Lithofacies and Transport for Clastic Sediments in Karst Conduits

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Abstract

Karstic aquifers carry a load of clastic sediment as part of their hydrologic function and these are an important part of the mechanism for storage and transport of contaminants. Indeed, solid contaminants can be considered as a form of clastic sediment. Although the sources of clastic sediments are usually well delineated, sediments from multiple sources are mixed and redistributed within the aquifer to produce the sediment deposits that remain stored in caves or the load of sediment discharged from karst springs. As an aid to the interpretation of clastic sediments in karst aquifers, we have modified a previously proposed facies concept with an emphasis on its implications for contaminant transport and storage. Five facies are defined in terms of particle size, degree of sorting, and sedimentary structures: backswamp facies, channel facies, diamicton facies, slackwater facies, and thalweg facies. The deposits represented by each set of facies characteristics in turn can be interpreted in terms of depositional mechanisms. The slackwater facies and channel facies are the most significant in terms of implications for contaminant transport and therefore receive greater emphasis than the other three in this discussion. The facies labeled slackwater facies are laminated deposits of clay to silt laid down in passages filled with stagnant water either flooded by inputs from upstream or backflooded from surface streams. This mechanism provides two pathways by which microorganisms or metals can be adsorbed onto clay particles and carried into the aquifer. The facies labeled channel facies consist of silts, sands, gravels, and cobbles carried in major conduits mostly by high velocity storm flows. Flows that transport sediments resulting in channel facies also can carry solid contaminants at various size scales and can act as storage sites for contaminants over long periods of time. Calculations show that hydraulic conditions required for transport leading to deposition of channel facies are consistent with observed discharge characteristics of major conduits.

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1 Introduction

One of the most important characteristics of karstic drainage basins is the ability of their subsurface conduit systems to transmit insoluble materials in a range of particle sizes from colloids and clays to cobbles and (occasionally) boulders. Clastic sediments are derived from a variety of sources including surface stream sediments washed in by sinking streams; materials from the overlying land surface injected through shafts, sinkhole drains, and open fractures at the base of the epikarst; and insoluble residues from the dissolution of the bedrock. The conduit system acts as a mixing chamber so that the sediments deposited in caves or discharged from karst springs are typically derived from multiple source areas and further have often lost the characteristics of the source material. There are also multiple mechanisms for transport of clastic sediments. Cave deposits provide a useful representation of the types of materials being transported through the aquifer so it would be helpful to devise a means for labeling and classifying these deposits. Much discussion of sediment sources, description of deposits, and mechanism of transport can be found in two reviews (White 2007; Herman et al. 2012).

Labeling various clastic sediment deposits as facies appeared in a discussion of sediment transport (White and White 1997) and in a study of cave sediments in the Cheat River Gorge, West Virginia (Springer and Kite 1997). The facies concept was expanded and given a new labeling by the present authors (Bosch and White 2004). That labeling was used in the review papers cited above and was found useful in the description of clastic sediments in the Butler Cave-Sinking Creek System, Virginia (Chess et al. 2010). Given the importance of clastic sediments in contaminant transport, we here further refine the facies concept of clastic sediments in caves and suggest their relevance to the storage and transport of certain classes of contaminants. We made changes to better integrate the nomenclature of cave sediment facies with traditional sedimentation terminology, as well as to calculate the hydrologic conditions that would have likely been required to produce the observed sediment deposits. More detail may be found in the thesis from which this paper is drawn (Bosch 2015).

2 The Facies Concept as Applied to Caves

The facies names presented in Bosch and White (2004) are backswamp facies, channel facies, diamicton facies, slackwater facies, and thalweg facies. The original classification was based on particle size and particle sorting but mixed a physical description with an interpretative mechanism. The locales described in the original publication were reanalyzed and objectively described, according to Miall's (1996) facies codes (Table 1). The facies types are sketched (Fig. 1) to show the populations in terms of particle size and sorting. The facies are drawn as separate areas for clarity. For most real sedimentary deposits, there would be no blank areas and the facies types would be less distinct and probably overlap.

