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Conduit enlargement in an eogenetic karst aquifer

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SUMMARY

Most concepts of conduit development have focused on telogenetic karst aquifers, where low matrix permeability focuses flow and dissolution along joints, fractures, and bedding planes. However, conduits also exist in eogenetic karst aquifers, despite high matrix permeability which accounts for a significant component of flow. This study investigates dissolution within a 6-km long conduit system in the eogenetic Upper Floridan aquifer of north-central Florida that begins with a continuous source of allogenic recharge at the Santa Fe River Sink and discharges from a first-magnitude spring at the Santa Fe River Rise. Three sources of water to the conduit include the allogenic recharge, diffuse recharge through epikarst, and mineralized water upwelling from depth. Results of sampling and inverse modeling using PHREEQC suggest that dissolution within the conduit is episodic, occurring only during 30% of 16 sampling times between March 2003 and April 2007. During low flow conditions, carbonate saturated water flows from the matrix to the conduit, restricting contact between undersaturated allogenic water with the conduit wall. When gradients reverse during high flow conditions, undersaturated allogenic recharge enters the matrix. During these limited periods, estimates of dissolution within the conduit suggest wall retreat averages about 4×10^{-6} m/day, in agreement with upper estimates of maximum wall retreat for telogenetic karst. Because dissolution is episodic, time-averaged dissolution rates in the sink-rise system results in a wall retreat rate of about 7×10^{-7} m/day, which is at the lower end of wall retreat for telogenetic karst. Because of the high permeability matrix, conduits in eogenetic karst thus enlarge not just at the walls of fractures or pre-existing conduits such as those in telogenetic karst, but also may produce a friable halo surrounding the conduits that may be removed by additional mechanical processes. These observations stress the importance of matrix permeability in eogenetic karst and suggest new concepts may be necessary to describe how conduits develop within these porous rocks.

1. Introduction

Most models of karst aquifers are commonly based on studies of dense, recrystallized limestone (i.e., telogenetic karst, Vacher and Mylroie, 2002). Within these aquifers, conduits are embedded in a network of joints, fractures, and bedding planes in a groundmass of otherwise low matrix porosity and permeability. Conduits develop along these initially narrow flow paths as a function of flow path geometry, water chemistry, and flow rates (e.g., Ford and Ewers, 1978; Palmer, 1991). As conduits enlarge, they capture more of the flow, thereby enhancing dissolution and further enlarging the conduits until only a few routes carry the majority of flow (e.g., White, 1988; Ford and Williams, 2007). Low matrix permeability of telogenetic aquifers keeps the flow focused within the developing conduit and allows enlargement through dissolution along the conduit wall.

The concepts of conduit flow in telogenetic karst aquifers allow dissolution rates to be estimated based on the magnitude of disequilibrium between the conduit water and carbonate minerals. Early calculations used kinetic models of calcite dissolution to derive expressions for the retreat of conduit walls (Dreybrodt, 1990; Palmer, 1991). These kinetic expressions have been used to model the early development of conduits (e.g., Groves and Howard, 1994; Kaufmann and Braun, 1999; Gabrovšek and Dreybrodt, 2001; Romanov et al., 2003a), morphologies of cave patterns (e.g., Palmer, 1991, 2001; Howard and Groves, 1995), leakage rates beneath dam sites (Romanov et al., 2003b), and the role of conduit growth on landscape evolution in a karst basin (Groves and Meiman, 2005). Recent studies have suggested that dissolution rates may be expressed as a function of flow velocity through the conduit, whereby dissolved $CaCO_3$ concentrations at a spring reflect the amount of dissolution along the conduit flow path (Grasso and Jeannin, 2002; Grasso et al., 2003). This understanding of how conduits develop appears to work for telogenetic limestone, especially

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where allogenic recharge to the conduit occurs through sinkholes and swallets (e.g., Palmer, 2001), but may not accurately reflect reaction-transport coupling in eogenetic karst aquifers that have orders of magnitude greater matrix permeability than their telogenetic counterparts (Vacher and Mylroie, 2002; Budd and Vacher, 2004).

High matrix permeability allows recharge to and discharge from aquifer storage, and limits the use of telogenetic models of conduit development for explaining eogenetic karst conduits. The exchange of water between conduits and matrix varies depending on hydraulic head between the conduit and surrounding aquifer, affecting both regional groundwater and spring chemistry (e.g., Katz et al., 1998; Crandall et al., 1999; Martin and Screaton, 2001; Moore et al., 2009). For example, water that drains from the surrounding aquifer contributes a substantial component of water flowing in the conduits that is commonly saturated with respect to aquifer minerals (e.g. carbonates; Martin and Dean, 2001; Florea and Vacher, 2006). This inflow to the conduit would be absent in telogenetic karst aquifers. Conversely, water lost from the conduit to the surrounding aquifer mostly occurs during high flow when water undersaturated with respect to carbonate minerals may drive dissolution within the aquifer matrix (Katz et al., 1998; Crandall et al., 1999; Screaton et al., 2004; Ritorto et al., 2009). This interaction between the conduit and surrounding aquifer should affect how conduits enlarge in eogenetic karst, whereby dissolution occurs within the aquifer matrix rather than primarily at the conduit wall. This mechanism would require a new conceptual model to describe conduit development in eogenetic karst.

