Groundwater

Issue Paper/

Introducing Transport "Surprises" in the Classroom: The Visible Fracture

by Michael Cardiff[1] and Ben Heinle[2,3]

Abstract

Heterogeneity in aquifer properties, and the influence of transport processes other than advection and dispersion, often produce transport "surprises" in that measurements become difficult to reconcile with predictions from the traditional advection-dispersion equation (ADE) that students are introduced to early in their hydrogeology training. Students should be aware of and prepared for the reasons why the ADE (as commonly applied) may not always "work" in the sense of generating valid predictions. Though the predictive limitations of the ADE have been frequently discussed in the hydrogeologic literature, our experience is that students are not appropriately skeptical of transport predictions. For this reason, we believe it is imperative that future generations of hydrogeologists are introduced to transport surprises early in their formative education. We present a laboratory activity, centered around a "Visible Fracture," which was presented in a laboratory class period of 75 min. The Visible Fracture consists of two sheets of Plexiglas surrounding a heterogenous fluid-filled aperture. Heated fluid is injected into the fracture, and thermochromic liquid crystal (TLC) materials are used to visualize the temperature both in the flowing fluid and in the surrounding Plexiglas "host rock." Visualization of the plume shows the complex shapes that can be produced due to macroscopic heterogeneity. Tracer particles within the fracture allow students to examine heterogeneous local advective velocities, and to observe retardation of the fluid temperature plume. Student self-reported knowledge surveys indicate greater conceptual understanding of transport non-idealities after experiencing this activity.

Introduction

Predicting solute transport in groundwater, and making management decisions based on these predictions, remains a key source of work for the practicing hydrogeologist. The next generation of practitioners, currently being trained in our classrooms, will likely continue to face the challenge of predicting transport for purposes such as wellhead protection and contaminated site remediation. In addition, future hydrogeologists are likely to encounter even more difficult transport problems in deeper fractured environments as they are called on to answer questions related to hydraulic fracturing, geothermal energy extraction and CO_2 sequestration. In preparing for these challenges, knowledge of a variety of transport modeling tools and—equally important—the limitations of these tools will be a crucial asset for the next generation of hydrogeologists.

To some extent, the practice of contaminant transport modeling has been commodified and standardized, and a common workflow for developing transport models is well-practiced by many hydrogeologists. Supplied with the basic (and often sparse) characterization information available for a particular aquifer system, a hydrogeologist may use available modeling tools for simulating Darcian flow. After generating a digital aquifer by using field data

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to define spatial properties including hydraulic conductivity and specific storage, a numerical flow model may be used to predict specific discharges, often performed using the well-known MODFLOW family of flow models (Harbaugh 2005; Langevin et al. 2017). The shape of aquifer streamlines may then be determined through particle tracking and, if effective porosity information is also supplied, nonreactive solute travel times may be predicted using software such as MODPATH (Pollock 2012). Finally, if predictions of solute concentration arrivals are desired then a transport model based on the advection-dispersion equation (ADE)—for example the commonly-used MT3D family of transport models (Zheng and Wang 1999)—may be coupled to the existing flow model and supplied with aquifer dispersivities to produce concentration predictions. This workflow is likely familiar to many hydrogeologists—indeed, a brief overview of the publications in Groundwater over the past year suggests its popularity. Throughout the 130 Groundwater publications from the past year, MODFLOW is mentioned in 37 separate works, MODPATH / particle tracking in 26 works, and MT3D / MT3DMS in 14 works (https://onlinelibrary.wiley.com/action/doSearch?SeriesKey=17456584).

Veteran hydrogeologists, however, are acutely aware of the difficulty of obtaining accurate transport predictions such as plume shapes, solute arrival times, or long-term concentration changes at monitoring locations. As Konikow (2011) notes, "Experience indicates that [simulating solute transport] is more difficult and less successful than [modeling groundwater flow and head distributions]." Often, a "surprise" from observations (Bredehoeft 2005) leads to a need for new thinking about aquifer properties and processes that are influencing transport, leading to reconsideration of how models are applied.

