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SEDIMENTOLOGY AND PALEOMAGNETISM OF SEDIMENTS, KARTCHNER CAVERNS, ARIZONA

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Clastic deposits in Kartchner Caverns consist of coarse deposits (breakdown, pebble gravel and micaceous sand) and fine-grained deposits (fault gouge and blocky clay). The coarse deposits are all related to the vadose history of the cave, while the fine-grained deposits are related to the phreatic history of the cave and, probably, to the beginning of vadose conditions. The illite clay in fault zones was possibly derived from the underlying Pinal Schist. The clay mineral rectorite is most likely a hydrothermal alteration of illite within the faults prior to the dissolution of the cave. The blocky clay unit is autochthonous sediment that was at least partially derived from residual fault gouge clay at the time of cave dissolution. The pebble gravels were deposited during different flood events in different parts of the cave, with a lateral fining of micaceous sand in back-wash areas. The blocky clay, pebble gravel, and micaceous sand are all paleomagnetically normal and date from the Brunhes/Matuyama normal (<~780 Ka). The clay mineral nontronite probably reconstituted from residual illite/rectorite under high pH, low Eh floodwater conditions within the cave environment.

Kartchner Caverns is in the Whetstone Mountains, ~13 km south of Benson, Arizona, USA, just west of Arizona State Highway 90. The cave is developed in a downdropped block of Mississippian Escabrosa Limestone. It is a wet, “live” cave, over 3 km long, that features a variety of sediments and speleothems. Kartchner Caverns is Arizona’s 25th and newest State Park.

Clastic deposits in Kartchner Caverns were studied with respect to their mineralogy, relative stratigraphic position, and absolute ages as determined by paleomagnetic dating and uranium-series dating of interbedded travertine. The clastic deposits in the cave vary in size from large breakdown pieces to cobbles and clay. The finer-grained particles constitute the muddy floor deposits of the cave, or fill fault zones exposed in the walls and roof of the cave. Figure 1 is a map of Kartchner Caverns showing sediment sample collection sites and other places mentioned in the text. Figure 2 shows the most prominent sediment sites plotted with respect to elevation.

DESCRIPTION OF CLASTIC DEPOSITS

COARSE DEPOSITS

Breakdown. The breakdown in Kartchner Caverns varies in size from large blocks such as at the Guano Pile in the Big Room, to smaller pieces where bedrock has been shattered along fault zones. Breakdown can be found within sediment, on top of sediment, or covered by thin layers of sediment deposited under flood-water conditions. The larger upper rooms of the cave are primarily collapse passages, formed when large sections of the ceiling collapsed to the floor. Large breakdown pieces from this collapse have sometimes blocked lower solutional passages; for example, the breakdown in the Rotunda Room blocks the Triangle Passage.

The Kartcher breakdown is either of the slab or chip variety (Davies 1949). Chip breakdown is predominent in such places as the Grand Canyon, where movement along faults has shattered the bedrock. The shattered rock fell to the floor as small pieces of chip breakdown.

It is likely that the breakdown process in Kartchner Caverns has been going on during the entire vadose history of the cave. Breakdown falls during the air-filled, vadose stage of cave formation and can be due to the following factors: (1) removal of buoyant support when the water level lowers below a passage horizon; (2) base-level backflooding; (3) undercutting by free-surface streams; (4) crystal wedging processes, and (5) earthquake activity (Ford & Williams 1989). All of these factors may have been operative in Kartchner, but (1) was probably the foremost factor.

