Graphical Shading Logs: An Improved Approach for Collecting High Resolution Sedimentological Data at Contaminated Sites

by Jessica Meyer, Jonathan Munn, Emmanuelle Arnaud, Jonathan Kennel and Beth Parker

Abstract
Predicting contaminant transport in groundwater requires an accurate representation of the subsurface geology controlling the spatial distribution of hydrogeologic parameters. Developing accurate geological models for sedimentary systems relies on quality sedimentological data collected from cores. Standard logging forms used to collect data from cores create a persistent data gap in hydrogeology because they hinder efficient collection of high-quality sedimentological data. These logging forms require time-consuming text descriptions of sedimentological characteristics and often result in inconsistent, poorly resolved data insufficient to support realistic geological models. We describe a graphical approach to core logging, the graphical shading log, that facilitates rapid, accurate capture of sedimentological data and a complementary database to store the raw data and interpretations. The visual format of the graphical shading log provides a roadmap of the parameters to log and their possible values, helping to ensure accurate and consistent data collection by loggers with a range of experience. Examples from sites with contaminated groundwater in glaciogenic sediments and siliciclastic and carbonate bedrock show how data from the graphical shading logs improved geological interpretations, supported the design of high-resolution multilevel systems needed to collect minimally blended hydrogeologic data, and helped to more accurately delineate hydrogeologic units. The format of the graphical shading log and complementary database are designed to be customizable and transferable between hydrogeologic settings providing a new tool to advance geological data collection and management. Improved sedimentological data and insight are critical inputs for process-based conceptual site models needed to effectively manage contaminant plumes in the subsurface.

Introduction
Over four decades ago attention was drawn to diffusion as a key process controlling contaminant transport in heterogeneous unconsolidated sediments (Gillham and Cherry 1982) and fractured rock (Foster 1975). However, the importance of diffusion as a dominant contaminant transport process was not fully appreciated until the impact of mass storage and re-release of chlorinated solvents from lower permeability zones on plume persistence and ineffective remediation was demonstrated and understood widely (Mutch Jr. et al. 1993; Parker et al. 1994; Parker and McWhorter 1994). Mackay and Cherry (1989) used simplified examples and illustrations to argue diffusion of contaminants from low permeability materials into advective pathways was responsible for the failure of many pump and treat systems to reach remediation objectives and Mutch Jr. et al. (1993) demonstrated the impacts of diffusion from the rock matrix back to the fractures on plume persistence in fractured rock using a numerical model. Early field evidence for diffusion controlled release of contaminants stored in low permeability zones in sandy aquifers was provided by detailed sampling of cores for the contaminants of concern combined with analytical and numerical modeling, and in some cases, regular sampling of conventional wells and multilevel systems (e.g., Ball et al. 1997; Liu and Ball 2002; Parker et al. 2004; Chapman and Parker 2005; Parker et al. 2008). Similarly, field evidence for diffusion of contaminants from the low permeability rock matrix to the fractures in sedimentary rock was provided by contaminant distributions derived from cores combined with synoptic sampling of a multilevel system (e.g., Sterling et al. 2005). Later, a visual sand tank experiment (Doner 2008) complemented by numerical modeling (Chapman et al. 2012) helped to make the impacts of diffusion driven release of contaminants stored in low permeability zones more intuitive and widely appreciated. These studies, and others, combined with broadly disseminated publications identifying the limitations of remediation due to diffusion (e.g., US EPA 2003; National Research Council 2004; Sale et al. 2008; Stroo et al. 2012; National Research...
Contrasts in permeability distributed throughout groundwater flow systems provide the opportunity for diffusive mass transfer between high and low permeability zones. In sedimentary deposits, zones with contrasting permeabilities are not distributed randomly (e.g., Fogg 1986; Anderson 1989). Sedimentary processes that produce predictable vertical stacking patterns and lateral changes in sediment properties (Miall 2000) result in similarly predictable permeability variations. As a result, facies analysis of sedimentary characteristics at a particular site combined with general depositional models can be used to deduce the past, site-specific depositional processes and environments. Understanding of the depositional processes and environments responsible for a set of sediments enables prediction of the three-dimensional (3D) distribution of sedimentary characteristics, geometry, and connectivity away from areas with detailed subsurface data. Accurately producing 3D geological models is critical for developing predictive conceptual and numerical models of groundwater flow and advection–diffusion controlled contaminant transport. These models depend on high quality data collected from cores and/or inferred from borehole or surface geophysics.

Although the importance of heterogeneous permeability distributions to contaminant transport is now well-established, collection of detailed, high-quality sedimentological data sets from cores is uncommon. Geological data from continuous cores at contaminated groundwater sites are often logged using standard borehole logging sheets. These logging sheets include a depth scale and adjacent columns to record the results of geotechnical tests performed in the field, a brief geological description of the materials, the Unified Soil Classification System (USCS) designation, a graphical representation of the primary lithology, and comments. The Wisconsin Soil Boring Log Form (https://dnr.wi.gov/topic/Groundwater/documents/forms/4400_122.pdf) is an example of a typical format.

While there is no doubt useful information can be recorded in such logs, this format hinders high quality geological data collection in several ways. An example is provided in Figure S1 to illustrate the following points. First, geological descriptions are given very little space on the overall log, making collection of the type and scale of geological information needed to support robust geological models very difficult. Second, recording the data as text in a paragraph format along a depth scale leaves loggers with too little room to describe more geologically complex intervals (e.g., a 0.5 m interval of interbedded sediments exhibiting a variety of sedimentary structures) and too much room for more homogenous intervals (e.g., a 3 m interval of well sorted, massive sand). The text descriptions are also often inconsistent with key parameters included for some depths, but not for others, and are often missing basic sedimentological information such as sedimentary structures, particle shape, and contact relationships. This inconsistency results in ambiguity for users of the data because it is not clear if a parameter was omitted because it was overlooked, consistent with the previously logged section (e.g., “same as above”), or not applicable.

