LITHOFACIES AND TRANSPORT OF CLASTIC SEDIMENTS IN KARSTIC AQUIFERS

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by
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ABSTRACT

Karst aquifers require transport of clastic sediments for the conduit system to remain open and thus to continue to be an eligible route for ongoing speleogenesis. Sediments are injected into the aquifer by sinking surface streams and through sinkholes, vertical shafts, open fractures, and other pathways from the land surface. Transport of clastic sediments tends to be episodic with sediment loads held in storage until moved by infrequent flood events. Although the overall mix of clastics depends on material available in the source area, distinctly different facies are universally recognizable depending on the flow dynamics within the conduit system. The facies are most clearly recognized when the source areas provide a wide variety of particle sizes from clays to boulders. In order of decreasing prevalence, one can distinguish (i) channel facies: usually well-sorted and often well-stratified silt through gravel carried as bedload at intermediate flow levels, (ii) slackwater facies: mostly clay and silt, carried as suspended load and deposited from floodwaters backfilled into the conduit system, (iii) thalweg facies: coarse gravel- to cobble-sized material, well-winnowed, forming armoring on underground streams that moves only during flood flow, (iv) backswamp facies: fine-grained sediments derived from the insoluble residue of the limestone, deposited under phreatic conditions with little lateral transport, and (v) diamicton facies: masses of unsorted, unstratified clays through boulders carried as a slurry during flood events.
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Preface

I completed the research for this thesis in the years 1996 through 1999. The bulk of the material for this thesis, including research results, was published in 2004. Here is the full reference:

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I am grateful to Roger Brucker for pushing me to think about this problem again after so many years. And thank you, Will, Rudy, and Lee for this unique and interesting opportunity to return to our research so many years later. Thinking about these problems again has rekindled my curiosity about sediment transport.

In addition to Will and Bette, so many people helped me with field work: Art and Peg Palmer, Joe Meiman, Chris Groves, Katie Shaw, Seth Spoelman, Virginia McDaniel, Megan Huber, Michelle Karle, Jon Jasper, Alan Glennon, Brice Leech, Dave Bieri, Darlene Anthony, Dorothy Vesper, Keith Wheeland, and Keith Christenson. Cave diver Jon Guizar collected the samples from Rock Spring. I am very grateful to Prof. James J. Van Gundy of Davis and Elkins College for sharing his observations and photographs of the effect of extreme flooding in Mystic Cave. For reading this thesis and giving useful feedback, I thank Tom Brucker and Michael Shamley. Thank you to so many more people, I can’t even begin to list . . . for hours and hours of great caving and for listening patiently to me ramble about sediment transport in caves.

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Dedication

I dedicate this thesis to my family. For Aaron, my amazing husband, my partner in all explorations, above and underground. And for Sammi, Zach, and Tyler: a pack of beautiful, motivational, and supportive kids. I am so grateful for all of you!
1. INTRODUCTION

Caves act as repositories for secondary deposits of many kinds, some locally derived such as breakdown from collapse of cavern roofs, some transported such as sand and silt carried by underground streams, and some the result of chemical deposition in the cavern void space such as calcite and gypsum speleothems. Many types of cave deposits have been studied, but those including clastic sediments, and in particular the transport thereof, had not received their due attention at the time of this research. Therefore, the present paper focuses on a specific subset of cave sediments: the clastic sediments derived from surface and subsurface weathering, and carried into and through the cave system by mainly fluvial processes. The lithologic characteristics of the clastic sediments reflect the hydraulic conditions that transported them. These characteristics can be described by a set of clastic cave sediment facies. The objective of this thesis is to define the various facies of clastic sediments, and the relation of these facies to transport mechanisms and the hydrology of groundwater flow in karst. This investigation has served as a foundation for the continued studies of cave sediments that have been conducted since.

1.1 Clastic Sediments in Karst Hydrology: Prior to 2004

Textbooks on karst hydrology provide descriptions and classifications of cave sediments (e.g. Bögli, 1980; White, 1988; Ford and Williams, 1989; Gillieson 1996). However, most of the early investigators of clastic sediments in caves have treated these sediments as static deposits, not unlike outcrops of sedimentary rock on the land surface. The stratigraphy and petrologic character of the sediments can be described and used to deduce hydraulic history and provenance. This can yield insights into the geomorphic and climatic history of the cave area. Such studies include work by Schmid (1958), Davies and Chao (1959), Frank (1969, 1971, 1972, 1973, 1974), Helwig (1964), Wolfe (1970), Bull (1978, 1981), Milske et al. (1983), and many others.

A somewhat different point of view is to consider the sediments to be an essential part of the hydrology of the groundwater basin in which the caves are located. There is, in effect, a flow field of clastic sediments in addition to the flow field of groundwater. Investigations from this point of view include the early, comprehensive, and often overlooked monograph of Renault (1968). White and White (1968) drew on fluid mechanics to interpret the mechanism of sediment transport in karst systems. Other descriptions of sediment-bearing cave streams likened them to surface drainage systems with braided streams, point bars, stream meanders, deep V-shaped canyons, and cobble armoring. Jones (1971) referred to these features as the “underground floodplain.” Newson (1971) emphasized the importance of flood flows in the transport of clastic materials. Much of the current interest in the hydrology of cave sediments arises because of their role in contaminant transport (Mahler et al., 1999; 2000).