If the solute being tracked is (at least presumedly) non-reactive, surprises in transport modeling are often traced to what we will call "heterogeneity effects," that is: (1) limited characterization of "large-scale" aquifer heterogeneity, or (2) an underlying assumption that the effects of "small-scale" heterogeneity can be upscaled as a Fickian macrodispersive process when it cannot (as discussed in, e.g., Molz 2015). In the case of the former issue, efforts to limit future transport surprise may focus on collecting more complete characterization data, for example via direct-push methods (Dogan et al. 2014) or hydraulic tomography (Cardiff et al. 2012, 2013). In the case of the latter issue, an alternative conceptual model such as the dual-domain framework may be tested (Liu et al. 2007).

The importance of additional processes in controlling transport—other than advection and diffusion—further more complicates our ability to make accurate, physically-based predictions for solutes. Aqueous, water-rock, and biologically-driven reactions may all influence solute transport and for a given aquifer it is often difficult to determine a priori what types of reactions will dominate transport of a given solute. This is to say nothing of the spatial distribution of all reactants, the effective rates of subsurface reactions, and the complex interplay between aquifer heterogeneity and potential reaction locations. These "process effects" may be unaccounted for or incorrectly represented in initial modeling, and may also require a re-consideration of the mathematics used. Use of models that neglect or improperly parameterize processes has probably led to an equal number of transport "surprises" (e.g., Gooseff et al. 2003; Haggerty et al. 2004).

Despite ongoing research and academic discussion about transport modeling approaches, there is perhaps uniform agreement on one key aspect of solute transport modeling: Making accurate solute transport predictions is hard. Obtaining successful predictions of solute transport at specific sites will, for the foreseeable future, likely depend on some combination of luck, lowered expectations (Konikow 2011), or exhaustive data collection (e.g., Bohling et al. 2012; Dogan et al. 2014). Given this state-of-the-science, we believe it is imperative that instruction in hydrogeology continue to emphasize the underlying assumptions (and their limitations) in applying the classical ADE at field scales, and thus prepare students for surprises.

Our goal in this work is to present and encourage methods of hydrogeologic instruction that can nurture healthy skepticism in nascent hydrogeologists regarding transport modeling. The experiment presented herein is one example that can generate surprise and make apparent limitations of the simple ADE model, if it is applied when heterogeneity effects and process effects are not properly accounted for. Our hope is that by experiencing such surprise early in their training, young hydrogeologists will be more likely to recognize and check for more complex transport conditions in their practice.

We present a laboratory experiment consisting of a "Visible Fracture," which provides an opportunity to visualize both heterogeneity effects and process effects in the context of fracture heat transport, and thus to explore the difficulties in predicting groundwater transport. The laboratory setup, which is relatively economical, can be replicated with commercial, off-the-shelf components and permits experimentation during a class period as short as 1 h. In the sections below, we describe the materials used in the setup of the Visible Fracture, the experimental procedure used during student instruction, and questions and problems that students may be asked in order to foster their thinking and curiosity. We present initial results—in terms of self-reported student learning outcomes from an undergraduate Hydrogeology class at the University of Wisconsin-Madison (UW-Madison)—to demonstrate the efficacy of this tool.

Experimental Setup: The Visible Fracture

Materials and Assembly

The main Visible Fracture assembly consists of two sheets of Plexiglas (a.k.a. PMMA acrylic glass)

