

HOW SPELEOTHEMS GROW: AN INTRODUCTION TO THE ONTOGENY OF CAVE MINERALS

CHARLES A. SELF

4 Tyne Street, Bristol, BS2 9UA ENGLAND self@globalnet.co.uk

CAROL A. HILL

17 El Arco Drive, Albuquerque, NM 87123 USA carolannhill@aol.com

Speleothems are secondary mineral deposits whose growth in caves can be studied by mineralogical techniques. One of these techniques is the ontogeny of minerals, which is the study of individual crystals and their aggregates as physical bodies rather than as mineral species. Ontogeny of cave minerals as a scientific subject has been developed in Russia but is poorly understood in the West. This paper introduces the basic principles of this subject and explains a hierarchy scheme whereby mineral bodies can be studied as crystal individuals, aggregates of individuals, associations of aggregates (termed koras), and as sequences of koras (ensembles).

Speleothems are secondary mineral deposits that form in caves (Moore 1952). This distinguishes them from primary mineral bodies such as the bedrock that encloses the cave, mineral veins in the bedrock, and sediments accumulated in the cave. These primary minerals are important as sources of material from which new mineral bodies (*speleothems*) can grow in response to specific physical and chemical processes operating within the cave.

A *cave mineral* is a homogeneous solid having a definite chemical composition and a 3-D ordered atomic arrangement, growing naturally as a secondary mineral deposit within a cave. More than 250 cave minerals are known (Hill & Forti 1997) but only 3 (calcite, aragonite, and gypsum) can be considered common. The term *cave mineral* refers to the mineral species of a deposit, whereas *speleothem* terms (such as *stalactite*, *cave pearl*, etc.) are used to describe their morphology. Neither of these terminology systems defines the growth mechanisms of *speleothems* or their genetic history.

The study of the origin and evolution of mineral bodies is termed *genetic mineralogy* and includes nucleation, initiation (on a growth surface), development, alteration, and disintegration. Genetic mineralogy was formulated in Russia as a separate field of study within mineralogy during the 1920s (Fersman 1935). By the 1950s, Grigor'ev had divided genetic mineralogy into 2 separate branches: *ontogeny* and *phylogeny* (these terms are familiar from biology and are used in a broadly similar sense by Russian mineralogists). *Ontogeny* is the study of individual crystals (mineral *individuals*), how these crystals combine as *aggregates*, and their development as physical bodies. *Phylogeny* is the study of mineral species and their paragenesis (i.e., their association with contemporaneous mineral species). *Phylogeny* closely corresponds to the Western view of genetic mineralogy, whereas *ontogeny* (and even the term itself) is unfamiliar to most Western mineralogists. With the publication of 3 books devoted to the ontogeny of mineral veins and ore deposits (Grigor'ev 1961; Grigor'ev & Zhabin 1975; Zhabin 1979), this line of study has become a well-established science in Russia.

Although *ontogeny* as a subject has its origins in the Russian mining industry, caves prove to be ideal for *ontogeny* studies. There are few common mineral species, yet there is a great variety in the *speleothem* forms that these minerals can take. Also, the mineral-forming processes in caves are sufficiently slow in most cases to promote the development of clearly defined structures and textures. This has allowed far more complex mineral bodies to be studied in caves than has been possible in mines. The leading figure in this move to cave-based research was Stepanov (1965, 1970, 1971, 1973, 1997) of the Fersman Mineralogical Museum in Moscow. Other significant contributions have been made by Maleev (1971, 1972), Moroshkin (1976, 1986), Slyotov (1985), Korshunov and Shavrina (1998) and, most notably, by Maltsev (1989, 1993, 1996a, b, c; 1997a, b, c; 1998). This paper is an overview, based primarily on the ideas developed and promoted by the late Victor I. Stepanov, who died in 1988, and by Vladimir A. Maltsev.

In the West, comparatively little work has been done on the structure and texture of *speleothems*, and the papers that have been published (e.g., Folk 1965; Folk & Assereto 1976; Kendall 1977, 1985, 1993; Kendall & Broughton 1977, 1978; Broughton 1983a, b, c; Jones & Kahle 1993) have neither a unity of approach nor a common terminology. The Russians have a considerable advantage in this respect, and it is one of the main purposes of this paper to demonstrate the language and conceptual framework of *ontogeny*, so as to make Russian-authored work more accessible to Western scientists.

Ontogeny as a concept is important to mineralogy because the same mineral species can display different physical forms, depending on the specific environment in which growth occurs. In caves, it is possible to study the different forms of *speleothems* together with their depositional environments. This has resulted in a large number of mainly descriptive mineralogy texts, as documented in *Cave Minerals of the World* (Hill & Forti 1997). It is now necessary to study cave mineralogy from a genetic perspective. *Ontogeny* explains not only *how* *speleothems* grow, but *why* there are different *speleothem* types.

The terminology of ontogeny can seem difficult to understand because it is unfamiliar to Western readers. Some terms are the same as in the West, some terms are new, while a third sort are familiar words that have been given a new and strictly limited sense. When the term *mineral* is used, it can mean several things. A mineral can be described by its chemical composition, its physical properties, or even its position in a classification scheme such as *A System of Mineralogy* (Dana 1837). Additionally, a view can be taken of minerals simply as material physical bodies. According to the thinking of Russian mineralogists, *minor mineral bodies* (MMBs) are physical mineral bodies that can be studied by mineralogic techniques, rather than by crystallographic or petrographic techniques. Specifically, MMBs have a “through” structure and/or texture and are a product of synchronous crystallization (or recrystallization) in some geometrically defined space. By *through* it is meant that the rules governing the growth of individual crystals also apply to aggregates composed of those individuals, and the rules that govern the growth of aggregates also apply to the higher hierarchical levels, so that a continuity of structure or texture can be traced all the way “through” the object. By *synchronous crystallization* it is meant that the crystallization (or recrystallization or destruction) of the individuals or aggregates that forms a MMB takes place at the same time over the entire body of the MMB.

The terms *structure* and *texture* have much tighter meanings in ontogeny than in western terminology, and cannot be used interchangeably or in a general sense. Structure describes the physical nature of crystal individuals and their bonding. Texture describes the geometric aspects of construction; i.e., the organization of mineral individuals or aggregates within a minor mineral body (Stepanov 1970, 1997). In the hierarchy of MMBs, structure and texture are contiguous regularities in that “through” structure links individuals with aggregates made of those individuals, while “through” texture can be traced from aggregates to the higher hierarchy levels. This continuity of structure and texture separates MMBs from more complex mineral bodies that have no such regularities. In the language of Russian mineralogy, such complex mineral bodies are termed *rocks* and are studied by petrographic techniques.

HIERARCHY OF MINOR MINERAL BODIES

The formulation by Stepanov (1970, 1997) of a specific and strictly defined term *texture* in mineralogy, separate from rock texture (as used in general geology), was a major advance that led directly to the development of the MMB concept. In turn, it became possible to see that MMBs could be organized into a hierarchical classification scheme. In mineral veins, only the first two hierarchy levels can easily be identified, but in caves 4 levels are discernable. This larger hierarchy—evident in the works of Stepanov (1971, 1997)—was outlined by Maltsev (1996b, 1997b). In this paper, we discuss the constituent parts of this hierarchy in more detail. This is not a complete analysis, and a fuller treatment is planned for sometime in the future.

Minor mineral bodies are classified according to their complexity of structure and texture. *Level* is used when MMBs of one level are built from MMBs of a previous level or levels. *Order* is used as a subdivision within a level and shows the level of complexity of the MMBs. Second-order MMBs are built from MMBs of the previous level, but in a more complicated manner than first-order MMBs. For example, multiaggregates (level 2, second order) are not built from aggregates (level 2, first order); they are built from individuals (level 1, either first or second order), but in a more complicated manner.

The hierarchy scheme of MMBs is *not* the same as the classification of speleothems into types and subtypes (e.g., Hill & Forti 1997). “Speleothem” is a descriptive term and can only be used to indicate the morphology of a MMB. In ontogeny, speleothems can appear on different organizational levels; i.e., they can be composed of individual crystals, crystal aggregates, or groups of aggregates. For example, selenite needles are individuals, flowstones and coralloids are both aggregates, but stalactites are multiaggregates.

(0) ZERO LEVEL: Subindividuals. The fundamental building block for all minor mineral bodies is the mineral individual (level 1). Simple (first-order) individuals are single crystals having no structure other than a crystallographic network. More complex (second-order) individuals, on the other hand, are composed of a number of different crystalline units known as *subindividuals*. Subindividuals also have no structure except for their crystallographic network, but they are at least partly separated by free space or a line of dislocation from neighboring crystal blocks. Inasmuch as subindividuals do not exist independently from each other, they are ascribed to a hypothetical “zero level” in the MMB hierarchy. A zero level is needed because complex (second-order) MMBs of the first level must be formed from MMBs of a previous level, not from first-order MMBs of the same level. Subindividuals (in the sense used here) are termed *crystallites* by some mineralogists, but in ontogeny the preferred use of this term is for the initial stage of crystallization of mineral individuals.