Writing out the text descriptions required by standard logging sheets is very time-consuming making it difficult to keep up with drilling. Consequently, some guidance documents recommend only describing the lithology, grain size, and color (Weight 2019). Some geological logging guides do not even mention capturing fundamental geological observations. Instead, these guides emphasize recording interpreted classifications (e.g., USCS, USDA soil texture, and lithostratigraphy) (Ruda and Farrar 2006). Although the USCS (ASTM 2017a, 2017b) is very useful for geotechnical studies and the USDA soil texture (USDA NRCS 2017) for drainage studies, these classifications alone do not provide the data needed to generate facies-based subsurface geological models beneficial to contaminant hydrogeology (Shultz et al. 2017).

The text format used for geological data collection also makes digitizing the logs very time consuming. Consequently, most of the geological data collected remains as handwritten (or sometimes typed) notes on the original field data collection sheet, archived in a report either in paper copy or as a pdf. When geological logs are digitized, it is common that only the bare minimum of information is extracted (often the grain size/lithology and/or a lithologic or stratigraphic interpretation) and stored in a Relational Data Management System (RDMS). In many instances, even the grain size information is not fully recorded where only the primary texture is entered into a database (i.e., First Attribute method of Russell et al. 1998), ignoring secondary and tertiary texture attributes, which may be very important in a hydrogeological context (e.g., sand with silt and clay may represent diamicton/till and will most certainly behave differently hydrogeologically compared with clean sand with no silt and clay). Consequently, interpretations and insight derived from the geological data, which was collected at great expense, are severely limited.

Description techniques commonly used in sedimentological studies provide a better model for geological logging for hydrogeologic studies. These studies commonly rely on what is referred to as a graphical log to capture sedimentological data from outcrops and cores (e.g., Nichols 2009; Farrell et al. 2013; Bristow 2020) and importantly are designed to capture diagnostic characteristics to reconstruct depositional conditions and create 3D depositional models (e.g., Eyles et al. 1983). Graphical sedimentary logs typically include a depth scale and several columns to capture key sedimentological parameters. The bulk lithology for an interval is recorded in the far-left column at the appropriate position along the depth scale and is represented using standard symbols. Grain size versus depth is plotted on a standard scale in the next column to the right. Often symbols representing the observed sedimentary structures at particular depths are overlain over the graphical grain size curve. Additional columns are used to note fossils (graphically) or other parameters important to the section being measured, record additional notes/descriptions, and interpretation of the data. The resulting data set is a mixture of symbolic and text information.

Although the graphical logging style used in sedimentological studies does a better job at capturing all the important sedimentological information from an outcrop or core,
it is still not particularly well suited for logging of cores collected at contaminated sites. Cores collected at contaminated sites are usually logged as they are drilled because storage and later logging is not feasible and/or because they are also being sampled to characterize the contaminant distribution in both the high and low permeability zones (e.g., Parker et al. 2004; Chapman and Parker 2005; Sterling et al. 2005; Lima et al. 2012). As a result, loggers do not usually have the benefit of being able to see the entirety of the core at once making it difficult to appreciate and capture the scale, relationships, and significance of changes in the parameters being logged. In addition, logging must proceed very quickly to avoid unnecessary exposure of the cores before sampling and to minimize standby time for the drilling crew.

Once collected, management of data from detailed sedimentological logs in a RDMS presents several challenges. First, sedimentological descriptions usually contain a mix of semiquantitative and qualitative data. Second, because different sedimentary environments result in different diagnostic sedimentary features, the parameters that should be logged are generally not consistent from site to site or even at the same site from the overburden to the bedrock. As a result of these challenges and because all the raw data is not generally digitized, many RDMS are not designed to store all the raw sedimentological data in a log. Instead, RDMS are designed to store interpretations of lithologic units, lithofacies, and/or stratigraphic units. Although they are set up to store interpretations, there are often no mechanisms to track the evolution of interpretations by different project personnel and through time. This type of evolution should be expected as new data becomes available and new scientific insights are gained, given the decades long life cycle of some contaminated sites. Geological data managed (or mis-managed) in this way are never fully utilized and project teams are often locked into the initial interpretations made in the field (often by the least qualified personnel) because the primary descriptive data is lost (or sequestered in reports) and/or because the data management systems themselves do not facilitate multiple interpretations of the same data.

A new approach to geological data collection and management is required to produce the style of geological information needed to support robust conceptual site models (CSMs), and in turn, the long-term management of legacy contaminated sites. The approach should include logging sheets that facilitate efficient, accurate, and consistent capture of high-resolution sedimentological data that can be efficiently digitized and a complementary RDMS structure to store all the data. Graphical shading logs are an approach to data collection from cores where the sedimentary characteristics of an interval are recorded by shading in the correct value at the correct depth on the log rather than writing out a description of the characteristics in paragraph form. The objectives of this paper are to (1) describe the graphical shading log approach to sedimentological logging of cores being collected to support investigations at contaminated groundwater sites, (2) present a RDMS schema developed specifically to house high resolution sedimentological data and the associated interpretations, and (3) demonstrate how these improved geological data collection and management approaches improved CSMs at real field sites.

Methods

Graphical shading logs are designed to facilitate capture of high-resolution primary sedimentological data to support a variety of classifications/interpretations, and even more importantly, revision of those classifications/interpretations as more data and insight become available. Here, we use the word sedimentological to refer to the physical, chemical, and biological characteristics of sediments and sedimentary rocks. These characteristics can be used to interpret the processes that formed the sediments. We use the words stratigraphic/stratigraphy to refer to the distribution of sediments/rocks in space and time. A primary purpose of stratigraphic studies is to determine the order and timing of events in Earth history. Stratigraphy that is arrived at through facies analysis of sedimentological data also helps to determine the environment in which the sediments formed, which ultimately helps to determine the 3D distribution of materials (geometry and connectivity) that can affect groundwater flow and contaminant transport away from data collection sites. We use the phrase geological model to refer to the conceptual framework that integrates sedimentological, stratigraphic, and geophysical data sets to represent the subsurface geology. Ultimately, that geological conceptual framework is used with other types of datasets to develop and iteratively refine the CSM.

