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Cave pearls: origin, morphology, growth and mobility

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Abstract: Among speleothems, cave pearls are commonly overlooked and hence have generated less research interest than more-obvious cave deposits such as stalactites, stalagmites, and curtains/shawls. Yet, when considered in detail, aspects of the creation and morphology of cave pearls, as secondary unattached mineral deposits, are more complex than they appear at first glance. Many variables influence their growth, structure and appearance; these factors deserve deeper investigation to help provide a better understanding of their creation parameters. This article summarizes published knowledge about – and previous discussions of – cave pearls and includes details of the author's related observations.

The parameters that create cave pearls with smooth or coralline (dendritic) morphology are discussed along with what prevents them from adhering to the cave floor substrate. Their morphology is typically related to their location beneath a drip point or whether they are partly or fully immersed in a pool of water. Whereas their continued detachment relies on being repeatedly moved or vibrated by the energy from direct impact of drips and/or compression waves created by bubble implosions when drips impact the pool surface. Unlike the mechanical waves related to surface ripples, the acoustic compression waves propagate through the entire water body to vibrate submerged cave pearls.

Although cave pearls composed of various minerals have been recognized and studied, emphasis is placed upon knowledge of those most-commonly described, which are created by deposition of calcite from saturated solutions of calcium carbonate. In agreement with the recommendations of several previous authors, it is emphasized that cave pearls should not be referred to as oolites, pisolites or oncolites, which are defined geological terms intended for use in classifying sedimentary rocks that exhibit superficially similar structures and textures but are of different derivation.

Keywords: calcium carbonate; calthemite; cave minerals; conulite; drip-water; microbes; oncolite; oolite; oolith; pisoid; pisolite; spaeloid; spelean pisoid; speleothem; vadoid.

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Introduction

In discussions of speleothems in caves, cave pearls are commonly overlooked or under-described in favour of the more prominent stalactites, stalagmites and sheet-like deposits (e.g. curtains, draperies, shawls). Despite this, cave pearls do deserve greater attention, because details of their creation are more complex and fascinating than they appear at first glance.

***Figure 1 (above)**: Part of a more extensive spread of cave pearls covering the floor of a cave chamber where water pours in from the ceiling during periods of monsoon rain. Cathedral Cave (KNI080), Ningbing Range, Western Australia. The largest pearl is 70mm in diameter.*
*[**All figures are by Garry K Smith, unless specified otherwise**.]*

***Figure 2 (right)**: Steve Bourne observes cave pearls in a shallow pool under a cave shower head in Drunken Forest Cave, Mulu, Sarawak.*

Many variable factors, including detailed location within the cave, supply of saturated solution, drip rates, drip height (a proxy for the kinetic energy of drips), air movement, cave temperature, and the partial or full immersion depth in saturated water, can all influence their growth and morphology. These and other variable parameters that influence cave pearl growth and morphology are discussed below.

Cave pearls typically form under a drip point or in a shallow cave pool (Figs 1 and 2). Their growth occurs due to deposition from a saturated solution of calcium carbonate ($CaCO_3$) or, less commonly, another mineral. The concentrically banded concretions range in size from as small as a sand grain up to 15cm in diameter or more. Normally they do not exceed 2–3cm in diameter before becoming attached to whatever substrate comprises the cave floor. Given ideal conditions, such as in Son Doong Cave, Vietnam, some pearls have grown to "*the size of basketballs*" (Jenkins, 2011, p.125).

Figure 3*: Coralline cave pearls c. 50mm in diameter, each weighing 85g, from cave KNI90, Ningbing Range, Western Australia.*
See also ***Figure 7B****, which shows a sectioned coralline cave pearl.*

Figure 4*: Cave pearls of various shapes, collected from Pau Atea Cave (Atiu Island) in the Cook Islands.*
Note*: the direction of view in* ***Image 4A*** *is chosen to emphasize that the pearl's shape resembles a flattened sphere.*

Figure 5*: Cave pearls* ***20mm in diameter*** *with a cross-section similar to that shown in* ***Figure 4A****; in this example, however, a thin horizontal flange of calcite has grown out from the pearls.*
Pau Atea Cave, Atiu Island, Cook Islands.

Another unusual example is in the Cave of the Marbles (Gruta de las Canicas), Tabasco, Mexico, where it has been estimated that 200 million cave pearls (averaging 1–1.5cm in diameter) cover the cave floor up to a metre or more in depth (Houston *et al*., 2008). To date it has not been determined what environmental conditions facilitated the formation of such vast quantities of cave pearls or why in this situation they have not become cemented together (Houston *et al*., 2008). Cave pearls are more commonly found in small clusters of just a few up to a hundred or more.

In limestone caves, including those in other carbonate-rich rock types, cave pearls are composed mostly of calcite and/or aragonite (Hill, 1992). Within caves formed in other non-carbonate bedrocks, cave pearls can be composed of other minerals, including goethite, whitlockite, carbonate-hydroxylapatite [now known as hydroxylapatite], smithsonite and hydrozincite (Hill and Forti, 1986; Shopov, 1993; Hill and Forti, 1997).

Because most cave pearls form in limestone caves and consist of calcium carbonate ($CaCO_3$), this article generally considers cave pearls that have been created by the deposition of calcite, which is the most stable and common $CaCO_3$ polymorph, followed by aragonite and vaterite.

In the mid-18th century, John Hill (1748) was the first author to describe these concretions as 'balls' that looked like polished marble. He also stated that when broken they revealed a nucleus around which were "*…a vast number of crusts, all of the same thickness and neatly and exactly cohering together …*". He classified them as "*Stalagmitae*" and divided then into five different types according to surface texture, thickness of layers, and colour. Three polished-surface specimens that clearly appeared to be cave pearls were classed as "*Stalagmodiaugia*", and two smaller varieties were called "*Stalagmoscieria*". Others with a rough crystalline surface were referred to as "*Stalagmodiaugium*".

