

Editorial

## Heterogeneity in sedimentary aquifers: Challenges for characterization and flow modeling

### 1. Introduction

The kernel of the idea for this special issue originated during the guest editor's appointment as a staff hydrogeologist at the Wisconsin Geological and Natural History Survey in Madison, Wisconsin, USA. While contributing to several hydrogeologic studies leading to the construction of a large regional groundwater flow model for the southeastern Wisconsin region, I was also studying the field hydrogeologic properties of a dolomitic shale aquitard which had previously been considered relatively uniform and homogeneous. During this time, I became aware of the difficulties reconciling the available hydrogeologic data and observations of geologic heterogeneity in bedrock aquifers and aquitards to the needs for parameterization of widely used finite-difference simulation models, a concern shared by colleagues at the Minnesota Geological Survey. Although significant contributions have been published on heterogeneity in unlithified sedimentary materials, notably Pleistocene glacial deposits, relatively few authors have described the origins and mechanisms for variation in hydrogeologic properties due to factors other than lithology in indurated sedimentary bedrock, much less practical methods for representing such heterogeneity in flow models. Furthermore, at professional meetings, such as the Annual Meeting of the Geological Society of America (GSA), while there are often sessions devoted to the hydrogeology of fractured rock, they tend to be dominated by presentations on fractured and heterogeneous crystalline bedrock, about which much work has already been published in connection with siting nuclear waste repositories.

Therefore, with the encouragement of my colleagues, I proposed a theme session at the 2003 GSA Annual Meeting, organized with Ken Bradbury of the

Wisconsin Geological and Natural History Survey, on the topic of "Heterogeneity in Sedimentary Aquifers: Challenges for Characterization and Flow Modeling". The topic was restricted to sedimentary deposits, but left open to unlithified or bedrock aquifers and aquitards, because of the uncertainty in the level of interest. The goal was to attract participation by both geologists who recognize that insights from depositional history, sedimentology, structural history, diagenetic processes and even bioturbation are valuable tools in identifying spatial variations in hydraulic properties, and hydrologists who want to take into account this information when evaluating aquifer systems and constructing groundwater flow models. The objective of this theme session was to bring together researchers working on different aspects of sedimentary geology, and hydrogeologists interested in new ways of evaluating hydraulic properties of these rocks. Many very interesting presentations were given, and the interdisciplinary interaction was very well received by the participants. At this conference, I was invited by a representative of Elsevier to serve as the Guest Editor for a special issue of this journal devoted to the same topic.

In inviting manuscript contributions to this special issue, I elected to focus again on indurated geological formations because of the relative neglect which this topic has received in contrast to unlithified formations. The journal *Sedimentary Geology* had published a previous special issue on the topic of Aquifer Sedimentology (129 (3–4)), and that issue focused largely on unlithified aquifers, as have several recently published compilations. For that reason, the focus of the research papers in this special issue is instead primarily on indurated bedrock aquifers. These papers represent a diverse cross-section of research that crosses the traditional boundaries of sedimentary geology and

hydrogeology, and present results that will be useful to researchers in both fields.

## 2. Contents

The research papers in this special issue on “Heterogeneity in Sedimentary Aquifers: Challenges for Characterization and Flow Modeling” span a broad range of approaches and methods. The first contribution (Eaton) sets the stage by presenting an overview of the methods and different conceptual frameworks used by hydrogeologists to translate the geological variability in aquifers and reservoir rocks into mathematical representations for flow modeling. While reviews of this type have been presented in the hydrogeologic literature before, none is particularly recent, and none attempts the breadth of the presentation here to a non-hydrogeologist readership. For example, comparisons between equivalent porous media and discrete network approaches to flow modeling, as well as comparisons between deterministic and stochastic approaches to characterization have been presented elsewhere but not always together. This contribution is not intended as a substitute for more comprehensive reviews elsewhere, but rather as an update to those works, to which interested readers are referred. Finally, the author proposes that, given the heterogeneity described in the following papers, the concept of hydrofacies that has long been used in describing unlithified aquifer materials, would be useful in describing indurated aquifers as well. This requires that a broader understanding of hydrofacies, not limited to lithologic variations in geologic formations, be adopted. Therefore, it is suggested that hydrofacies be operationally defined instead on the basis of flow model resolution using a particular representative elementary volume (REV) or structure of a specific size and shape. Such an approach could be a useful tool in the rapidly evolving interdisciplinary and cutting-edge work that is currently underway to understand the hydrology of these complex systems.

The nine other papers that make up this special issue are organized thematically in three groups, from geologic through hydrogeologic characterization to flow modeling applications.