Graphical Shading Log Approach

The general layout of graphical shading logs is designed to capture data along a depth scale (typically about 1 cm per 10 cm of core depth) and support efficient, high-resolution logging (~3–5 cm or 0.1 ft) of sedimentological data as cores are drilled and sampled for the contaminants of concern and/or the properties controlling flow or contaminant transport (Figure 1). Although the logging forms presented here were designed to collect sedimentological data, the same format and shading approach could be used to collect parameters relevant to igneous or metamorphic rocks. Recording the data along a depth axis (i.e., logging to scale) offers several important benefits. First, logging to scale facilitates accurate capture of the data because the log visually reflects the core making it easier to catch errors. Second, the graphical shading log done to scale encourages the logger to think about and question the patterns and relationships they see in the core as additional runs of core are logged, which improves the quality of the log. Last, although it might be counter intuitive, in our experience, logging to scale is faster than logging in a tabular format because it is much easier to keep your place in the log. These logs are also designed so that the distance from the top of the run is what is recorded rather than the absolute depth (Figure 1). This helps to ensure depth accuracy because the logger is not required to calculate the absolute depths on the fly, they simply log what they see on measuring tape affixed to the core tray specifically designed to support high-resolution core logging and sampling (Figure S2).

Graphical shading logs must be customized based on the geological/hydrogeological setting where they are used to ensure data relevant to interpreting the depositional environment and post-depositional processes are captured. The parameters and parameter values included in the log are
determined based on literature descriptions of the stratigraphic units expected to be present at the site and data previously collected from cores or nearby outcrops (Figure 1). Some parameters will be required regardless of the specific setting (e.g., general lithology, color, grain size, sorting, sedimentary structures, bedding thickness, and contact relationships), but the relevant values for those parameters may vary. For example, the sedimentary structure “hummocky cross-stratification” is only going to be relevant in a marine or lacustrine setting where large storm waves can be generated. Additionally, parameters might include rounding of particles, clast lithology, sediment disturbance index, cementation index (for rock), indicators of diagenesis, and fossil content. Although not explicitly shown in this example, parameters representing standard soil classifications (e.g., USCS or USDA textural classes) can be included in the log if desired. Doing so allows the logger to record the primary observations informing the interpretive classification as well as the classification itself in an efficient manner. Capture of the primary observations in addition to the classifications is critical to support refinement of the initial classifications if additional data become available and/or to allow alternative classifications and depositional interpretations, which are so critical for creating robust 3D subsurface geological models. The final two columns in the log are usually reserved for graphics and text comments (Figure 1). The graphics column allows loggers to draw an image of a structure or other feature they observe but cannot identify or is not captured by one of the parameters (Figure 1; 0.9–1.5 ft). The comments parameter allows for some additional text information. However, the idea is to limit the amount of information captured as text. If a piece of information is repeatedly being captured in the graphics or comments column then the log sheet design should likely be revised to capture that information graphically.

Consistent description or quantification of values from core to core and from logger to logger is important. Thus, standard reference sheets and established procedures as provided by the graphical shading logs are utilized to maintain consistency. For example, use of a hand lens and an appropriate grain size reference card is critical for accurate capture of the primary, secondary, and tertiary grain sizes present in each section of the core. We use the Udden–Wentworth scale (Udden 1914; Wentworth 1922) for siliciclastic materials and the Dunham (1962) classification for carbonates. Similarly, a Munsell chart is utilized to describe the color of each section of the core under consistent wetness conditions. Accurate descriptions of qualitative parameters like sorting, rounding, and degree of cementation or sediment disturbance are guided by graphical or text descriptions of each possible value in custom or publicly available reference sheets (e.g., https://midwestgeo.com/fieldtools.php; ASTM 2017b; Stow 2005; Schoeneberger et al. 2012).

Logging is done in the field as the cores are drilled and typically starts by identifying intervals or beds within the core where all the parameters have consistent values. These intervals or beds are demarcated by drawing horizontal lines across the full log sheet at the appropriate depths. The logger then examines each identified interval or bed to determine the correct values for each of the listed parameters. The logger records these observations by simply shading in the correct value for each depth interval in the core. If the parameter is described by a single value, then the column for that value is shaded (Figure 1; grain size: 0.3–0.7 ft). If a range is required to describe the parameter, then multiple adjacent columns spanning the range are shaded (Figure 1; sorting: 0.0–0.3 ft). Shading can also be used to indicate the relative proportion/abundance or intensity of some parameters. For example, a poorly sorted interval might include a mix of clay, silt, very fine sand, and coarse sand (Figure 1;...
grain size: 0.7–0.9 ft). The relative proportion of each grain size can be indicated based on the type of shading used: solid (primary: 50–100%), double crosshatch (secondary: 10–50%), and single diagonal lines (minor: <10%). Parameters that change gradually across an interval can be represented by a shift in shading and/or an additional parameter can be added to describe the contact between units (e.g., sharp, irregular, gradational, and diffuse). The format of the log and use of shading to record values allows the logger to effectively capture subtle or gradational changes in properties in a fraction of the time it would take to write the observations out as text. If a parameter is absent, the logger notes it as N/A confirming the parameter was looked at and not found rather than missed or forgotten.