(1) FIRST LEVEL: Mineral Individuals. Individuals are mineral bodies that grow from a single crystal nucleus or embryo (crystallite), during one phase of crystallization, and which have a “through” crystallographic structure (Godovikov *et al.* 1989). Crystallites are minute crystal grains that represent the initial stage of crystallization, and which act as seeds for further crystal growth (Fig. 1). When crystallites are widely separated from each other, they grow freely into separate first-level mineral individuals. But when they grow close together, there is competition for growth space and a second-level MMB (a mineral *aggregate*) is formed. It should be emphasized that mineral individuals are *not* speleothems (except in a few special cases). They are the building blocks from which speleothems are made.

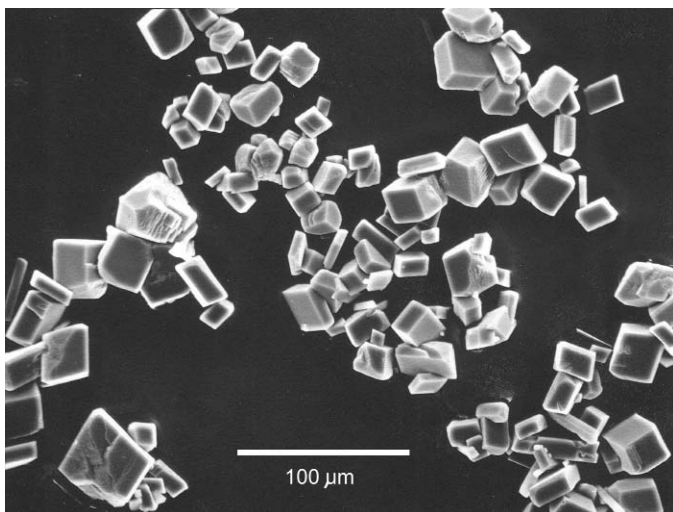


Figure 1. Calcite crystallites grown in the laboratory from a supersaturated solution by the degassing of CO₂. SEM photomicrograph by Art Palmer.

(1.1) First-Order Individuals. In the simplest case, mineral individuals are single crystals having no other structure except a standard crystallographic network, which is determined by the mineral species itself. First-order individuals can be described by their isometric, columnar, acicular, filamentary, or tabular habit, or by their euhedral, subhedral, or anhedral form. First-order individuals can, in some cases, be considered speleothems; for example, calcite, gypsum or fluorite crystals that have grown alone and independently from a hydrothermal water (Fig. 2A: p. 145) or subaerial environment (Fig. 2B: p. 145).

(1.2) Second-Order Individuals. Second-order individuals are single crystals that subdivide or split into a number of subindividuals, single crystals that have their growth inhibited on some crystal faces or edges, single crystals that incorporate crystallites into their crystal lattice, or single crystals that are twinned (Shafranovskiy 1961). In some cases second-order individuals can look as if there is a co-growth of several crystals, but this is an illusion. Subindividuals of second-order individuals are not separate from each other. They grow from the same nucleus and have a joined crystallographic network (Fig. 3: p. 145). Second-order individuals grow in response to certain environmental conditions, particularly oversaturation – a common occurrence in caves due both to CO₂ loss and evaporation of thin films. Many of the different subdivisions in this category depend on the degree of separation between subindividuals (Godovikov *et al.* 1989).

(1.2.1) Split Crystals. When a crystal individual splits apart during growth, it forms a number of subindividuals, a sheaf-like structure, or in its final form, a spherulitic structure (Fig. 4). Different minerals have a different “splitting ability” depending on their crystal structure. For example, aragonite has a higher splitting ability than calcite under usual cave conditions, and therefore it is almost always found in caves as split acicular crystals. Splitting is also quite common in calcite, but

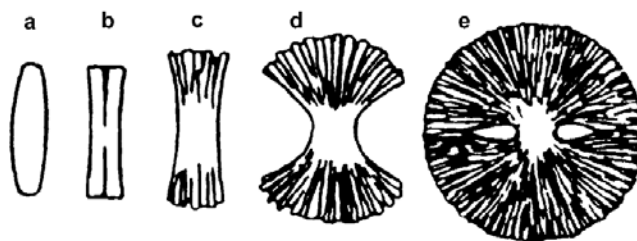


Figure 4. Drawing of successive stages of splitting during crystal growth: a = no splitting, b and c = simple splitting, d = “sheaf” structure, e = spherulite. From Grigor’ev (1961).

this splitting is not easily seen with the naked eye. Gypsum needs a rather high oversaturation to become split, but splitting can occur in some cases (e.g., growth from a porous sediment). Splitting may be due to a crystal receiving extra molecules in its layers (*mechanical splitting*), or to when certain ions (e.g., Mg as well as Ca) are present in the parent solution (*chemical splitting*) (Grigor’ev 1961). According to the level of supersaturation or impurity concentration (which can change during growth), splitting will take on different grades, which results in a number of subforms for split crystals (Fig. 5: p. 146).

(1.2.1A) Spherulites. Spherulites are second-order individuals having either a radial or curving radial structure due to the splitting of crystals. If growing in free space, they are spherical in form (Fig. 6: p. 145); if nucleated on a substrate, they grow as hemispheres (see Fig. 9a). Spherulites are composed of straight subindividuals, but often the subindividuals themselves continue to split. Constraints of growth space around the central axis of the crystal then direct this splitting outward to produce a curving radial structure (seen in the “twin leaf” splitting of Fig. 5c: p. 146). The shape of such spherulites is a property of both the crystal nucleus and its split branches. If part of the growth surface becomes mechanically blocked, the unobstructed “rays” will continue their growth in the form of a new spherulite (Fig. 7). This composite body is still a mineral individual, not an aggregate. Spherulites are widespread in caves as components from which many speleothems are built.

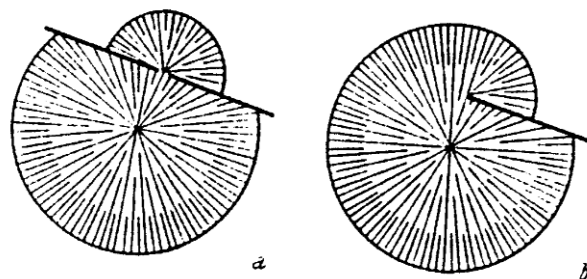


Figure 7. Spherulites encountering obstacles: (a) when a subindividual passes through a hole, it spreads out and grows into a new spherulite, and (b) when a spherulite is only partially obstructed, growth “goes around” the obstacle. From Maleev (1972).

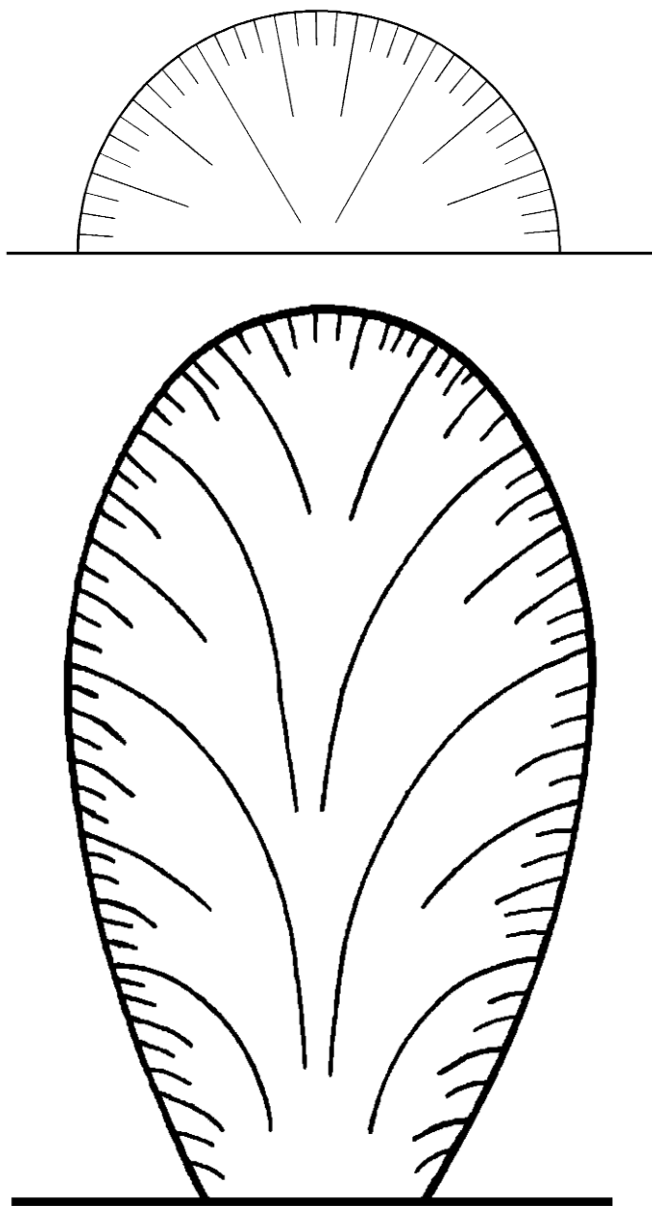


Figure 9. Comparison of spherulites and spheroidalites. (a - top) Spherulites are composed of straight subindividuals. If splitting occurs mostly at an early growth stage, a radial structure is produced. If there is continuous splitting, then structural lines will curve away from the central axis because of intense crowding of subindividuals (e.g., as in Fig. 5c). (b - bottom) Spheroidalites are composed of curved subindividuals and display asymmetric growth and growth layers of unequal thickness.

