Studies of Cave Sediments

Physical and Chemical Records of Paleoclimate

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Revised Edition

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PREFACE

John E. Mylroie and Ira D. Sasowsky*

Caves occupy incongruous positions in both our culture and our science. The oldest records of modern human culture are the vivid cave paintings from southern France and northern Spain, which are in some cases more than 30,000 years old (Chauvet, et al, 1996). Yet, to call someone a "caveman" is to declare them primitive and ignorant. Caves, being cryptic and mysterious, occupied important roles in many cultures. For example, Greece, a country with abundant karst, had the oracle at Delphi and Hades the god of death working from caves. People are both drawn to and mortified by caves. Written records of cave exploration exist from as early as 852 BC (Shaw, 1992). In the decade of the 1920's, which was rich in news events, the second biggest story (as measured by column inches of newsprint) was the entrapment of Floyd Collins in Sand Cave, Kentucky, USA. This was surpassed only by Lindbergh's flight across the Atlantic (Murray and Brucker, 1979).

Cave science also has a long history, with many accounts appearing as early as the sixteenth century (Shaw, 1992; 2000). The term *speleology* has become accepted as the defining term for the scientific study of caves (Moore and Sullivan, 1997), yet the discipline has had difficulty integrating with mainstream sciences. This difficulty has two roots. First, the hidden and arduous nature of most caves means that non-specialists rarely visit them. Second, the bulk of data on caves has come from the recreational caving community, which has cast aspersions on the legitimacy of speleology. Caving for recreation has been considered a fringe activity by society. The journalistic terms "spelunking" and "spelunker", used to describe the activity and the individual, respectively, have emphasized the view that cave explorers are odd people (from personal experience, we can say that a few most certainly are). Those who explore for recreation call themselves "cavers". Over 95% of the cave maps in existence were made by these men and women, who produce them without compensation, for the pure pleasure of creation. And, yet, these maps form the basis for almost all scientific studies within caves. Imagine an analogous situation for the earth sciences, if recreational cartographers drew most of the topographic maps in the world at night, after their day jobs were over.

Some of the criticism of speleology as an immature science has been justified. The difficult, time-consuming and arduous nature of cave exploration has created a lack of

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manpower in the ranks of cavers and cave scientists. The vast majority of cave scientists around the world began as recreational cavers. Much of the early science done now seems lacking in quality or incomplete. Through time, exploration techniques and technology improved, and concurrently the science of speleology matured. As a result, the science produced has both improved and broadened.

The studies presented in this book concern caves formed by dissolution of soluble bedrock, as an integral part of the production of a karst landscape. This excludes other types of caves (lava tubes, sea caves, talus caves, etc.), which are different, but interesting in their own right. Today, the earth science study of caves falls into two regimes: applied research (land use problems); and basic research (caves as data repositories).

The land use problems in cave and karst areas are legion. These include water quality, flooding, and land subsidence. Such problems have attracted significant governmental (from a regulatory viewpoint) and environmental consultant (from a problem-solving viewpoint) interest. Today, a semi-annual conference on the Engineering and Environmental Impacts of Karst (e.g. Beck and Herring., 2001) draws an international audience to a venue filled with case-histories and technique evaluations.

However, the focus of this book is on the basic quality of caves as data repositories – allowing for the investigation of problems on geologic, not human, timescales. Caves are unique landforms in that they exist within, instead of on, the earth. They create an environment that is predisposed to preservation. As surface landforms age and evolve, the record of their previous condition is destroyed by weathering, and removed by erosion. Not so with caves, where the processes of destruction is greatly delayed, and therefore information is preferentially preserved. Valleys enlarge and deepen as base level lowers, and their former morphology disappears, but in adjacent caves the lowering of base level means the abandonment of conduits and the development of new flow paths deeper down. While active, these cave passages recorded evidence of water flow velocity, water table position, and flow direction in the morphology of their passage walls. In-washed clastic sediment, sometimes inter-layered with chemical precipitates, preserve additional data on active conditions. When abandoned, the cave passages may persist for millions of years. In this setting, they collect additional clastic and chemical deposits that reflect conditions of the environment on the surface above.

The papers in this book have two main stories to tell. One is that retained in the clastic sediments that entered the cave during its active and senescent phases; the chemical precipitates, or speleothems tell the other story. A dominant theme that is carried throughout is the paleoclimatic record that these cave deposits hold.

The initial chapter by Rachel Bosch and Will White describes how clastic sediments enter into caves, how they are transported in conduits, and how they are deposited. This chapter sets the basic framework for the clastic chapters that follow. In chapter 2, Barbara Mahler and her co-authors examine clastic sediments in terms of their water quality implications, from both the inorganic and organic view. Chapter 3, by R. J. Musgrave and J. A. Webb, provides both a case study from Australia, as well as a detailed discussion of paleomagnetic analysis as a geochronological tool in cave sediment studies. Ira Sasowsky and co-authors present in chapter 4 a U.S. case history of clastic sediment deposition and paleomagnetic analysis that provide a measure of the potential rapidity with which cave sediments can collect. Leo Lynch and co-authors present a case study in chapter 5 that shows how sediment provenance can be determined from X-ray diffraction techniques; their results indicate that sediments that were thought to be autogenic were in fact allogenic, with implications for surface contaminant transfer. Chapter 6, by Elizabeth Knapp and co-authors, shows how use of weathering degree, and paleomagnetic analysis in a Virginia, USA cave can be used to determine the timing and climatic conditions of sediment influx into a cave. Paul Burger, in Chapter 7, describes the use of clastic sediments to determine ice advance and retreat events in the Colorado Rockies, USA, in an area of difficult logistics. The clastic section of the book ends with chapter 8, in which France Šušteršič uses the remnants of caves as found on the surface, and their internal deposits, to look at caves in Slovenia as part of degraded cave systems at the end of their useful life as data repositories.