Other information typically captured on standard borehole logging sheets is also captured when using graphical shading logs, but is collected on separate, specifically designed data sheets. For example, drilling information, including the top and bottom depths of each run, times associated with drilling activities, recovery, and Rock Quality Designation (RQD) distances, are all recorded on a run data sheet. Loggers are not asked to sum RQD qualifying lengths or calculate RQD in the field. The data sheets provide space to record each qualifying RQD length and RQD calculations are done later by the RDMS. A separate data sheet is also used to record detailed observations about depth discrete features like fractures that are particularly relevant to some investigations in clays or rock. In addition, data sheets have been designed to capture drilling water levels and a wide variety of different types of samples, both in terms of media (e.g., sediment or rock) and analysis type. Except for the graphical shading log for sedimentological data, all the field sheets have been implemented both on paper and in iOS and Android app format with a cloud-based database serving as the backend for temporary field data storage until the data are migrated into the main RDMS. The graphical shading logs are still implemented on paper because the process of completing the log to scale encourages deeper observation and thinking about the core and because, in our experience, there is not yet a combination of hardware and software options that effectively supports this style of graphical logging in the field.

Database Structure for Detailed Sedimentological Data and Interpretations

The consistent, quantified, and digital nature of the data in graphical shading logs supports efficient and accurate digitization either by entering the information in a tabular format or by tracing the log using specialized software. Tabular data entry starts by setting up a table in a spreadsheet program to mimic the structure of the log sheet. The depth interval data are recorded in the rows and each parameter occupies a column, or series of columns if relative proportion or abundance was indicated. The values for each parameter can be used to generate lookup tables listing the accepted values for each parameter. The data from each interval is then entered into the table.

An alternative approach is to use specialized software that allows users to trace the graphical log into a scaled workspace that captures the data digitally. For example, Dreher et al. (2010) describe a custom piece of software created to digitize graphical logs for cores collected using a Vibracore method. Although several pieces of commercially available software could be used to digitize graphical shading logs, the CoreCAD™ module of WellCAD™ (https://www.alt.lu/products-wellcad/) is the only one the authors know of specifically designed to support this type of digitization. The CoreCAD™ workspace is set up to reflect the parameters and values included in the log. Standard libraries are established to represent the values for each parameter either via a symbol, color, or a plotted value. Each page of the graphical shading log is then clipped to the top and bottom depths of the scale bar. The clipped images are then imported into CoreCAD™ and arranged in the workspace in depth order and to scale. Each interval is defined by tracing the interval on the image of the log and then the values for each parameter are selected. At the completion of the process the sedimentological information contained in the original logs is visually represented in WellCAD™ and the values for each parameter are captured in tabular format in the underlying database. These data can be stored in WellCAD™ or exported as a .csv file for migration into an RDMS.

Regardless of the way the data is digitized, we recommend storing geological data in a RDMS. Storing the data in a database facilitates easy querying of the data for use in a wide variety of visualization packages and for use in the statistical analysis of hydrogeological data within and across specific stratigraphic intervals. Storing the geological data in a database also allows for direct and full description of the metadata that should accompany the geological information but is typically stored in the header or footer in visualizations.

We have developed a schema that facilitates capture, storage, visualization, and use of high-resolution geological information that includes both the raw, sedimentological data and subsequent depositional and/or stratigraphic interpretations. The schema development process revealed several important design elements. Conceptually, data are collected from a station (i.e., a borehole) at a site. Each site represents a broad area where studies focused on the same hydrogeologic system are taking place and a station essentially represents an x-y location and its evolution through time. Data are either collected from discrete depths or from a depth interval at each station. There are several tables that store information describing each station and how it has changed through time (Figure 2; Project Data Tables, frame on middle left side). For example, the Stations table simply lists the stations that have existed at a site and the Stations-Details table describes, in broad terms, how each station has evolved through time from an open borehole/corehole, to a temporarily lined borehole/corehole, to a well or a multilevel system, to abandonment, if that occurs. The DrillingDetails table describes all the drilling steps associated with constructing a particular station. The StationComponents table houses the as-built data for each station. The SurveyDetails, XYSurveyData, and ElevSurveyData house all the survey information. Changes to depth references (i.e., casing gets cut off, ground surface is changed) happen fairly frequently. To account for these changes and ensure the appropriate
survey data is paired with each data point, start and end applicability dates/times are used for each survey data point.

Several basic ideas guided the schema for the raw data collected from cores. First, data is collected based on the distance from the top of the core run to what is being logged (Figure 2; Geological Log Data, top frame). Consequently, the tables that house raw sedimentological data are all related to the RunDetails table, which stores the run information. Queries are then used to relate the RunDetails table to the tables housing the raw sedimentological data to calculate the final depths for each interval. RQD data for consolidated core runs and run times are stored in separate tables (Figure 2; Geological Log Data, top frame). Second, data are stored in two separate sets of tables depending on whether the parameter logged is depth discrete or occurs across a depth interval. Depth discrete data are stored in the FeatureDetails and FeatureData tables and might include fractures or other secondary porosity features, depth discrete staining, and mineral accumulations. Interval data are stored in the SedLogDetails and SedLogData tables and include all the data collected on the graphical shading logs. The SedLogDetails and FeatureDetails tables store the metadata (i.e., the site, station, who collected the data, when the data was collected, the run number, the distances from the top of the run, distance units). The SedLogData and FeatureData tables include the foreign key from the SedLogDetails and FeatureDetails tables respectively to form the relationships between the details and data tables, a parameter field, and a value field (Figure 2; Geological Log Data, top frame). This format for the data tables provides flexibility to accommodate changes in the parameters logged based on differences in geological/hydrogeological setting and/or based on different questions of interest at different times without having to add numerous null values to the tables each time a new parameter is added. The format requires that all parameter
values be stored as numbers or text. Many pieces of geological information are semi-quantitative or qualitative, so a text field is used. Numeric representation of specific parameters is accomplished by using simple lookup tables and queries to relate text descriptors to consistent numeric equivalents. For example, degree of sorting is stored in the SedLogData table as very poor, very poor to poor, poor, poor to moderate, moderate, moderate to well, well, well to very well, and very well. A lookup table defines linearly increasing numeric values for each descriptor as 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, and 5, respectively, and then a query is used to translate the stored text descriptors into numeric values when needed.