Early in the 19th century, Jacques Louis comte de Bournon (1808, 174–175) called similar cave concretions "pisolites". He was the first author to recognize the role and importance of movement and rotation caused by water, which generally stopped them attaching to the floor substrate. More than 60 years later, Boyd Dawkins (1874, p.66) was the first to describe rounded concretions from a cave in Caldy Island, off the southeastern coast of Pembrokeshire in southern Wales. In particular he noted that they were observed in cave pools and should be called '*cave pearls*' in recognition of their lustre. It was another 55 years before Hess (1929) wrote the first related mineralogical article to be published in a strictly scientific journal, describing the cave pearls of Carlsbad Cavern, in the Guadalupe Mountains of New Mexico, USA (Hill, 1987).

Historically, cave pearls have been referred to by many names including: ooliths, oolites, pisolites, oncolites, vadoids, spaeloid, and spelean pisoid (Donahue, 1969; Shaw, 1992; Hill, 1992, 1996; Hill and Forti, 1997; Flügel, 2010). It is considered here that these terms should not be used to describe cave pearls, because they are geological terms used internationally to describe similarly banded concretions and related rock types with specific internal structures, including those unrelated to cave environments. These terms and their applicability are discussed further under the heading '*Concretions outside the cave environment*' below.

Appearance

Cave pearl shapes can vary considerably, ranging from spherical or cylindrical, through to irregular forms (Figs 3, 4, 5) (Hill, 1992). Instances of hexagonal and cubic-shaped cave pearls have also been recorded in various parts of the world (e.g. Roberg and Caron, 1983; Hill and Forti, 1997). Most cave pearls appear as shades of white or grey but can also exhibit a range of other colours and shades, influenced by water chemistry.

Pure calcite may be essentially colourless, tending towards opaque or translucent white, whereas shades of colours such as yellow, orange, red, brown and black are recorded as occurring where introduced impurities such as organic compounds (e.g. tannins or fulvic and humic acids) and trace elements (e.g. copper or iron) are deposited along with the calcite (Fig.6).

Most spherical cave pearls develop around a small and compact nucleus, such as a sand grain (Fig.7A) (Hess, 1929; Hill, 1992), whereas cylindrical or irregular shaped pearls tend to have a larger, elongated, or irregular nucleus, e.g. rock, bone, or shell fragments, *etc*. (Fig.7B, 7C). Although cave pearls that begin to grow as a coating around a relatively large irregular nucleus will initially retain the overall pre-existing shape, most of them will eventually tend towards greater roundness as more calcite layers are deposited, smoothing-over any original sharp corners and edges (Hill, 1992).

The external surface texture of cave pearls can range from smooth, hard and shiny, through to soft and crumbly coralloid. Smooth polished pearls form in locations subjected to the impact of drips, or in rapidly moving water, causing agitation so that both abrasion and carbonate precipitation occur. In contrast, pearls with rough coatings and possibly a dendritic morphology occur in quieter water (Hess, 1929; Donahue, 1969; Hill and Forti, 1997). Because the word 'pearl' is typically associated with a biogenically formed oyster pearl – a near-spherical polished object – cave pearls with rough coralline (dendritic) morphology are commonly overlooked and not identified with the same term as their smoother counterparts. Yet, both smooth and coralline cave pearls are mobile concretions (i.e. not attached to the cave floor/substrate) that have formed in a cave, with concentric layers around a nucleus.

Origin and morphology

Cave pearls are found in a range of settings including from on top of flowstone or mud floors/substrates, through to totally immersed in shallow cave pools. A pearl starts growing when $CaCO_3$ is precipitated from solution, crystalizing around a nucleus that might be as small as a sand grain but can be a larger object such as a pebble, a piece of bone, a broken piece of straw stalactite, or a shell fragment, *etc*. (Fig.8). Within carbonate rock dissolution caves, $CaCO_3$ in the form of calcite is the predominant mineral deposited as cave pearls (Ford, 1978). Calcite is commonly deposited by abiogenic precipitation, but there are many recorded instances of microbial communities contributing to the precipitation of calcite layers as cave pearl surfaces (e.g. Jones, 2009; Gradziński *et al*., 2012; Melim and Spilde, 2018; Richter, 2020). It appears that microbial involvement in the formation of cave pearls is most commonly evident in those that form in pools and without significant impact of dripping water (Gradziński, 2003; Jones, 2009). In contrast, those formed in splash pools commonly lack evidence of microbial involvement (Donahue, 1965; Nader, 2007).

As successive concentric layers of calcite are deposited on its outside, a cave pearl becomes larger and more rounded. As pointed out by Nader (2007), the number and thickness of a cave pearl's growth zones (layers) is not related directly to its size. Generally, the individual concretions can grow larger in locations where their movement or vibration is caused by water with relatively high kinetic energy, such as those associated with cave showerhead formations or waterfalls (Figs 1, 2) (Forti, 1983b). If a pool dries up, cave pearl growth may remain dormant for many months or years, until $CaCO_3$-saturated water once again flows into the pool or drips onto the pearls, enabling renewed calcite deposition.

Cave pearl internal structures can range from finely crystalline concentric rings (Fig.7A) through to a coarsely crystalline dendritic structure (Fig.7B). The detailed situation or location of a pearl, the saturation of its feeder solution, and the temperature of its crystallization can all impose strong influences on its internal and external morphology and its composition.

***Figure 6**: Pink cave pearls in Barralong Cave, Jenolan, New South Wales, Australia. The colour is most likely due to a small amount of tannin from vegetation (as opposed to iron) being deposited along with the calcite.*