(1.2.1B) Spherulite Bunches. Spherulite bunches may be thought of as three-dimensional sectors of spherulites (their incomplete development being due to a strongly directional supply scheme). The subindividuals growing from a single nucleus form a stalk (a well connected bunch) or a splay of crystals (a poorly connected bunch). This shape depends on the

growth speed of crystals. Slow growth results in well connected bunches, fast growth in poorly connected splaying bunches. Examples of speleothems built from spherulite bunches are most kinds of helictites and some kinds of anthodites and frost-work. Spathites and beaded helictites are sequences of spherulite bunch splays, with new bunches growing from subindividual “rays” of the previous bunch in the manner of a daisy chain (Fig. 8A, B: p. 146). If more than one “ray” becomes a focus of new growth, then branching will occur.

(1.2.1C) Discospherulites. Discospherulites are spherulites that have preferred crystal growth in two, rather than three, dimensions. Some kinds of cave rafts display discospherulitic growth, where the surface of a cave pool confines crystal growth to a plane. However, the supersaturation grade must be high enough to allow for split growth, or other types of rafts will form.

(1.2.1D) Spheroidalites. Spheroidalites are spherulites with nonsymmetrical structure (Godovikov *et al.* 1989). They have elongated and curved subindividuals, whereas spherulites have straight subindividuals (Fig. 9). Asymmetric growth of the fibers of a spheroidalite causes angular unconformities between the fiber orientations in different growth zones. Because of this asymmetry, growth layers in spheroidalites are of unequal thickness, whereas growth layers in a spherulite are always of the same thickness and display spherical concentric zonality. Most coralloids display spheroidalitic growth.

(1.2.1E) Sphero-crystals. Sphero-crystals are chemically split second-order individuals, so perfectly split that boundaries between subindividuals are at a molecular level, and physical properties (such as cleavage) become generalized across the whole crystal (Shubnikov 1935). This results in growth surfaces that are smooth and bright in appearance (e.g., botryoidal malachite or chalcedony; Fig. 10: p. 147). Although sphero-crystals are composed of subindividuals, the separate fibers are not visible even under microscopic examination. However under crossed nicols (polarizers), sphero-crystals display a “Maltese cross” extinction.

(1.2.2) Skeleton Crystals. Skeleton crystals are second-order individuals where preferred growth occurs along crystal edges or corners rather than on crystal faces (Fig. 11: p. 147). Such a growth pattern makes these crystals appear “lacy” or empty inside (e.g., “hopper” crystals). Skeleton crystals form where the supersaturation grade is high enough to promote rapid growth, but where the supply of material is insufficient to allow massive growth. For carbonate speleothems, it is possible to get skeleton growth without a high grade of supersaturation if CO₂ loss is oscillatory or periodic—for example, the actively dripping tips of stalactites (see Fig. 34: p. 150).

(1.2.3) Twin Crystals. A twin crystal begins as a simple individual, but at some point it continues its growth as two (or more) parts reflected across some definite plane called a *twin plane*. One part continues the “parent” crystallographic network, while the other(s) grows from the twin plane(s) with a reflected crystallographic network. Twin crystals typical of a cave environment are selenite needles (Fig. 12: p. 147) and the

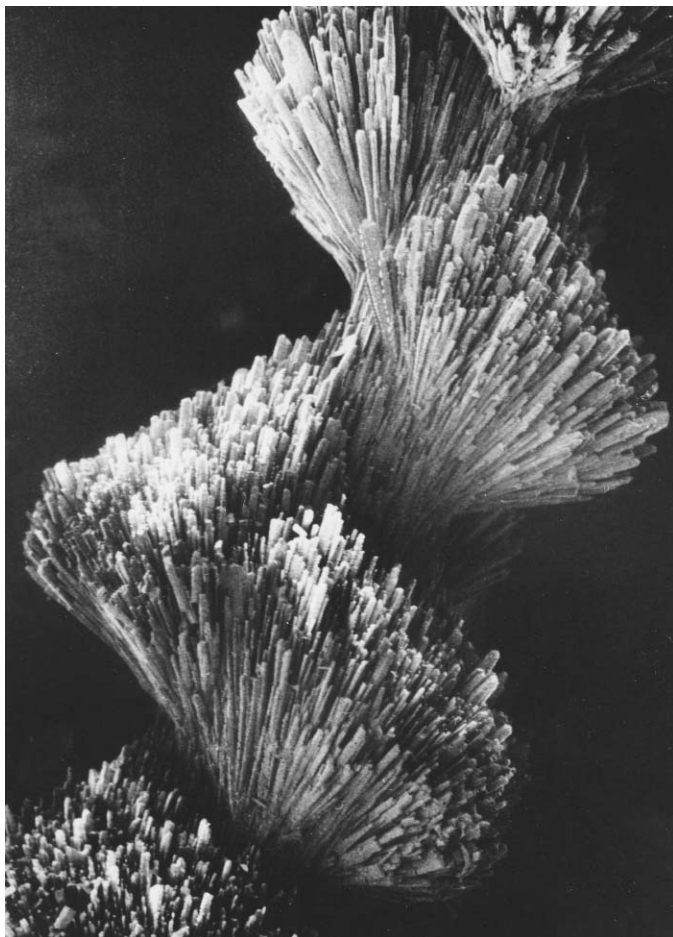


Figure 13. Scanning electron micrograph of an aragonite helictite from a cave in France, diameter 2 mm. Note how the split crystals are symmetrically screwed around the axis of the helictite. Photo by Patrick Cabrol.

twinned branches of gypsum chandeliers. (Note: There are other types of twins that look like an intergrowth of two or more individuals, but even these are thought to begin from a single nucleus.)

(1.2.4) Screw Crystals. Screw crystals are the result of screw dislocations in the crystallographic network where molecular layers have small regular rotations along a crystallographic plane so as to produce spiral layers (Fig. 13). In screw crystals, subindividuals cannot be separated because the dislocation is continuous (rotational around the greatest growth vector), and each molecular layer is a new crystal block fractionally rotated on the previous molecular layer. Screw dislocations are most common among filamentary crystals (e.g., gypsum cotton and selenite needles), but they can also occur in some types of helictite.

(1.2.5) Block Crystals. Block crystals (sometimes called “mosaic growth”) are crystals whose separate parts (known as *blocks*) are slightly rotated in relation to each other (Grigor’ev 1961) (Fig. 14). When spatial nucleation continues around a growing crystal, crystallites of several-molecule size can

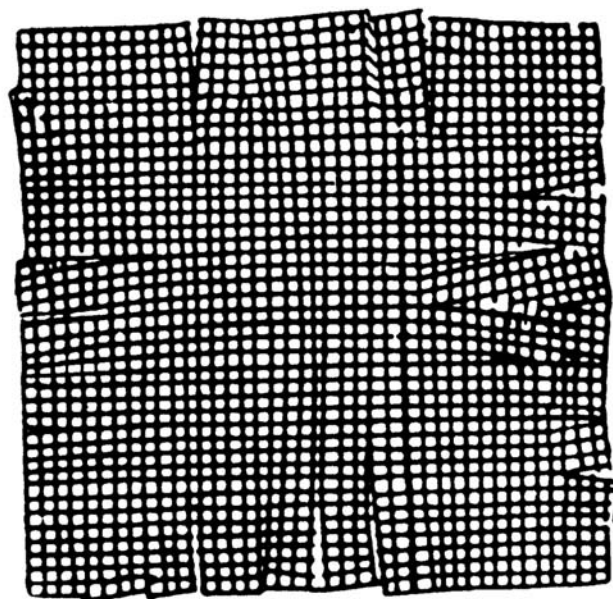


Figure 14. Schematic structure of a block crystal. The lattice of one “block” passes continuously into the lattice of another through a zone of dislocation. From Grigor’ev (1961).

become closely aligned to the growing crystal by electrostatic forces (Jushkin 1973). The crystallites become incorporated into the main crystal, with the crystallographic network of one block passing continuously into that of the next through a zone of dislocation. Block crystal growth is common for vein minerals such as pyrite and for subaquatic hydrothermal speleothems. Such mosaic growth has also been found in calcite and gypsum speleothems that have precipitated under normal cave conditions (B. Onac, pers. comm., 2002).