The second part of the book examines chemical precipitates, or speleothems, as both geochronological tools and paleoclimatic indicators. Chapters 9-11 form a comprehensive resource for scientists interested in the use of speleothems for these indicators, written by people with tremendous experience in the techniques involved. William White, in chapter 9, provides a review of calcite speleothem chemistry and formation, creating the necessary foundation for the later chapters. In chapter 10, Jeff Dorale and co-authors clearly and concisely present an in-depth discussion of the U/Th and related dating techniques as applied to speleothems. Following in chapter 11 is a cautionary presentation by Russ Harmon and co-authors about the use of oxygen isotopes in speleothems for paleoclimatic interpretations. Chapter 12, by Peter Kolesar and Alan Riggs, begins a series of case history studies of speleothems from a variety of sites with an analysis of the depositional environment of the famous Devils Hole calcite. The case histories continue with a series of studies from high altitude or high latitude sites. Cristoph Spötl and co-authors present in chapter 13 an intriguing study of speleothems in a cave in the Austrian Alps that has alternated between ice-cover and ice-free conditions, both in the geologic and the historical record. Chapter 14, by Stein-Erik Lauritzen and Joyce Lundberg, shows how a speleothem from a Norwegian cave at the Arctic Circle reveals the duration and conditions of oxygen isotope stage 11, over 400,000 years ago. Half a world away from Norway, Steven Turgeon and Joyce Lundberg in chapter 15 examined the geochronology and isotope chemistry of speleothems from a cave in Oregon, USA, using growth-rate determinations to carry the speleothem record beyond 500,000 years. In chapter 16, Victor Polyak and Necip Güven present data from caves in the Guadalupe Mountains of New Mexico, USA, where silicates in speleothems were used to show time and temperature conditions needed to mature amorphous silica into trioctahedral smectite and quartz.

Finally, in chapter 17, Donald McFarlane and Joyce Lundberg show how the interplay between speleothems, clastic deposits, and bones can be used to determine aspects of deposition in caves of the West Indies. This concluding chapter brings together many elements presented in earlier chapters to synthesize both a paleoclimatic and paleontological interpretation.

Within this book, we have attempted to present a comprehensive treatment of cave deposits. We are indebted to the patience and skill of the contributing authors. We are also bound to honor and thank the many amateur scientists and cave explorers who have helped cave scientists locate, explore, map and analyze the caves from which important data are collected. We can think of no other scientific discipline where the amateur plays as important a role in the development and advancement of a field.

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CONTENTS

LITHOFACIES AND TRANSPORT OF CLASTIC SEDIMENTS IN KARSTIC AQUIFERS

Rachel F. Bosch and William B. White*

1. ABSTRACT

Karst aquifers demand continuous transport of clastic sediments if the conduit system is to remain open. Sediments are injected into the aquifer by sinking surface streams and through sinkholes, vertical shafts, open fractures, and other pathways from the land surface of sufficient aperture to permit gravity- and inwash-driven transport. Much 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 clastic material depends on material available in the source area, distinctly different facies are 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 stream power, one can distinguish (i) diamicton facies: masses of unsorted, unstratified clays through boulders carried as a slurry during high energy flood events, (ii) thalweg facies: coarse gravel to cobble size material, well winnowed, forming armoring on underground streams that moves only during flood flow, (iii) channel facies: usually well sorted and often well stratified silt though gravel carried as bedload at intermediate stream powers, (iv) slackwater facies: mostly clay and silt carried as suspended load and deposited from floodwaters backfilled into the conduit system, (v) backswamp facies: mostly clay derived from the insoluble residue of the limestone, deposited under phreatic conditions with little lateral transport.

2. 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. Textbooks on karst hydrology commonly provide descriptions and overall classifications of cave sediments (e.g. Bogli,

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1980; White, 1988; Ford and Williams, 1989; Gillieson 1996). The classifications are all generally similar although they differ somewhat in detail. The present paper focuses on a specific sub-set of cave sediments: the clastic sediments derived from surface and subsurface weathering and carried into and through the cave system by mainly fluvial processes.

Most of the investigators of clastic sediments in caves have treated them as static deposits, not different in kind from 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 ground water basin in which the caves are located. There is, in effect, a flow field of clastic sediments in addition to the flow field of ground water. 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 stream bed was predominantly angular to subangular sand and gravel-sized clasts. A terrace composed of sand and gravel was deposited two meters above the normal stream level.

The lithologic characteristics of the clastic sediments reflect the hydraulic conditions that transported them. These characteristics can be described by a sedimentary facies:. Our objective in this paper is to consider the various facies of clastic sediments and the relation of these facies to transport mechanisms and the hydrology of ground water flow in karst

3. CLASTIC SEDIMENTS IN FLUVIOKARST DRAINAGE BASINS

3.1 Inputs of Clastic Sediments to Caves

Karst 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 so 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 and have been found to span the time scale from the late Pliocene to the Present (Schmidt, 1982)

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 karst 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 karst 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 karst 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 karst 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.

