THE EARLIEST TIME OF KARST CAVE FORMATION

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Abstract
The earliest cave genesis is constructional cave formation, as in tufa caves and reef macro-porosity, which occurs simultaneously with carbonate rock deposition but without in situ dissolution. Syngenetic caves form by dissolution in unlithified sediments, as syndepositonal caves; and by dissolution in lithified but diagenetically immature carbonate rocks, as eogenetic caves. Carbonate burial results in diagenetic maturity, and produces mesogenetic caves by hypogenic processes. Re-exposure of diagenetically-mature carbonates on the earth's surface results in telogenetic caves. Marble caves form in metamorphosed carbonates derived from mesogenetic or telogenetic conditions.

Keywords: carbonates, caves, constructional caves, diagenetic maturity, eogenetic, karst, syndepositional, syngenetic

INTRODUCTION

The term syngenetic karst was first presented by Joe Jennings in 1964 at the 20th International Geographical Congress in Great Britain (Williams & Jennings, 1968). The term was subsequently published four years later by Jennings (1968) in a paper entitled "Syngenetic Karst In Australia". Syngenetic karst became a standard term to describe caves and karst that had formed in young and diagenetically-immature carbonate rocks. The foundation for Jenning's ideas came from investigations by himself and a number of workers in western and southern Australian eolian calcarenites in the late 1950's and early 1960's (Grimes, 2006 and references therein), but Jennings (1968) did not provide a specific definition for syngenetic karst. The abstract of the paper (Jennings, 1968, p. 41) states: "To a certain degree karst processes have gone on concurrently with the consolidation of calcareous shell sand into aeolian calcarenite, i.e. the karst is partially 'syngenetic'." In his Introduction, Jennings (1968, p. 45) treats the terms "consolidation" and "lithification" as equivalent, and considers diagenesis as part of the lithification process. In two subsequent texts on karst Jennings again states that syngenetic karst is karst development during consolidation: "Some caves occur in only partially consolidated sands even today." (Jennings, 1971, p. 198) and "syngenetic ... in that its development accompanied consolidation of the sands" (Jennings, 1985, p.222). Starting with Monroe's (1970) definition of syngenetic karst as "Karst developed in eolian calcarenite where lithification and karstification of dune sands occurred simultaneously", later karst dictionaries and the Glossary of Geology (Neuendorf, et al., 2005, p. 651) have all used variants of that theme, though not necessarily restricted to dune calcarenites.

Many subsequent authors (e.g. James & Choquette, 1984, p.176; Ford & Williams, 1989, p. 445; Grimes, 1994, 2004; Lundberg & Taggart, 1995, p. 178; and White 1994, 2000) have followed Jennings in using syngenetic karst for "contemporaneous with consolidation/lithification". As Jennings (1968) was using Australian eolian calcarenites as his primary examples of syngenetic karst, the youthfulness of these rocks led some later karst workers to assume that syngenetic karst was solely an immediate post-depositional phenomena. However, Jennings' 1968 discussion of the term extends it from the post-depositional environment of consolidation and lithification well into the realm of diagenesis, an on-going and somewhat open-ended process in sedimentary rocks. Use of the term “consolidation” also opens the possibility that syngenetic caves would include karst caves developed as the carbonate sediments were being deposited.

The purpose of this paper is to re-visit the term “syngenetic karst” with respect to a larger body of literature involving cave and karst development in young carbonates that has appeared since the 1960’s, and to address the boundary condition of the earliest possible developmental time frame for initiation of karst caves. Carbonates have been selected as the representative karst rock to use in this presentation, as other common karst rocks (e.g. gypsum and halite) are not as easily discussed in terms of diagenetic maturity.

CARBONATE ROCKS: DEPOSITION, LITHIFICATION, AND DIAGENESIS

The idea of syngenetic karst is perhaps better understood when it is placed in a broader view of carbonate sediment deposition and rock development. A hierarchy of cave development conditions can be established based on the post-depositional evolution of carbonate porosity into three time-porosity stages that conform to carbonate rock maturation as stated by Choquette & Pray (1970, p. 215): "the time of early burial as eogenetic, the time of deeper burial as mesogenetic, and the late stage associated with erosion of long-buried carbonates as telogenetic". Vacher & Mylroie (2002, p. 183) defined “the term eogenetic karst for the land surface evolving on, and the pore system developing in, rocks undergoing eogenetic, meteoric diagenesis.” Using this broad model as a framework, syngenetic karst can be seen to include the entire eogenetic portion of rock maturation. Jennings (1968, p. 45) is somewhat obscure as to when lithification stops, but he clearly differentiates between rocks that are diagenetically mature, and rocks that are not; only the latter could develop syngenetic karst. Once rocks undergo deep burial, the mesogenetic stage of Choquette & Pray (1970), they can no longer be considered either syngenetic or eogenetic.