Facies and/or stratigraphic interpretations of the raw sedimentological data are stored separately (Figure 2; Geological Interpretation Data, bottom right frame). This separation is critical to allow evolution of interpretation over time without compromising access to the original descriptive data. The schema for interpretations includes two sets of tables. One set of tables, StratDesc and StratUnits, houses descriptions of defined stratigraphic units recognized regionally and depth picks for those units at each station based on site specific data. The other set of tables, FaciesDesc and Facies Units, houses descriptions of facies defined for the study area and picks for those units at each station based on site specific data. The style of both the stratigraphy and facies tables allows users to store all versions of each interpretive grouping as well as all versions of the picks for those units. This flexibility is important because investigations at some contaminated sites have been ongoing since the 1970s or 1980s. Early investigations at the site would have used the 1970s version of the lithostratigraphic nomenclature while current investigations at the site might be using a more recent version of the nomenclature. The ability to track different versions of the same type of stratigraphic units allows users to retain both sets of stratigraphy in the database making comparisons and/or joint use of newer and older interpretations easy and reliable (Figure 2; StratVersion and FaciesVersion fields in the StratDesc and FaciesDesc tables respectively). In addition, re-evaluation of depth picks for stratigraphic units happens fairly frequently as new data is collected or new insight into the geological system is gained through new collaborations with researchers and/or consultants. Consequently, the tables also provide the ability to store multiple versions of depth picks for the same units (Figure 2; StratPickVersion and FaciesPickVersion fields in the StratUnits and FaciesUnits tables, respectively). A template of this schema in Microsoft Access, including example data sets in the tables is included as a separate file in the Appendix S1.

The digitized, tabular geological data is migrated into the RDMS using import (i.e., temporary) tables and stored procedures. Constraints (e.g., required fields, data types, uniqueness, violation of relationships, and specified checks) defined for the RDMS automatically validate the data during the migration. Once the information has been entered into the database, queries can be used to produce a variety of outputs. For example, queries can be used to select and format the data for visualization and interpretation in 1D and 2D cross-sections with other complementary data sets in free software such as SedLog (Zervas et al. 2009) and PSIACat or in commercially available packages like LogPlot, Strater, and WellCAD™. Visualization of the raw data is used as an additional data validation step before the data is used for interpretation or calculations. Queries can also be used to select and prepare stratigraphic unit picks to support generation of surfaces and 3D volumes. Another benefit of storing geological data and information in a relational format is the ability to easily, consistently, and accurately summarize other data sets based on their relationship to facies or stratigraphic unit boundaries or other geological features. For example, hydrogeologists are often interested in statistically summarizing measured hydrogeological properties (e.g., porosity, bulk density, fraction of organic carbon, permeability, and specific storage) based on the stratigraphic or hydrogeologic unit that corresponds to the measurement. Queries can be written to compare the depths of the measurements to the top and bottom depths of stratigraphic or hydrogeologic units to assign the correct unit to each measurement and then calculate the required statistics. This method is preferred over having to manually assign the stratigraphic unit(s) to each data point because those assignments would have to be made for multiple data sets and they are difficult to update through time as interpretations change or new data is collected. In addition, the database can be utilized to assemble and format the data required by software such as gINT™ to produce the borehole logs required by regulatory agencies.

Results and Discussion

The graphical shading log approach introduced here was developed through trial and error by the people doing the logging at three sites where research was being conducted on the transport and fate of organic contaminants in sedimentary rock (Parker et al. 2012; the Wisconsin site (WI site), the California site (CA site), and the Ontario study area (ON study area). Hydrogeologic research at the WI site is focused on a mixed organic solvents DNAPL source zone and the associated dissolved phase plumes (Lima et al. 2012; Steelman et al. 2017; Lima et al. 2018; Steelman et al. 2020) migrating through nearly flat lying Cambrian and Ordovician silicilastic rocks deposited in an epeiric sea overlain by Quaternary unconsolidated sediments deposited in an ice marginal setting (Meyer et al. 2008, 2016; Harvey et al. 2019). Studies at the CA site are focused on transport and fate of TCE through a turbidite sequence of Cretaceous silicilastic rocks dipping at 30° (Sterling et al. 2005; Cilona et al. 2016; Pierce et al. 2018). The Ontario study area includes several long-term research sites where groundwater in flat lying Silurian dolostone deposited in sub-tropical epeiric seas are contaminated by TCE or metolachlor (Perrin et al. 2011; Kennel and Parker 2018; Parker et al. 2018) as well as the broad area surrounding Guelph, Ontario where numerous contaminant hydrogeology investigations in both the Quaternary sediments and underlying carbonate bedrock have been conducted (e.g., Best et al. 2015; Opazo et al. 2016; Allen et al. 2017).

Evolution of the Graphical Shading Log Approach

Early versions of the log used first at the WI site were a hybrid of graphical logs commonly used by sedimentologists and the shading log approach introduced here. For example, parameters like grain size, sorting, rounding, and
cementation index were captured by shading in appropriate values; whereas, the major lithology and structures were noted using established symbols and or text descriptors (Figure 3a). Symbology for the structures was difficult to keep consistent between loggers and the mix of symbolic notation and shading made digitization of the log less efficient. Consequently, revised versions of the log captured sedimentary structures using a shading approach (Figure 3b). The dominant lithology continues to be recorded symbolically because it is a well understood visual cue helpful for keeping your place in the log and understanding the large-scale geological changes with depth. Although the dominant

Figure 3. Example graphical shading logs from the WI research site showing the evolution of the approach.
lithology is captured symbolically, secondary materials (shaley/clayey, silty, sandy) are recorded by shading the appropriate parameter because it is often difficult to differentiate the lithologic patterns used to represent a mix of lithologies (Figure 3b). That is, it is difficult to sort out the difference between a silty sandstone or a shaley sandstone based on symbols alone.

