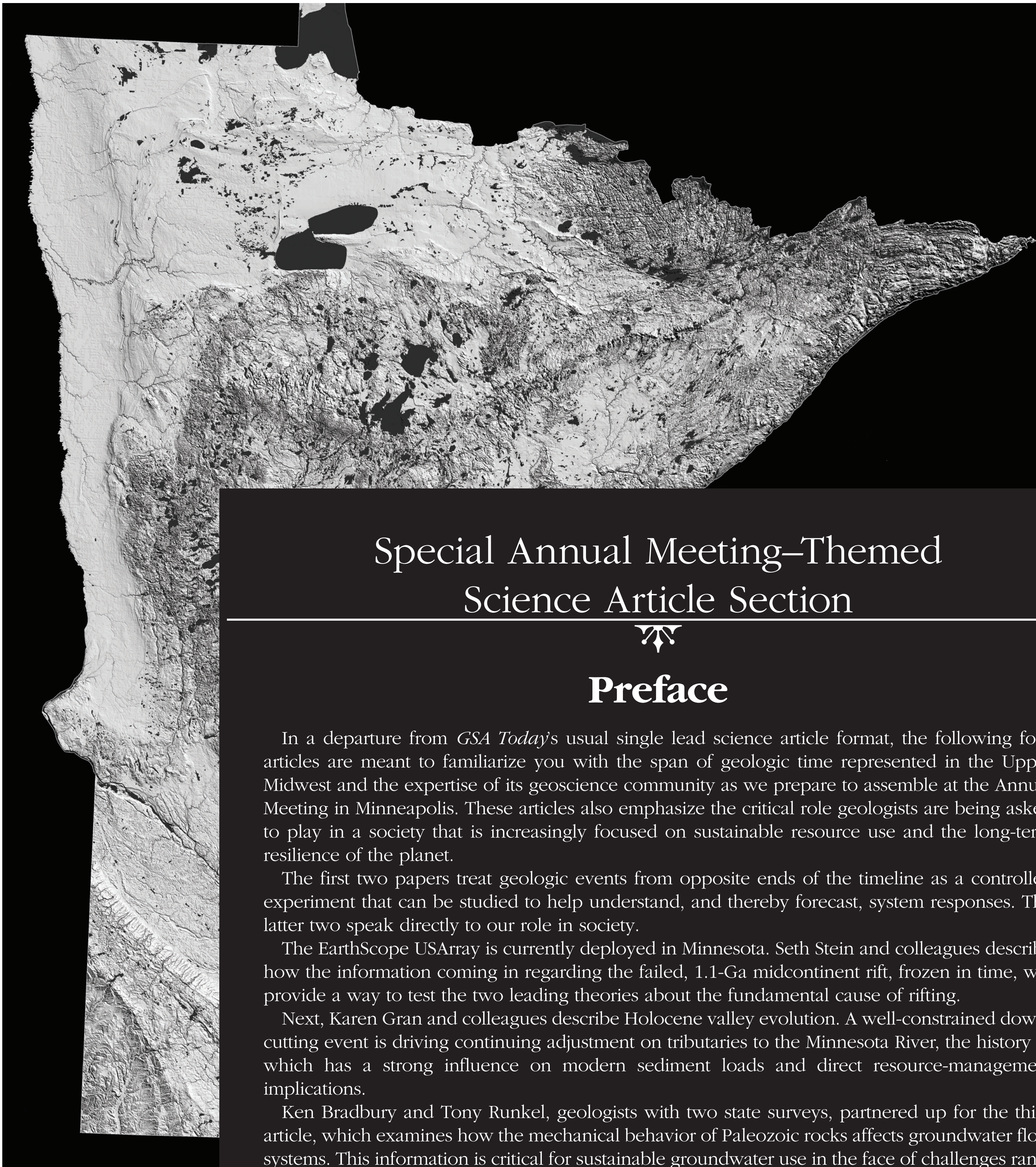

Special Annual Meeting–Themed Science Article Section

Preface

In a departure from *GSA Today*'s usual single lead science article format, the following four articles are meant to familiarize you with the span of geologic time represented in the Upper Midwest and the expertise of its geoscience community as we prepare to assemble at the Annual Meeting in Minneapolis. These articles also emphasize the critical role geologists are being asked to play in a society that is increasingly focused on sustainable resource use and the long-term resilience of the planet.

The first two papers treat geologic events from opposite ends of the timeline as a controlled experiment that can be studied to help understand, and thereby forecast, system responses. The latter two speak directly to our role in society.

The EarthScope USArray is currently deployed in Minnesota. Seth Stein and colleagues describe how the information coming in regarding the failed, 1.1-Ga midcontinent rift, frozen in time, will provide a way to test the two leading theories about the fundamental cause of rifting.

Next, Karen Gran and colleagues describe Holocene valley evolution. A well-constrained down-cutting event is driving continuing adjustment on tributaries to the Minnesota River, the history of which has a strong influence on modern sediment loads and direct resource-management implications.