### 2.1. Geological conceptual models

The first group includes papers that take a primarily geologically based approach to developing conceptual models to describe the structure, mechanical stratigra-

phy, geotechnical characteristics and fault properties in different geological settings as a guide to understanding their hydrogeological properties. In many carbonates in particular, since the matrix porosity is so low, fractures constitute the major interconnected flowpaths, and understanding the spatial distribution of such fracture networks is challenging. Graham–Wall examines the sedimentology and structural geology of peritidal and basinal carbonate sequences in fold-thrust settings. She shows how the differing geometry of pressure–solution surfaces, acting as mechanical layer boundaries, control the development of fractures in these rocks. Cooke et al. summarize recent work on the structural controls on fracture development in relatively undeformed carbonate sequences. They present conceptual models, based on field data and numerical experiments, of how fracture propagation is terminated at weak or ductile mechanical interfaces in two different case studies. The results are then applied to a qualitative assessment of the previously undocumented mechanical stratigraphy of a third carbonate sequence, showing how predictions of fracture networks may be made. These two studies illustrate how careful geological characterization of carbonates can provide important insights into the major controls on fracture flowpaths in these rocks.

The other two papers in this first group take somewhat different approaches to identifying the spatial variation in hydrogeologic properties in a recent carbonate aquifer and a fault system, respectively. Gaswirth et al. use extensive geotechnical analysis (triaxial strength and tensile tests) on core plugs to identify different categories of induration in a dolomitized subregional confining unit in the Floridan aquifer. They then demonstrate how rock strength is correlated with the degree of porosity and fracturing as a way of predicting patterns of hydraulic conductivity variation within this formation. Heffner and Fairley present an unusual technique, using a geostatistical analysis of surface temperature data in a geothermal system, to quantify the distribution of flowpaths in the plane of a normal fault. Faults are a well-known example of heterogeneity in sedimentary aquifer systems that have been the focus of specialized study, but are often ignored in regional hydrogeologic characterization studies because little to no data exist on their properties. The analysis of Heffner and Fairley suggests that hydraulic architecture of such features may vary from existing idealized conceptual models, and illustrates the need for development of new indirect observational approaches such as theirs to understand the hydrology of usually inaccessible faults.

## 2.2. Hydrogeologic characterization

The second group of papers in this special issue takes more of a direct approach to characterization of hydrogeologic properties in indurated bedrock aquifers. The first paper, by Davis et al., is a good transition from the previous papers because it uses intensive data collected from channel sandstone outcrops, as well as laboratory analysis of carbonate cementation, to develop a conceptual model for permeability heterogeneity. The method they present uses analyses of uncemented permeability, original porosity and cement fraction to predict the resulting cemented permeability they observe from in situ measurements on the outcrops. The variation of cementation in clastic deposits is an often-overlooked factor in flow and transport processes that determines petroleum reservoir quality as well as aquifer productivity.

The next two contributions, by Runkel et al. and Tipping et al., present regional hydrogeologic characterizations of sandstone-dominated and carbonate-dominated sequences respectively in the upper Midwestern U.S. They use extensive field-based observations combined with downhole geophysical well logging and hydraulic testing techniques to compile a regional hydrogeologic framework for each of the geologic sequences they have characterized. In both cases, this comprehensive approach results in a new delineation of aquifer and aquitard units, primarily because of their focus on fractures and other secondary porosity features. Runkel et al. studied the Franconia–Ironton–Galesville sequence and demonstrate that, in contrast to previous work, equivalent porous medium assumptions and lithologic variations are not sufficient to understand the hydrogeology of these primarily clastic formations.

Tipping et al. studied a primarily carbonate sequence, the Prairie du Chien Group, and found that depending on the distribution of stratigraphically controlled secondary porosity features, the dolomitic sequence can be subdivided into two aquifers and one intervening aquitard unit. Like the case of the Franconia–Ironton–Galesville units studied by Runkel et al., the hydrogeology of these sedimentary sequences is regionally predictable because of the preferential occurrence of secondary porosity along bedding planes independent of the depth of burial. One interesting result of the Runkel et al. analysis is that hydrogeologic properties of the primarily clastic units they studied constitute a spectrum between classical porous media and karst features typical of the Prairie du Chien unit studied by Tipping et al.

## 2.3. Flow modeling applications

The final two contributions to this special issue of *Sedimentary Geology* are studies that use numerical models to simulate groundwater flow through heterogeneous sedimentary aquifers. In both cases, the authors use unconventional methods to represent similar types of geologic heterogeneity to that described by previous papers in this issue. Both studies use the widely available MODFLOW finite difference code. Swanson et al. used their flow model to investigate the hydrologic significance and lateral extent of bedding-parallel preferential flow in a sandstone aquifer as a source for spring discharge. They found that explicitly incorporating a layer representing high-conductivity, regionally significant zones of preferential flow results in a better spatial distribution and simulation of discharge volumes among springs in a wetland setting.

Quinn et al. simulate flow in another heterogeneous setting that is particularly difficult to characterize: a karst aquifer. They use surface geophysical observations of lineaments, and karst features such as sinkholes and springs to infer the location of conduits that channel disproportionate amounts of flow. Using the drain package feature of MODFLOW, they simulate the discharge along these conduits, and how they dominate flow by draining the broader aquifer represented as an equivalent porous medium. Highly heterogeneous flow in a karst aquifer is rarely amenable to simulation in an equivalent porous medium model unless it is at a regional scale in which flow can be averaged over large areas. The contribution of Quinn et al. is an example of a method to reconcile the difficulties of simulating flow through such a heterogeneous aquifer system with the use of a conventional equivalent porous medium model.

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