Early versions of the log also included a siliciclastic grain size axis following the Udden–Wentworth scale (Udden 1914; Wentworth 1922) and the Dunham (1962) carbonate classification axis in the same column because the section of interest included both rock types (Figure 3a). Although this was efficient for capturing the grain size/carbonate classification for both systems, it did not allow for capture of other parameters more specific to carbonate systems. So, log sheets tailored to carbonate rocks were developed (see Carbonate Rock Log Example below).

Other minor changes also contributed to improvement of the log. For example, multiple columns of the log sheet were initially used to capture the dominant Munsell color as well as secondary and more minor colors (Figure 3a). However, use of the log showed the additional columns went unused and that primary and secondary color information could be captured utilizing one column on the sheet (Figure 3b). A graphics parameter was also added to allow loggers to draw structures or other features they could not identify to facilitate identification later (Figure 3b, third column from the right).

The handwritten log shown in Figure 3b was digitized, and that data was input into the RDMS described in Section 2.2. Standardized lookup tables were created to relate text descriptors to numeric values. Queries were then written to select, filter, and format the data appropriately for plotting in WellCAD™ (Figure 3c). WellCAD™ can be used to create a digital version of the paper log or other custom visualizations to meet regulatory requirements for borehole logs.

Insight for Contaminated Site Characterization and CSMs Provided by Graphical Shading Logs

The following sections describe examples of the graphical shading logs used at the WI site and ON study area for siliciclastic and carbonate rock and unconsolidated glaciogenic sediments and compare data sets collected using graphical shading logs to those collected using standard logging techniques. These examples highlight the benefits of the graphical shading log approach for a variety of geological and hydrogeologic settings both in terms of efficiency and quality of data collected. The examples are also used to show how data from the graphical shading logs, managed using the RDMS and plotted in profile alongside other data types, improved stratigraphic interpretations, supported the design of depth-targeted multilevel systems needed to collect minimally blended hydraulic and groundwater chemistry data, and helped to more accurately delineate hydrogeologic units.

Siliciclastic Rock Example—WI Site

Once the high-resolution sedimentological data are plotted in profile, they can be co-plotted with many other types of profile data (e.g., geophysical, geochemical, hydraulic, and well construction) to support a variety of depositional and/or stratigraphic interpretations. For example, identification of maximum flooding intervals (MFIs), important sequence stratigraphic units, in the Cambrian aged sediments throughout the upper Midwest US relies on identification of a combination of characteristics. These MFI characteristics include very fine-grained sandstone with subordinate siltstone and shale, poor stratification due to pervasive bioturbation and soft sediment deformation, and markers of condensed sedimentation including intraclasts, glauconite, carbonate, and iron precipitates (Runkel et al. 2007). The high-resolution logs of grain size, sediment disturbance index, and sedimentary structures (i.e., intraclasts) were plotted together with the natural gamma log to support identification of these intervals in each hole (Figure 4) and then represented in cross-section to inform the geometry and lateral extent of each interval (Meyer et al. 2016; Figure 7). The detailed sedimentological logs were also a key dataset used to design high-resolution multilevel systems (MLSs) (i.e., numerous depth-discrete, minimally blended monitoring intervals in a single system) (Meyer et al. 2014). Head profiles collected from these MLSs showed abrupt changes in head with depth providing direct evidence for changes in the vertical component of hydraulic conductivity across specific depth intervals correlated with the sequence stratigraphic units (Figure 4). Meyer et al. (2016) combined the sequence stratigraphy and depth discrete vertical gradients to delineate robust hydrogeologic units (HGU}s for the site at the plume scale (16 km²) that serve as the foundation for the conceptual and numerical models of groundwater flow and contaminant transport.

Over 130 boreholes were previously logged at the site, but most were completed from cuttings generated from air or mud rotary drilling (e.g., HSI GeoTrans 1998, 1999; GeoTrans Inc. 2003a). These logs typically only indicate the primary lithology for the materials being logged and an interpretation of the lithostratigraphic unit. Several cores were also logged using the standard paragraph style regulatory form (GeoTrans Inc. 2003b, 2004) described in Section 1. An example of these standard logs is provided in Figure S3. The geological descriptions were provided as a single paragraph for each run. Details for different intervals within a run were noted by providing a depth interval before specific portions of the text descriptions. So, although the metadata for each run was logged to scale, the actual geological information was not. Even though complete cores were available, these logs also focused primarily on lithology and qualitative descriptions of color. The parameters most important to identifying key sequence stratigraphic units including detailed grain size trends, degree of sediment disturbance, and markers of condensed sedimentation were not logged at all. Although these logs contain useful data, the text format of the descriptions makes it very difficult to use these logs to design high resolution MLSs and/or to compare data between core locations to support stratigraphic interpretations.

Carbonate Rock Log Example

The graphical shading logs have also been customized to capture sedimentological data for Silurian dolostone in southern Ontario. These dolostone units have been the focus of intense geological (e.g., Armstrong and Carter 2010;
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Figure 4. An example showing how interpretations of sequence stratigraphic units and hydrogeologic units at the WI site were supported by interpretation of sedimentological data captured in graphical shading logs combined with geophysical logs and high-resolution hydraulic head profiles. These data are from the MP-19D graphical shading log shown in Figure 3a. GS, grain size; SDI, sediment disturbance index.

Carter et al. 2019; Brunton and Brintnell 2020) and hydrogeologic investigations (e.g., Perrin et al. 2011; Munn 2012; Opazo et al. 2016; Allen et al. 2017; Parker et al. 2018; Priebe et al. 2018; Brunton and Brintnell 2020) for the past two decades because of their importance to private and municipal water supplies. In this Silurian sequence, important stratigraphic changes are associated with relatively subtle changes in rock properties making them difficult to log consistently and accurately, particularly for those with minimal experience logging dolostone. Geological investigations of these rock units indicated that changes in the carbonate classification; dolomite crystallinity; fossil type, abundance, and size; intensity and size of macro-porosity; and the presence of stylolites or styloseams were key attributes needed to distinguish stratigraphic units (Munn 2012; Brunton and Brintnell 2020). Consequently, the graphical shading logs customized for the Silurian dolostone emphasized these parameters and created a consistent set of values for each parameter that were visually distinguishable in core (Figure 5).