(1.2.6) Complex Individuals. In some cases second-order individuals display two or more structural features at the same time. Dendrites display a branching pattern due to both crystal splitting and skeletonization (i.e., they are composite split-skeleton crystals; Fig. 15). In caves, dendritic crystals (e.g., frostwork and cave coral) usually form in the high evaporation conditions of a capillary film environment. Selenite needles are also complex individuals, inasmuch as they are skeletonized, twinned, and split—all at the same time (Maltsev 1996c).

(2) SECOND LEVEL: Mineral Aggregates. Mineral individuals very seldom occur singly; they grow multiply over a substrate surface as mineral *aggregates*. Aggregates are much more than simply a group of individuals of the same mineral species growing together. Interaction between individuals directly affects and limits the growth of each crystal. During such “group” or “common” growth, there is *competition* between the mineral individuals constituting the aggregate. Most speleothems are mineral aggregates.



Figure 15. Longitudinal (a - left) and transverse (b - right) sections of dendritic structure in an aragonite helictite, Cave of the Winds, Colorado, 20x, viewed in cross-polarized light. The “branches” are due to crystal splitting and skeletonization. Note the roughly triangular central feeding channel, which shows that this helictite is an aggregate of three crystals. Photos by George Moore.

Most aggregates form where growing individuals compete for space by physically contacting one another. In such a situation, contact faces (also called *induction surfaces*) develop between neighboring individuals, leaving a group growth front comprised of the crystallographic terminations of many individuals (Fig. 16: p. 147). However, aggregates do not necessarily have to be in direct physical contact for competition to occur. An example of indirect competition for the supply solution is when growth is in a plastic substrate such as porous clay, where interaction between crystals is due to the closure of feeding pores in the clay as a result of crystallization pressure. When growth is in a capillary film environment, there is competition for the loss of solvent molecules and interaction is by convection of water vapor and CO₂ between individuals. The mineral individuals constituting an aggregate have contact faces when they are in direct competition, but display true crystal faces when they are in indirect competition.

Competitive growth on a substrate surface normally leads to a reduction in the number of individuals constituting the aggregate, a situation called *selection*. The main selection mechanisms are:

(1) *Geometric selection*: The mineral individual whose greatest growth vector during competitive growth is best aligned for mass-transfer with the environment is the one that will continue its growth at the expense of neighboring individ-

uals of other orientations.

(2) *Substrate selection*: The mineral individual (or mineral aggregate) growing from a convex substrate protrusion during competitive growth will continue its growth at the expense of its neighbors growing from flat or concave surfaces.

(3) *Primogeniture selection*: The mineral individual (or mineral aggregate) that nucleates on a substrate first has a better chance of continued growth than one that nucleates later.

(4) *Random selection*: In some cases, a mineral individual (or mineral aggregate) experiences a cessation of growth when it has no obvious natural disadvantage compared to its neighbors. Such selection is unpredictable.

The most influential process during the early stages of crystal growth is geometric selection. The crucial elements of this selection process are: (1) initiation of separate centers of crystallite growth; (2) the beginning of competition of these crystal individuals for growth space; (3) selection and a reduction in the number of competing individuals according to a geometric rule; and (4) continued growth with no further selection because the geometric rule forbids it (Fig. 17). There are several geometric rules for selection, but perpendicularity to the substrate is the most common. This rule applies to most mineral veins and to many common varieties of speleothems (e.g., dripstone, flowstone, pool spar).

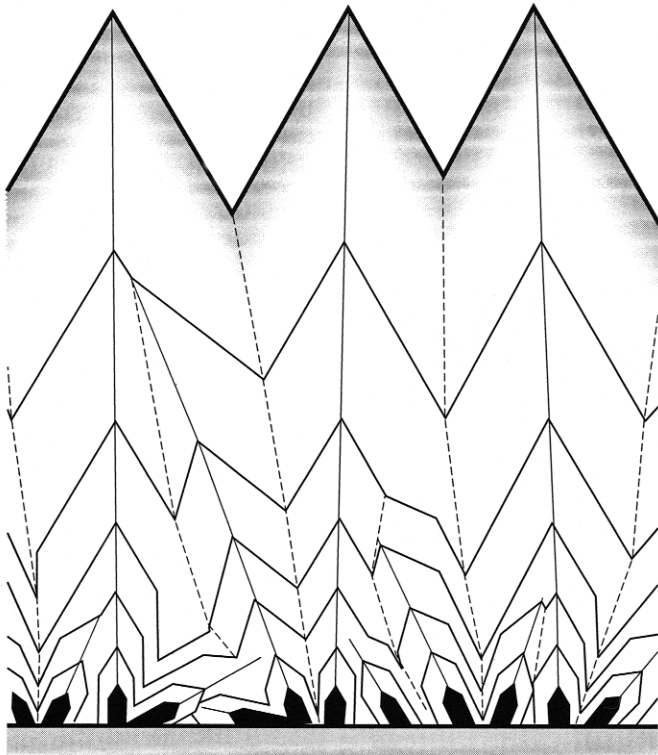


Figure 17. Geometric selection on a flat growth surface. From Kantor (1997).

(2.1) **First-Order Aggregates.** In ontogeny, first-order aggregates are simply termed *aggregates*, while second-order aggregates are termed *multiaggregates*. For cave minerals, aggregates can be defined as: “intergrowths or co-growths of individuals (either first- or second-order) of the same mineral species, which develop simultaneously on a common growth surface and which possess a homogeneous texture.” (Note: aggregates can also form in free space by crystallization from viscous solutions and melts, but this is not relevant to speleothems in caves.) It is important to stress here that only simultaneous growth of similar individuals of the same mineral species can form first-order aggregates. Most speleothems are aggregates. Aggregates can be subdivided according to the different textures that are produced by competitive growth.

(2.1.1) **Parallel-Columnar Aggregates.** Examples of parallel-columnar texture, sometimes known in the West as “palisade fabric” (Folk 1965), dominate the collections of amateur mineralogists. Mostly these are groups of crystals with well-formed terminations, taken from vugs in simple mineral veins. If visible to the naked eye, these crystal aggregates are called *druses*, where each crystal is a mineral individual within a composite aggregate of crystals. These individuals only have crystallographic faces on their end terminations, with their sides being contact surfaces with other individuals (Fig. 17). Each druse crystal has had to compete with other individuals, and is a survivor of geometric selection at the aggregate druse growth front.

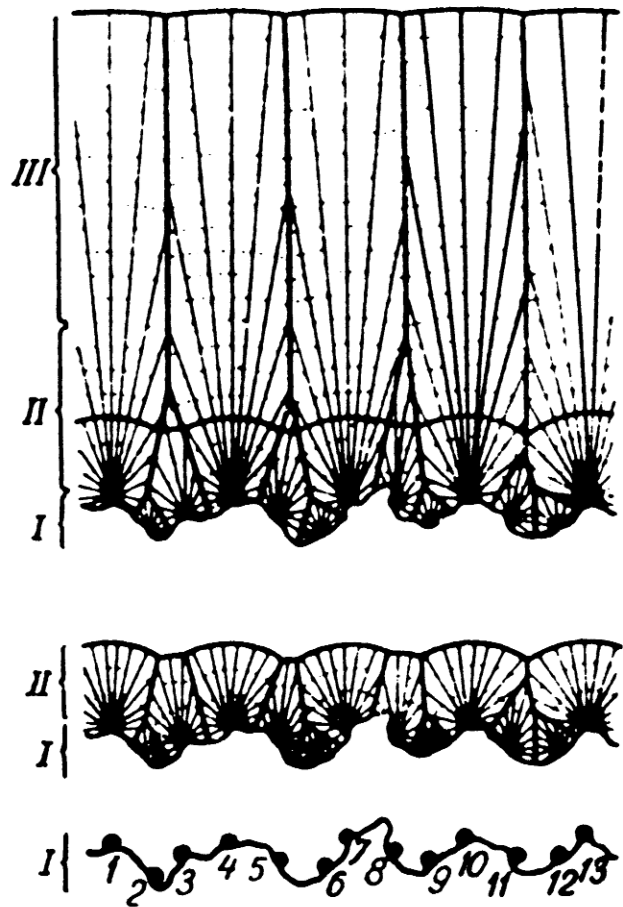


Figure 19. Diagram showing the group growth of spherulites on an irregular substrate: I) Growth of discrete spherulites; II) substrate selection between competing spherulite individuals; and III) geometric selection between competing subindividual spherulite rays. From Grigor’ev (1961).