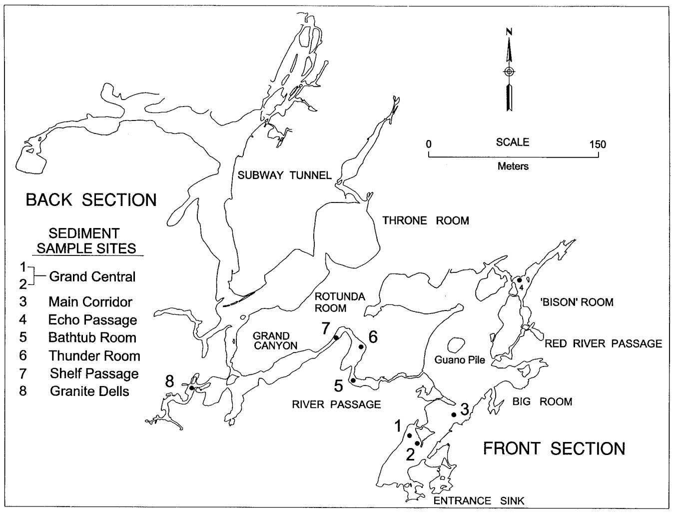

Figure 1. Map of Kartchner Caverns showing location of the sediment sample collection sites (black dots), and other locations mentioned in the text.

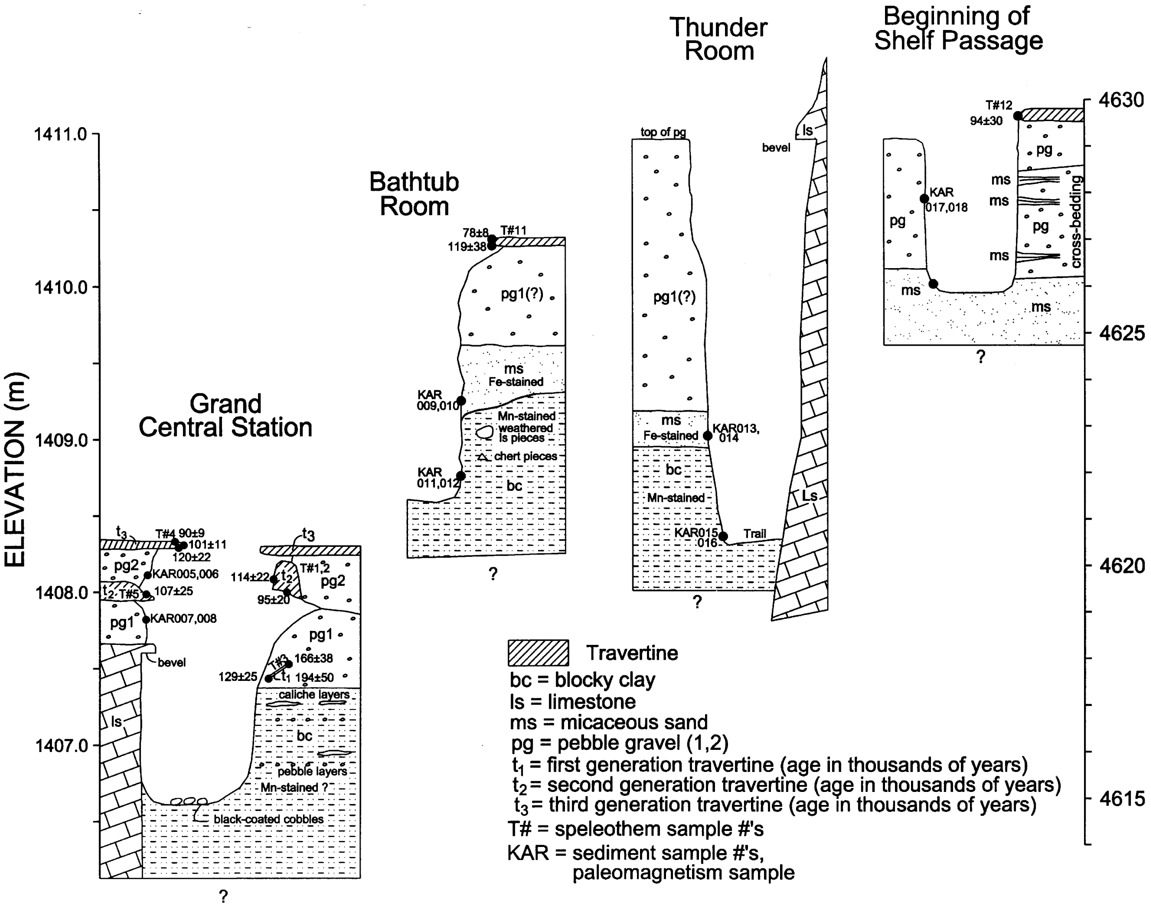

Figure 2.