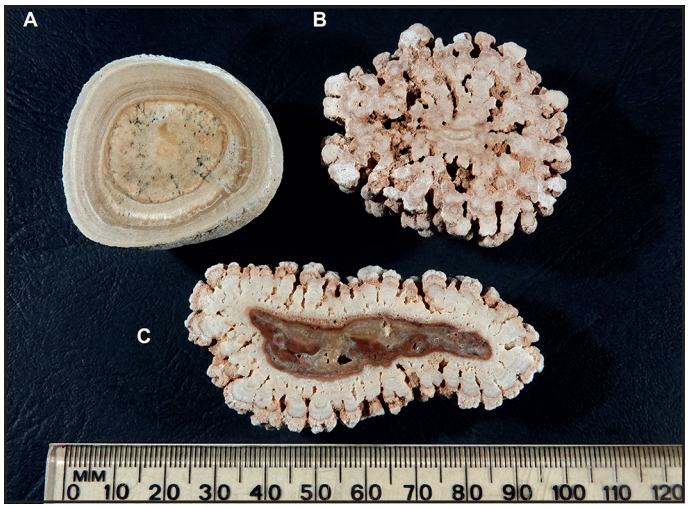

***Figure 7**: Sectioned cave pearls. **Note** the shape and size of their nuclei. **A** and **C** are from the Cook Islands, **B** is a coralline ball from KNI90 cave, Ningbing Range, Western Australia. **Note**: **7C** is a cave pearl formed around an elongated nucleus – a shattered piece of dark-coloured calcite.*

***Figure 8**: A currently dry gour pool containing snail shells at various stages of being coated in calcite to become cave pearl nuclei. KNI159 cave, Ningbing Range, Western Australia.*

Smooth and polished pearls form either below actively dripping sources of water that hits them or splashes onto them (Figs 1, 6, 10), or where water circulates rapidly past them as they grow. Most commonly their concentric growth layers are made up of microcrystalline calcite. An article by Donahue (1969) reported that agitation of cave pearls can also cause abrasion at the same time as precipitation creates compact laminations with a smooth surface and with continued growth their geometric shape tends towards near spheroidal.

An article by Forti, (1983a) reported that dripping water will agitate cave pearls, but does not rotate, nor round or polish them. Other authors have suggested that cave pearls ***can*** be rotated by drip water within the bounds of their mass versus drip impact or water agitation (Hill, 1992). Initial rounding of any sharp edges or protrusions on an irregular nucleus is most obviously promoted by motion-related abrasion. As the pearl becomes larger, abrasion from vibration and rotation becomes less and the cave pearls become more rounded because the outer layers of fine-grained calcite crystals, are growing in all directions at the same time. Increased sphericity is promoted because the greatest amount of calcite can be deposited on the smallest surface area, thus creating a round form even if the initial nucleus was an irregular shape (Forti, 1983a). As mentioned above, a cave pearl's shape also depends upon the size and shape of the nucleus, together with the number and thickness of concentric calcite layers.

Growth layers within cave pearls are clearly recognizable to the naked eye in polished sections and can be studied in greater detail under a binocular microscope or in thin-section using a petrographical microscope (Nader, 2007). Such layers may be defined by variations in colour and/or crystal structure (Fig.7). Typically, the layers or rings relate to seasonal variations in the local environment (wet, dry, temperature, airflow), which are responsible for changes in water supply, the degree of calcite saturation (which can alter crystal structure), and differences in layer thickness. Introduced impurities, such as detrital particles (e.g. silt and clay) and tannin from decaying vegetation, will highlight some growth-layer boundaries by imposing changes in colour.

The author has observed that rough, coralline or cauliflower-shaped, cave pearls with a dendritic structure are found typically in shallow (≲300mm-deep) pools, generally fully immersed at various depths (Figs 3, 7B–C, 15, 16). It is postulated by Martini and Grimes (2012) that such deposition has occurred in an environment alternating between subaquatic and sub-aerial (evaporation). Hence, the rough, coralline-type crystals grow on the pearl's surface. Such coralline-type pearls (Figs 3, 16) – some of them described as 'coral balls' – appear to be more common in areas of tropical karst (Martini and Grimes, 2012). Their growth (calcite deposition) is aided by the more-rapid diffusion of carbon dioxide (CO_2) into cave air that is well ventilated, as is common in the warmer conditions of tropical karst caves. Cut sections of these coralline-textured cave pearls display laminated, dendritic (outward-expanding columns) that may branch as the pearl grows larger (Fig.7B, C). Regardless of these locally specific variations, cave pearls displaying a range of morphologies are encountered in karst areas across all climate zones (Fig.4).

Considering the sectioned cave pearl shown as Figure 7A, its centre has a coralline appearance consistent with a dendritic crystal structure resembling those shown by the outer layers of the pearls in Figures 7B and 7C. A similar dendritic structure is seen lining the pools and rimstone dams from which the latter two specimens (Figs 7B, 7C) were found. Given that this dendritic structure only occurred across the floor substrate and up to the rim of the cave pools where the pearls were found, it would be expected that the pearl shown sectioned in Figure 7A began growing completely immersed in pool water. Subsequently its depositional environment changed, and the pearl continued its growth in a location where splashing or running water caused a transition of crystal growth to produce smooth concentric rings. Without application of a scanning electron microscope (SEM) examination, or another type of highly detailed analysis, the possibility of microbial activity cannot be ruled out. Hence, the history of a cave pearl's formation cannot be presumed categorically solely based on its *in situ* visual appearance.

An unusual cave pearl formation mechanism was identified by Viehmann (1963) when describing cave pearl fields in Gheţarul de la Scărişoara, a glacier cave in Romania. The transformation of water into ice within the cave caused separation of calcite as cryptocrystals, to create micropearls that continue growing and if favourable conditions prevail, can result in the growth of fields of cave pearls (Viehmann, 1963). In a study of cave pearls in ice caves of the Carpathian Mountains, Slovakia, Zak *et al*. (2013) identified that initial crystal aggregates were formed by cryogenic precipitation during freezing of drip water, and that they always occur at sites where liquid water cannot accumulate. The pearls are prevented from becoming attached to the cave floor/substrate by being embedding in cave ice during freezing, and these particles eventually find their resting place during the thawing processes that cause their movement (Zak *et al*., 2013). Whenever freezing is/was involved in the formation of cave carbonate grains, the latter should be referred to as cryogenic cave carbonates (Zak *et al*., 2008).

Cave pearls can form with unusual shapes, such as some of those observed by the author during a research project in Pau Atea Cave, Atiu Island, Cook Islands (Fig.4). Another unusual variation in cave pearl morphology is depicted in Figure 5. Whereas the initial cave pearls grew in the shape of a flattened sphere, a thin horizontal calcite flange (*c*. 1mm thick) has grown outwards from the pearl, presumably when the pool water remained calm and its level remained stable for a lengthy period (Fig.5).