Parallel-columnar aggregates grow by geometric selection perpendicular to nominally flat substrates, as described above and as shown in Figure 18 (p. 147). But in the natural world the substrate is seldom perfectly flat, and so a more complicated selection scheme operates. Geometric selection at first favors growth perpendicular to each irregularity of the substrate, but as the individuals reduce in number and increase in size, the most successful are those oriented toward the bulk volume of the solution. Where there are major irregularities of the substrate (compared with the size of the growing crystals), substrate selection also operates, and crystals growing in hollows become entrapped in the bulk growth of those growing from ledges and protrusions. The overall effect is a leveling out of the growth front and a progressive trend toward more closely parallel growth of the surviving crystals. When the individuals are themselves split, geometric selection determines which subindividuals survive at the growth front while sub-

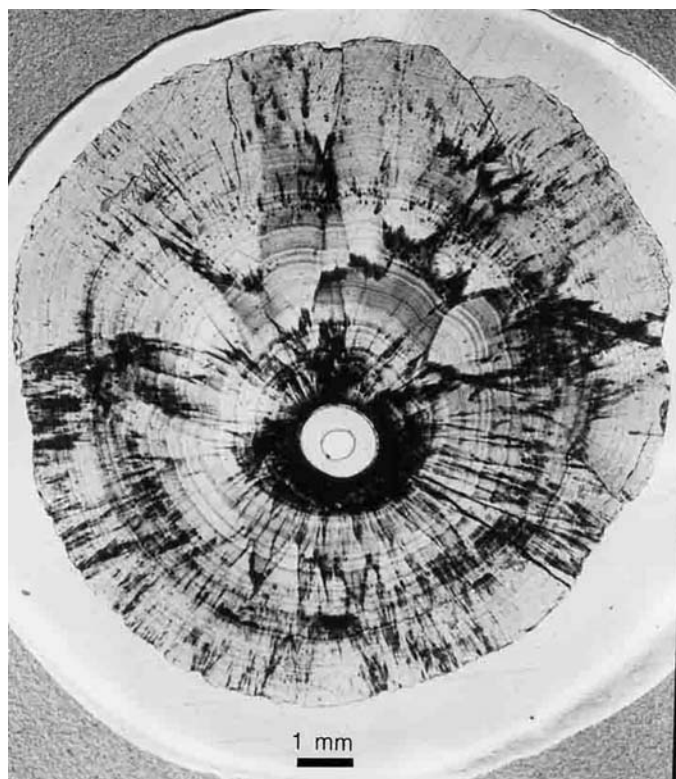


Figure 20. Cross-section of a cave pearl (a core spherulite) showing a radial arrangement of individuals due to geometric selection. Photo by Paolo Forti.

strate selection determines from which individuals they derive (Fig. 19).

(2.1.2) Spherulitic Aggregates. Spherulitic texture is a variant of parallel-columnar texture whereby the substrate, instead of being flat or slightly irregular, is sharply convex. Geometric selection produces crystals growing perpendicular to the substrate, but the curvature of this substrate produces a radiating fan of crystals rather than a roughly parallel growth of crystals. It is important to distinguish between spherulitic *structure* in mineral individuals (which is the result of crystal splitting) and spherulitic *texture* in mineral aggregates (which is the result of geometric selection). These are very different effects, and the term “spherulitic” simply refers to the external form of these quite different minor mineral bodies. Of the subtypes of spherulitic aggregates, the following two are particularly important:

(2.1.2A) Core Spherulites. Core spherulites are aggregates of mineral individuals growing in a radial manner away from a growth center (Godovikov *et al.* 1989). This radial arrangement is due to geometric selection between multiple individuals where only those crystals survive whose direction of maximum growth coincides with the radius of the core nucleus (i.e., a core spherulite is a spherical aggregate around a nucleus). A prime example is a cave pearl with a grain of sand at its center (Fig. 20).

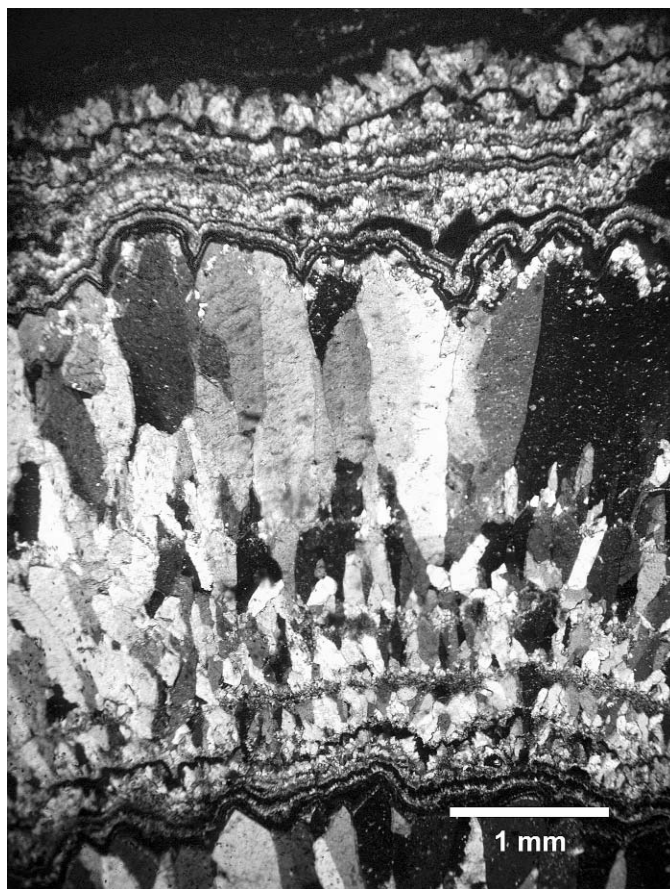


Figure 21. Polarized thin section of spherulitic aggregate texture in a calcite flowstone, Wind Cave, South Dakota. Note the repeated episodes of geometric selection after growth interruptions. Photo by Peg Palmer.

(2.1.2B) Irregular Spherulites. If the substrate is irregular, geometric selection causes a spherulitic texture to appear in the aggregate around each substrate protrusion. Such spherulitic crusts can develop in a subaqueous environment (e.g., pool spar) or in a subaerial environment (e.g., flowstone). If the supply of material is by diffusion of solute or by laminar flow of the feeding solution, the thickening crust will trend toward parallel-columnar growth (Fig. 21). This is normal in the case of pool spar and for flowstone deposited on very gentle slopes. On steeper slopes, turbulent flow promotes rapid growth on substrate protrusions and the development of microgours. On steep walls, the seepage water collects into rivulets that (because of an increased feeding rate) produce a locally thicker crust or even draperies.

(2.1.3) Radial-Fibrous Aggregates. Radial-fibrous aggregates are an important variation on both parallel-columnar and spherulitic aggregates where some (or all) of the individuals have begun to split. They make up the texture of many speleothem types, including flowstone and dripstone. Commonly they are interlayered with parallel-columnar (or spherulitic) aggregate crystals in these speleothems (Folk & Assereto 1976; Kendall & Broughton 1977, 1978; Kendall

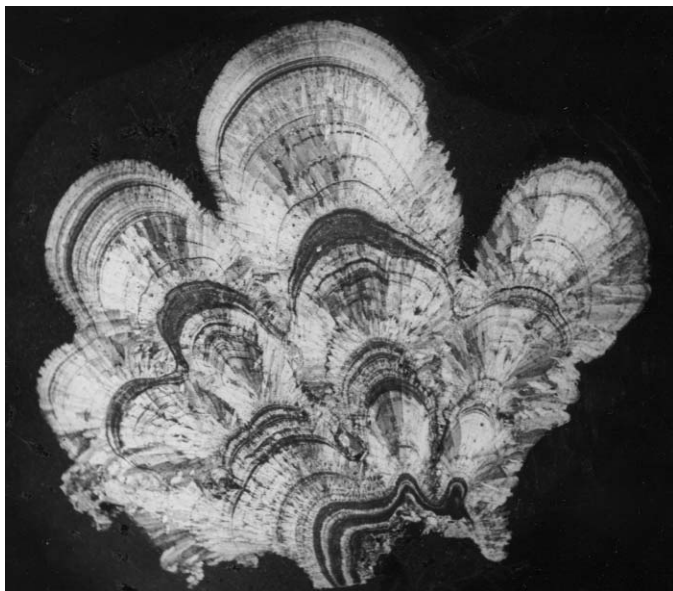


Figure 23. An early stage of branching of coralloids showing their subindividual structure in a thin-section photo (crossed polarizers, 24 mm across). Calcite cave coral from Soldiers Cave, California. Photo by George Moore.