Prominent sediment locations in Kartchner Caverns plotted with respect to elevation, interbedded travertine (t_1, t_2, t_3), and paleomagnetic sample (KAR) collection sites.

Pebble gravel. The pebble gravel contains clasts up to 1.2 cm in diameter in a matrix of smaller pebbles, sand, silt and clay. A hand-lens inspection of the pebble gravel indicates that this unit is made up of ~80% quartz pebbles, 10% quartzite pebbles, and 10% sand-, silt-, and clay-sized particles. The largest clasts are the quartzite pebbles.

In Grand Central Station, the pebble gravel came into the cave in at least two episodes, as determined by uranium-series dating of interbedded travertine (Ford & Hill 1999). A broken stalactite (t_1 = 194-129 Ka) is encased in the oldest pebble gravel (pg1), which was then covered with a small amount of travertine (t_2 = 115-95 Ka or so) (Fig. 2). Later, more massive travertine (t_3 = 110-90 Ka or so) covered pebble gravel pg2. From the closeness of dates on t_1, t_2 and t_3 travertine material, and the lack of any travertine material between the three, it seems as if the pg1 and pg2 pebble gravels may have been rapidly placed into the cave, perhaps with each gravel unit forming in a single, separate event. Finally, the whole sequence was downcut by late-stage vadose stream activity, and the second (t_2) and third (t_3) generations of travertine were left as hanging canopies of flowstone or dripstone—such as the 'hanging' t_2 stalagmite along the west wall of Grand Central Station (Fig. 2).

In the Thunder Room-Shelf Passage, the top of the pebble gravel is at the same level as the undercut bevel in the wall limestone (Fig. 2), indicating that the same backflood water may have been responsible for both phenomena. In the Shelf Passage, the pebble gravel is graded (coarser at bottom to finer at top), very faintly cross-bedded, and interbedded with micaceous sand. Slump features show that the sediment slumped towards the center of the passage as the passage was being downcut.

In Granite Dells, the pebble gravel contains large (up to 0.3 m in diameter) granite cobbles and boulders that must have slumped into the cave from the surface. Surface gravel above Granite Dells resembles the pebble gravel in the cave except that it lacks the fine-grained silt and clay fraction. Mica crystals in the granite pieces have a gold-like appearance and are very noticeable. In the pebble gravel within the cave, the mica is covered with mud but is observable when the gravel is washed.

Micaceous sand. Micaceous sand occurs directly beneath the pebble gravel and above the blocky clay in the Bathtub Room (Fig. 3), in the Thunder Room, and intermittently in size-sorted pebble gravel at the beginning of the Shelf Passage (Fig. 2). It is a laminated sand, the laminae being highlighted by iron-rich sections. It is a very fine-medium sand (0.1-0.4 mm) composed of approximately 95% quartz sand and 5% mica flakes. The micaceous sand contains no larger clasts within it.

FINE-GRAINED DEPOSITS

Fault gouge clay/silt. The fault zones exposed by the cave are filled with quartz veins and clasts, calcite, and/or a red to orange hematitic clay matrix. An example of this type of clay is the 'red fault clay' in the ceiling of the Main Corridor (Fig. 1), which is composed of an equal mixture of calcite and rectorite-illite clay. The calcite occurs both as disaggregated fragments and also as scalenohedral crystals, which may mean that some of the calcite was deposited before final movement along the fault zone (the disaggregated fragments), while some formed later, after final movement (the scalenohedrons). The clay mineral rectorite occurs as twisted scales and has formed from, and has mostly replaced, illite.