The transport of sediments in conduit systems is episodic with abrupt movements during storm flow and little movement during low flow conditions. In very few cases have investigators been able to directly observe the effects of flood pulses in rearranging clastic sediments. One such observation was made in Cave Springs Cave near Lexington, Virginia (Doehring and Vierbuchen, 1971). Prior to Hurricane Camille in August 1969,
the cave stream carried a sediment load of primarily mud with some well-rounded chert pebbles. After the storm the sediment remaining in the streambed was predominantly angular to sub-angular sand- and gravel-sized clasts, and a terrace composed of sand and gravel had been deposited two meters above the normal stream level.

**1.2 Recent Developments in Clastic Sediments in Caves: 2004–2015**

The findings of this MS work led to a number of advances in the field of clastic sediment transport in karst. Several studies have employed the language suggested here for the identification of sediment facies in caves. For example, they are included in a detailed review of clastic sediments in fluvio-karst by Herman, Toran, and White (2012). This classification system has also been used in other studies of cave sediments (Brown, 2008 and Rossman 2010). In addition, site-specific studies have been performed of clastic sediments in caves to determine the origins, depositional modes and processes, and directions of paleodrainages. Diverse locations have been studied such as Mallorca (Fornós et al., 2014), Sarawak (Lin, 2013), Italy (Martini, 2011), and Romania (Häuselmann et al., 2010). A chronology for overlying sediment deposits was established using speleothem dating. These sediments were then interpreted to discuss paleohydrology of caves (Springer et al., 2009; González-Lemos et al., 2015). Applications of clastic sediment studies to the larger picture of speleogenesis have been presented with respect to maze caves (Palmer, 2011) and in a discussion of upward-directed dissolution in response to alluviation of cave streams (Farrant and Smart, 2011).
2. CLASTIC SEDIMENTS IN FLUVIOKARST DRAINAGE BASINS

2.1 Inputs of Clastic Sediments to Caves

Karstic aquifers receive inputs of sediment from sinking streams and from storm runoff into sinkholes. Runoff from overlying caprock may flush sediment down vertical shafts, and carry fragments of the caprock material deep into the carbonate aquifer. In addition, diffuse infiltration through overlying soils and the epikarst may transmit soils vertically into the underlying conduit system. All of these materials are commingled to yield the modern day cave sediment piles. As base levels are lowered, entire flow paths in karst are often abandoned, resulting in higher elevation, dryer, ancestral cave passages. Once these passages are abandoned, the sediment deposits in them will not be exposed to erosive forces that might rework them. Cave sediments in abandoned passages preserve the final episode of deposition. They have been found in a study in Mammoth Cave, Kentucky, to span the time scale from the late Pliocene to the Present (Schmidt, 1982; Granger et al., 2001).

![Profile sketch showing various sediment inputs to a fluviokarst aquifer representative of many of the karst areas of the eastern United States.](image)

The sources for clastic sediments in the fluviokarst carbonate aquifers found commonly in the eastern United States are shown in schematic form in figure 1. This conceptual model is appropriate when a portion of the drainage basin lies on non-carbonate rocks. Drainage basins such as this provide the following sources for clastic sediments:

(i) **The clastic load from allogenic surface basins carried into the karstic aquifer by sinking streams.** The character of these materials depends on the geology and relief of the allogenic drainage basins. In the eastern United States, the rocks underlying allogenic
drainage basins are typically shales and sandstones. However, allogenic basins may contribute granitic or basaltic weathering products or indeed any rock material that happens to underlie the allogenic surface stream basins. Influxes of glacial till are common in some basins. Low-relief basins may carry only fine silts and clays. High-relief allogenic basins may carry loads of pebbles, cobbles and boulders. On those tributaries with no surface overflow routes, any and all clastic materials derived from the allogenic basins will ultimately be carried into the karstic aquifer. In the case of sinking streams with no surface overflow routes, simple mass balance arguments demand that transported clastics must be carried through the karstic aquifer.

(ii) Soils and regolith from the karst surface flushed into sinkholes by storm runoff. Also carried underground would be glacial tills, volcanic ash, and any other movable material accumulated on the land surface. Sometimes these materials are injected directly into the karstic aquifer through the open throat of the sinkhole. In other cases, the sediments are accumulated in the bottom of the sinkhole and then are released abruptly to the subsurface through piping failures. These materials may or may not be distinct from the allogenic sediments depending on the contrast between the regolith on the carbonate rocks compared with the regolith on the non-carbonate rocks of the allogenic catchments.

(iii) A steady flux of soil carried into the aquifer through open fractures at the base of the epikarst. Often there is a continuum of apertures in the fracture system making up the vadose zone of karstic aquifers. Larger aperture fractures allow clastic material to descend to the active groundwater system. Some of this material is carried into the conduit system where it becomes part of the sediment load.

(iv) Sediment influxes from overlying rock formations. Some aquifers receive input from surface runoff and perched groundwater bodies above the vadose zone of the main carbonate aquifer. Examples would be the sandstone- and shale-capped carbonate aquifers of the Cumberland Plateau and the Mammoth Cave area. Clastic material ranging from clays to sandstone boulders are carried into the underlying conduit system by means of vertical shafts and open fractures in the vadose zone. In many cases these coarse grained materials simply crash down the shaft under the action of gravity without intervention of fluvial processes.

(v) Weathering residuum. Dissolution of the bedrock to form the conduit system will leave behind the insoluble residue in the limestone. This weathering residue includes clays, silts and sands as well as silicified fossil fragments and chert rubble. The insoluble component may make up only a few percent of the carbonate bedrock or it may make up a substantial fraction of the entire rock mass. The weathering residuum will be added to the sediment flux derived from other sources.