1985) (Fig. 22: p. 148). The change to radial-fibrous texture is due to a decrease in solution supply, the mass-transfer of solutions changing from gravitational flow to a gravitation-influenced capillary thin-film flow. If the solution supply decreases further, radial-fibrous texture may lead to interruptions in growth.

(2.1.4) Branching Aggregates. A great variety of branching aggregates grow by evaporation in a capillary film environment. These include corallites, crystallictites, and many intermediate forms. Branching aggregates are aggregates of crystals displaying a compound branching form (Fig. 23). They are not the same as dendritic individuals (section 1.2.6), which display a branching pattern due to the splitting and skeletonization of crystals (compare Figs. 15 and 24, p. 148).

The competition in the case of branching aggregates is indirect and includes competition between nearby branches on the same bush. Molecules of solvent (water vapor and CO₂) leaving one branch adhere to neighboring branches, thus slowing their growth. For this reason, competing branches *never* touch each other and the strongest growth is always out towards the open void of the cave (Fig. 24: p. 148). For a single aggregate, there is competition between individuals but not selection. The situation changes when these aggregates grow together in close proximity. Substrate selection very strongly favors growth from protrusions (Fig. 25: p. 148), and aggregates situated there develop rapidly (Slyotov 1985). Less favorably situated aggregates find it increasingly difficult to lose solvent molecules, and their growth is suppressed or distorted away from nearby large bushes. The effect of substrate selection is very much stronger in the capillary film environment than in the subaqueous environment because of this need

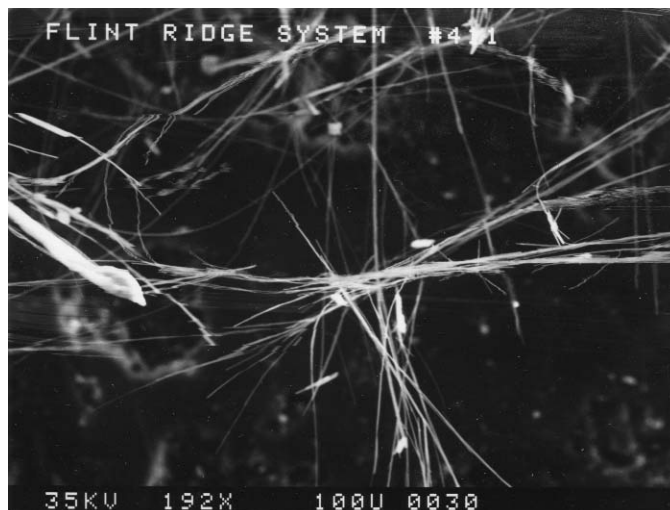


Figure 27. Scanning electron microscope image of individual filamentary crystals of cave cotton, Mammoth Cave, Kentucky. Photo by Will White.

to lose solvent molecules. If solvent is not lost, the capillary film cannot supply new solution (and new solute) and the aggregate cannot grow.

(2.1.4A) Corallites. Corallites are aggregates composed of spheroidalite individuals and so have a rounded form and a branching pattern due to the uneven growth and bent splitting of spheroidalites (Fig. 23). They are the product of thin capillary water films that have a condensation origin or appear because of the slow spread of water due to very weak trickling. Prime examples of corallites are thin-film-generated varieties of coralloids (popcorn and cave coral). Note that *corallite* is an ontogeny term and should not be confused with the speleothem type “coralloid” of Hill & Forti (1997).

(2.1.4B) Crystallictites. Crystallictites are branching aggregates built from faced crystals (Serban *et al.* 1961; Moroshkin 1976). They form in a capillary film environment as an analog of corallites, but without the splitting of individuals that is characteristic of corallites. The branching of crystallictites is usually noncrystallographic—it is due to branching of the aggregates themselves. However, a full range of intermediate forms exists between corallites and crystallictites (Fig. 26: p. 148), displaying different degrees of crystal splitting. Also, there can be interconversions between corallites and crystallictites. Because the type and propensity for crystal splitting depends on mineral species, crystallictite aggregates are typical for minerals such as gypsum and aragonite, whereas corallite aggregates are more characteristic of calcite. Aragonite frostwork is a prime example of a crystallictite (Fig. 24: p. 148).

(2.1.5) Fibrous Aggregates. Fibrous aggregates are built from filamentary individuals (Fig. 27), and grow from a porous substrate that may be solid (such as the cave walls or breakdown blocks within a cave) or plastic (such as cave sediments, particularly clays). In the West, fibrous aggregates

have many fanciful names such as “hair”, “cotton” (Fig. 28: p. 149), “beards”, “flowers”, and “needles” (Hill & Forti 1997), but in Russia they are known collectively as “antholites” (not to be confused with the speleothem type “anthodite”). Fibrous aggregates are always composed of soluble minerals such as gypsum, epsomite, mirabilite, or halite. The reason why no calcite “flowers” and “needles” exist is because carbonate solutions simply do not carry enough solute.

The growth mechanism of fibrous aggregates is purely by evaporation of the solvent and takes place close to the ends of pores in the substrate. The unique feature of fibrous aggregates is that they grow from the base, with new growth pushing the previous growth out into the cave void (Fig. 29: p. 149). This growth mechanism means that selection between individuals is impossible and there is only competition between pores. For growth from a solid substrate, the pores feeding the center of an aggregate often have a stronger supply than those feeding the periphery, leading to different growth rates. For well connected aggregates such as gypsum flowers, this causes the aggregate to burst into separate curving “petals”. For loosely connected aggregates such as hair, the fibers may become tangled and form beards.

For growth from a plastic substrate such as cave clay, competition between pores leads to a very different situation. The capillary pressure and the crystallization pressure together press the substrate, causing only certain favorable pores to remain open while other surrounding pores collapse. This is a very specific type of selection for plastic substrates and explains the wide separation between individuals (e.g., selenite needles) in this environment compared with growth from a solid substrate (e.g., beards).

(2.1.6) Interactive Aggregates. The growth of any aggregate depends on environmental factors that are local to the growth front of the individuals of which it is composed. In most cases, these environmental factors are identical to those affecting other nearby aggregates, so we can talk of a *parent environment* controlling mineral growth over a significant part of a cave. However, not all mineral aggregates are passive products of a parent crystallization environment. There is a class of minor mineral bodies, called *interactive aggregates*, which grow under local conditions that the MMB itself creates. These local conditions are significantly different from the general environmental conditions of the crystallization space as a whole. In the case of helictites (and shields), a high capillary pressure is maintained in their central channels, which results in solute deposition when the feeding solution loses pressure in the open void of the cave. For this reason, helictites grow without regard to the force of gravity or the direction best suited for evaporation in the capillary film environment.

There are many different types of eccentric MMBs that are included in the speleothem term “helictite” (Hill & Forti 1997). In a detailed study (Slyotov 1985), one particularly common type was shown to be a parallel co-growth of spherulite bunches, tightly bonded and growing in strictly defined sectors (Figs. 15 and 30, p. 149). A fine central chan-

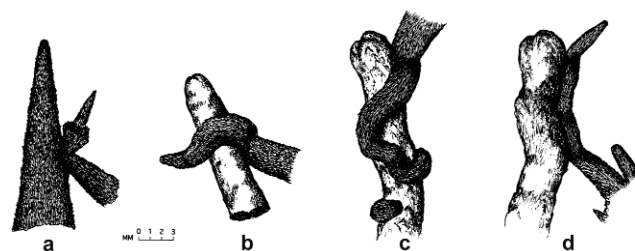


Figure 31. The “behavior” of helictites when meeting an obstacle: (a) reflection, (b) rounding, (c) sliding without separation, and (d) sliding with separation. From Slyotov (1985).

nel supplies a local capillary film spot on the helictite’s tip, where there is competition for solute between the sectors but *not* selection. Small local variations affecting the wetted spot promote different growth rates between the sectors, but the sector boundaries are strictly maintained. This results in sudden changes in growth direction for the aggregate as a whole (so helictites can twist or turn in any direction). Moreover these variations are unique to each helictite; when groups of ordinary calcite helictites were studied by Moore (1954, 1999), their growth-front azimuths proved to be random.