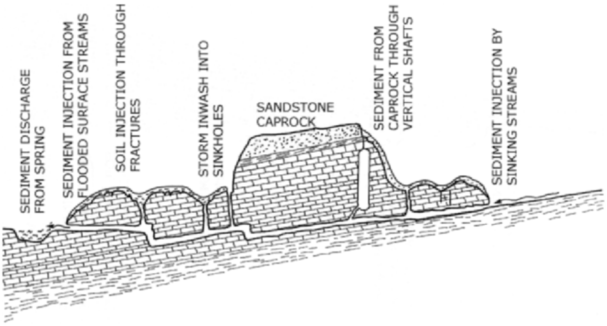

Figure 1. Profile sketch showing various sediment inputs to a fluviokarst aquifer representative of many of the karst areas of the eastern United States.

(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 karst aquifers. Larger aperture fractures allow clastic material to descend to the active ground water 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 ground water 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 ground water basin discharges to a large surface stream, flooding of the surface stream can flush sediments through the spring orifice back into the karst 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.

3.2 Sediment Flux in Karst Drainage Basins

The overall flux of sediment through the karst surface and ground water 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. Back-flushing 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. It is assumed in this model that no other terms can change sign.

$$S_a + S_i + S_d + S_w \pm S_s = \pm S_f \tag{1}$$

where S_f is the total sediment flux emerging from the karst aquifer, S_a is the sediment carried underground by sinking streams, S_i is the sediment flushed underground by storm

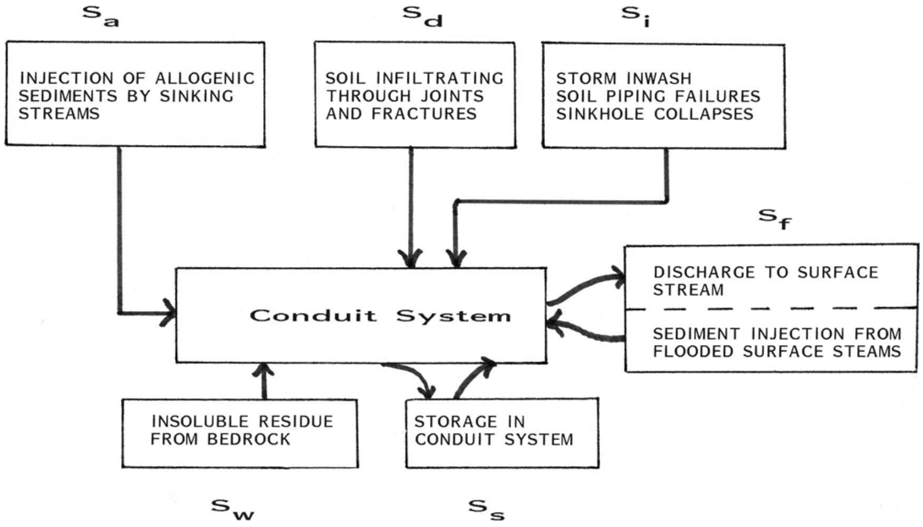

Figure 2. Flow sheet for sediment budget within a karst aquifer.

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

$$\left[\frac{\partial S_s}{\partial t}\right]_{ave} \leq 0 \qquad (2)$$

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 ground water flow path, and allogenic recharge will be forced back onto surface routes.

3.3 Importance of Storm Flow

Karst spring hydrographs have a range of responses from those with little or no response to storms to extremely flashy responses with storm flows increased by 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 karst aquifers is episodic with the main movement 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 will be necessary to relate sediment facies to flood hydrographs rather than to mean or base flow discharge through the conduit system. Ground water 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.

4. FACIES OF CAVE SEDIMENTS

4.1 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. The thalweg facies was the coarse grained, winnowed material making up the stream bed while the bank facies formed the banks of the stream. Valen et al. (1997) applied the sediment description derived for glacier caves (Eyles, 1983) to cave deposits. This system is more a stratigraphic labeling for the sediments than a facies. Springer and Kite (1997) examined the caves of the Cheat River Canyon in West Virginia. These caves open directly on the river bank 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 introduces a diamicton facies for sediments with a range of grain sizes and lack of stratification. The present work is closer to Gillieson's classification.

4.2 Proposed Facies

The various inputs of clastic sediment are commingled in the conduit system. Depending on the transport processes, the sediments are reorganized into distinct facies. The sedimentary facies that were devised based on transport mechanisms are:

Channel Facies
Thalweg Facies
Slackwater Facies
Diamicton Facies
Backswamp Facies

The distinction between the facies is mainly made on particle size and on the degree of sorting as indicated schematically in Figure 3. 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.