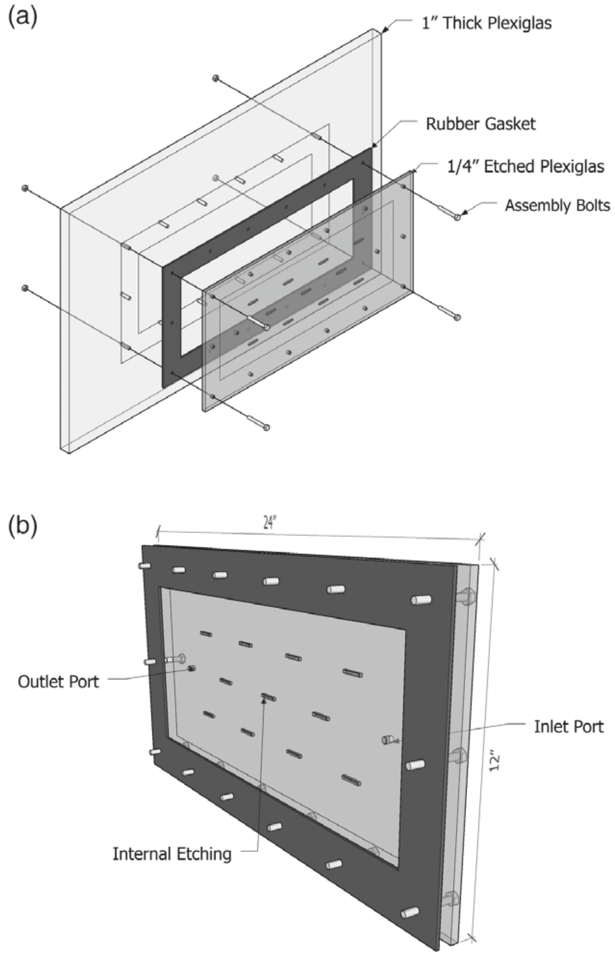

Figure 1. Fracture apparatus design drawings. (a) Isometric view of complete fracture assembly (some bolts removed to simplify diagram). TLC sheet is adhered to the 1″ thick Plexiglas back, on the side facing away from the viewer. (b) View of interior of flow cell before attachment to Plexiglas back.

separated by a small aperture and assembled to act as a flow-through cell for fluid (Figure 1a). One Plexiglas sheet, designated as the "back" of the experiment, consists of a 24″ by 36″ sheet, 1″ thick. The second Plexiglas sheet, designated the "front" sheet, is 12″ by 24″ and thinner, at 1/4″ thick. The front sheet is attached to a thin adhesive rubber gasket (~0.8 mm), which produces a small aperture between the two sheets. The front Plexiglas sheet is plumbed with an inlet and outlet port on its exterior face, while the interior face—in the area where the rubber gasket is not present—is etched with a pattern of heterogeneities (Figure 1b). A set of aligned holes in the back Plexiglas and front Plexiglas pass through the area of the rubber gasket, into which bolts are inserted and tightened. Once bolted together, the Plexiglas sheets form a flow-through cell with a heterogeneous interior. The apparatus is similar to a Hele-Shaw cell setup, which has been used in demonstration of many hydrogeologic processes (e.g., Elder 1967; Mango et al. 2004; Kneafsey and Pruess 2010). Fluid reservoirs are attached to both the inlet and outlet ports, and a water level elevation

Table 1
Fluid Mixture Used in Visible Fracture Experiments

Component	Quantity
Glycerol	5040 g (4000 mL)
White polyethylene microspheres	2 g
Encapsulated TLC microsphere slurry	3 g
Water	455 g (455 mL)
Total	*5500 g*

difference between these two reservoirs will generate fluid flow.

The experiment, further described in the next section, uses heat transport as a proxy for studying solute transport. We monitor the evolving heat plume through special materials known as thermochromic liquid crystals (TLCs) which display a varying color as a function of temperature. On the exterior face of the back Plexiglas sheet, an adhesive-backed polyester TLC sheet is installed, allowing temperature observations of this "host rock" face. We observe temperature and flow within the fracture fluid via a glycerol-based mixture containing micro-encapsulated TLC tracer particles and white plastic microspheres, mixed in proportions described in Table 1. The chosen fluid mixture ensures that encapsulated TLCs and microspheres remain roughly neutrally buoyant during flow. Furthermore, this fluid is more viscous than water and thus more forgiving, in that changes to the head gradient only slowly increase the flow rate within the fracture. The TLC materials used in our setup have a temperature range of between approximately 25°C and 30°C, over which a color spectrum between red (cold) and blue (hot) appears in the materials. Below 25°C, the TLC shows no visible color (the "black out" temperature), and above 30°C, the TLC remains blue ("blue out"). If desired, calibration curves can be created by repeatedly photographing cooling fluid, obtaining color representations in the HSV (hue, saturation, value) colorspace and then plotting the hue (H) component against measured temperature (see Figure 2).

The cost of the individual specialized materials used in constructing the Visible Fracture flow cell, along with current suppliers, is summarized in Appendix S1, Supporting information and is less than $1000 total. Beyond the specialized materials, standard tools (drills, wrenches, etc.) and expendable materials (sandpaper, paints) are necessary to assemble the apparatus. A list of tools and expendable materials, along with detailed instructions on assembling the apparatus, are also provided in Appendix S1.