A rare form of cubic pearls resembling sugar cubes was reported by Robèrge and Caron (1983) occurring in Castleguard Cave, Canada. Four nests containing cubic cave pearls were observed, with the largest containing more than 300 pearls, each measuring between 5 – 7mm across. Analysis of one pearl confirmed that they were composed of calcite and had formed by accretion around an original spherical nucleus 0.4 – 0.6mm across. Robèrge and Caron (1983) postulated that they probably occurred because of enduring high-stability conditions, during which water supply to the pool was a trickling film causing restricted precipitate supply and highly regular packing in their nests.

In some cases the growth of cave pearls can be influenced by microbes. Pearls from dried-out rimstone pools in Old Man Village Cave on Grand Cayman, British West Indies, were studied by Jones (2009), who found that pearl growth in this cave involved both abiogenic (chemical precipitation) and biogenic (microbial) processes influenced by water flow. The microbes trapped and then bound detrital grains to the surfaces of the pearls and consequently mediated precipitation of the fibre-like crystals indirectly. His study determined that, "*Despite the lightless environment of the cave, the evidence clearly shows that the microbes and their associated extracellular polymeric substance (EPS) played a critical role in the growth and development of the cave pearls.*" (Jones, 2009, p.689).

Cave pearl growth rate (increase in diameter) is influenced by many factors, including prevailing rainfall, drip rates, solution saturation, air movement, temperature, *etc*., whereas no growth occurs during periods without a supply of saturated solution. Placing this in perspective, a speleothem's growth rate "… *can only be taken as the rate for the place and time*" (Hill and Forti, 1997, 185–187). For example, in a cave with limited ventilation the average increase in diameter could be as low as 0.05 – 0.15mm per year. Under favourable conditions Melim and Spilde (2011) measured growth rates of 0.4 – 5.5mm per year for pearls growing in a limestone mine, and they attributed this to rapid CO_2 degassing enhanced by the mine ventilation.

Occasionally, opportunities arise whereby the precise age and growth-rate of cave pearls can be determined by their relationship to a chain of events. At Wombeyan (NSW, Australia), the Junction show-cave was closed to the public in November 2019 due to abnormally dry conditions and bushfires. In February 2020, while the cave was still closed, the area experienced a major flooding event, which caused considerable damage to the cave's electrical wiring and associated lighting. With the influx of seepage water and continued rainfall events during the next few years, cave pearls and flowstone began growing across a section of the concrete pathway (above the flood level) inside the show-cave. The author observed that by May 2024, with the show-cave still closed to the public, hundreds of white cave pearls up to 10mm in diameter had formed in shallow rimstone pools across a 2m-long section of concrete path used for cave tours (Fig.9). Simultaneously, shallow rimstone pools up to 10mm deep had been forming on parts of the pathway. It is reasonable to assume that only sand-size grains would have been lying on the concrete path at the time of the cave's closure in 2019. If these particles became the cave pearls' nuclei, a growth rate (increase in diameter) exceeding 2mm per year is indicated. In another instance, in Teufelshöhle (Germany), cave pearls began to form during 1951 following a sand-wall collapse, which provided a definite timeline when all growth of these pearls occurred after 1951 CE (Richter *et al*., 2020).

As is the case with stalagmites, the age of cave pearls can be measured using the uranium–thorium (U/Th) dating technique, with results from each growth ring indicating a different period of growth. When compared with some other speleothems, cave pearls are commonly regarded as being of relatively young age (hundreds to a 1000 years), as a reflection of their rapid growth rate (Hill *et al*., 1997).

Most sub-spherical to spherical crystalline deposits displaying a concentric or radial structure that are found in caves, are composed of calcium carbonate (Hill and Forti, 1997). Depending upon the detailed geology of their local surroundings, both above and below ground, they can also be composed of silica, siderite, calcium phosphate, iron silicate or iron oxide (Selley, 2000; Flügel, 2010; Kalinina *et al*., 2024; Britannica, 2026).

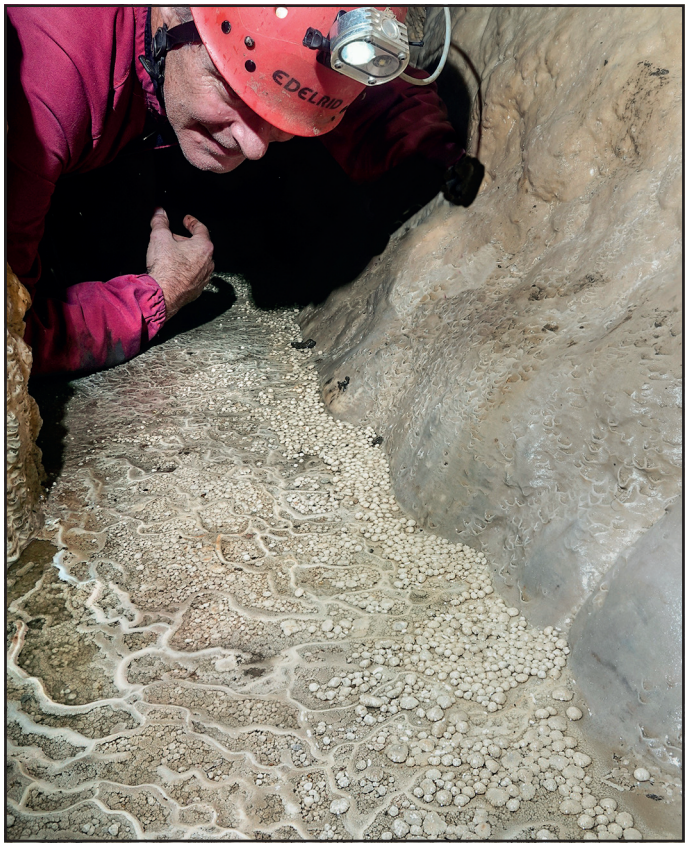

Figure 9*: Cave pearls up to 10mm in diameter, that grew in 4 years on a concrete pathway; Junction Cave, Wombeyan, New South Wales, Australia.*

Cups and nests

A shallow-depth depression may occur on the cave floor/substrate beneath any single drip point. Such depressions may subsequently become coated in calcium carbonate and later could contain cave pearls. An individual pearl may sit in its own 'cup', or a group of pearls might sit in a 'nest', so called because the cave pearls look like birds' eggs in a nest (Figs 6, 10). Cave pearls are also found covering small or large areas of cave floor (Fig.11) or pools, measuring up to tens of metres in length and width. One such example is in Sistema la Ventae Cave, Mexico, where an estimated 10 million pearls exist in a single large pool (Hill and Forti, 1997).