In Australia, the terms “soft rock” and “hard rock” have been utilized by the speleological community to differentiate caves developed in rocks at the two extremes of diagenetic maturity (Grimes, 2006). These are general, nonspecific terms, but they appear regularly in the speleological literature in that country. The problem these terms create is that they imply hardness and diagenetic stage are equivalent. While older, diagenetically mature rocks are commonly much harder than young, diagenetically immature ones, some rocks are deposited with a high degree of cementation, such as depositional micrites, even though they have not undergone burial.

We must emphasize that geologic processes operate at different rates in different areas. For example, some New Zealand Oligocene carbonates are telogenetic as a result of the vigorous tectonic burial and uplift at a plate boundary, while rocks of similar age in Florida, on a passive continental margin, are still eogenetic. The age or hardness of the rock can be misleading, what is important is the diagenetic character of the rock at the time of cave genesis.

THE EARLIEST CAVES IN CARBONATE ROCKS

Once a carbonate deposit is formed, how quickly after that deposit’s formation can caves develop? Does the carbonate deposit have to be lithified to any extent - does it have to be rock? Cave development early in the history of a carbonate deposit may influence later dissolution in the subsequent carbonate rock.

CONSTRUCTIONAL CAVES

Tufa caves are an excellent example of constructional caves in carbonates. They develop where precipitation of calcareous tufa on slopes leads to overhanging ledges that then seal by further precipitation to enclose or partially-enclose chambers (Bögli, 1980, Fig. 13.51). While the sealed void is produced by CaCO3 deposition, it was dissolution of the CaCO3 elsewhere that provided the raw material for the construction of the void. Another example of constructional caves is in coral reef development, where cavities can be created by coral growth. As with tufa caves, they have not formed by dissolution, but by carbonate precipitation. It is not intended here to provoke an argument about whether tufa caves and reef macro-porosity are karst or pseudokarst, but to merely use them as examples of caves created as constructional features during carbonate rock deposition (note that both examples bypass a soft-sediment stage and precipitate directly as rock). Constructional caves represent the earliest mechanism by which caves can form in carbonate rock, but they are not karst caves formed by in situ carbonate dissolution.

SYNGENETIC CAVES

Syngenetic caves, as presented by Jennings (1968) and later workers previously mentioned, describe cave development while the sediment consolidates. Carbonate sediment deposition and compaction are part of the consolidation process, which with cementation, is lithification. However, diagenesis can initiate within a carbonate sediment deposit prior to lithification (Neuendorf, et al., 2005, p. 176). It is therefore possible to make an admittedly subtle differentiation in the timing of cave development as regards carbonate deposition and lithification.

Syndepositional Caves

Syndepositional caves are karst caves formed by dissolution while the carbonate sedimentary unit containing the caves is still being deposited. Two examples can be examined. In one hypothetical case, an eolian calcarenite is deposited across the axis of a small surface stream perched on non-carbonate rock. Water may continue to flow along the contact, and through the high porosity of the eolian sand (commonly >30%). Dissolution could be initiated in the lower portions of the eolian body while the upper portions are still undergoing deposition. While such eolian carbonate material is poorly consolidated and barely lithified, the great geochemical mobility of CaCO3 in surficial meteoric environments means that early grain-to-grain miniscus cementation, sufficient to avoid soft sediment flow, can keep the initial dissolution voids intact so that conduit flow can be maintained. Once deposition of the eolian body ceases, a calcrete crust develops rapidly and stabilizes the dune (Carew & Mylroie, 1995; 1997 and references therein). Later eolian activity may on-lap the original eolian unit, but that original unit has been isolated as a single depositional event. Depending on the length of time between depositional events, the initial dune may develop a terra rossa paleosol. Once a calcrete crust has formed, however, the eolian body has passed from the syndepositional cave formation environment into the later post-depositional cave formation environment.

A second example of syndepositional cave formation involves lagoonal carbonates that are immediately overlain by beach sands. Such progradation of carbonate sands is common in CaCO3 depositional environments such as the Bahamas (e.g. Carew & Mylroie, 1995; 1997). The seaward migration of the terrestrial beach environment allows the fresh-water lens of the coastal area to also extend seaward, and invade the now-covered lagoonal carbonates. In this environment, mixing dissolution can create voids within the lagoonal and beach facies even as the beach continues to grow above the incipient voids, and beach and lagoonal sediments are being deposited in adjacent areas. This cave development occurs without a sea-level change, as a result of a progradational sedimentation event. We classify such caves as syndepositional, and they have been described in the Bahamas from San Salvador (Florea, et al., 2004) and New Providence (Mylroie, et al., 2006).