Experimental Procedure

Before an experiment, we assemble the flow-through cell with wrench-tightened bolts to create a fluid-tight seal. Next, we fill the inlet reservoir with the glycerol mixture heated to a constant temperature (a

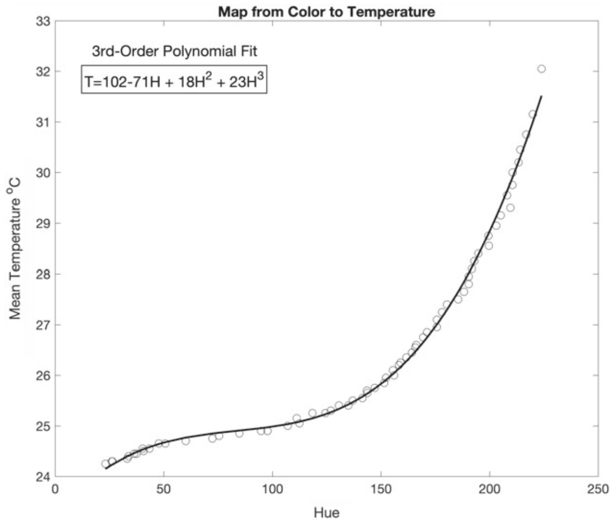

Figure 2. Conversion between hue and temperature based on laboratory calibration data from a cooling experiment.

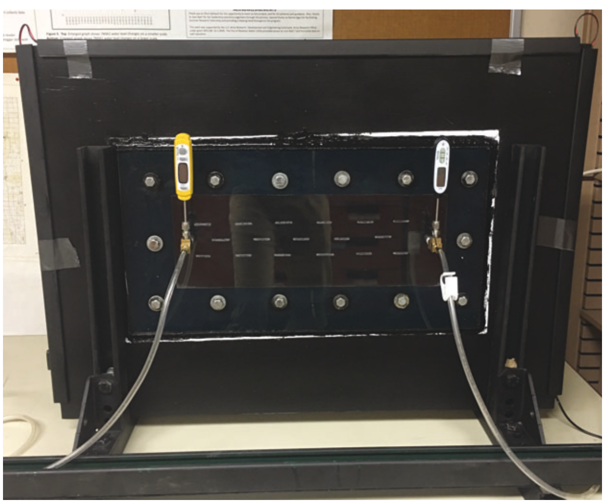

Figure 3. Laboratory setup at beginning of experiment. A simple steel frame was used to orient fracture vertically, so that solid temperature could be viewed on back of the apparatus (away from camera). Junctions at inlet and outlet of fracture allow measurement of fluid temperatures by thermometer.

commercial sous vide immersion circulator provides an economical method to achieve this). We then open the inlet and outlet valves briefly in order to allow the inlet tubing to come to equilibrium with the heated glycerol mixture. LED strip lights, placed along the top and side edges of the back Plexiglas sheet, provide illumination for the TLC fluid. A picture of the complete setup prior to the experiment commencing is shown in Figure 3.

When the experiment starts, valves to the inlet and outlet reservoir are opened, allowing heated fluid to flow into the Visible Fracture. We verify fluid flow by observing the movement of the white tracer microspheres within the fracture. Due to the strong temperature gradient between incoming heated fluid and the room-temperature Plexiglas "host rock," heat diffuses rapidly into the Plexiglas, and the fluid inside the fracture will stay near room temperature for some time, during which the TLC microspheres will display as colorless against a black background. As the temperature gradient between fluid and Plexiglas decreases, less heat diffusion into the solid will occur, and a heated region will develop within the fracture fluid, visible as a colored plume that evolves from red to blue. The plume should show effects of flow heterogeneity, as fluid flow will be faster in etched portions of the flow cell due to increased fracture aperture. By etching portions of the Plexiglas with relatively long features (relative to the scale of the flow cell), we encourage irregular plume shapes to develop that would vary from those predicted by a traditional, macro-scale ADE. Eventually, heat diffusion within the Plexiglas will cause a solid temperature plume that is visible on the back TLC sheet. An example of the fluid heat plume development midway through an experiment is shown in Figure 4. At this point in the experiment, the solid temperature plume on the back Plexiglas had only begun to show near the fluid inlet location.