(vi) Sediments derived by base-level back-flushing. If the groundwater basin discharges to a large surface stream, flooding of the surface stream can flush sediments through the spring orifice back into the karstic aquifer. Typically, conduit systems have low gradients so that even modest rises of stage in the surface stream can force water long distances into the aquifer. This is, in effect, an elaborate form of bank storage except that flow reversals carry sediment. Back-flooded sediment depends both on the available source material and on the reversed flow velocity that can be achieved as the flood pulse moves down the surface channel. In Mammoth Cave, back-flooded sediments were found to be fine silts and clays (Hendrickson, 1961). Springer and Kite (1997) found much
coarser material in the caves of the Cheat River Gorge in West Virginia that were due to very large flood events.

2.2 Sediment Flux in Karst Drainage Basins

The overall flux of sediment through the karst surface and groundwater basin system can be expressed in terms of a sediment budget (fig. 2). The various fluxes are shown as input terms all balanced against a single output term at the karst spring. Backflushing from the surface stream is included by the ± sign on the spring sediment discharge. A negative sediment discharge would appear in the budget as a positive increase in storage.

\[ S_a + S_i + S_d + S_w + S_s = \pm S_f \]  

where \( S_f \) is the total sediment flux emerging from the karstic aquifer, \( S_a \) is the sediment carried underground by sinking streams, \( S_i \) is the sediment flushed underground by storm runoff into sinkholes, \( S_d \) is the sediment settling into the conduit system through fractures, \( S_w \) is the weathering residuum from dissolution of carbonate rocks and \( S_s \) is the quantity of sediment either deposited in storage or removed from storage. Of importance is the storage term. The net storage averaged over long periods of time must satisfy the relation

\[ \left[ \frac{\partial S_s}{\partial t} \right]_{ave} \leq 0 \]  

[2]

If the net change of sediment in storage does not satisfy equation [2], the conduit system will ultimately clog up, thus blocking the high capacity groundwater flow path, and allogenic recharge will be forced back onto surface routes.

![Figure 2. Flow sheet for sediment budget within a karstic aquifer.](image)
2.3 Importance of Storm Flow

Karst spring hydrographs have a range of responses. At one end, there are those with little or no response to storms. At the other extreme are systems with very flashy responses to storm flows, showing increases of a factor of 100 over base flows. The flashiness of the response depends on the degree of development of the conduit system and on the fraction of allogenic recharge in the drainage basin. Flashy drainage systems are generally more effective at clastic sediment transport.

Movement of sediments through karstic aquifers is episodic with the main transport taking place when pulses of storm water pass through the system. This is the time during which conduits are often under pipe-full conditions so that, with rare exceptions, no observers are present. It is therefore necessary to relate sediment facies to flood hydrographs rather than to mean or base-flow discharge through the conduit system. Groundwater basins with a low storm response can move sediment but the sediments will not show the range of structures found in the more flashy basins.
3. FACIES OF CAVE SEDIMENTS

3.1 Previous Systems of Facies Classification

Pickle (1985) examined the sediments in Parker Cave, Kentucky and divided them into a bank facies and a thalweg facies. He defined thalweg facies as the coarse-grained, winnowed material making up the streambed while the bank facies formed the banks of the stream. Valen et al. (1997) applied the sediment description derived for glacier caves (Eyles and Eyles, 1983) to cave deposits. This system is more a stratigraphic labeling for the sediments than a facies. Springer and Kite (1997) examined the sediments in caves of the Cheat River Canyon, West Virginia, that open directly on the riverbank and so are subject to the intense flooding of the Cheat. Springer and Kite divided the cave sediments into three main categories: phreatic, vadose, and residual. Each of the phreatic and vadose categories was subdivided into four facies descriptions. Phreatic facies include a diamicton facies, laminated sand facies, silt clay rhythmite facies, and sandy clay loam facies. The vadose facies include gravity deposit facies, travertine facies, overbank facies, and cave stream facies. The Springer and Kite system includes such sediments as breakdown (gravity deposit facies) and various chemical sediments (travertine facies), which are not included in the present discussion. One of the more mechanism-oriented facies classifications is that of Gillieson (1986) who attempted to classify sediments in terms of water flow type and depositional energy. The key parameters are the particle size and the degree of stratification. Gillieson also introduced a diamicton facies for sediments with a range of grain sizes and lack of stratification. The present work is closer to Gillieson’s classification.

3.2 Proposed Facies

Drawing on observations in several caves by the author and drawn from the literature, this paper classifies the sediments and interprets them according to depositional mechanism. The distinction between the facies is mainly made on particle size, sedimentary structure, and the degree of sorting, as indicated in table 1. The actual content of any given sedimentary sequence depends on available source material so the contrast between facies types may be indistinct if a range of source materials is not present. The facies types are sketched in figure 3 to show the populations as completely distinct in order to locate them on the diagram. For most real sedimentary deposits, the facies types would be less distinct and probably overlap.
<table>
<thead>
<tr>
<th>Facies Code</th>
<th>Facies</th>
<th>Sedimentary structures</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gcm, Srh</td>
<td>crudely bedded to massive gravel, granule to cobble; vf to coarse sand</td>
<td>horizontal bedding to unbedded; ripple cross-bedding to horizontal bedding</td>
<td>channel cave deposit</td>
</tr>
<tr>
<td>Gh</td>
<td>gravel, pebble to boulder</td>
<td>well-sorted, open framework, well-winnowed</td>
<td>thalweg cave deposit</td>
</tr>
<tr>
<td>Gmm</td>
<td>massive, matrix-supported clay to boulder</td>
<td>chaotic, unsorted, unbedded</td>
<td>diamicton cave deposit (debris flow)</td>
</tr>
<tr>
<td>Fl</td>
<td>clay to vf sand</td>
<td>fine lamination</td>
<td>slackwater cave deposit (overbank or waning flood)</td>
</tr>
<tr>
<td>Fsm</td>
<td>clay to silt</td>
<td>massive with possible chert fragments and/or fossils</td>
<td>backswamp cave deposit</td>
</tr>
</tbody>
</table>