The term “syndepositional caves”, as presented here, is somewhat argumentative. If cementation initiates in the lower part of a continuously depositing unit, as the upper layers are still being laid down, is that lower region still part of the depositional environment? The important point to be made is that karst cave development by dissolution of carbonate material can occur in the exact same environment, at the exact same time, where carbonate deposition is on-going, if not at the exact same spot. It is difficult to present an earlier time of karst cave formation.

Eogenetic Caves

Once the carbonate sediment has been deposited as an identifiable unit, any subsequent cave and karst development is post-depositional, but occurring initially in a diagenetically-immature, partially lithified rock and therefore under syngenetic conditions. The term "post-depositional" is unbounded, it would encompass not only eogenetic conditions as described by Choquette & Pray (1970), but also their mesogenetic and telogenetic realms. It is therefore useful to subdivide the post-depositional phase by following the Choquette & Pray (1970) classification scheme: eogenetic caves, mesogenetic caves, and telogenetic caves. The eogenetic phase is a subset of the syngenetic condition. The end of syngenetic cave development may be conveniently considered to be the end of eogenetic conditions for the host carbonate rock. Choquette & Pray (1970) describe the time of early burial as eogenetic; early burial implies a transition from the depositional to the post-depositional environment. Vacher and Mylroie (2002, p. 215) describe eogenetic karst as forming in "rocks undergoing eogenetic, meteoric diagenesis"; the use of the term "rock" also implies a post-depositional environment. For these reasons, the term "eogenetic caves" is used here for the post-depositional, partially-lithified, and diagenetically-immature stage of cave formation, a subset of the syngenetic cave environment.

MESOGENETIC CAVES AND TELOGENETIC CAVES

The syngenetic environment, including the eogenetic stage, ends when the carbonate rock undergoes burial diagenesis, entering the mesogenetic environment. Diagenesis advances and the rock becomes fully lithified and diagenetically mature. Such burial removes the carbonate rock from the surficial meteoric environment, and hence from the epigenic environment of Palmer (1991). Dissolution to form karst caves in the mesogenetic setting can only occur by fluids decoupled from the surface hydrology, described by Palmer (1991) as hypogenic caves. So all mesogenetic caves are hypogenic caves.

The reappearance of diagentically-mature carbonate rocks at the earth's surface places them in the telogenetic environment, the cave and karst situation common in continental interiors. Most telogenetic caves are epigenic, as the definition of the telogenetic condition is reappearance of the limestone into the surficial weathering environment. The metamorphosis of limestone into marble presupposes that the rock has gone at least as far as the mesogenetic condition, but does not eliminate the option of the limestone first having a residence time in the telogenetic environment before re-burial to metamorphic conditions creates the marble. Given the loss of bedding plane partings, and the presence of boudinage, isolated schist bodies, and other aspects of marble structure, it is not unreasonable to consider marble an additional step in carbonate maturity, even if metamorphism is considered a step beyond diagenesis.

CONCLUSION

The relationship of earliest time for the development of karst caves to the deposition of the carbonate sediments that host karst caves, and the subsequent stages of karst cave formation, are as follows:

1) Constructional caves are the earliest possible type of cave to form when carbonates are deposited, but they are not karst caves produced by in situ dissolution. Tufa caves and coral reef macro-porosity are examples.

2) Syngenetic caves are those produced during the consolidation, diagenesis, and initial lithification of carbonate sediments. They fall into two categories:

A) Syndepositional caves form as the body of carbonate sediment is being deposited, as the very earliest diagenesis and lithification allows mechanical support of the dissolutional void produced, even as carbonate deposition continues uninterrupted at that site.

B) Eogenetic caves form in carbonate rocks after deposition of the unit ceases, and lithification and diagenesis continue under meteoric conditions.

3) Mesogenetic caves form after burial removes carbonate rocks from epigenic, meteoric diagenesis, and hence the syngenetic and eogenetic environments. The isolation from meteoric waters results in mesogenetic cave formation being an obligatory hypogenic process.

4) Telogenetic caves form after uplift and surficial exposure of formally mesogenetic carbonate rocks.

5) Marble caves form after metamorphism of the carbonate rocks, can start from either the mesogenetic or telogenetic condition, and can occur in either hypogenic or epigenic conditions.

In summary, karst caves can begin to form as soon as carbonate sediments are placed in the meteoric environment, with cementation and dissolution occurring simultaneously to create a void with enough mechanical strength to reach cave size. Karst cave evolution proceeds through several stages of diagenetic maturity, each of which leaves a unique signature in the caves thus formed.

This paper had two goals: first, to explain the origin of the term syngenetic, and how that term has been used and applied; and second, to fit that term into a continuum relating carbonate rock maturity to speleogenesis, especially the earliest possible karst cave formation. Given that constructional caves may not be karst caves, syngenetic caves in the syndepositional setting provide the earliest end-member in the total time spectrum of karst cave origin.

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