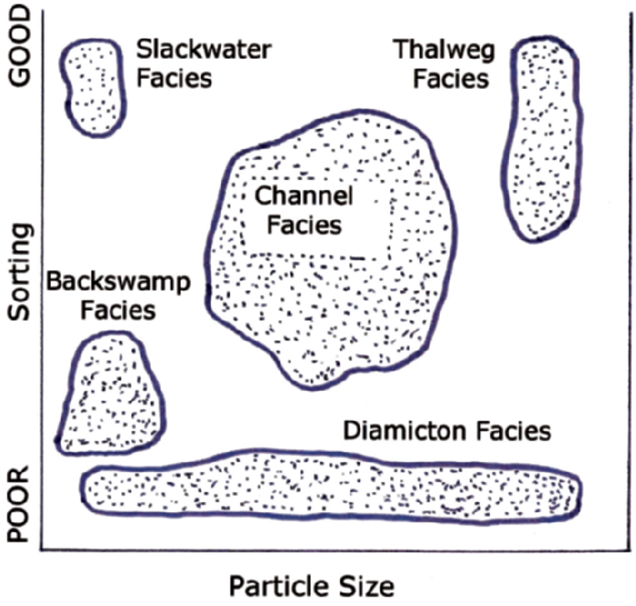

Figure 3. Schematic representation of sediment facies in terms of sorting and particle size.

4.3 Channel Facies

The channel facies 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 bed lithology 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 which result from various flow conditions at a time when the passage was an active streamway. Channel facies represent a diverse collection of materials 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.

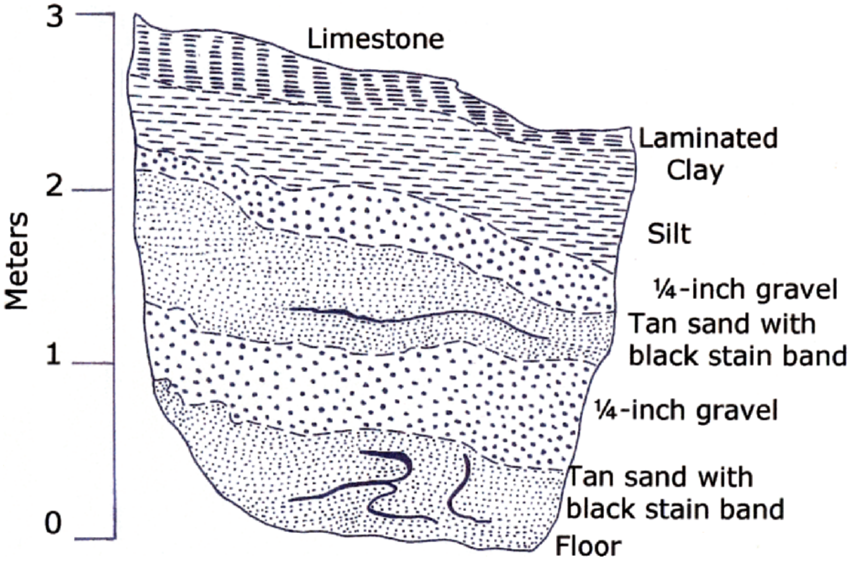

Figure 4. A representative cross-section of channel facies sediment. The Chaperon, a filled side passage on Rose's Pass, Mammoth Cave, Kentucky. From Davies and Chao (1959).

Channel facies sediments are transported mainly as bedload. The varying particle sizes found from bed to bed appear to represent different flow regimes. The ability of any given flow regime to transport sediment is determined by the boundary shear between the moving water and the movable sediment bed. The boundary shear is related to flow velocity through Newton's stress law:

$$\tau = \frac{1}{8}\rho f v^2 \tag{3}$$

where τ is the boundary shear in Nm^{-2}, ρ is the density of the fluid in kgm^{-3}, f is a dimensionless friction factor, and v is the water velocity at the boundary in $msec^{-1}$. The critical boundary shear necessary to move particles of a given size has been determined experimentally for a great variety of particles (Vannoni, 1977). For the particle size range from 0.5 to 100 mm, the data can be fitted approximately by least squares regression to the empirical equation

$$\tau_c = 0.067 D_{50}^{1.08} \tag{4}$$

where τ_c is the critical boundary shear and D_{50} is the average particle size in mm. Because the boundary shear varies as the square of the flow velocity, equations (3) and (4) provide a basis for understanding the winnowing and variation in particle size seen in channel deposits where the material was obtained from the same source area.

4.4 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 called the thalweg facies following a suggestion by Pickle (1985). The creation of a thalweg facies requires a flowing stream with a moderate flow velocity even during normal flow conditions. A simple calculation of the required boundary shear for sediment movement illustrates the effectiveness of the winnowing process. To move sand and silt requires a boundary shear of only 0.15 Nm^{-2} whereas moving 30 cm cobbles requires a boundary shear of 165 Nm^{-2} . Moderate flows – annual high flows, not exceptional floods – will provide the boundary shear necessary to strip away sand and silt sized sediment. Only exceptional floods will provide the boundary shear necessary to move cobbles and boulders so these materials tend to accumulate in the stream bed thus forming the thalweg facies.

4.5 Slackwater Facies

The term "slackwater" facies is applied to the sequence of fine-grained clays and silts transported into the conduit system as suspended load. 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 has time to settle out. Settling velocity increases with the square of the particle size according to Stokes law

$$\omega_i = \frac{2(\rho_s - \rho)\, g\, d_i^2}{9\eta} \tag{5}$$

where ω_i is the fall velocity of particle i, ρ_s is the density of the sediment particles, ρ is the density of water, g is the acceleration of gravity, d_i is the diameter of particle, i, and η is the viscosity of water. If flood waters are backed up into conduits on the order of one meter in diameter, sand sized particles, even if initially suspended by the flood waters, will deposit within a few meters. Because the fall velocity varies with the square of the particle size, clay and fine silt can be carried distances of hundreds to thousands of meters with a fall of less than the diameter of the conduit. As a result the slackwater facies in most systems is 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 backflooded from surfaced streams.