**Table 1.** Classification of sedimentary facies in caves, using the facies codes introduced by Miall (1996).

**Figure 3.** Schematic representation of sediment facies in terms of sorting and particle size.
3.3 Channel Facies

The facies interpreted as channel cave deposits, referred to as the channel facies, in keeping with its proposal in Bosch and White (2004), represent sediments that have been sorted or partially sorted by transport along the conduit. They make up the bulk of the clastic sediments found in cave passages. When seen in stratigraphic section, channel facies are found to consist of distinct beds of silts, sands, and gravels. These materials are often well sorted within a given bed but sediment size and structure changes rapidly along the stratigraphic section. A typical “stratigraphy” is illustrated with a drawing from Davies and Chao’s 1959 report (fig. 4). The 3-meter passage is filled to the roof with bedded sands and gravels that result from various flow conditions at a time when the passage was an active streamway. Channel facies represent a diverse collection of sediments that could easily be subdivided into various subfacies as needed to describe specific sites. Because the detailed characteristics of the sediments depend on both flow regime and source materials, it does not seem useful to make further generic subdivisions of the facies.

![Figure 4](image-url)

**Figure 4.** A representative cross-section of channel facies sediment. The Chaperon, a filled side passage on Rose’s Pass, Mammoth Cave, Kentucky. From Davies and Chao (1959).
3.4 Thalweg Facies

In some caves, active streams have cut through the channel facies to form a secondary stream channel with bed material consisting of gravel, cobbles, and boulders. This coarse-grained material from which most of the sand and clay has been winnowed out is interpreted as thalweg cave deposits, following a suggestion by Pickle (1985). These deposits are here referred to as thalweg facies (Bosch and White, 2004). The creation of a thalweg facies requires a flowing stream with a moderate flow velocity even during normal flow conditions. Annual high flows, but not necessarily exceptional floods, can provide the boundary shear stress necessary to strip away sand- and silt-sized sediment. Only exceptional floods will provide the boundary shear stress necessary to move cobbles and boulders so these materials tend to accumulate in the streambed, thus forming thalweg facies.

3.5 Slackwater Facies

The term slackwater facies is applied here to the sequence of fine-grained, laminated sediments transported into the conduit system as suspended load (Bosch and White, 2004). Muddy floodwaters back up into all solution openings including blind side passages. These waters become ponded during which time all or a portion of the suspended load may settle out. Settling velocity increases with the cube of the particle size according to Stokes law, valid for quartz-density particles smaller than about 100 µm,

\[
\omega_i = \frac{(\sigma - \rho)gd_i^2}{18\eta} \text{ m s}^{-1} \tag{5}
\]

where \(\omega_i\) is the fall velocity of particle \(i\), \(\sigma\) is the density of the sediment particles, \(\rho\) is the density of water, \(g\) is the acceleration due to gravity, \(d_i\) is the diameter of particle, \(i\), and \(\eta\) is the viscosity of water (Allen, 1985). If floodwaters are backed up into conduits on the order of one meter in diameter, sand-sized particles, even if initially suspended by the floodwaters, will deposit within a few to about one hundred meters of horizontal transport at typical cave flow velocities. Because the fall velocity varies with the square of the particle size, clay and silt can be carried horizontal distances of a few to many kilometers with a fall distance of less than the diameter of the conduit. As a result, the slackwater facies in most systems are made up of only the smallest particle size material. Slackwater facies can be deposited from suspended load carried in the normal flow direction or from suspended load in water back-flooded from surface streams.

Slackwater facies are found in most caves, usually as the final layer at the top of a deposit. The slackwater facies appears at the top of the section in figure 4 as the laminated clay overlying the channel facies. Even when passages are nearly plugged with sediment or blocked by breakdown, they can still be flooded with muddy water during periods of high water levels. As a result, casual inspection of undisturbed cave sediments often reveals only the topmost clay layer, giving the misleading impression that the entire deposit is composed of fine clay and silt. Slackwater facies overlying the much coarser
sand and gravel of the channel facies may have misled J Harlan Bretz (1942) into thinking that the “red unctuous clays” were much more widespread than they really are. Bretz used the red unctuous clays as supporting evidence for his theory of cave origin by slow-moving, deeply percolating groundwater. Reams (1968) devoted much of his PhD dissertation into showing that the red unctuous clays are only a superficial layer over what here is being called a channel facies.

Springer and Kite (1997) used the term “slackwater facies” to describe sediments that back-flooded into shallow caves along the Cheat River in West Virginia. With cave entrances opening directly into the river valley, these slackwater sediments have larger particle sizes and also include flotsam that floated into the cave on the flood crest. Otherwise their use of the term is essentially the same as that presented in this paper.