Interactive aggregates have a most peculiar additional property termed *behavior* when interacting with obstacles. According to Slyotov (1985), when a growing helictite makes a perpendicular impact on an obstacle, growth is stopped. If the approach is oblique, the aggregate may show reflection, rounding, or adherence to the obstacle’s surface (Fig. 31). The reason for this may be found in a property of spherulite individuals, whereby when their growth surface is mechanically blocked (see section 1.2.1A, Fig. 7), the unobstructed rays of the spherulite serve as the focus for new growth. Exactly the same thing happens for spherulite bunches. In the case of helictites, changes in the growth of the bunch impacting an obstacle causes a change in growth direction for the aggregate as a whole.

For most aggregates, interaction only occurs between individuals (in the form of competition). For branching aggregates, there is some limited interaction with obstacles in that mineral growth slows down and stops before impact (due to an inability to lose solvent molecules). Interactive aggregates, however, are fully interactive with the general environment in which they grow, because their growth processes are not directly controlled by that environment.

(2.1.7) Other Aggregates. In addition to the main aggregate types described above, we will briefly mention some others. *Granular aggregates* form when a mineral species (or mineral habit) has similar growth speeds in different directions, or when frequent interruptions of growth combine with recrystallization or new nucleation to subvert the role of geometric selection. Granular aggregates commonly occur during bulk crystallization from viscous solutions and melts, whereas

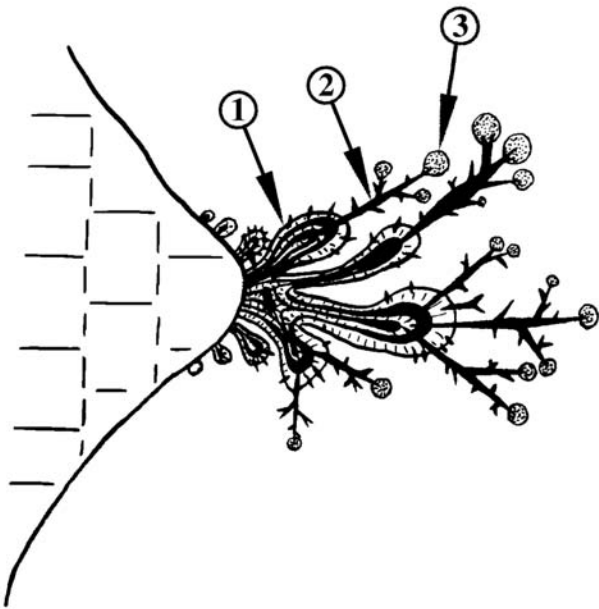


Figure 32. Drawing of a multicorallite bush: (1) calcite popcorn, (2) aragonite crystallite needle, (3) hydromagnesite efflorescence. By Vladimir Maltsev, from an unpublished manuscript.

in caves with seasonal humidity cycles, they can be found in the evaporative deposition of soluble species such as gypsum.

Ice is a common cave mineral, forming many of the aggregate types described above. Ice can also form *sublimation aggregates*, which are built from skeleton crystals but branched in a special manner. *Plastic-substrate aggregates* of ice or gypsum have special textures and grow deep within clay sediments. *Monocrystalline aggregates* are the result of total recrystallization into one single individual; flaws within the new individual often retain traces of the previous aggregate texture. *Hybrid aggregates* have textures intermediate between the main types described above; they will be discussed later (section 2.2.3).

In all the above examples, crystallization takes place on an inert substrate. For *controlled-nucleation aggregates*, the orientation of individuals is predetermined. One example is autoepitaxial growth on a textured substrate (e.g., gypsum growing from gypsum crystals in the wall rock, typical for the caves of Podolia, Ukraine). Another is the growth of some varieties of cave rafts, where individuals align perpendicular to the surface because of electric forces associated with surface tension. This category is not so important for cave mineralogy, but growth on textured substrates is very important in ore mineralogy.

(2.2) Multiaggregates. *Multiaggregate* is a new category in minor mineral body hierarchy. It was first introduced by Maltsev (1996b), although the concept was originally suggested by Stepanov (1973) as “typical paragenetic pairs of aggre-

gates.” Multiaggregates are an intergrowth or co-growth of different types of aggregates that form simultaneously and syngenetically in the same crystallization environment. They are either polymineral or polytextural, as compared to simple aggregates, which are always monomineral and texturally homogeneous.

(2.2.1) Polymineral Multiaggregates. A typical multicorallite is a branching MMB that is formed of calcite popcorn from which grows aragonite frostwork that is often tipped with a soluble mineral such as hydromagnesite (Figs. 32 and 39, p. 152). All three mineral species form simultaneously from the same capillary solution and in the same crystallization environment. However, because of evaporation the Mg/Ca ratio of the capillary film steadily increases from the base of each multicorallite branch toward the tip. In this way, a multicorallite changes the chemistry of its feeding solution, giving rise to changes in morphology, crystal-splitting grade, and even the mineralogy of the crystals being deposited. In such speleothems, continuous recrystallization clearly also takes place, otherwise hydromagnesite would coat all the surface of the aragonite needles and not just remain on the growing needle tips. Because of continuous growth throughout all parts of the multicorallite, magnesium is also redissolved in the root part of each branch. This recycling of the Mg ion, even if from a rather low original concentration, creates the conditions whereby aragonite growth becomes possible (inasmuch as the Mg ion promotes aragonite growth but is not significantly incorporated within the mineral itself). Complete evaporation of the remaining solution on the tips of the aragonite needles allows high-Mg minerals such as hydromagnesite or huntite to be deposited.

Another example is a pseudohelictite, a type of solid quill anthodite consisting of a central aragonite needle sheathed in spherulitic aggregate calcite (Fig. 33: p. 150). Both minerals grow simultaneously. The aragonite needle defines the general geometry of the multiaggregate and the branching directions, while the calcite overgrowth suppresses the crystalline defects of the needle and, thus, limits the branching frequency.

(2.2.2) Polytextural Multiaggregates. Multiaggregates do not need to involve the co-growth of different mineral species. There are also monomineral multiaggregates that are polytextural. The most common example of this is the ubiquitous cone-shaped calcite stalactite. This speleothem contains the mineral calcite simultaneously growing as a “crown” of skeleton crystals that forms at the tip of the stalactite from drip water due to mechanical agitation and CO₂ loss during dripping (Fig. 34: p. 150), a monocrystalline tube that forms by recrystallization of these skeleton crystals, and a spherulitic aggregate outer layer that is deposited as a result of regular degassing of CO₂ (Maltsev 1997c). Soda straw stalactites are also multiaggregates since they contain both skeleton crystals and monocrystalline growth. It is important to note that conical stalactites are not soda straws overgrown by a later surface crust—the three textures form together and simultaneously.

(2.2.3) Hybrid Multiaggregates. One of the central tenets of ontogeny is that the texture of a minor mineral body is directly related to its crystallization environment. However, the boundary between different crystallization environments is not always clearly defined. For example, corallites grow in the capillary film environment by evaporation. If the feeding supply is sufficiently strong to cause slow dripping from the aggregate, a hybrid MMB (a corlactite) may form with features of both a corallite and a stalactite—the branches of the corlactite are partially cemented together, and the statistical trend of their orientation shows a weak gravitational control. Crystallinites similarly hybridize with stalactites, to form crystallactites. Names for these hybrid textures were first proposed by Victor Stepanov in 1983, but only appeared in print when part of his archive was published posthumously (Stepanov 1997).

If significant evaporation occurs in a gravitational water environment, similar hybrid textures may be expected. However, conical stalactites are multiaggregates of three textures, not all of which are available for hybridization. Only the outer spherulitic aggregate part can hybridize with corallites (or crystallinites), so the resulting MMB looks somewhat like a corlactite but with a soda straw inside (Maltsev 1997c). By contrast, stalagmites are simple spherulitic aggregates and so can fully hybridize with corallites. Depending on the balance between dripping and evaporation, a range of hybrid forms from almost “pure” stalagmite to almost “pure” corallite is possible. Hybridization between helictites and soda straws is also known.

Hybridization of texture is an important concept because it explains how some of the most interesting and unusual speleothems grow (Fig. 35: p. 150). However, speleothems can change texture as a result of a change in environmental conditions. Care needs to be taken to distinguish between true hybridization caused by a combined (or mixed) environment, and a sequential change of texture.

(2.3) Pseudoaggregates. Some speleothems are disordered and have no “through” structure. They cannot be considered as true aggregates and do not fit into the hierarchy of MMB. However, these anomalous mineral bodies can take part in the formation of higher levels of the MMB hierarchy (koras and ensembles), and so behave as if they were some form of aggregate. Such anomalous mineral bodies are called *pseudoaggregates*.