The central question we address in this paper is how high matrix porosity and permeability of eogenetic karst aquifers affect the magnitude and distribution of conduit and matrix rock dissolution. We use groundwater chemistry, geochemical reactions, and the physical and chemical variations of a first-magnitude spring draining a portion of the Upper Floridan aquifer (UFA) to estimate magnitudes and locations of dissolution within a 6-km long conduit network. Although recharge to the conduit occurs primarily by allogenic runoff, diffuse recharge through the rock matrix and deep water upwelling also source the conduit (Ritorto et al., 2009;

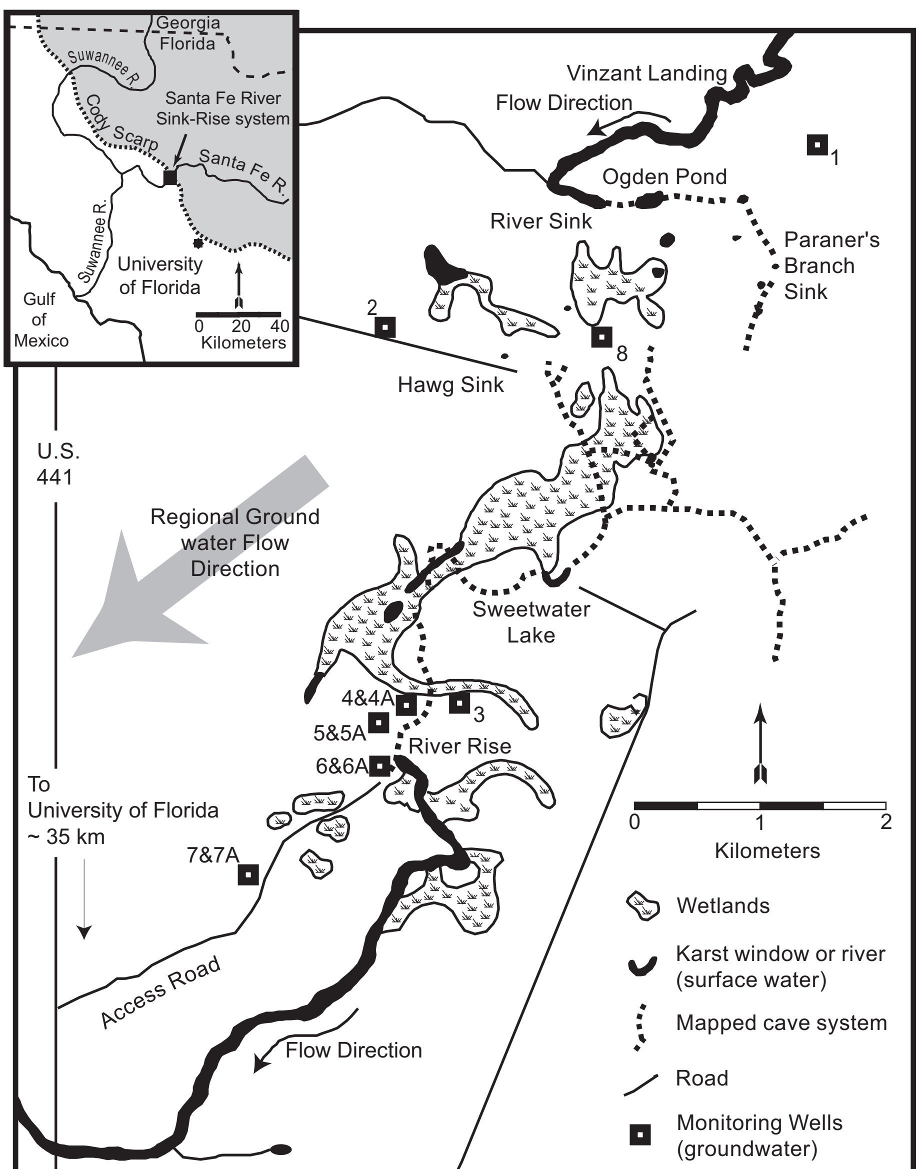

Fig. 1. Site location of the Santa Fe Sink-Rise system showing locations of surface water and ground water sampling sites. Insert map shows location of Santa Fe Sink-Rise system in relation to north-central Florida. Dotted line in insert represents erosional edge of the Hawthorn Group to the northeast (gray area) marking the confined portion of the Upper Floridan Aquifer, with the white area representing the unconfined portion of the UFA where the Hawthorn is absent (from Moore et al. (2009)).