Slackwater facies are found in most cave deposits, usually as the final layer to be deposited. The slackwater facies appears at the top of the section in Figure 4 as the laminated clay overlying the channel deposits. 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 deposits 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 ground water. Reams (1968) devoted much of his Ph.D. 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 backflooded 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.

4.6 Diamicton Facies

A diamicton facies was introduced by Gillieson (1986) from 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. 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 facies require the most energy for transport of any of the sedimentary facies. They will thus be restricted to high gradient drainage basins. Diamicton facies seem to be uncommon in contemporary drainage basins. Nethertheless, there is much evidence for diamicton facies in old cave deposits suggesting much higher energy flood flows perhaps associated with periglacial climates.

4.7 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. 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.

5. FIELD DOCUMENTATION OF CAVE LITHOFACIES

The sections that follow give specific descriptions of some sites that illustrate the facies concept. Sediment samples were collected, sieved, and weighed to generate particle size distributions. These data are shown on the ϕ scale commonly used in sedimentary petrology. The scale is defined

$$\phi = -\ell g_2 \frac{d}{d_o} \qquad (6)$$

where $\lg_2$ = base 2 logarithm ($\lg_2 x = 3.3219 \log x$), d = grain size in mm, and d_o = reference particle size = 1 mm.

5.1 Channel Facies

5.1.1 Mammoth Cave: Columbian Avenue

One of the most comprehensive studies of channel facies was undertaken in Columbian Avenue in the Flint Ridge section of Mammoth Cave. 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. Channel facies 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 a cave, 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 distance along cave passages.

Columbian Avenue is an 800 m 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 – 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 three meters.

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 facies 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 facies in general and indeed the variation in bed thickness and bed continuity is mostly more pronounced than it is in the Columbian Avenue examples. A stratigraphic section can be constructed at any particular point along a cave

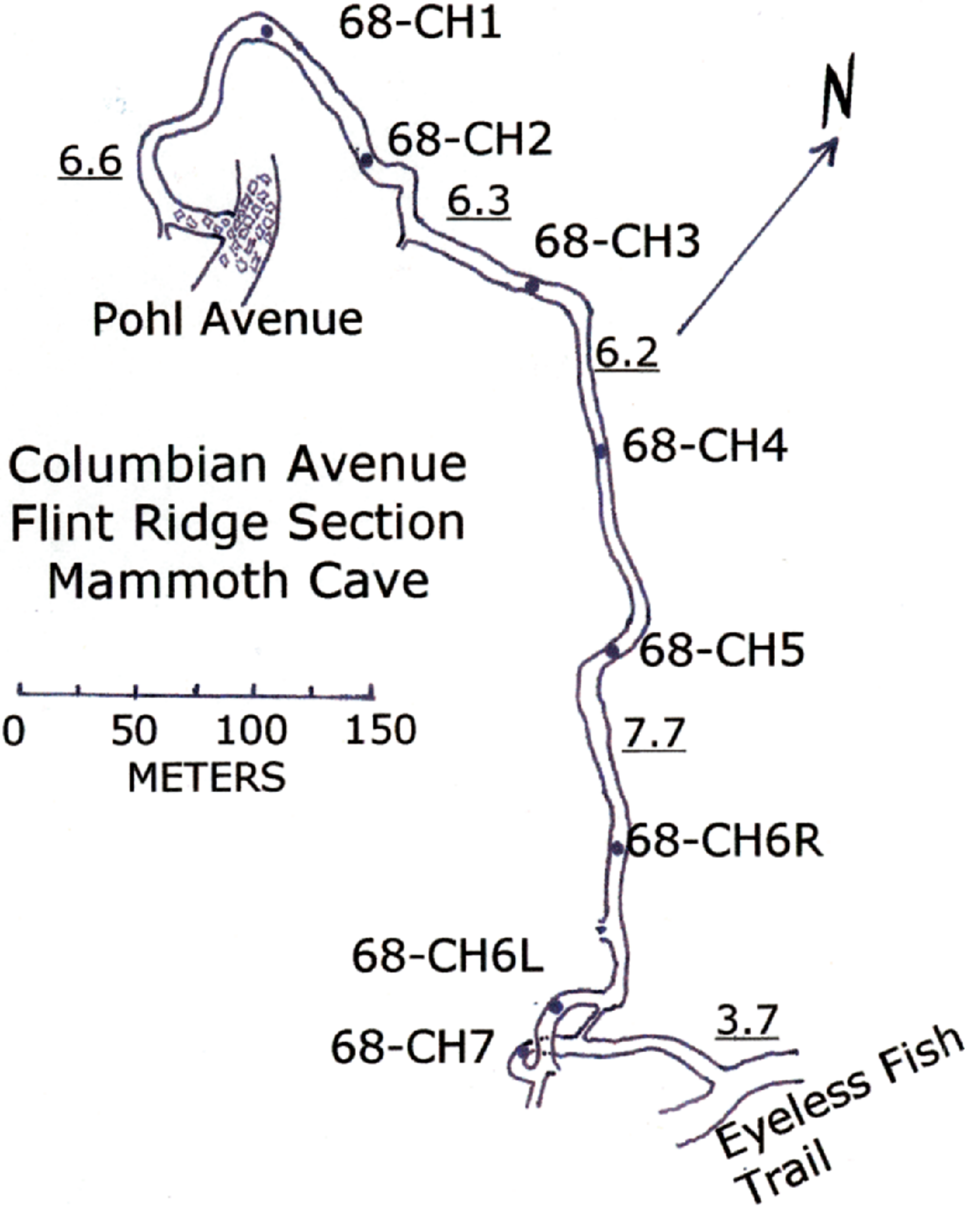

Figure 5. Map of Columbian Avenue, Flint Ridge section of Mammoth Cave showing location of sediment pits. Underlined numbers are elevations in meters above pool stage of Green River. Base map adapted from Brucker and Burns (1964).