Situations exist where technically a cup or nest fits the description of a *conulite*, which is a drip depression coated in calcite or another secondary mineral (Smith, 2023). The example of a 'nest' of cave pearls shown in Figure 12 has, however, formed in a drip-hole created in a mud floor that was subsequently coated in layers of $CaCO_3$. Technically this speleothem can be described as a conulite containing cave pearls.

Figure 10*: 'The Birds Nest' of cave pearls that has formed in the flowstone floor of Mollochs Chamber, Temple of Baal, Jenolan, New South Wales, Australia.* ***Note*** *the Australian 10c coin (23.6mm diameter) for scale.*

Figure 11*: Cave pearls cover an area of gradually sloping flowstone floor in KNI83 cave, Ningbing Range, Western Australia.*
Note *the AA battery for scale.*

Figure 12*: An example of a 'nest' of cave pearls created in a mud-floor drip hole that was then coated in layers of $CaCO_3$. Technically, this speleothem could be called a 'conulite' containing cave pearls. Dalley's Sink Hole (M35), Buchan, Victoria, Australia.*

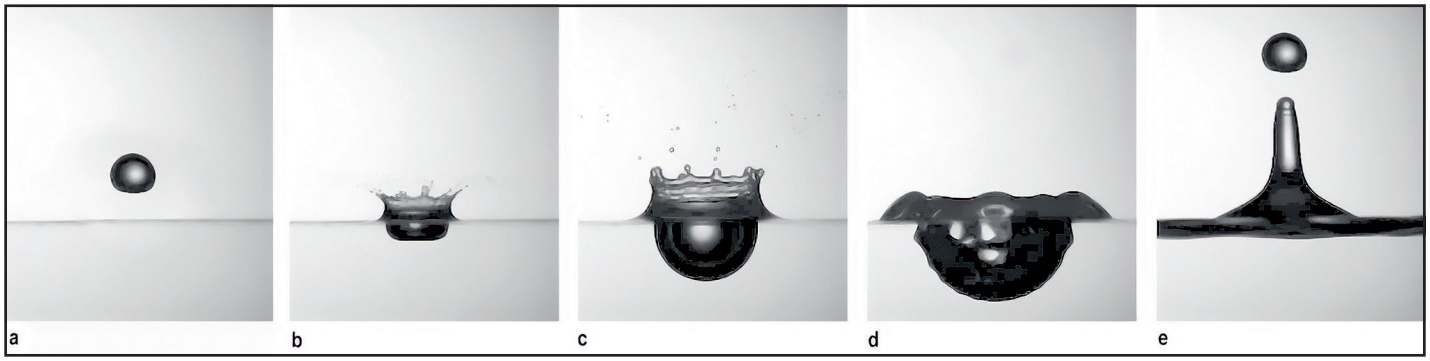

***Figure 13**: Chronological sequence of a 2.8mm-diameter water-drop hitting a pool surface to create surface waves and a bubble below the surface that implodes to create a pressure wave that is transmitted through the pool water to vibrate cave pearls, thus stopping them from becoming cemented to the pool's floor substrate. As the bubble implodes, a spout of water and a breakaway droplet are ejected from the top (Fig.13-e); upon their collapse these add to the creation of surface waves.*
***Note** that the profile can vary with drops of different diameters (mass) and impact speeds.*
*[**Images** after Bisighini and Cossali, 2010].*

***Figure 14**: A shallow rimstone dam full of cave pearls in Pau Atea Cave, Atiu Island, Cook Islands.*

***Figure 15**: Cave pearls shown* in-situ *in KNI90 cave, Ningbing Range Western Australia. See also Figure 3 and Figure 7B. AA battery for scale.*

***Figure 16**: A 70mm-diameter coralline cave pearl that has not yet attached to the cave floor/substrate. The pool was dry when photographed in KNI184 cave, Ningbing Range, Western Australia.*

What prevents a cave pearl becoming cemented to the cave-floor substrate?

Occasional small movements of cave pearls caused by vibrations from drip impact or flowing water, prevent them from becoming attached to each other or to the cave floor (Hess, 1929; Maltsev, 1997). Partly submerged cave pearls that are impacted directly by falling drops are vibrated continually or moved, possibly even gradually rotated, preventing them from attaching to the floor as new layers of $CaCO_3$ are deposited over their surface. At the same time, $CaCO_3$ layers are being added to the pearls and to the cave pool substrates upon which they sit.

Typically, pearls located beneath drips that fall a greater distance can grow to larger sizes than those forming under drips falling a short distance. This reflects the kinetic energy of the solution drops as they impact on the pearls or the shallow pool surface, causing movement of the pearl that is sufficient to inhibit the growth of interlinked crystals that would cement it to the substrate. In other words, the availability of relatively higher energy in the drip/pool water allows the pearl to grow larger until its mass reaches a value where the water is unable to move it or cause vibration. Consequently, the pearl becomes attached to the cave floor. As stated above, larger cave pearls can form beneath waterfalls or cave showerheads where conditions are turbulent.

Considering that drips are not actually hitting them to cause movement and prevent attachment, why do totally submerged cave pearls in a relatively calm, shallow ($\lesssim$300mm), rimstone/gour pool not attach to the pool floor? The author has failed to locate any publication that includes a complete and conclusive explanation. According to Self (2012), the Russian caver and mathematician Vladimir Maltsev provided a possible reason, claiming that acoustic waves produced as drips enter a cave pool, prevent mobile cave pearls from becoming attached to the pool-floor substrate. Whereas he published brief details of this hypothesis (Maltsev, 1997, 146–147), he included neither supporting calculations nor experimental or observational data.