Another occurrence of fault gouge clay is found at the end of the Red River Passage. This clay is composed of 80% greenish-gray, finely-laminated illite, with minor angular quartz clasts and red colloidal hematite between laminae (Hill 1999, Fig. 6). The illite is weakly foliated, but the foliation is mimetic, meaning that the foliation of the mineral occurred before its deposition and lamination as a sedimentary deposit, perhaps when it was part of the underlying Pinal Schist.

Fault gouge material sloughs off of the ceilings and walls of the cave to accumulate on the floor beneath fault zones in a number of places. Such residue collected near Grand Central Station can be classified as a very fine-medium grained silt (0.005-0.02 mm). Probably this residue has been size-sorted; therefore the fault gouge material can be considered to be a clay, with a fine-grained silt fraction.

Blocky clay. The blocky clay unit is a floor clay composed of various clay minerals plus detrital and organic matter, which has compacted into separate 'blocks'. The blocky clay unit directly underlies micaceous silt and pebble gravel in the Bathtub Room (Fig. 3), in the Thunder Room, and the pebble gravel unit pg1 in Grand Central Station (Fig. 2). In these three localities, its 'block' segments are covered with thin, black, manganese-rich coatings. In the Bathtub Room, the unit encloses angular chert fragments (fallen roof breakdown) and fossiliferous limestone pieces. Harder 'caliche' layers occur in sections of the blocky clay in Grand Central Station, and there is a possible erosional unconformity between sections of the blocky clay and micaceous sand in the Bathtub Room (Fig. 2).

The composition of the blocky clay unit in the Throne Room contains an equal mix of illite clay (half altered to rectorite) and quartz needles (slender, doubly-terminated prisms). In addition, there is an abundance of organic fiber in the clay. The illite occurs in radially disposed domains and may replace feldspar.

At the Echo Passage-Bison Room junction, a transition can be seen between unconsolidated nontronite clay to compacted blocky clay over a vertical distance of ~1 m. As the clay dried and compacted, it broke up into separate 'blocks'. Black material then migrated to the surfaces of these blocks, depositing as thin layers of manganese and other metallic material (Hill 1999, Fig. 7).

Unconsolidated clay. Mud is encountered in numerous places in Kartchner Caverns, especially in the Back Section. The unconsolidated mud of the Subway Tunnel is composed mostly of the pasty, greasy, sticky clay mineral, rectorite, and it is possible that the 'mud' in the entire Back Section is, at least partially, composed of this mineral. The 'mud' in Echo Passage is composed of nontronite.

PALEOMAGNETIC DATING OF SEDIMENTS

All of the floor sediments—the blocky clay unit and the different pebble gravel units—are paleomagnetically normal. Since these sediments have been correlated with uranium-series ages on interbedded travertine (Ford & Hill 1999), it is surmised that they all date from the Brunhes/Matuyama normal (<~780 Ka) rather than from an earlier normal. Locations where sediment samples were collected for paleomagnetic dating are shown in Figure 2 (KAR).

INTERPRETATION OF THE SEDIMENTOLOGY

The coarse- and fine-grained deposits in Kartchner Caverns have different origins. The coarse deposits are all related to late-stage vadose events in the cave, whereas the fine-grained sediments have a more complex history, one extending back to the time of faulting and one involving the alteration and replacement of clay minerals. Since the fine-grained sediments are older, they will be discussed first.

FINE-GRAINED DEPOSITS

The origin of the fault gouge clay/silt is speculative. It is known that illite fills the faults and that this mineral was altered to rectorite *in situ*, but what is not known is if there was an even earlier mineral precursor of illite *in situ*. In other words, did minerals like the feldspars and micas originally fill the faults before altering to illite (and then rectorite), or was the illite clay the original constituent of the faults?