The names given to the facies imply a mechanism of deposition as outlined below. Further detail and explanation are given in the original publication (Bosch and White 2004).

Channel facies are the subsurface equivalent of surface stream sediments. Like surface stream deposits, their movement is episodic, carried by flood flow events. Unlike surface streams, however, karst conduits can shift from open channel flow to pipe flow if the flood discharge is sufficient to fill the conduit. This partially contributes to the discontinuous sequence of clays, sands, gravels, and cobbles distributed along the conduit at deposition sites dictated by the irregular geometry of the conduit itself.

Thalweg facies are well-winnowed remnants of the channel deposits. Base flow and moderate flows in cave

Table 1 Classification of sedimentary facies in caves

Facies code	Facies	Sedimentary structures	Interpretation
Fsm	Clay to silt	Massive with possible chert fragments and/or fossils	Backswamp cave deposit (insoluble residue)
Gcm, Srh	Crudely bedded to massive gravel, granule to cobble; very fine to coarse sand	Horizontal bedding to unbedded, ripple cross-bedding to horizontal bedding	Channel cave deposit
Gmm	Massive, matrix-supported clay to boulder	Chaotic, unsorted, unbedded	Diamicton cave deposit (debris flow)
Fl	Clay to very fine sand	Fine lamination	Slackwater cave deposit (overbank or waning flood)
Gh	Gravel, pebble to boulder	Well-sorted, open framework; well-winnowed	Thalweg cave deposit

In these facies codes, *F* indicates a facies dominated by fine-grained sediment; *G* gravel-dominated; and *S* sand-dominated. The lowercase letters refer to sorting and sedimentary structures present: *c* crudely bedded, *m* massive or matrix supported, *r* ripple cross-bedding, *h* horizontal bedding, and *l* laminated

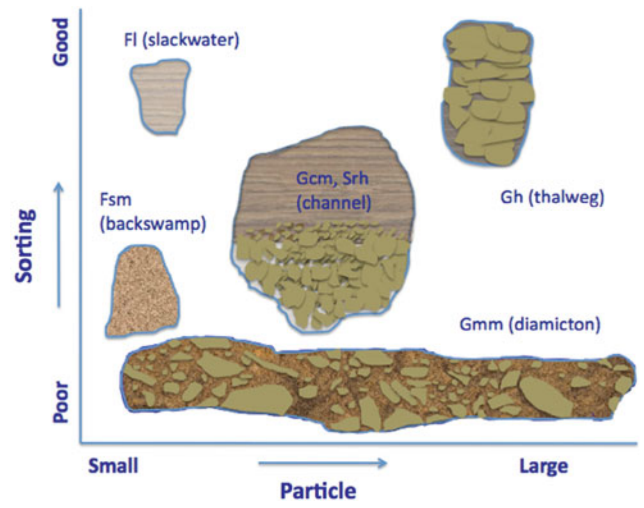

Fig. 1 Qualitative sketch showing the division of cave sediments into facies based on grain size and sorting, including Miall's (1996) facies codes

streams winnow out clays and sands leaving the coarse fraction as a stream bed deposit.

Slackwater facies are deposited from suspended particles in muddy floodwaters that entered either as overbank flows or as backflooded water from surface streams. As a result, they are fine-grained and thinly laminated with the laminae marking subsequent flood events. Channel facies, thalweg facies, and slackwater facies are all very common and are associated with aquifers containing (or that contained in the past) active conduit systems.

Diamicton facies are the result of debris flows where materials of all particle sizes are taken into suspension and flow down high gradient passages. Diamicton facies are uncommon because the geological conditions needed are uncommon.

Backswamp facies is the not entirely satisfactory name given to the residual insoluble material left by dissolution of the bedrock and sifted down from the epikarst. The composition of the backswamp facies depends entirely on the characteristics of the insoluble fraction of the bedrock. Backswamp facies are found in caves formed by percolating groundwater with little stream action.