Investigation of what could underlie Maltsev's claim regarding acoustic (compression) waves caused by drops, reveals several questions and parameter variables. Firstly, it should be explained that the sound (acoustic wave) associated with a drip is not caused by the water-drop's impact with a pool surface, but by the implosion of a cavitation bubble produced as the drip punches through the water surface (Fig.13). The further that the drop falls before impacting a pool surface, the greater the compression wave produced, within boundaries related to the drop's mass and terminal velocity. In contrast with the mechanical waves of a surface ripple, these compression waves travel through the entire water body. If Maltsev's theory is correct, it provides a viable explanation of why totally submerged cave pearls are not fused to the pool substrate (including to any adjacent pearls) as they continue to grow (Figs 14, 15, 16).

A falling drop's kinetic energy is governed by its mass and velocity. The larger the drop and greater the speed, the more energy can be converted on impact into a compression wave to move or vibrate a cave pearl. Given sufficient time, pearls will nevertheless become fused to the calcite beneath them, whether on the limestone floor of a pool or on a pre-existing flowstone substrate (Fig.17). Typically, this happens either when a cave pearl becomes too large to be vibrated by falling water drops or compression waves, or where there is insufficient running water to cause movement. In both cases, calcite deposition continues over and around the pearl's base. In other words, in any given situation, once a cave pearl becomes so large that the impact of drops or compression waves in pool-water lacks the energy required to cause it to vibrate, continued deposition of $CaCO_3$ from surrounding saturated solution forms crystals across the conceptual annular gap around the point-contact(s) between the pearl and the cave floor substrate.

In considering the kinetic energy (mass and velocity) of falling water-drops, it is useful to look first at factors related to a different type of speleothem. Typically, straw stalactites in caves are 4.5 to 6.45mm in diameter (Smith, 2021). The volume and diameter of corresponding drops are relatively constant, and both are related to the outside diameter of the straw tip where they develop and from which they eventually fall (Collister and Mattey, 2008; Smith, 2021). The larger the straw tip diameter, the larger the diameter and volume of any related drops. Studies by Collister and Mattey (2008) identified that for a straw of known diameter the drip volume is relatively constant when the drip-rate is less than one drip every ten seconds (<10 s). When the drip-rate increases, however, the volume of each drop also increases. Larger diameter stalactites will produce drops of greater volume, because they are not being created from water emitted from the central canal of a slender straw stalactite. Another overriding consideration is that, when water drops are falling, a point is reached where air resistance begins to dominate over surface-tension forces, thus causing the break-up of drops larger than 6.1mm in diameter into smaller drops, if the length of the fall is great enough (Dighe *et al*., 2024). A generalized critical falling distance at which large drops will break into smaller drops cannot be provided, because the value is highly variable depending upon the water-drop's initial size, air flow velocity and direction, and air density related to barometric pressure and altitude.

A 6mm-diameter water drop has a terminal velocity at sea level (one atmosphere: 101.3 kPa) of 9.17 m/s, but at an elevation of 2270m (77 kPa) its terminal velocity would be 10.51 m/s (Hinkle *et al*., 1987). Minor variations of these values are to be expected because of changes in air temperature and pressure. The quoted terminal velocity measurements highlight that the kinetic energy of a falling water-drop varies with altitude and barometric pressure (Hinkle *et al.*, 1987).

For example, if a 7mm drop falls only a metre or two, it probably will not break up. Thus, it will retain its larger size/mass but will reach neither its terminal velocity nor its maximum kinetic energy. Assuming for convenience that the largest solution drops forming in a cave are 6mm in diameter, at sea level they would reach terminal velocity after falling approximately 12m in still air at 20°C (Wang and Pruppacher, 1977; Hinkle *et al*., 1978). Slightly less fall height is required for a 5mm-diameter drop to reach its terminal velocity. Thus, in caves where the ceiling is higher than *c*.12m, water-drops will not gain more energy during their fall. Hence, the drop diameter and the distance it falls, correlate with the direct impact force on a cave pearl or with the bubble implosion compression wave that vibrates coralline pearls submerged in a pool. Clear and instructive graphs depicting various diameter drops and their velocity after falling from different heights and at different altitudes, are provided by Hinkle *et al*. (1978). For example, at sea level with an atmospheric pressure of 101 kPa, a 6mm-diameter water-drop reaches 4.4 m/s after falling 1m,

Figure 17*: Many of the larger cave pearls shown here in Figtree Cave, Wombeyan, New South Wales, Australia, have fused to the substrate and become part of the cave floor.*

≈5.9 m/s after 2m, ≈6.9 m/s after 3m, ≈7.5 m/s after 4m, ≈8 m/s after 5m, ≈8.3 m/s after 6m, and ≈8.8 m/s after 7m, following which the acceleration declines rapidly as the water-drop approaches its terminal velocity of 9 m/s after falling 12m.

Another factor can exert a slight influence on the intensity of a water-drop's implosion compression wave upon impact with a pool surface. Typically, as a drop falls its shape oscillates, even when reaching terminal falling velocity (Rimbert, 2020; Smith, 2021). The state of the drop's oscillation upon impact with the pool surface can affect the bubble-size created on entry to the pool and the amount of energy subsequently released as a compression wave from the implosion of a cavitation bubble (Dighe *et al*., 2024; Liu, 2017). For example, if the falling water-drop is "flatter" on impact, it produces a smaller bubble than that created by a drop of the same mass that is elongated vertically at the instant of impact with the pool surface. Thus, for a given drip mass, a vertically elongated drop will produce a slightly larger compression wave on impact.

Considered overall, rather than in terms of single water-drops, the production and interactions of compression waves in a pool can be highly complex, especially in situations where multiple drips of different volumes are falling more-or-less concurrently and possibly from different heights. This complexity can lead to establishment of a significantly energetic impact surface in the underlying pool, with interaction of pressure waves enhanced and/or reduced. Thus, the energy transmitted to the cave pearls can also vary greatly, in highly complex ways.