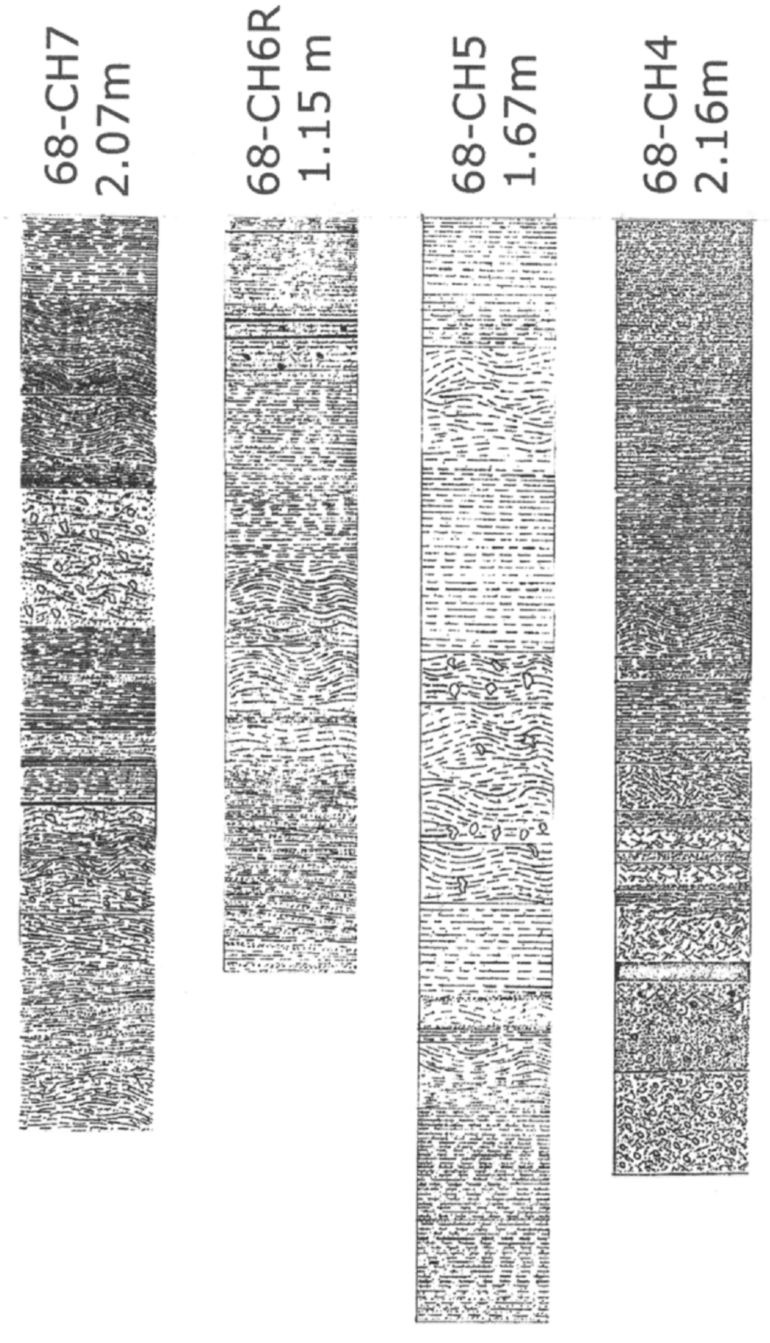

Figure 6. Series of stratigraphic columns along Columbian Avenue, Flint Ridge section of Mammoth Cave Kentucky showing lithologic characteristics of channel facies. Columns are keyed to core locations shown in figure 7. Note the total column thickness; original columns were drawn to two different scales. Original data from Carwile and Hawkinson (1968).

passage, but these sections are not very useful for the interpretation of depositional processes.

5.1.2 Mammoth Cave: Logsdon/Hawkins River

The karst aquifer of which the Mammoth Cave System is a part consists of a well-defined set of ground water 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. The master trunk 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 at several points upstream from the confluence (Fig. 7). These samples were sieved and distribution functions 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.

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.