3.6 Diamicton Facies

A diamicton facies was introduced by Gillieson (1986) in his studies of the high relief caves of the New Guinea highlands. Diamictons are unsorted and unbedded sediment masses consisting of a chaotic mixture of all particle sizes from clay to boulders. They have a wider variety of sediment sizes than talus piles, with larger, angular blocks supported in a diverse matrix of finer-grained, sub-angular and rounded sediments. These are interpreted as debris flows in which the entire sediment mass is entrained and moves as suspended load. Some of these masses may result from extreme floods in otherwise air-filled passages. Some debris flows may take place under water. The diamicton facies is recognized by complete absence of bedding and sorting. Such properties are easier to recognize when a wide range of particle sizes is available in the source area. Diamicton deposits seem to be uncommon in contemporary drainage basins. Nevertheless, there is much evidence for diamicton deposits in old cave deposits suggesting an association with periglacial climates.

3.7 Backswamp Facies

The term backswamp facies is here used to label sedimentary deposits that consist mainly of weathering residue of the bedrock and infiltrate material filtering into the conduit system from overlying soils with little or no lateral transport (Bosch and White, 2004). The term backswamp was chosen because some caves, especially maze caves, tend to function hydrologically much like swamps. Large volumes of water move through them but because of the large total cross-section, velocities are very low. As a result, sediment transport is limited and residual weathering products tend to accumulate with little lateral transport. Depending on the percentage of insoluble residue in the parent bedrock, backswamp facies may occupy a substantial portion of passage cross-sections. Backswamp facies generally consist of clay and fine silt sized material although the deposits may contain chert fragments, silicified fossils, and other insoluble residue extracted from the bedrock.
4. FIELD DOCUMENTATION OF CAVE LITHOFACIES

The sections that follow categorize the deposits of seven different cave systems in the eastern United States to illustrate the utility of this classification system. Sediment samples were collected, sieved, and weighed to generate particle size distributions. These data are shown on the $\phi$ scale commonly used in sedimentary petrology. The scale is defined as

$$\phi = -\log_2 \frac{d}{d_0}$$  \hspace{1cm} [4]

where $\log_2 = \text{base 2 logarithm}$, $d = \text{grain size in mm}$, and $d_0 = \text{reference particle size} = 1 \text{ mm}$.

4.1 Channel Facies

4.1.1 Mammoth Cave: Columbian Avenue

One of the most comprehensive studies of channel deposits was undertaken in Columbian Avenue in the Flint Ridge section of Mammoth Cave. Columbian Avenue is an 800-meter long elliptical tube that has apparently acted as a cutoff passage draining the higher lying Pohl Avenue to the baselevel Eyeless Fish Trail (fig. 5). Eyeless Fish Trail lies almost at the pool stage of Green River and floods with even modest rises in Green River. Pohl Avenue floods only when Green River stage exceeds 8 to 10 meters. The upper end of Columbian Avenue is 7 meters above pool stage; the downstream end is at 3.7 meters. Sand and silt sediments fill the passage to depths of as much as 3 meters.

Because the results were reported only in a senior thesis (Carwile and Hawkinson, 1968), a summary of some of the key descriptive information is given here. The channel deposit sediments consist of interbedded clays, silts, sands, gravels, cobbles, and boulders with widely varying distributions of particle sizes and widely varying degrees of sorting. At any particular location in many caves, the clastic sediments often exhibit a distinct sequence of beds. However, the measurements in Columbian Avenue show that these bed sequences cannot be traced for any great horizontal distance along cave passages.

Carwile and Hawkinson established a series of sections through the entire sediment pile in Columbian Avenue by digging trenches across the passage down to the bedrock floor. They then pressed sections of 5 cm wide x 2 cm deep steel trough against the walls of the pits in order to extract cores of the sediments. From samples of the cores, they determined grain size distributions, analyzed the clay minerals, and constructed stratigraphic columns (fig. 6). The channel deposits are moderately well sorted and well stratified but even in this ideal location – a uniform, low gradient tube with no side passages – the beds cannot be traced from one section to the next. These characteristics seem to be typical of channel deposits in general, and indeed the variation in bed thickness and bed continuity is usually more pronounced than it is in the Columbian Avenue examples. A stratigraphic section can be constructed at any particular point along
a cave passage, but these sections are not very useful for the interpretation of depositional processes.

Figure 5. Map of Columbian Avenue, Flint Ridge section of Mammoth Cave showing location of sediment pits. Underlined numbers are elevations in meters above pool stage of Green River. Base map adapted from Brucker and Burns (1964).
Figure 6. Series of stratigraphic columns along Columbian Avenue, Flint Ridge section of Mammoth Cave Kentucky showing lithologic characteristics of channel deposits. Columns are keyed to core locations shown in figure 5. Note the total column thickness; original columns were drawn to two different scales. Original data from Carwile and Hawkinson (1968).
The karst aquifer of which the Mammoth Cave System is a part consists of a well-defined set of groundwater basins each of which has multiple inputs and all of which drain ultimately to springs on Green River (Quinlan and Ewers, 1989). One of the largest is the Turnhole Basin. One of the master trunks draining to the Turnhole Spring has an internal confluence of two very large tributaries known as Hawkins River and Logsdon River. Stream sediments were sampled in this study using PVC pipes to collect push cores at several points upstream from the confluence (fig. 7). These samples were sieved and distribution functions were plotted (fig. 8). Samples taken from the same tributary produced very similar distribution functions. Comparison between the two tributaries shows that the sediments being transported down the two rivers are dramatically different in spite of the similar hydrogeologic setting.

Figure 7. Sketch showing sampling locations at the confluence of Logsdon River and Hawkins River, Mammoth Cave, Kentucky. The well casing is for a test well used for hydrologic measurements.