Pearls in man-made structures

Calcite concretions that resemble cave pearls can be found outside the natural 'cave' environment. Whereas they might have the same appearance and be formed by the same process as those in caves, technically they ***cannot*** be classified as 'speleothems', which must fit the definition: "*a secondary mineral deposited in a cave*" (Moore, 1952). Further clarifications of the term and its scope are provided by Hill and Forti (1995, 1997) and Shaw (1992a). As introduced by Moore (1952), the term "speleothem" is derived from the Greek words *spēlaion* 'cave' + *théma* 'deposit'.

Calcite pearls (secondary mineral deposits), that have formed in "manmade structures" such as mines, tunnels and under concrete structures, are now described as "*calthemites*", not "*speleothems*" (Smith, 2016, 2021, 2023). Fine examples of such concretions are the calcite pearls found in a lead mine beneath limestone strata in one of the Durham Dales of the northern Pennines, UK, as illustrated on the front cover of *Cave and Karst Science*, Volume 39, No.1, for April 2012. In this instance, the pearls were created by identical chemistry to those formed in active limestone caves, but because they formed in a mine they cannot be classified as "*speleothems*". Having been accreted in a manmade tunnel (a mine), should these pearls be considered collectively as "*calthemites*", as are calcite stalactites and flowstone that form in concrete tunnels?

It should also be noted that the chemistry responsible for the deposition of secondary calcite deposits under concrete structures differs significantly from that facilitating calcite deposition in limestone caves or mines within calcareous strata (Smith, 2016, 2021, 2023). Generally, calcite "speleothems" form in a limestone cave when CO_2 is degassed from calcium-rich solution (typically pH 7.5–8.5), whereas "calthemites" form in or beneath manmade concrete structures when CO_2 is absorbed from the air into an already calcium-rich solution (typically pH 9–13.5) (Smith, 2016, 2021).

A relatively rare exception to this scenario is seen in Poole's Cavern (Derbyshire, UK), where hyperalkaline solutions derived by leaching from lime-production waste materials have precipitated calcium carbonate and formed speleothems in the natural limestone cave (Hartland *et al*., 2010; Newton *et al*., 2015). The chemistry involved at Poole's Cavern parallels that of $CaCO_3$ deposition from degrading concrete leachate.

Concretions outside the cave environment

Various types of concretion can form in surface environments such as calcium-carbonate-saturated streams, hot springs, and seepage areas above ground. These include:

- pebbles similar in appearance to cave pearls are locally common. Although they are formed by the deposition of calcium carbonate around a nucleus, such pebbles are not speleothems, but are described variously as ooids, pisoids (or pisoliths), and oncoids;
- Travertine dams and cascades commonly form in surface streams with $CaCO_3$-saturated flows;
    - Rounded, concentrically laminated pebbles can form in the pools behind the dams, as calcite layers are deposited around mobile fragments of gravel or organic material (Fig.18).

Sub-spherical crystalline deposits with concentric or radial structure <2mm in diameter are classified as *ooids*, and those >2mm are called pisoids (Kalkowsky, 1908; Donahue, 1969; Young, 1989; Thomas and Groves, 2002; Scholle and Ulmer-Scholle, 2003; Pentecost, 2004; Kalinina 2024). The term *ooid* was introduced by Kalkowsky (1908) to distinguish the individual, egg-shaped, concentrically layered grains that accumulate then lithified to make up much of the rock-type described as *oolite*. As described, ooids are spherical to egg-shaped concretions consisting of concentrically laminated layers of carbonate or non-carbonate, and are commonly associated with shallow marine, warm (subtropical/tropical) environments (Flügel, 2010, 142–143). Historically, many different names have been used in published literature to describe ooids, e.g. diagenetic ooids, vadose ooids, caliche ooids and cave pearls (Flügel, 2010, p.157).

Figure 18*: A 40mm-diameter pisoid. A mobile fragment of gravel in the above-ground creek bed has been coated in concentric layers of calcite.* ***Note****: the left-hand image shows the smooth outer surface of the pisoid, and the right-hand image shows a polished cross-section.*
Sample from Rossiter Creek, Windy Gap, New South Wales, Australia.

In historical literature the term "pisoid" has been used interchangeably with "pisolith" to describe an individual layered concretion, but the description "pisolith" is also applied to the rock-type composed of pisoids. Pisoids are similar in appearance to ooids but may differ in origin and depositional environment, and are larger in size, commonly ranging from several millimetres to centimetres in diameter. They can form in various environments, including marine settings, hot springs (travertine pisoids), shallow subtidal ponds, and within vadose (subaerial) replacement palaeo-caliche deposits. Depending upon their origin, they fall within several sub-categories including: vadose-marine pisoids; fluvial pisoids; caliche pisoids; siliceous pisoids; spelean pisoids (cave pearls); *etc*. (Hill, 1992; Flügel, 2010, 158–160). Another term that may be encountered – vadose "pisoliths" (pisoids) – describes forms created in caliche crusts beneath the weathered zones of ancient and modern soils (Dunham, 1969). Whereas Carol Hill (1992) concedes that cave pearls are effectively a type of "pisoid", which is a general term used for any concentrically banded concretions of pea-size and body shape, she also points out that while there are many similarities, there are a few differences between pisolites and cave pearls.

When ooids or pisoids accumulate and are cemented together, commonly but not inevitably by calcite, they form rock-types called oolites or pisolites respectively (Thomas and Groves, 2002; Scholle and Ulmer-Scholle, 2003). The term oolite or oölite (from the Ancient Greek ᾠόν (*ōión*) 'egg stone') is used to describe a sedimentary rock formed almost entirely from ooids. Pisolite (from the Ancient Greek πίσον *(píson)* 'pea') is also a sedimentary rock, in this case composed largely of pisoids. Therefore "oolites" and "pisolites" are defined geological terms that should only be used to describe rock-types consisting of ooids or pisoids. Neither term should be used to describe cave pearls (Hill, 1992, 1996; Hill and Forti, 1997).