The Gasport formation is an important water supply aquifer in southern Ontario and regional studies indicate the overlying Niagara Falls Member of the Goat Island formation often has a low transmissivity and can serve as an aquitard in many areas (Brunton and Brintnell 2020). Distinguishing between the finely crystalline crinoidal grainstone of the Niagara Falls Member and the coarsely crystalline crinoidal grainstones of the underlying Gasport Formation is also important because the contact between the two represents an unconformity often associated with dissolution enhanced fractures and/or karst (Brunton and Brintnell 2020). The data captured by the graphical shading log at a field site just south of the City of Guelph, Ontario clearly shows a shift from a packstone with medium crystallinity to a packstone with coarse crystallinity; which, together with other evidence, helps to place the contact between the Gasport Formation and the Niagara Falls Member (Figure 6).

High resolution core photos taken in the field prior to sampling the core are a tremendously useful complementary data set but do not replace detailed sedimentological logs because changes in lighting, wetness, and other photo parameters can create artifacts in the image that can be misinterpreted. For example, the high resolution core photos show how difficult it is to distinguish the shift in crystallinity between the packstones of the Niagara Falls Member and Gasport Formation (Figure 6; photos 5 and 6). Even if the shift in crystallinity were easy to recognize in photos, the core photos are difficult to utilize in profiles to support interpretations with other data sets because the vertical scale has to be very small in order to see the images clearly (Figure 6).

The graphical shading logs also supported further evaluation of the aquitard properties of the Niagara Falls Member. The graphical logs were used, in conjunction with other data sets, to design temporary high-resolution multilevel monitoring systems for collection of pressure and temperature at numerous depth discrete intervals (Pehme et al. 2014). The resulting head profile shows the upper portion of the Niagara Falls member is where most of the head loss associated with the aquitard occurs at this location (Figure 6). Other studies in sedimentary rock have also noted that sections of the stratigraphy that function as aquitards (i.e., restrict vertical flow as indicated by an increase in vertical gradient) are often thinner than the stratigraphic unit they are commonly
associated with because they are controlled by fracture connectivity (Meyer et al. 2008; Meyer et al. 2014; Meyer et al. 2016). Both this example for the Silurian carbonate rocks (Figure 6) and the Cambrian siliciclastic rocks (Figure 4) show the importance of these high resolution sedimentological data sets to designing multilevel systems that will collect the minimally blended hydraulic head data needed to accurately delineate aquitard units in sedimentary rock sequences.

The graphical shading log approach was developed as part of ongoing academic research at sites where groundwater in bedrock aquifers is impacted by contamination. Field data collection at these sites is conducted primarily by graduate students with diverse academic backgrounds including undergraduate degrees in geology, environmental science, and civil, water resource, or environmental engineering. For example, the log presented in Figure 5 was completed by someone with very little background in geology. Students coming from non-geology disciplines often struggle when asked to log cores, particularly when they have no prior experience and have to log them quickly, because they do not know what parameters to log and lack the vocabulary to describe what they see. Students with backgrounds in geology will be more familiar with geological terms and sedimentological processes, but will probably only have logged a core or two during their course work. The situation is similar outside academia where often the most inexperienced personnel are tasked with supervising drilling activities and logging the cores recovered. As a result, logging cores during drilling events can be a stressful experience for inexperienced loggers and often does not produce high quality geological logs.

The graphical shading log approach supports loggers with a range of experience by providing a visual roadmap of the parameters of interest and the acceptable values for those parameters. As a result, loggers have more time to focus on

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**Figure 5.** Example graphical shading log from borehole BH-01 designed for the Silurian dolostone in the Guelph, Ontario area. The depths represented on the log are 21.4–23.0 m (70.1–75.3 ft) below ground surface.

**Figure 6.** Guelph, ON study area example showing how a subset of data from the BH-01 graphical shading log (Figure 5) supports the pick between the Gasport Formation and Niagara Falls member at 30.1 m bgs. The high-resolution head profile indicates the upper portion of the Niagara Falls Member has the largest head loss and functions as the important aquitard interval at this location.
high quality descriptions. Visuals or text descriptions of each value are provided on comparison reference cards or sheets to help ensure accuracy and consistency in the descriptions. Even with good reference sheets, we have also found it is critical to spend a small amount of focused time describing core together with new loggers in order to help them identify features correctly and consistently. The scaled, graphical format of the shading log also makes it easy for loggers to translate what they are seeing along the core to data on the sheet and facilitates real-time validation of the data because any parameters that were missed appear as a blank space in the log. The resulting data sets provide rich information for project personnel with more geological training who are focused on interpreting subsurface stratigraphy.

**Unconsolidated Glaciogenic Sediments Example**

The graphical shading log approach was originally developed to support logging of sedimentary rock cores. However, the approach has also been extended to unconsolidated sediments associated with a variety of depositional environments. For example, a graphical shading log was developed to capture sedimentological data from rotosonic cores of sediments deposited in an ice marginal environment while those sediments were being sampled for volatile organic contaminants at the WI site (Harvey et al. 2019). The surficial sediments at the WI site are dominated by diamict and sand of the Horicon Member of the Holy Hill Formation (Clayton and Attig 1997). Knowledge of typical facies and facies associations in ice marginal environments (Colgan et al. 2005), descriptions from regional literature (Mickelson 1983; Attig et al. 1988; Clayton and Attig 1997; Colgan and Mickelson 1997), and logs from previously drilled boreholes at the site (Parker et al. 2006) were used to assemble the parameters and parameter values appropriate for these sediments (Figure 7a and 7b). Because the sediments at the site are dominated by diamict (i.e., mixture of clay, silt, sand, and gravel; sometimes referred to as till), particular attention was paid to capturing the relative abundance of all recognized grain sizes. Sorting, type of contact, sedimentary structures, scale of bedding, plasticity of clay, and several parameters focused on description of gravel-sized particles were also included in the log (full log provided in Figure S4).