Logsdon River has been explored upstream from the confluence for more than seven kilometers. It more or less parallels the escarpment at the southern edge of the Mammoth Cave Plateau and is a master drain for the karst as far northeast as Roppel Cave. It is known to receive recharge from valley drains and vertical shafts and also from the sinking streams and sinkhole inputs on the Sinkhole Plain to the southeast. The Logsdon River sediments are mainly silts and fine sands with 40%–60% of the material smaller than the smallest sieve size used. The river velocity needed to transport the fiftieth percentile grain size of this sample would be about 0.18 m s⁻¹.
The ultimate source of Hawkins River is not known because the main river sumps a short distance upstream from the confluence. The Hawkins River sediments are more uniformly distributed over the range of silt to gravel with less than 10% of the material smaller than the smallest sieve size used. The river velocity needed to transport the fiftieth percentile grain size of this sample would be about 0.30 m s\(^{-1}\). These stream velocity calculations are detailed in the Appendix, and are in the same range as observed flows in cave streams (Palmer, 2007).

The contrast between the two tributaries could be a matter of provenance, a contrast between sediment derived from the Plateau compared to sediment derived from the Sinkhole Plain. It would also be a matter of transport with Hawkins River being the higher energy stream.

**Figure 8.** Particle size distribution in Hawkins and Logsdon Rivers. Logsdon River: diamonds = site 1; asterisks = site 5; open circles = site 4. Hawkins River: solid square = site 2; triangles = site 3.
4.1.3 Rock Spring

Rock Spring, Centre County, Pennsylvania, is the drain for a 14.2 km$^2$ groundwater basin. The basin is elongate along the trend of the Appalachian folding. Roughly one third of the basin is in folded Ordovician limestones; the remainder is underlain by Ordovician and Silurian shales and sandstones that make up Tussey Mountain. More than 50% of the recharge is mountain runoff that sinks in a series of swallets along the flank of the mountain. The master conduit that feeds the spring is developed parallel to strike and thus parallel to the mountain. Rock Spring has been used as a test site for a variety of karst water investigations. See Jacobson and Langmuir (1974) for a more detailed description.

The conduit that feeds Rock Spring is entirely in the phreatic zone. It has been explored by SCUBA diving for roughly 400 meters. The conduit carries a flux of clastic sediments. The diver reports a lift tube where the flow rises about 4 meters up a slope. Channel facies sediments collected from bottom and top of the lift tube were dried and sieved. The resulting grain size distribution (fig. 9) reveals little difference between the sediments at the bottom and the top of the tube. These sediments are being swept down the conduit by pipe flow and quite clearly follow undulations in the pipe.

![Figure 9. Grain size distribution in feeder conduit of Rock Spring. Diamonds = bottom of lift tube; squares = top of lift tube.](image-url)
4.2 Thalweg Facies

4.2.1 Tytoona Cave

Tytoona Cave, Blair County, Pennsylvania provides an example of the thalweg facies. Tytoona Cave is a segment of trunk passage carrying an active stream that drains a substantial portion of Sinking Valley (fig. 10). The cave is subject to flooding. The stream flows in a wide, shallow channel with an armoring of gravel-sized sandstone and siltstone derived from the Silurian clastics that make up the ridges bounding Sinking Valley. Surface runoff from the ridges carries the clastic material into the karst drainage system.

The streambed in Tytoona Cave consists of winnowed gravels at the surface. This surface layer is generally about the thickness of the diameter of the largest grain size represented, typical of armor layers. Near the cave entrance, the largest particles are cobbles and boulders, some as large as 40 cm in diameter. Qualitatively, the armor layer exhibits a fining trend downstream where the largest gravel size is 7 cm just upstream from a pool and low ceiling reach known as the “duckunder”. Downstream from the duckunder are gravels with clasts as large as 13 cm. These fine downstream to about 2.5 cm just upstream from the terminal sump. Beneath the winnowed cobble layer is a deposit generally consisting of sands mixed with gravels. Grain sizes beneath the winnowed layer are finer than the armor layer and also appear to exhibit a downstream-fining trend.

Figure 10. Map of Tytoona Cave, Blair County, Pennsylvania showing sample locations (courtesy of W.B. White).
Sediment samples were collected from Tytoona Cave with sampling sites spaced at about 30 m intervals (sample sites are shown by number on figure 10). Two samples were taken at each site using a shovel. The first sample was taken from the well-winnowed armor layer. The second sample came from directly below the first. These were collected to a depth of about 7.5 cm below the bottom of the first sample. Both sets of samples were dried, sieved, and the particle size distributions were plotted (fig. 11-a,b). The sediments sampled from below the armor layer did indeed show a general downstream fining trend. The winnowed armor layer shows a much narrower distribution of sizes than the underlying material. The thalweg facies consists entirely of coarse (8–32 mm) grains. Unfortunately, the accessible segment of Tytoona Cave is only a small fraction of the total conduit so that particle size distributions along the entire drainage channel cannot be determined.

Stream velocities in Tytoona Cave would have been about 1.7 m s\(^{-1}\) to transport the fiftieth percentile size sediments sampled from the bed surface, and about 0.84 m s\(^{-1}\) to move the deeper bed materials. These calculations are detailed in the Appendix, and match with what would be expected during flood flow conditions in Tytoona Cave (White, 2015).