Another type of concretion that resembles a cave pearl is an oncoid. This term is derived from the Greek word '*onkos*', meaning 'nodule', 'volume', or 'mass' and refers to the lumpy or nodular appearance of the concretions. They can range in size from about 2mm up to several centimetres in diameter and typically have an irregularly shaped external concretion, superimposed upon internal calcite laminae. Although such structures form around a central nucleus such as a pebble or shell, the deposition of calcite layers over their surface has been aided by cyanobacterial growth, in similar fashion to the build-up of stromatolites (Logan *et al*., 1964; Selley, 2000, p.401; Rodrigues *et al*., 2022). Oncoids can be found in freshwater environments exposed to some degree of daylight, which supports the growth of cyanobacteria. Rock composed of oncoids that are cemented-together, is described as oncolite (Scholle and Ulmer-Scholle, 2003). More information regarding the role of cyanobacteria in deposition of $CaCO_3$ from solution is presented by Smith (2018). In partial contrast to the current views concerning oncoid development, Richter (1983) explains that in ooids, no organisms are visible as participants in the construction of the ooidic laminae, though the ooid formation may be controlled by microorganisms.

A classification of coated grains proposed by Peryt (1983) is based on the notion that they form through chemical precipitation (e.g. ooid, vadoids) or biogenic encrustation (e.g. rhodoid, oncoid) and makes no allowance for grains that formed by both processes. Within the classification, Peryt categorizes biogenically encrusted grains created by red algae as "rhodoids", and those related to green or blue-green algae, and bacteria, as "oncoids". He also lists coated grains created by chemical precipitation as "ooids" (created in the phreatic environment) and "vadoids" (created in the vadose environment).

In a discussion published in the book "*Coated Grains*" cited above – edited by Peryt (1983) – Richter (1983) suggested that because the generic terms 'vadoids' and 'rhodoid' are confusing and unwarranted they should be avoided. Both Peryt (1983) and Richter (1983) refer to coated grains where "vadoid" is used to describe grains formed in the vadose zone environment above the water table, and "rhodoid" describes a type of calcareous nodule formed in warm to cool, clear, shallow marine environments. Numerous examples are provided by Richter to illustrate the potential confusion. Although commonly of pisoid-size (2 – 10mm), vadoids can be smaller and these cases have been termed 'diagenetical ooids', 'calcrete ooids', 'vadose ooids' or simply 'ooids' (Richter, 1983). Additionally, in the same discussion, Richter (1983) provides justification that cave pearls should not be called "vadoids".

Historically, many terms have been used in literature to describe concentrically banded concretions that have accreted around a nucleus (Richter, 1983; Hill, 1992; Hill and Forti, 1997). The more the subject of laminated concretions is explored, the more it becomes apparent that some definitions are conflicting and overlapping across various publications. Helpful examples of why other terms should not be used to describe cave pearls are provided by Hill (1992). It is also the current author's opinion that only the unambiguous term 'cave pearl' should be used to describe these unattached concretions found in caves, leaving the other terms for their intended purpose of describing aspects of lithologies unequivocally within rock classification schemes.

Summary

This paper was researched and written with the intention of comparing results of cave-pearl research and observations from many authors, and to bring saliant points together within a single article. The outcome includes details of the known facts surrounding the growth, morphology and environmental conditions that facilitate the creation of cave pearls. Some of the key aspects presented and discussed in the main text are reiterated below.

Cave pearls are concentrically banded unattached speleothems that are formed under a drip point or in a shallow cave pool, by deposition of a mineral – most commonly $CaCO_3$ as calcite – from a saturated solution. Precipitation of calcite usually begins around a nucleus that may be as small as a grain of sand or larger objects such as a pebble, piece of bone, shell, broken cave straw or stalactite, *etc*. Cylindrical or irregular pearls tend to have larger, elongated or irregular nuclei, and tend to retain that overall shape but become more rounded as the mineral layers are deposited.

Cave pearls can be opaque or translucent white when more of less pure calcite is deposited. Colour variations including yellow, orange, red, brown and black occur when introduced impurities – such as detrital particles (e.g. silt and clay), organic compounds (e.g. tannin) and/or other minerals – are deposited along with the $CaCO_3$.

Smooth and polished cave pearls form beneath active water-drips that fall from some distance above and either hit them directly or splash them. They also form under waterfalls and in other situations where water circulates rapidly past them. Generally, their concentric growth layers are made up of compact small crystals. The impact of falling drops or running water either hitting or splashing the pearls, causes small, random but recurring, movements, and this agitation prevents them from becoming attached to the cave floor by crystal growth, while $CaCO_3$ layers are being deposited on their surface.

Coralline cave pearls (sometimes called 'coral balls') typically grow in situations where they remain completely immersed in a shallow pool with negligible water flow. Internally, they have a morphology of laminated dendritic outward-expanding columns of crystals that may branch as the pearls grow larger. Cave pearls with a coralline appearance that are totally immersed in water are prevented from becoming attached to the substrate by the effects of acoustic waves causing slight vibration of the pearls. Such acoustic waves are not caused by water-drops hitting a pool surface, but by implosions of cavitation bubbles produced as the drip punches through the water surface. Unlike the mechanical waves related to surface ripples, the acoustic waves propagate through the entire water body.

The further the solution drop falls before impacting a pool surface the greater the compression wave produced within the boundaries of the drop's terminal velocity and mass. Larger cave pearls are typically found under active waterfalls and cave shower heads or in areas where drips have fallen from some distance, while in sheltered low-ceiling areas, only smaller cave pearls are normally found. When a cave pearl becomes large enough so that the water has insufficient energy to cause it to vibrate, then deposition of $CaCO_3$ from saturated solution begins cementing it to the cave floor.

Cave pearls should be described only by that name. Terms such as vadoid, oolith, oolite, pisolite or oncolite should not be used, because they are geologically defined terms used to describe rocks.

Conclusion

To reduce potential for confusion, it is the author's opinion and recommendation that only the term 'cave pearl' (with no limitations related to size or shape) should be used to describe these unattached, concentrically laminated speleothems found in caves. Other terms used in the past to describe cave pearls, should only be applied as originally intended for the geological description of rocks.

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