The growth of the fluid and solid heat plumes will depend on the exact design of the flow-through cell as well as on several experimental parameters, which may be modified as desired. A table of the experimental parameters used for our setup during in-class experiments is provided in Table 2. We found that these choices resulted in a fluid heat plume that showed clear changes in extent over a span of 5–10 min, while also allowing

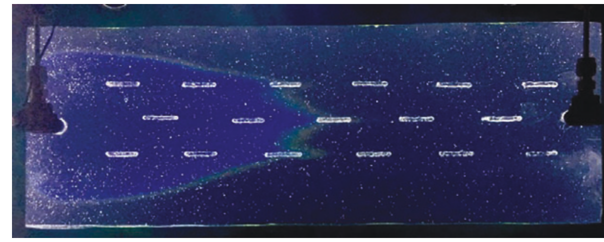

Figure 4. Shape of heat plume during middle stage of experiment. Colors enhanced to highlight heat plume and impact of flow heterogeneity on plume shape.

Table 2
Experimental Parameters for Setup Used During In-Class Experiments

Parameter	Value
Heated reservoir temperature	45°C
Entering fluid temperature at inlet	35°C
Ambient room temperature	22°C
Fracture aperture in un-etched areas	0.8 mm
Fracture aperture in etched areas	1.5 mm
Fluid elevation difference between inlet & outlet reservoirs	65 cm
Distance between inlet and outlet ports	39.5 cm

enough time for the solid heat plume to develop over a span of roughly 1 h.

Instructional Use/Demonstration

Course Background

We used the Visible Fracture apparatus as a demonstration during lab sections of the 4-credit course GEOS-627 "Hydrogeology" at UW-Madison. This class consisted of 65 students, with the majority being undergraduate seniors (46 students), in addition to 13 juniors and 6 graduate students. For laboratory work throughout the year, students were organized into 4 sections of roughly 16 students each. During this particular laboratory exercise, the process of heat diffusion in solids was introduced while drawing analogies to solute "matrix diffusion," and students then performed observations of flow and transport within the Visible Fracture. To assess the experiment's effectiveness, students were requested to take a short, online pre- and post-lab survey about their knowledge of transport processes. In this remainder of this section we describe the details of how the lab was carried out for each section, and the results of student surveys.

For broader context, GEOS-627 is a class focused primarily on physical hydrogeology, with some chemical and contaminant hydrogeology. The course schedule consists of (in order) approximately 9 weeks covering physical hydrogeology, aquifer testing, and modeling, 3 weeks focusing on groundwater geochemistry and chemical evolution of groundwater, and a final week introducing solute transport and contaminant hydrogeology topics. The Visible Fracture exercise was carried out during the final full week of classes.

Laboratory Assignment & Logistics

At the beginning of each laboratory period, the section's students were first divided into 4 groups of 4–5 students each, and the instructor or teaching assistant (TA) gave a brief description of the lab logistics and expected learning goals. Three of the groups remained in the laboratory room for an activity investigating heat diffusion in solids, while the fourth group was taken to a separate room where the Visible Fracture was setup. After a roughly 15 min exercise involving the Visible Fracture, this group would return to the laboratory room and a new group would be shepherded to the Visible Fracture experiment. All 4 groups completed both exercises within a 75 min laboratory period.

For students in the laboratory room, the 3 groups were supplied with a thermometer, a heating pad (warmed to $\sim 40^{\circ}$C), and several pieces of Plexiglas, roughly $1'' \times 1''$ each, with varying thickness. A TLC "dot" sticker was adhered to each Plexiglas piece, and students were given a conversion chart to understand the relationship between temperature and color. At the beginning of this experiment, each student group placed all of the Plexiglas pieces on top of the heating pad, and then recorded color changes at roughly 1 min increments over at least 15 min (see Figure 5). TAs were directed to discuss with the groups the diffusive process of heat and to draw analogies between heat diffusion and solute diffusion.