4.2.2 Butler Cave

The Butler Cave-Sinking Creek System, Bath County, Virginia (White and Hess, 1982) is developed with a master trunk passage along the axis of a syncline. Tributary passages are developed along the flank of the syncline. These serve as inlets for clastic sediments flushed down the sides of Jack Mountain into a set of swallets. As a result, the...
trunk passage contains extensive beds of sand, gravel, and sandstone cobbles. The central portion of the trunk passage presently acts as an overflow channel and carries water only during flood events. Flood flow is injected from the flanks of Jack Mountain at high velocities, and as a result the thalweg facies is very well winnowed with only the coarsest cobble material remaining. The photograph (fig. 12) was taken in the trunk channel near Sand Canyon (map in White and Hess, 1982) at a location where there are no nearby inlet points. The coarse material is mainly sandstone cobbles, which have been carried down the low gradient trunk channel.

**Figure 12.** Photo of thalweg facies in Butler Cave main stream channel. Photo by Will White.

### 4.3 Slackwater Facies

Most caves that contain clastic sediments contain slackwater facies. The slackwater facies material consists of a layer of clay or perhaps clay and silt that makes up the topmost layer of the sediment. Caves subject to flooding collect a layer of slackwater facies every time the cave fills with water.
4.3.1 Mammoth Cave

Mammoth Cave provides excellent exposures of slackwater facies (fig. 4). At the tops of most sediment piles is a layer, seldom more than a few centimeters thick, of thinly layered clay and very fine silt. Some of these sedimentary layers are varved, apparently representing an annual cycle of flooding with the rise and fall of the ancestral Green River. X-ray examination of the material reveals mainly quartz. Clay minerals are a relatively minor component (Davies and Chao, 1959; Carwile and Hawkinson, 1968).

4.4 Diamicton Facies

4.4.1 Mystic Cave

Diamicton facies, by their nature, do not lend themselves to direct observation during formation. There may be one example known from anecdotal evidence, that of Mystic Cave, Pendleton County, West Virginia. During the great West Virginia flood of 1985 (Clark et al., 1987) a mass of soil and regolith on the order of 1000 m$^3$ was torn from a field above one of the cave’s entrances and flushed through the cave (Van Gundy and White, 2009). Mystic Cave consists of a single conduit with a small surface stream sinking at one end and flowing through the cave for roughly 1000 meters to emerge at a spring. A tributary stream enters the cave about two-thirds of the distance downstream. The mass of material torn loose during the storm was flushed through the cave as a single debris flow. Later, masses of unsorted clastic material ranging from clays to cobbles were found piled on flowstone and wedged in crevices, very much like the diamicton facies. The characteristic of the diamicton facies is that entire sediment piles are mobilized and move as a single debris flow. In this particular example, the November, 1985, storm was calculated to have a greater than 500-year return period in the Potomac River Valley of Pendleton County. Diamicton facies appear to record rare events in the cave depositional history.

4.4.2 Butler Cave

The Butler Cave-Sinking Creek System in Virginia contains large deposits of what appear to be a diamicton facies. These occur in the tributary caves oriented down the flanks of the syncline (White and Hess, 1982; Chess et al., 2010). These dip passages have a much steeper gradients than do most cave passages. The upstream ends of the tributaries are along the flanks of Jack Mountain, a quartzite capped ridge that is the source of much of the sediment. Although the updip ends of the passages are now occluded by breakdown and surface weathering material, it appears that the sediment was flushed into the passages from the mountainside. These deposits are plastered into recesses in the passage walls and fill side passages. The sediment is mostly sandstone. There is no evidence of bedding and no sorting. A completely chaotic mix of particle sizes ranges from sandstone clasts 10 to 20 cm across down to fine sand and clays (fig. 13).
The distribution of sediment masses in the dip-slope passages suggests a debris flow that swept down the passage under completely pipe-full conditions. Recesses and side passages served to break the dynamics of the flow and thus trap localized masses of sediment. It is suspected, although not proven, that the initiation and transport of the diamicton flows was related to climatic conditions much wetter than presently occur in this part of Virginia.

4.5 Backswamp Facies

4.5.1 Hindman Cave

Backswamp facies can be difficult to identify because weathering residuum from the limestone is difficult to separate from other fine-grained clastics. Hindman Cave, Armstrong County, Pennsylvania (White, 1976) may provide a good example of backswamp facies. Hindman Cave, like other complex maze caves developed in the Pennsylvanian Vanport Limestone, has a low gradient and little evidence for stream flow. The sediment consists of fractions of a meter to more than a meter of wet clay. This material appears to have been derived from the insoluble residue from the limestone with some contribution from overlying fireclays and shales.
5. CONCLUSIONS

Clastic sediments deposited in conduit systems can be divided into five categories of interpretation, based on descriptive facies, listed in order of qualitatively decreasing prevalence: channel, slackwater, thalweg, backswamp, and diamicton. Channel facies comprise the most commonly observed assemblages of sediments, recognized by sediments ranging in size from very-fine sand to cobble, with well-sorted sediments in distinct beds, but with structure rapidly changing along the section. Channel and thalweg facies are mainly transported as bedload, with the thalweg being deposited from higher-energy flows. Thalweg facies are characterized by well-sorted, open framework, well-winnowed gravels, with a bed thickness about the same as the sediment grain size. Fine-grained, laminated deposits, most often seen at the top of a section, are interpreted as the slackwater facies. Diamicton facies are those chaotic, unsorted, unbedded assemblages of sediment in which larger, angular blocks are supported in a diverse matrix of finer-grained, sub-angular and rounded sediments. Diamicton facies and slackwater facies are deposited from suspended loads, with the diamicton facies being deposited from much higher-energy waters as debris flow, and slackwater flows being deposited from lower-energy overbank or waning-flood conditions. Finally, backswamp facies, recognized by massively deposited fine-grained sediments with possible chert fragments and/or fossils, describe residual infiltrated clastic sediments deposited in place with little horizontal transport.
6. FUTURE DIRECTIONS