Ken Bradbury and Tony Runkel, geologists with two state surveys, partnered up for the third article, which examines how the mechanical behavior of Paleozoic rocks affects groundwater flow systems. This information is critical for sustainable groundwater use in the face of challenges ranging from the presence of live viruses deep beneath Madison, Wisconsin, USA, to evolving cones of depression that change hydraulic gradients.

Finally, Cathy Manduca introduces readers to the process of producing an educated citizenry (and a well-prepared geoscience community) that understands the ways that Earth and society are linked. The article also illustrates the need to act collectively to share experiences, develop them into classroom activities, and accurately diagnose student challenges.

Carrie Jennings, Minnesota Geological Survey
Vice Chair, 2011 Annual Meeting Organizing Committee

Recent advances in the hydrostratigraphy of Paleozoic bedrock in the Midwestern United States

Kenneth R. Bradbury, *University of Wisconsin–Extension, Wisconsin Geological and Natural History Survey, 3817 Mineral Point Road, Madison, Wisconsin 53705, USA, krbradbu@wisc.edu; and* ***Anthony C. Runkel,*** *Minnesota Geological Survey, 2642 University Avenue W, St. Paul, Minnesota 55114, USA*

Relatively undeformed Paleozoic bedrock forms the most widely used aquifers in Minnesota and Wisconsin (Fig. 1). Increasing demand for groundwater and concerns about contamination of deep aquifers have led to the need for a more comprehensive understanding of the hydrogeologic attributes of these strata than was deemed suitable just a few decades ago. Modern field techniques, coupled with advances in numerical modeling, are providing new insights into bedrock groundwater flow systems and redefinition of the classic divisions of the section into regional aquifers and aquitards. In Minnesota and Wisconsin, we commonly undertake borehole flowmeter logging, optical and acoustical borehole imaging, temperature profiling, short-interval packer testing, multi-level hydraulic head measurement, and dye tracing to evaluate the hydrogeology of bedrock formations. These techniques are widely available today but were beyond the reach of most field hydrogeologists only a few years ago.

Advances in our understanding of groundwater flow through fractures have been a critical outcome of recent hydrostratigraphic research. For example, clusters of bedding-parallel (subhorizontal) fractures that are commonly restricted to relatively discrete stratigraphic intervals can dominate flow systems (e.g., Muldoon et al., 2001; Runkel et al., 2006a; Tipping et al., 2006; Swanson et al., 2006). They are now documented not only in carbonate rock, but also in friable sandstone aquifers and in aquitards of greatly variable lithic properties (Eaton and Bradbury, 2003; Runkel et al., 2006b; Meyer et al., 2008). Although the distribution of bedding-perpendicular (subvertical) fractures remains poorly understood in comparison, integration of mechanical stratigraphy (the subdivision of rock into discrete intervals [mechanical units] according to the structures found in those intervals [Underwood et al., 2003]) with hydrostratigraphic data is leading us toward potentially significant advances in understanding vertical groundwater flow paths. Discrete stratigraphic intervals apparently resistant to the development of through-going vertical fractures appear to play a key role in limiting hydraulic connection between the major aquifers. Demonstration of stratigraphic control on fracture systems both parallel and perpendicular to bedding has provided us with better predictability in groundwater flow paths and velocities.

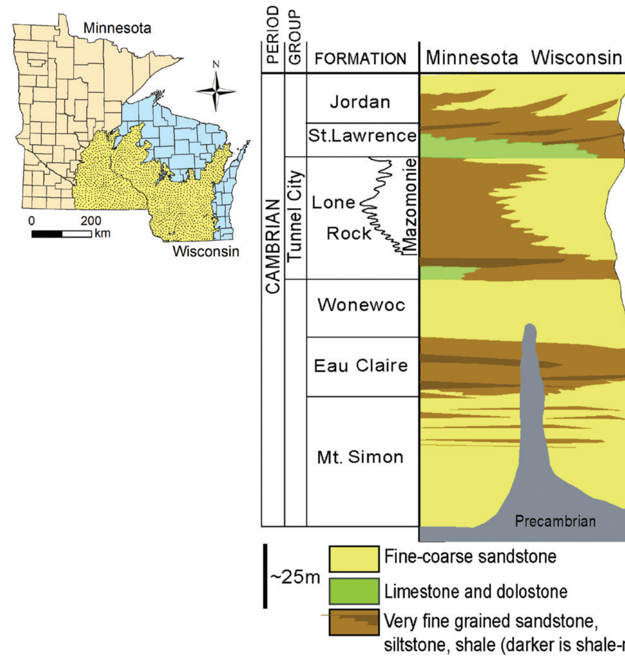

Figure 1. General distribution of the Cambrian-age units (stippled) and generalized Cambrian stratigraphic column in Minnesota and Wisconsin, USA. These rocks form several regionally important bedrock aquifers.

Research combining many of these techniques has provided new insights into aquitard properties, and the concept of aquitard integrity (Cherry et al., 2006). For example, the Cambrian St. Lawrence and Ordovician Platteville aquitards are now recognized as complex "hybrid" hydrogeologic units. These aquitards have well-developed conduit systems accommodating rapid horizontal flow analogous to karstic aquifers (e.g., Green et al., 2011). From a vertical perspective, under certain geologic conditions they appear to have only very limited integrity, and in other conditions appear to contain discrete intervals highly resistant to vertical flow. This aquitard research will also be highlighted as part of a Twin Cities Metro field trip associated with the 2011 annual meeting (Anderson et al., 2011).