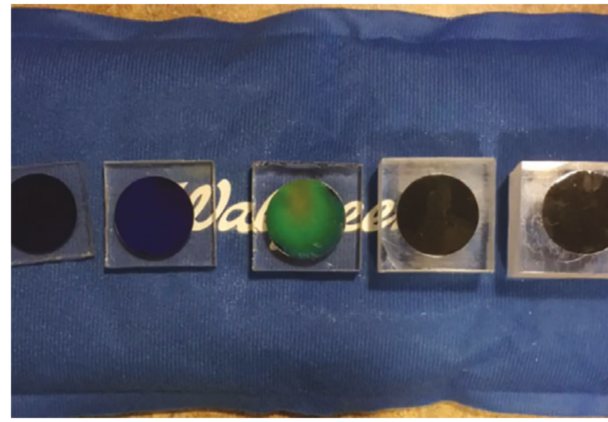

Figure 5. Experimental setup for monitoring heat diffusion. Plexiglas squares, $1'' \times 1''$, are arranged in increasing thickness from left to right on a heating pad, with TLC "dot stickers" showing color change. Image recorded roughly 4 min after placement of Plexiglas on heating element.

For students in the Visible Fracture room, the instructor first introduced the apparatus and explained the experimental setup. The instructor provided a brief refresher on fracture flow including the so-called "cubic law," and then tasked the students with collecting data to answer questions about the apparatus. At the fracture outlet, one or more students timed the amount of flow through the apparatus over a time interval of 1–2 min, using a graduated cylinder. Meanwhile, the other students used rulers and a stopwatch to measure the amount of time required for white tracer particles to travel a distance of 2 cm, and calculated fluid velocity. Measurements of tracer particle velocity were recorded both in etched and un-etched portions of the fractures. Once all students had collected this data, the instructor brought the group together as a whole and marked the current location of the leading edge of the fluid heat front using an erasable marker. One to two minutes were then spent discussing the experiment and asking probing questions—for example, "Does the plume have a regular shape like idealized figures from the text?" or "How do the etched openings seem to be affecting transport?" Finally, at the end of this time, the location of the heat front's leading edge was marked again, and a velocity for the heat front was calculated based on these measurements. The contrast between fluid velocities and heat plume movement that students saw is visualized in Figure 6 (see also Video S1). Often students noted, on their own, that the heat front appeared to be moving much more slowly than the fracture advective velocities (as calculated from the tracer particles). If students did not automatically note this, however, the instructor would lead a brief computation of the heat front's velocity.

Laboratory Assignment/Assessment

The laboratory assignment associated with both the heat diffusion and Visible Fracture activities

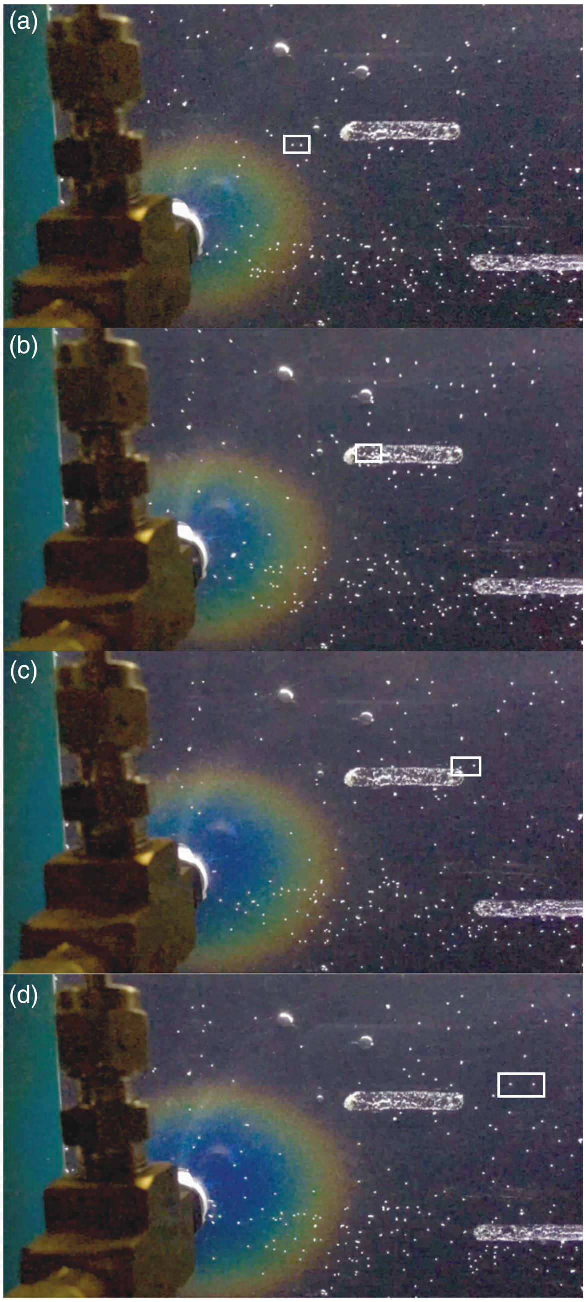

Figure 6. Video frames, each separated by 6 s, taken near fracture inlet. A pair of tracer particles that can be followed throughout the video are highlighted by white box, demonstrating retardation of heat (color) plume.