3 Calculation of Transport Thresholds for Channel Facies

Cave deposits can be examined to interpret the paleohydraulic conditions that would have been necessary for their deposition. We may then observe present-day flows and make good predictions as to what kind of sediment deposits and therefore what kind of contaminants we would expect to result. These implications can be applied to contaminants that are transported in similar modes to the sediments discussed here, as well as to contaminants that move in aqueous solution. We present the calculations here for transport of channel facies as one example of deriving paleohydraulic conditions. Similar derivations, with differing levels of complexity, may be performed for the other four facies, ranging from straightforward analytical calculations to multi-component computer modeling.

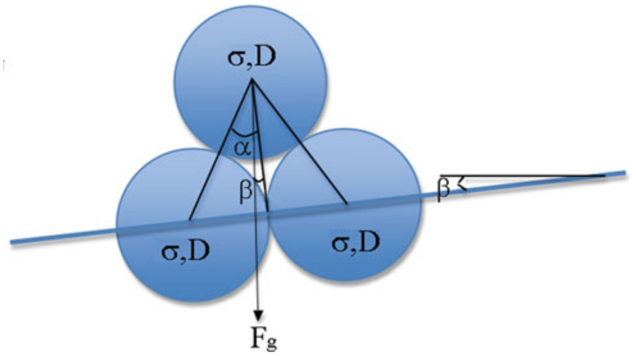

Fig. 2 Sketch for entrainment of a particle resting on identical particles

In the real world, there is the fairly complex arrangement of sediment grains of varying density, size, and shape resting on several other grains, each of a different size and shape from the first grain and from each other. That situation can be addressed using modeling software. For this work, to simplify the mathematics and to obtain rough estimates for the flow conditions that may have been present to transport sediments, several assumptions have been made. We first choose to address a two-dimensional problem of one grain resting on two grains. Second, we assume that all three of these grains are spherical and have the same diameter, *D*. These three grains are assumed to be resting on a streambed of uniform, linear slope, *S* as illustrated in Fig. 2.

An expression for determining the threshold shear stress necessary to entrain a given particle can be obtained from balancing the torques exerted on a grain about the contact points with the grains below. This balance of torques, as presented by Allen (1985), yields Eq. (1). This can only be applied to grain sizes larger than 60 μm since it does not account for grain-to-grain cohesion forces (Huang et al. 2015). Here, we will take the simplest case, where each grain is spherical and is resting on a bed of same-sized grains, also having diameter *D*.

$$\tau_{cr} = \frac{2D(\sigma - \rho)g}{3\cos\beta}\tan(\alpha - \beta) \tag{1}$$

where

τ_{cr} is the critical shear stress at the threshold of entrainment ($\mathrm{N\ m^{-2}}$),

D is the diameter of the sediment grain to be transported (m),
σ is the density of the grains (2650 kg m^{-3}),
ρ is the density of the fluid (1000 kg m^{-3}),
g is acceleration due to gravity (9.80 m s^{-2}), and
α is the angle between the line connecting the centers of the grains and the perpendicular to the bed, and β is the angle that the bed tilts away from the horizontal.

Therefore,

$$\tau_{\mathrm{cr}} = \frac{10,780D}{\cos\beta}\tan(\alpha - \beta) \tag{2}$$

Examining Fig. 2, it is apparent that because we have assumed equal diameters for the grains being considered, the triangle connecting the center points of the three spheres is equilateral, with each side of length D, and therefore, $\alpha = \frac{\pi}{6}$. Here, then, is the equation that will be applied to each set of field data:

$$\tau_{\mathrm{cr}} = \frac{10,780D_{50}}{\cos(\tan^{-1}S)}\tan\left(\frac{\pi}{6} - \tan^{-1}S\right) \tag{3}$$

where D_{50} is the fiftieth percentile grain size sampled at the given field site and S is the slope of the streambed at the sampling site.