The diamict at the site is very sandy (48–89% sand in the matrix) and was classified by Harvey et al. (2019) as clast-poor or clast-rich intermediate to sandy diamict based on the classification scheme presented by Hambrey.

Figure 7. Example graphical shading logs and subsequent stratigraphic unit (SU) interpretations for unconsolidated Quaternary sediments deposited in an ice marginal environment at the WI site. The full log is shown in Figure S4 to provide an example of all the parameters logged and their values.
and Glasser (2003). Others have reported difficulty in distinguishing between diamict dominated units within the Horizon Member because the texture of the sediments is so similar (Whittecar and Mickelson 1979). The detailed core logs, facilitated by the graphical shading approach, showed several of the diamict units were relatively homogeneous in terms of primary grain size and abundance of gravel (Figure 7; SU3, 8.7–11.3 mbgs) whereas, other diamict units included numerous sand interbeds (Figure 7; SU1, 14.7–18.9 mbgs). This level of detail allowed for identification of six distinct lithofacies. Facies associations examined along two cross-sections and supported by results from surface resistivity surveys were then used within the context of the regional stratigraphic framework to delineate stratigraphic units (SUs), inform their potential lateral geometry between cores, and reconstruct their depositional history (Harvey et al. 2019). Differentiation between some SUs was made possible by the detailed description of the variable properties of diamict units (e.g., Figure 7; SU3 vs. SU4). Interpretation of stratigraphic units made use of the detailed sedimentological data from core together with the lateral facies variability and large scale geometry identified from geophysical surveys: the SU1 diamict was interpreted as ice marginal debris flow deposits; whereas, the SU3 diamict was interpreted as a subglacial till (Figure 7). Understanding the depositional history of the deposits allowed for the construction of an improved stratigraphic model for the site that more accurately reflects the geometry/lateral continuity of the sediments, which is critical for accurate modeling of groundwater flow and contaminant transport (Steelman et al. 2020).

Conclusions
The standard sheets used in logging cores hinder collection of the types and resolution of sedimentological data needed to create CSMs that support investigations at contaminated sites. This paper describes a new style of logging sheet, the graphical shading log, to support accurate, consistent, and efficient high-resolution sedimentological data collection from cores during drilling. The logging approach is complemented by a database schema designed to store raw geological data and interpretations of those data. The geological data can then be queried and reformatted for visualization in a wide variety of software and/or used to summarize other types of data associated with specific interpreted lithologic or stratigraphic units.

Here we show the benefits of graphical shading logs by describing examples where the logs have been used as part of research at sites focused on characterizing groundwater flow and contaminant transport in siliciclastic and carbonate rocks and glaciogenic sediments. First, the graphical shading log format makes it easy to go beyond basic descriptions of the general lithology and color to capture other key sedimentological data like grain size trends, sedimentary structures, contact relationships, and other indicators of specific depositional and post-depositional processes. These improved geological logs are critical to the sedimentological and stratigraphic interpretations needed to improve our understanding and prediction of heterogeneity in hydrogeologic parameters (e.g., K, porosity, fraction of organic carbon) in the subsurface. Second, unlike the standard text-based description of sedimentological characteristics, the graphical shading log format facilitates efficient collection and digitization of all the data making it a cost-effective approach to data collection. Digitization of the geological data ensures it is archived properly and makes querying and reformating the data for visualization or interpretation in a wide variety of software programs easy and reliable. Third, the layout of graphical shading logs works like a roadmap for the data that needs to be collected facilitating the collection of high-quality logs by inexperienced loggers and loggers with more geological expertise. Assisting inexperienced loggers is critical for academic research, where most field data collection is done by graduate students just developing their expertise and in the private sector where often the most junior personnel are tasked with supervising drilling and logging the cores or cuttings. In addition, although the examples described here were focused on sedimentary rock and unconsolidated sediments, graphical shading logs are designed to be customized to match the geological setting; and therefore, could also be applied to core description for igneous and metamorphic rocks. Overall, graphical shading logs help to ensure that the initial investment of funds and time required to collect and log cores is translated into geological and hydrogeologic insights needed to improve our understanding of contaminant transport and fate and support site decision making.

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Supporting Information
Additional Supporting Information may be found in the online version of this article. Supporting Information is generally not peer reviewed.

Appendix S1: Supporting Information.
Appendix S2: Access Template Supporting Information.

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**Biographical Sketches**

**Jessica Meyer**, corresponding author, was previously a PhD Research Associate with the Morwick G360 Groundwater Research Institute and the School of Engineering at the University of Guelph, 50 Stone Road East, Guelph, ON, N1G 2W1, Canada. Jessica is now an Assistant Professor with the Department of Earth & Environmental Sciences, University of Iowa, Iowa City, IA 52242; jessica-meyer@uiowa.edu.

**Jonathan Munn** is an Assistant Professor with the Morwick G360 Groundwater Research Institute and School of Engineering at the University of Guelph, 50 Stone Road East, Guelph, ON, N1G 2W1, Canada.

**Emmanuelle Arnaud** is an Associate Professor with the School of Environmental Sciences and the Morwick G360 Groundwater Research Institute, University of Guelph, 50 Stone Road East, Guelph, ON, N1G 2W1, Canada.

**Jonathan Kennel** is a Postdoctoral Fellow with the Morwick G360 Groundwater Research Institute and School of Engineering at the University of Guelph, 50 Stone Road East, Guelph, ON, N1G 2W1, Canada.

**Beth Parker** is the Director of the Morwick G360 Groundwater Research Institute and a Professor in the School of Engineering at the University of Guelph, 50 Stone Road East, Guelph, ON, N1G 2W1, Canada.