consisted of a series of conceptual questions and short computational questions to be answered by each student individually. For the heat diffusion activity, students were asked to plot their data and approximate what temperature profiles in the solid Plexiglas would look like (i.e., temperature vs. distance from heating element) at several time snapshots. The students were also asked to make predictions about how they expected the temperature profile to evolve if more time was allowed. This question allowed graders to assess the degree to which students recognized the relationship between diffusion length scales and time.

For the Visible Fracture activity, students were asked to use their particle tracking data to estimate the fracture's aperture, and its changes in etched areas. Similarly, the students were asked to predict how the flow would change if the aperture of the fracture were doubled. In assessing heat transport, the students were asked to calculate an effective retardation coefficient for the speed of heat movement within the fracture and describe physically how this effective retardation occurs. Finally, the students were asked to predict how the system would respond if the inlet reservoir were instantaneously switched to room-temperature fluid. Based on these questions, graders were able to assess whether students were able to manipulate the cubic law for fracture flow, and the degree to which students understood concepts such as matrix diffusion and back-diffusion. The lab exercise, without answers, is provided as Appendix S2.

Feedback & Self-Reported Learning Outcomes

Students in the class were asked to take a brief online survey before and after the laboratory, which consisted of the following question:

> *"For each of the following terms, rate how sure you feel about being able to describe this process, clearly and accurately, to a peer:*
>
> - *Solute advection*
> - *Solute diffusion*
> - *Matrix diffusion*
> - *Solute retardation*
> - *Back-diffusion/rebound*
> - *Transport in fractured rock"*

We asked students to rate their confidence in describing these processes on a scale of 1 to 5, as follows: 5 = very sure; 4 = somewhat sure; 3 = neither sure or unsure; 2 = somewhat unsure; 1 = very unsure. In the pre-lab survey, students were instructed to answer based only on what they had learned in-class and from earlier readings. After surveys were completed, the students were not able to view or revisit their initial answers. For the post-lab survey, we asked the students to consider their answer based on what they had learned in-class, from readings, and during the laboratory exercise. In addition to the surveys, students could provide feedback through anonymized comments about the laboratory exercise. As motivation for completing the surveys, students were offered two extra credit points toward their laboratory grades if they completed both surveys on-time. The instructors emphasized that the extra credit points, which represented approximately 1.5% of students' laboratory grade, would be delivered regardless of the responses on the surveys. Most students participated in the survey (58 out of 65 students responding).

A summary of the survey results and a simple statistical analysis is presented in Table 3. Students on average ranked themselves as slightly unconfident in describing each solute transport process (i.e., survey means below 3.0). The fact that this material had so recently been introduced may have influenced students' confidence in these

Table 3
Results of Student Self-Surveys and Statistical Analysis of Changes

Topic	Pre-lab Survey Average	Post-lab Survey Average	P-Value	95% CI for Improvement Value	
Solute advection	2.47	2.74	0.066	−0.02	0.57
Solute diffusion	2.76	3.4	0.0014	0.26	1.02
Matrix diffusion	2.26	2.71	0.0068	0.13	0.77
Solute retardation	2.22	2.79	0.0012	0.23	0.9
Back-diffusion/Rebound	2.34	2.81	0.0079	0.13	0.8
Transport in fractured rock	2.52	3.5	3.0E-05	0.55	1.42

Note: A paired two-sample T-test was used to test the null hypothesis that there is no difference between population means at 95% significance level.

concepts. That said, statistically significant increases in students' confidence were recorded—at the 95% significance level—following the laboratory exercise. In particular, students self-assessed strong gains in their comfort describing transport in fractured rock, solute diffusion, and solute retardation. This numerical analysis is supported by the qualitative information in students' anonymous comments, several of which mentioned the usefulness of visualizing transport processes, and noted that this visualization helped reinforce understanding of transport concepts.