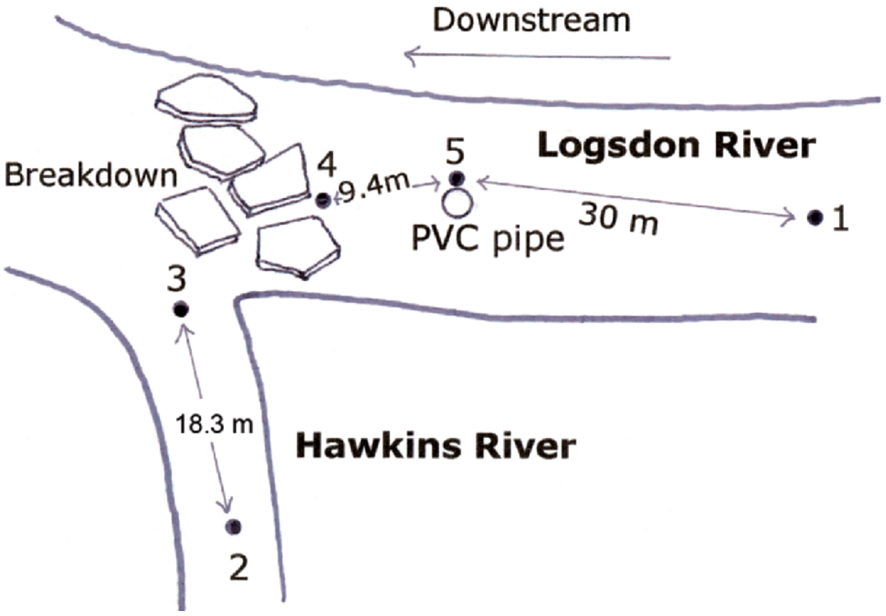

Figure 7. Sketch showing sampling locations at the confluence of Logsdon River and Hawkins River, Mammoth Cave, Kentucky. The PVC pipe is a test well used for hydrologic measurements.

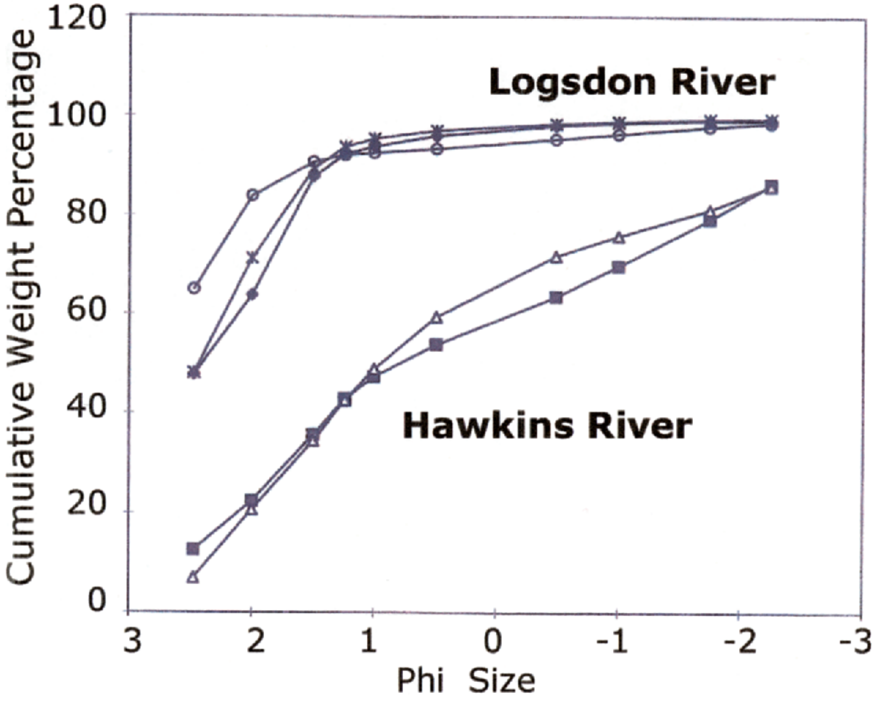

Figure 8. Particle size distribution in Hawkins and Logsdon Rivers. Logsdon River: diamonds = site 1; asterisks = site 5; open circles = site 4. Hawkins River: solid square = site 2; triangles = site 3.

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 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.

5.1.3 Rock Spring

Rock Spring, Centre County, Pennsylvania, is the drain for a 14.2 km^2 ground water 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 Orodvician and Silurian shales and sandstones that make up Tussey Mountain which trends northeast-southwest along the trend of the Appalachian folding. 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 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.

5.2 Thalweg Facies

5.2.1 Tytoona Cave

Tytoona Cave, Blair County, Pennsylvania provides an example of 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.

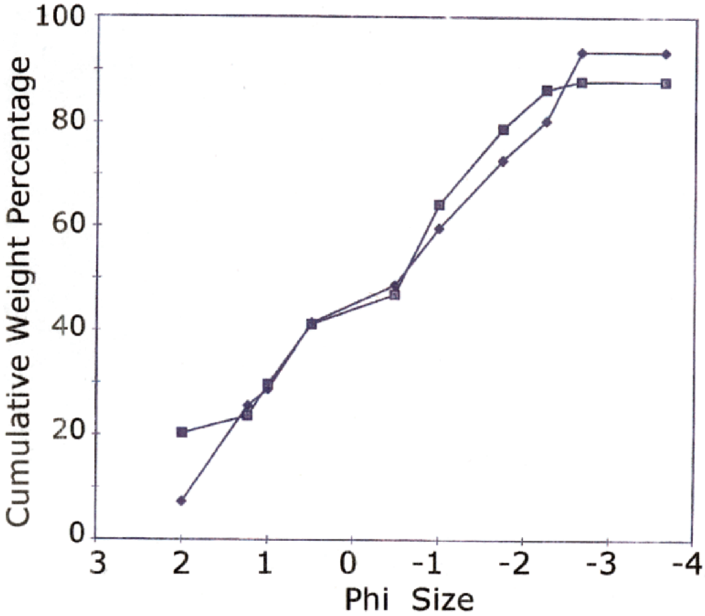

Figure 9. Grain size distribution in feeder conduit of Rock Spring. Diamonds: bottom of lift tube; squares: top of lift tube.