Two clues seem to present themselves in this regard. One clue is the presence of 'birdsnest' quartz near or in the fault zones. These quartz needles probably grew into a clay matrix during the time when hot, silicifying solutions permeated the fault zones. If feldspar-mica debris did at first fill the fault zones, it must have altered quickly to illite-rectorite clay so that the quartz needles could grow into this clay matrix.

The second clue is the illite-filled fault zone at the end of Red River Passage. This illite is thinly laminated and contains angular quartz, much as one would expect of a sedimentary deposit. This illite displays mimetic foliation, which means that the foliation was assumed from some precursor mica or feldspar mineral *before* deposition and lamination of the clay. This opens up the question of whether the Pinal Schist (a foliated rock) might have been the original source of illite to the fault in Red River Passage. Might ascending solutions have carried clay material up the fault zones from the Pinal Schist and deposited it as a sedimentary deposit within some type of paleokarst cavity? How far below the Escabrosa block the Pinal Schist resides is not known exactly, but Graf (1989) showed it as being less than 30 m. The laminated illite in the Red River Passage must be very old. It predates the cave (it is truncated by it) and its beds tilt northeast to east, not southwest as do the Escabrosa Limestone beds (Jagnow 1999). Either the illite was emplaced and tilted before the tilting of the Escabrosa block, or later movement along the fault zone caused the illite layers to tilt in a direction opposite to that of the bedrock. Curiously, the Red River fault cannot be traced to the surface (Jagnow 1999).

It is uncertain if the blocky clay unit is autochthonous in origin, as suggested by Graf (1989), if it is allochthonous, or if it might be a combination of both. In Grand Central Station, the blocky clay has sections of pebble gravel in it (Fig. 2), and in the Thunder Room it is mixed with organic matter. These occurrences both suggest an allochthonous origin for the blocky clay unit. However, rectorite clay fills the 'red fault zone' in the Main Corridor and is also the main component of the Subway Tunnel 'mud', which suggests that some 'mud' might be autochthonous fault-derived residual material. Similarly, illite is the main component of the fault gouge clay in Red River Passage and it is also the main mineralogical component of the blocky clay in the Thunder Room. Perhaps, then, the blocky clay is a combination of allochthonous and autochthonous sediment. Volume considerations favor this interpretation as does the Thunder Room blocky clay, which consists of illite and quartz needles (dissolved from the fault zone?), feldspar, and organic material (possibly brought in as allochthonous debris).

Another uncertainty exists for the origin of the nontronite clay in the Echo Passage. Nontronite is a mineral known to be derived from granitic terranes where the clay forms from the alteration and breakdown of mica minerals, and it is possible that alaskite granite and/or Pinal Schist debris could be the source of mica for the nontronite. However, granitic pebble gravel and micaceous sand do not actually occur within the Echo Passage. There is the added problem in that the nontronite and black manganese material expelled from the nontronite is enriched in metal. Such an enrichment must have involved some kind of hydrothermal activity where the faults acted as conduits for ore fluids. These factors suggest that the nontronite constituents were derived from residual fault gouge material (illite-rectorite) as the cave passages dissolved.

The following 'best-guess' scenario for the fine-grained clay deposits in Kartchner Caverns is suggested:

1. Illite was deposited in fault zones by hydrothermal solutions ascending through the Pinal Schist and into the above-lying Escabrosa Limestone. These same solutions brought up silica and iron (and other minor metallic constituents), which were deposited along with the illite in the fault zones as quartz and hematite. Hydrothermal solutions also altered some of the illite to rectorite.
2. Calcite was deposited in the fault zones as the temperature decreased. Late movement along the faults disaggregated this calcite and some of the older vein quartz.
3. Cave dissolution exposed some of the illite-rectorite fault gouge clay and this material formed the blocky clay unit.
4. Finally, vadose flood water of high pH and low Eh altered residual illite-rectorite clay to nontronite on the floor of Echo Passage.