Extension to Other Exercises

While the Visible Fracture has only been used to-date in an upper-level undergraduate classroom, there is opportunity to extend its use into other coursework and employ further quantitative analyses. The basic experiment may be extended to examine solute back-diffusion, or to assess the capabilities and limitations of particular transport models. As one example, in a contaminant transport-focused class, an ADE model could be developed with a homogeneous thin aquifer (the fracture) that did not take into account heat loss to the host rock. Comparing this model result against laboratory experiments would highlight the influence of both heterogeneity and unmodeled processes on transport results.

The Visible Fracture similarly presents a simple platform for exploring the impact of different scales of heterogeneities on transport. In the limit where etched heterogeneities become sufficiently small relative to the scale of transport, the use of the macroscopic ADE for simulating transport could demonstrate success in applying the lessons of stochastic hydrogeology. Alternatively, long sinuous features etched into the Plexiglas could demonstrate the impact of larger heterogeneities on producing irregular plumes and unexpected early breakthrough.

Glycerol-based fluids are subject to significant thermal effects—in fact, the Visible Fracture experiment will produce somewhat faster transport velocities toward the end of the experiment due to heat-thinning. This coupled flow and transport process also provides further avenues for investigation. In a class covering highly coupled flow systems, such as the complex THMC (thermal/hydraulic/mechanical/chemical) environment of geothermal reservoirs, more advanced models could be applied to the Visible Fracture and simulate these coupled effects. Such an exercise may be appropriate in an upper-level graduate course.

Discussion

Students early in their hydrogeologic study likely come away with two central mathematical laws in their toolbelt: Darcy's and Fick's. Broadly, under conditions that are met at most shallow hydrogeologic sites, Darcy's law can be expected to work quite well. Students should, of course, be prepared for the complications of density-dependent flow, turbulence, or other factors that can invalidate this tool. More often than not in practice, though, this empirical relationship between head gradients and discharges can be implemented within a conservation equation without fear. In cases where it cannot, pressure-based formulations, Richards' equation, and the Darcy-Forchheimer equation represent well-accepted alternatives for applications in multi-phase flow, variably-saturated flow, and non-laminar flow, respectively. In addition, there are broadly-agreed upon guidelines as to when these more complex formulations may be necessary and appropriate.

In contrast, when we instruct students in observing and predicting transport processes, we believe that the experiences presented to students should model the substantial heterogeneity and process uncertainty that accompanies most real field investigations. Unlike Darcy's law, the practical range of validity of the Fickian approach to dispersion modeling is the subject of continuing misunderstanding and misapplication, and multiple alternative models including dual-domain models, memory functions, fractional ADEs and others have been suggested as upscaled methods for addressing heterogeneity effects (e.g., Carrera et al. 1998; Benson et al. 2000; Feehley et al. 2000). Similarly, upscaling of reactive processes to relevant scales is a continual challenge and source of debate, with little agreement on the appropriate models that can be selected, a priori, for a particular field-scale setting. If our exercises and experiences with transport in the classroom suggest that simple homogeneous ADE models can be applied to field data without worry, we believe that we are not accurately representing the state of our science or preparing our students as realistic practitioners. Transport experiments that are outside of the idealized realm of the computer but can also be performed in reasonable timeframes—such as those that use heat as a proxy—provide a quick lesson in transport non-idealities that may take many months or years to be internalized in the field.

To amplify a suggestion made recently by Frind and Molson (2018): "what is needed is … a better understanding of the strengths and weaknesses, and the proper use, of existing models. Methodologies and models will continue to evolve. Perhaps a "New Literacy" among model users might be a better objective to strive for." The experimental setup and exercises described here represent one effort to encourage this "New Literacy" among the next generation of hydrogeologists. Education and experimentation that generates conceptual surprise about transport predictions, we believe, will continue to enhance student understanding and foster healthy skepticism in our predictions. If students are able to experience surprise about the impact of aquifer properties and processes on transport in a laboratory setting, perhaps we will produce a new generation of hydrogeologists that is less surprised in their professional practice.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article. Supporting Information is generally *not* peer reviewed.

Appendix S1. Assembly of the Visible Fracture
Appendix S2. Example Laboratory Exercise
Video S1. Video of Tracer Particle and Heat Transport near Fracture Inlet

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