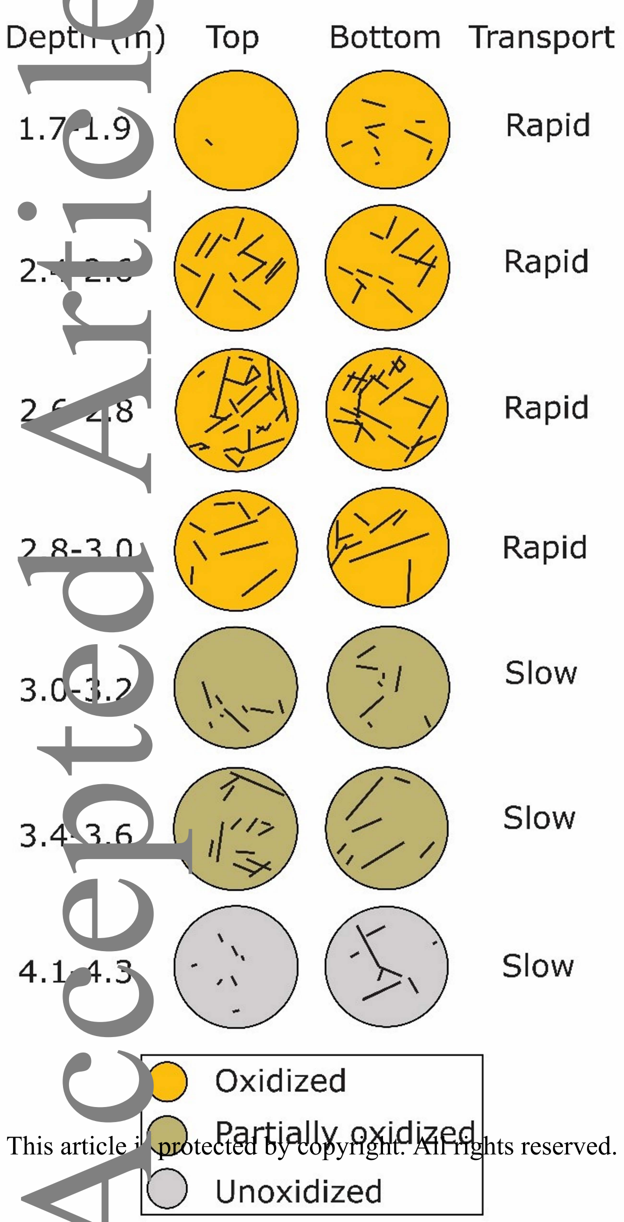

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