Ongoing evaluation of the Cambrian Eau Claire Formation in southern Wisconsin provides an example of modern bedrock aquitard studies. The Eau Claire consists of generally fine-grained sandstones, siltstones, and mudstones (Aswasereelert et al., 2008) and lies stratigraphically between two important coarser-grained sandstone aquifers—the overlying Wonewoc Formation (Upper Cambrian) and underlying Mount Simon Formation (Middle Cambrian). This stratigraphic position has caused the Eau Claire Formation to be considered a major regional aquitard, yet

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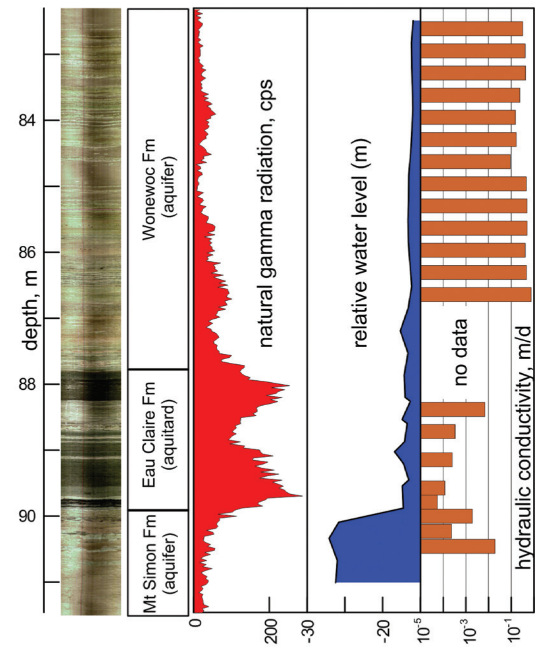

Figure 2. Hydrogeologic data across the Eau Claire aquitard. Optical borehole image (left) shows shaley facies. Relative water levels show head drop at base of aquitard. Horizontal hydraulic conductivity based on straddle-packer tests (no data collected between 87 and 88 m); cps—counts per second; m/d—meters per day.

historically the hydrogeologic characteristics of the Eau Claire Formation were confusing. Subsurface logs indicate that its thickness ranges from absent to >75 m, and parts of the formation yield significant amounts of water to wells. Recent evaluation of numerous downhole geophysical logs, especially gamma-ray logs, combined with studies of well cuttings and outcrop observations show that the Eau Claire Formation consists of five lithofacies ranging from fine-grained sandstone to shale (Aswasereelert et al., 2008), arranged as complexly stacked, discontinuous packages that form a heterogeneous and anisotropic aquitard. Two hydrogeologically critical components are low hydraulic conductivity mudstones and siltstones and high permeability sandstones.

A key part of modern aquitard hydrogeology is the integration of multi-level hydraulic head measurements into hydrostratigraphic analysis. In south-central Wisconsin, regional groundwater withdrawals from the confined Mount Simon aquifer have created a regional cone of depression. As a result, vertical hydraulic gradients are downward: The elevation of the shallow water table can be many feet above water levels in deep wells. Careful measurement of this hydraulic gradient through the Eau Claire Formation has shown that the major head loss occurs near the very bottom of the formation, where >12 m of head drop corresponds to an interval of <3 m of shale and siltstone identified by borehole geophysical logs and cuttings (Fig. 2). This same interval shows very low hydraulic conductivity in short-interval straddle-packer tests. Collectively, these data lead to the conclusion that the Eau Claire aquitard, as opposed to the Eau Claire Formation, is only a few meters thick and is discontinuous, ranging from absent to ~9 m thick across the study area. Regional groundwater modeling has demonstrated that this relatively thin unit exerts a major control on regional groundwater flow in the ~300-m-thick bedrock aquifer system and that it is critical in protecting deep wells from contamination.

Combining these hydrogeologic techniques with recent advances in water quality measurements provides new insights into aquifer vulnerability. For example, ongoing work has documented the presence of human enteric viruses in deep wells in Madison, Wisconsin, USA (Borchardt et al., 2007; Bradbury et al., 2010). These viruses originate near the land surface, and their presence in deep wells suggests a very rapid transport path. Movement through cross-connecting wells is one such pathway, but transport along fractures or windows in aquitards are also possibilities. Ultimately, understanding of the mode(s) of transport of the virus and other contaminants is dependent on the level of understanding of the hydrostratigraphy.

Current studies link these new hydrostratigraphic advances to water sustainability issues at a variety of scales. A recent Twin Cities metro-wide (southeastern Minnesota, USA) compilation depicting the 3-D distribution of hydrochemical facies, including contamination zones, interpreted within the context of a well-developed hydrostraphic framework, provides important new bases for decision making as the region grapples with resource sustainability. These are exciting times for hydrogeologists interested in bedrock groundwater flow systems in the Midwest, as we learn that rocks long considered "layer-cake" aquifers and aquitards contain fascinating complexity.

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