COARSE-GRAINED DEPOSITS

All of the coarse-grained clastic deposits are related to vadose events in the cave. As the water table dropped, breakdown collapsed to the floor, blocking some of the lower solutional passageways. Later, flood water dumped sand and gravel into the cave where they covered the fine-grained blocky clay unit. The following observations apply to the interpretation of the coarse-grained deposits in Kartchner:

1. The pebble gravels in the cave are essentially the same as surface gravels above the cave except for the fine-grained fraction. Thus, the pebble gravels were probably locally derived, entering the cave during times of heavy storms.
2. The age of the blocky clay, micaceous sand, and pebble gravel are all between 780 Ka and 100 Ka based on the travertine and paleomagnetic dating results (Ford & Hill 1999). The pebble gravels correspond to the time of greatest travertine growth in the cave—during the Sangamon interglacial where a wetter climate could have produced storms capable of moving surface gravels into the cave. It can be estimated from Hjulstrom's diagram for the transportation and deposition of sediment (Hjulstrom 1931), that the velocity of the water depositing the pebble gravels must have been between 10 and 90 cm/s; either that, or the gravel could have also partially slumped into place.
3. The Granite Dells cobbles/boulders in a matrix of pebble gravel had to have slumped into place. Granite Dells is very near the surface, and pirated surface runoff probably transported surface sediment into the cave at this location sometime in the past (176 Ka?); (Ford & Hill 1999, Table 1).
4. The micaceous sand probably represents a lateral-fining equivalent of the pebble gravel. The first particles to deposit in a back-wash situation are large pebbles; then, when the velocity has decreased markedly, the fine-grained fraction (mica flakes, fine sand, silt and clay) settles out. The fine-grained fraction typically grades laterally from the center of passages and are finest-grained in deep recesses. Thus, the pebble gravel over micaceous sand/silt may represent two episodes of flooding, the first less violent or extensive than the second. For example, for the Bathtub Room sediment sequence (Fig. 2), flood event #1 may have deposited pebble gravel in another part of the cave and mica sand as a laterally-fined sediment in the Bathtub Room. A more violent flood event, #2, could have brought gravel into the Bathtub Room, creating the

Figure 3. Blocky clay (lower, dark unit), micaceous sand (middle, iron-stained unit), and pebble gravel (upper unit), Bathtub Room. Scale is 16 cm long. Photo by Bob Buecher.

sequence where pebble gravel overlies micaceous sand. The interbedded graded sequence of pebble gravel-micaceous sand in the Shelf Passage (Fig. 2) attests to the probable cyclic and repetitive nature of the sediment-filling process in parts of Kartchner Caverns.

CONCLUSIONS

1. The illitic fault gouge clay is the oldest clastic unit in Kartchner Caverns. Its origin is speculative, but the illite probably derived from feldspars and micas of the underlying Pinal Schist before the dissolution of the present cave passages.
2. Illite was probably altered to the mineral rectorite by hydrothermal solutions. This is shown by high-temperature quartz needles which have grown into the rectorite along the fault zones.
3. The blocky clay unit is partly autochthonous in origin, having derived from the illite-rectorite fault gouge clay during the dissolution of the cave. However, it may also be partly allochthonous as suggested by sections of pebble gravel and organic matter within this unit. It is likely that the blocky clay unit represents the time of shallow-phreatic dissolution of the cave at or near the water table, and also the beginning of vadose conditions within the cave.
4. The vadose pebble gravels were brought into the cave by flooding, or from the slumping of surface deposits into the cave.
5. The micaceous sand unit probably represents a lateral-fining facies of the pebble-gravel deposits.
6. The blocky clay unit, the pebble gravels, and the micaceous sand are all <780 Ka from paleomagnetic dating of these units.
7. The mineral nontronite probably reconstituted from precursor illite-rectorite in a high pH, low Eh, floodwater environment within the cave.

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