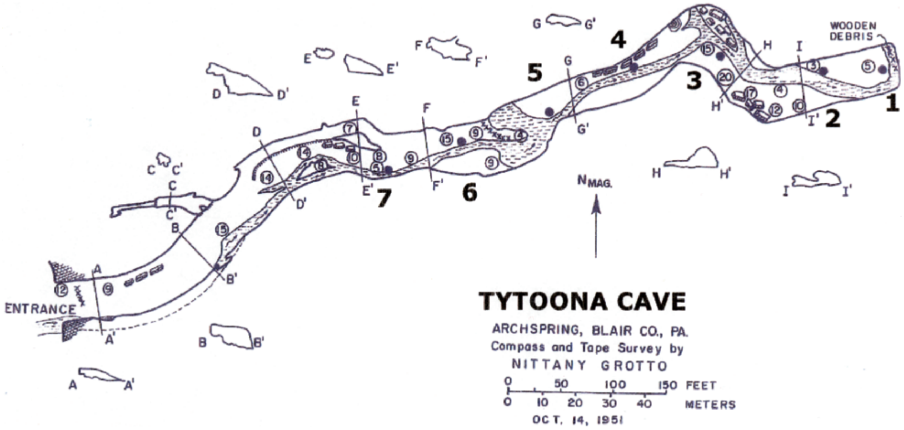

Figure 10. Map of Tytoona Cave, Blair County, Pennsylvania showing sample locations.

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. Near the cave entrance, the largest particles are cobbles and boulders, some as large as 40 cm in diameter. Qualitatively, the armor layer exhibited a fining trend downstream to a largest gravel size of 7 cm just upstream from a pool and low ceiling reach known as the "duckunder". Downstream from the duckunder are gravels with particles 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.

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 distribution 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.

5.2.2 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

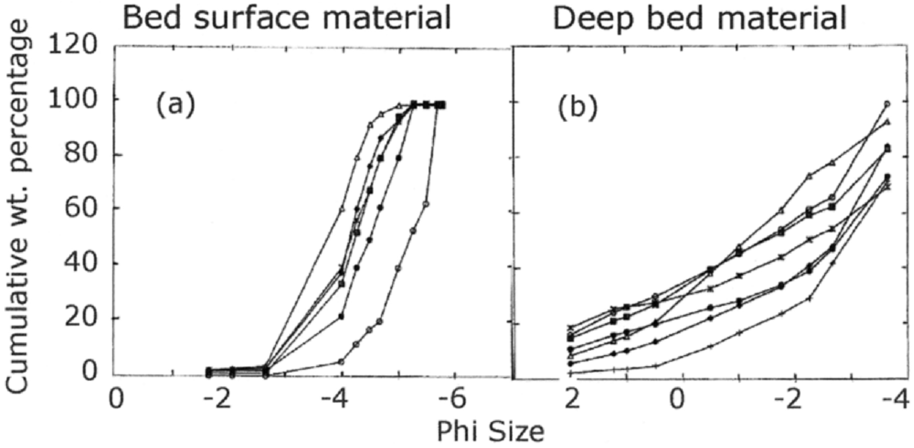

Figure 11. Thalweg facies in Tytoona Cave. (a) Armor layer making up the surface of the stream bed sediments. (b) Sediment lying directly below surface layer. There is both a surface and a subsurface distribution for each sample site. These are keyed to the site numbers shown on figure 10: diamonds = site 1; solid squares = site 2; triangles = site 3; open circles = site 4; asterisks = site 5; solid circles = site 6.

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.

5.3 Slackwater Facies

Most caves that contain clastic sediments contain slackwater facies. The slackwater facies material consists of the 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.

5.3.1 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 cm thick, of thinly layer 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.

5.4 Diamicton Facies

5.4.1 Mystic Cave

Diamicton facies, by their nature, do not lend themselves to direct observation. 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 (J.J. Van Gundy, personal communication). Mystic Cave consists of a single conduit with a small surface stream sinking at one end, 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.

Figure 12. Photo of thalweg facies in Butler Cave main stream channel.

5.4.2 Butler Cave

The Butler Cave - Sinking Creek System, Virginia, USA contains large deposits of what appear to be a diamiction facies, These occur in the tributary caves oriented down the flanks of the syncline (Hess and White, 1982; Chess et al., in preparation). 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 Mountains, 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 mountain side. These deposits are plastered into recesses in the passages walls and fill side passages. The sediment is mostly sandtone. 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 suggest 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.

Figure 13. Photo of diamiction facies. Dave's Gallery in Butler Cave.

5.5 Backswamp Facies

5.5.1 Hineman Cave

Clean backswamp facies are difficult to identify because weathering residue from the limestone is difficult to separate from other fine grained clastics. Hineman Cave, Armstrong County, Pennsylvania (White, 1976) may provide an example. Hineman 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.

6. CONCLUSIONS

Clastic sediments deposited in conduit systems can be conveniently be divided into five facies depending on the mechanism of deposition. The channel facies comprises most observed sediment piles and can be subdivided further depending on the objectives of a particular investigation. Diamicton facies and slackwater facies are deposited from suspended loads. Channel facies and thalweg facies are transported as bedload. The backswamp facies is defined to describe those residual in infiltrated clastic sediments that are deposited in place with little horizontal transport.

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