τ_{cr} can be used to calculate shear velocity (m s^{-1}), $u_* = (\tau_{\mathrm{cr}}/\rho)^{1/2}$, which can then be used to estimate a stream flow velocity, u, also in m s^{-1}.

$$u = \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right), \text{ or substituting } u = \frac{(\tau_{\mathrm{cr}}/\rho)^{1/2}}{\kappa}\ln\left(\frac{z}{z_0}\right) \tag{4}$$

where κ, 0.40, is the von Kármán constant (Bailey et al. 2014), and z/z_0 is the roughness factor, which has been found to be about 9 for rough cave floors and walls through simulation of cave flow conditions (Bird et al. 2009). Applying these values yields an estimation of flow velocity needed to move the fiftieth percentile diameter of the sediments that were sampled:

$$u = 0.17\sqrt{\tau_{\mathrm{cr}}} \tag{5}$$

Equation (5) was used to calculate the flow velocities needed to move the channel facies sediments from the Hawkins and Logsdon Rivers in Mammoth Cave (KY) and from Tytoona Cave (PA) using the data published by Bosch and White (2004). These velocities, presented in Table 2, are in the same range as flow velocities observed in cave streams (Palmer 2007). The fastest flows calculated, at 1–2 meters per second, match what would be expected during flood flow conditions in Tytoona Cave. It appears that these very rough calculations of the hydraulics of channel facies produce a reasonable agreement between sediment size and the stream velocity needed to move them.

4 Application of the Facies Concept to Contaminant Transport

The different sediment facies have different implications for the type of contaminant transport and the extent of contamination possible. The two most important are the channel facies and the slackwater facies.

Channel facies are stream deposits in conduits which have, or have had in the past, water moving at velocities comparable to those shown in Table 2. Boundary shears sufficient to carry sand, gravel, and even cobbles are also sufficient to carry solid waste in the form of cans, bottles, garbage, and in some cases old tires. Trash dumped in sinking surface streams can be carried underground and transported long distances. When velocities decrease due to ponding behind some blockage in the conduit, the trash becomes incorporated into the channel facies sediments where derivative decomposition products can be leached out over long periods of time.

Channel facies sediments themselves are porous media. Contaminants in the form of non-aqueous phase liquids (especially DNAPLs) can be adsorbed into the sediment pile which acts as a storage site. Channel facies sediments are moved during extreme floods so there is the potential for contaminant release long after the original spill.

A portion of the same suspended fine-grained particles that settle to become the slackwater facies are also discharged directly from karst springs, especially during flood flow when the spring waters may become muddy. It has been well-established from examination of spring waters that pathogens and metals are transmitted adsorbed onto clay particles. The sediments that remain in the conduit as

Table 2 Sediment data, stream water surface slope, and sediment transport characteristic calculations for cave streams

Site	D_{50} (m)	S	τ_{cr} (N m^{-2})	u_* (m s^{-1})	u (m s^{-1})
Logsdon River	0.00018	0.001*	1.12	0.033	0.180
Hawkins River	0.00050	0.002	3.10	0.056	0.299
Tytoona Cave—bed surface	0.016	0.01	97.3	0.312	1.70
Tytoona Cave—deep bed	0.0040	0.01	24.3	0.156	0.839

Water surface slopes estimated based on present stream geometries with the exception marked * where S was obtained through measurement of water surface slope at time of sediment sampling slackwater facies are likely to carry contaminants which become incorporated in the sediment pile to be released at some later time when the pile is mobilized by floodwaters.

5 Conclusions

Clastic sediments deposited in conduit systems can be divided into five categories based on descriptive facies: backswamp, channel, diamicton, slackwater, and thalweg. These facies can be interpreted in terms of depositional conditions, which provide evidence of transport conditions that were present during contamination events. Such findings may be used to predict expected distribution of contamination in karst systems. Coarse debris injected by sinking streams and from sinkhole dumps is most likely to be associated with the channel facies. Pathogens and some organic molecules are adsorbed onto clay particles and may be associated with the slackwater facies.

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