This work was primarily concerned with consolidating the existing work on clastic sediment deposits in caves, integrating it with field observations in several caves, and proposing a universally acceptable language for classifying those sediments. The facies classification proposed here has been in use continuously since 2004 for karst sediment research. The direction forward concerns the multiple roles clastic sediments play in speleogenesis. The long-standing speleogenesis story leans heavily upon the dissolution of limestone from pore spaces to enlarged fractures to conduits. In order for this dissolution to take place, insoluble sediment must be transported through the spaces, clearing the way for more dissolution. In addition, in larger conduits, abrasion by clastic sediment transport upon limestone can reveal more limestone for dissolution, which can loosen more insoluble material that needs to be transported, which can reveal more limestone for dissolution and thus continue the speleogenetic process. These coupled interactions describe just part of the complexity of speleogenesis and the need for an inclusive model of all components of the system.

Combining kinematic dissolution processes with mechanical forces required for transport of solid material will result in a more complete characterization of the true dynamic nature of speleogenesis. The resulting interdependent model is multiphasic, multicomponental, and time dependent: as surfaces experience dissolution, new surfaces are available for dissolution; as material is removed by dissolution, insoluble clastics become available for transport; as materials are shifted and abraded in transport, new surfaces are made available for dissolution and new insoluble clastics are freed; as acidity levels vary, kinematic dissolution rates change; as meteoric water levels change, forces increase resulting in turbulent flows, accordingly; and all of this occurs in the continual presence of Earth’s gravity. During active speleogenesis, these processes occur simultaneously in constantly changing multi-factor interactions. This view of speleogenesis can be referred to as the speleogenetic interaction model and is proposed as the next step in describing a more complete system that leads to cavern formation.
APPENDIX

FLOW PROPERTIES CALCULATIONS

In the real world, there is the fairly complex case of a grain of sediment of some density, size, and shape resting on several other grains, each of a different size and shape from the first grain and each other. That situation can be addressed using modeling software. For this work, so that I can tackle the math on paper and think about the flow conditions that may have been present to transport these sediments, several assumptions have been made. I am first choosing to address a two-dimensional problem of one grain resting on two grains. Second, I 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. This arrangement is illustrated in figure A.1.

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 in Allen’s text, Physical Sedimentology, yields equation [A.1] (1985). 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 I will take the simplest case, where each grain is spherical and is resting on a bed of same-sized grains, also having diameter D.

\[
\tau_{cr} = \frac{2D(\sigma - \rho)g}{3\cos \beta} \tan(\alpha - \beta) \quad \text{N m}^{-2}
\]

where

\( \tau_{cr} \) is the critical shear stress at the threshold of entrainment,
\( D \) is the diameter of the sediment grain to be transported,
\( \sigma \) is the density of that grain (2650 kg m\(^{-3}\)),
\( \rho \) is the density of the fluid (1000 kg m\(^{-3}\)),
g is acceleration due to gravity (9.8 m s\(^{-2}\)),
\( \alpha \) is the angle between the line connecting the centers of the grains and the perpendicular to the bed, and \( \beta \) is the angle that the bed tilts away from the horizontal.
Therefore,
\[ \tau_{cr} = \frac{10,780D}{\cos \beta} \tan(\alpha - \beta) \quad \text{N m}^{-2}. \]  
[A.2]

Examine the figure A.1, it is apparent that because I 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:
\[ \tau_{cr} = \frac{10,780D_{50}}{\cos(\tan^{-1}S)} \tan \left( \frac{\pi}{6} - \tan^{-1}S \right) \quad \text{N m}^{-2}, \]  
[A.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.

\(\tau_{cr}\) can be used to calculate shear velocity, \(u = \left(\frac{\tau_{cr}}{\rho}\right)^{1/2}\), which can then be used to estimate a stream flow velocity, \(u\).

\[ u = \frac{u_*}{\kappa} \ln \left( \frac{z}{z_0} \right), \quad \text{[A.4]} \]

or, substituting,
\[ u = \frac{\left(\frac{\tau_{cr}}{\rho}\right)^{1/2}}{\kappa} \ln \left( \frac{z}{z_0} \right) \]

where \(\kappa, 0.40\), 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:
\[ u = 0.17 \sqrt{\tau_{cr}} \quad \text{m s}^{-1}. \]  
[A.5]
These velocities, presented in table A.1, are in the same range as observed flows in cave streams (Palmer, 2007). The fastest flows calculated, at 1 to 2 meters per second, match with what would be expected during flood flow conditions in Tytoona Cave (White, 2015).

<table>
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<th>Site</th>
<th>D_{50} (m)</th>
<th>S</th>
<th>\tau_\alpha (N m^{-2})</th>
<th>u_\ast (m s^{-1})</th>
<th>u (m s^{-1})</th>
</tr>
</thead>
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<td>0.001*</td>
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<td>0.033</td>
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<td>0.002</td>
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<td>0.056</td>
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<td>0.01</td>
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<td>0.312</td>
<td>1.70</td>
</tr>
<tr>
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<td>0.01</td>
<td>24.3</td>
<td>0.156</td>
<td>0.839</td>
</tr>
</tbody>
</table>

* S obtained through measurement of water surface slope at time of sediment sampling.

**Table A.1.** Sediment data, stream water surface slope, and sediment transport characteristic calculations for cave streams. Water surface slopes estimated based on present stream geometries with this exception: * S obtained through measurement of water surface slope at time of sediment sampling.
REFERENCES


White, W.B., personal communication, April 9, 2015.