A consistent feature of pseudoaggregates is that the original place of nucleation of any crystal individual is different from its final resting place on a substrate. This produces a chaotic arrangement of crystals, for which there can be no “through” structure. For tufaceous deposits and chemogenic moonmilk, the crystallization displacement is usually quite small. But in the case of cave cones, where sunken cave rafts accumulate at the bottom of a pool, this distance can be measured in meters. Cave rafts are true aggregates, having structural and textural regularities. A jumbled pile of rafts does not collectively possess these features, but a cave cone does have

a definite morphology that repeats itself in the cave environment (which itself is a textural feature). It clearly forms from the same crystallization conditions as rafts and shelfstone, and so can join with those speleothems in the higher levels of MMB hierarchy.

(2.3.1) Tufaceous Mineral Bodies. Some of the most massive stalactites, stalagmites, and flowstones in caves are formed not of hard crystalline calcite, but of a light and porous calcareous material composed of disordered microcrystals. It is common to find such tufaceous material alternating with crystalline layers. Such speleothems may be of a purely mineral (nonorganic) composition, but they commonly have a significant organic (bacterial or algal) content, particularly in the daylight zone of caves where calcite deposition is aided by photosynthesis. Tufaceous deposits in caves are usually made of calcite, but in metaliferous mines many other mineral species have been identified.

Tufaceous mineral bodies tend to grow massively and rapidly, with new nucleation outpacing the development of “through” structure. Such bodies are formed from turbulent gravitational water streams, where oversaturation of the feeding solution is caused by mechanical agitation and CO₂ degassing. This leads to nucleation of calcite crystals within the feeding solution, mainly around cavitation bubbles, rather than directly on the substrate surface. There is no opportunity for competition to start (such competition would lead to the formation of a regular aggregate), and the crystals coagulate together in a disorderly manner, producing light and porous speleothems. The nature of the dripping water environment allows the morphology of these tufaceous MMBs to mimic those made from crystalline material, so all of the common (laminar flow) gravitational water speleothems have their tufaceous analogs. In addition, most rimstone dams (gours) are built of tufaceous calcite because turbulent flow over their rims causes mechanical agitation and rapid degassing. Tufaceous mineral bodies can also form as a result of sudden pressure or temperature changes, for example from crack-fed solutions in artificial structures such as tunnels, bridges, etc. (Fig. 36: p. 151).

(2.3.2) Moonmilk. Moonmilk is a microcrystalline to nanocrystalline coagulation of disordered acicular individuals, porous and plastic in nature, and containing 40-80% water by weight. Moonmilk may be of biogenic origin, chemogenic origin, a residual precipitate of bedrock or speleothem weathering, or of mixed origin (Hill & Forti 1997). Moonmilk deposits are often composed of calcite, but they can also be composed of other carbonate, sulfate, phosphate, or silicate minerals. Chemogenic moonmilk forms under conditions of high oversaturation in a dripping/flowing water environment, and so can form speleothems similar (but on a far smaller scale) to tufaceous deposits (Fig. 37: p. 151).

At present, only chemogenic carbonate moonmilk has been studied from an ontogenetic perspective (Stepanov 1997). A case could be made for considering speleothems of biogenic origin as a specific environment within ontogeny, but this is a

debate for the future. Weathering residues are sediments and therefore cannot be studied in ontogeny.

(3) THIRD LEVEL: Assemblages of Aggregates. The division of physical mineral bodies into individuals and aggregates is an 18th Century concept. However, *aggregate* was then a very broad term, even including rocks within its scope. This situation was not resolved until Stepanov (1970) found a new formulation of *aggregate texture* that excluded rocks. This led directly to the concept of minor mineral bodies and the understanding that an aggregate is a relatively low-ranking MMB within a larger hierarchy. This larger hierarchy is still poorly known among mineralogists, even in Russia, inasmuch as it has been derived mainly from observations of speleothems in caves. Above the level of aggregate, there seemed to be a class of MMB that had the same sense of texture as an aggregate, but lacking the structure of an aggregate. This new and more complicated type of MMB was given the name *kora* by Russian speleologists.

(3.1) Koras. *Kora* is a Russian word meaning “crust” in a broad sense. For Russian mineralogists, the term has two meanings: As an aggregate term and as a hierarchy term. (“Crust” is also used more loosely in English texts as a speleothem term; Hill & Forti 1997.) Here, we use *kora* strictly as a hierarchy term.

A *kora* is an assemblage of texturally similar aggregates, growing together at the same time and in the same crystallization space, and forming from the same environmental conditions. The concept was first suggested by Fersman & Shcherbakov (1925) as a term uniting the different forms of stalactites, stalagmites, draperies and flowstones that grow together in a dripping water environment—they called this “the stalactite-stalagmite *kora* of calcite” (Fig. 38: p. 151). Stepanov’s great contribution was to extend the concept of *kora* to other aggregate assemblages. Examples include the tufaceous calcite *kora*, the corallite *kora*, the antholite *kora*, etc. (Stepanov 1971, 1997).

A strict definition of *kora* was given by Stepanov (1997): “A *kora* is an association of aggregates that appears in all the space of synchronous crystallization, during episodes of the crystallization cycle when the phase state of the crystallization medium remains constant for significant intervals of time.” In current usage, aggregates, multiaggregates and pseudoaggregates can all be included in *koras*, because at this level there is no distinction between them. We must note that for *koras*, the concept of “through” *structure* no longer applies—only “through” *texture*. In the case of polytextural multiaggregates such as conical stalactites, the dominant spherulitic aggregate texture is *kora*-forming and allows them to join with stalagmites and flowstones (which have only this texture).

The great advantage of studying *koras*, as compared to aggregates, is that variations in structure become apparent when the whole crystallization space is studied as a unit. For example, in a capillary film environment crystallites may grow in one part of a chamber, corallites in another part, and

intermediate forms in between. Without the *kora* concept, this would seem to be two groups of aggregates with some hybrid forms. With the *kora* concept, it becomes obvious that corallites and crystallites are texturally the same and that the only difference between them is the degree of crystal splitting in the structure of the individuals that form the aggregate. This is an example of variations of structure within a crystallite-corallite *kora*.

The concept of *kora* denotes the union of texturally similar crystallization products generated together by the same environment. However, over very long periods of time the cave environment can change. As different mediums of crystallization replace one another, new *koras* can be generated thereby initiating a change in textures throughout the whole space of synchronous crystallization. For example, corallites growing on stalactites and corallites growing from rock walls can together form a corallite *kora* (if they are of the same generation), but the stalactites themselves are not part of that *kora*—they are from an earlier stalactite-stalagmite *kora*.

(4) FOURTH LEVEL: Assemblages of Koras. A fourth hierarchy level in mineral ontogeny was first suggested by Stepanov in a series of lectures given at Moscow State University during the 1970s. He named this new and more complex minor mineral body an *ensemble*. Some years after Stepanov’s death, the term was introduced into print by Maltsev (1993).

(4.1) Ensembles. The ensemble concept is fundamentally different from that of other terms used in MMB hierarchy. The factor of a regular change is involved. Crystallization environments evolve over long periods of time, becoming successively drier until a new wet phase marks the start of the next crystallization cycle. These cycles are not always complete, but the sequence remains the same (Stepanov 1971). For the first three levels in MMB hierarchy, the mineral bodies form in a stable crystallization environment during a single episode and from one feeding mechanism. To study an ensemble, we must examine all the mineral growth of the current crystallization cycle; i.e., since the last general inundation of the crystallization space, or its last general drying out. For ensembles, the concept of “through” texture is different because it involves a sequence of textures evolving through time (Fig. 39: p. 151). An ensemble is usually described by a “diagnostic set” of minerals or speleothems and can include any MMB.

In many limestone caves fed by meteoric water, the crystallization cycle begins with stalactites, stalagmites, and flowstone. Later in the cycle, this dripstone and flowstone may become overgrown by knobby popcorn concretions. Here a stalactite-stalagmite *kora* is replaced by a corallite *kora* as a dripping (gravitational) environment dries out and becomes a capillary film (evaporitic) environment. The overgrowth may be sharply defined, as in this example, or it can be a gradual transition (crystalline stalactite-stalagmite *kora*, seasonal overgrowth of radial-fibrous aggregates, continuous radial-fibrous aggregates, corallite *kora*).

Each cave or cave system, because of its own particular set of environmental parameters, has only a limited number of ensembles. Generally, these are different for different caves, although some ensembles may be typical for an entire cave region. For example, the caves of the Guadalupe Mountains, New Mexico, were developed in dolomitic limestone by a sulfuric acid mechanism. In these caves, there is a particularly well-displayed ensemble comprising gypsum blocks deposited during the original sulfuric acid speleogenesis episode, and younger gypsum stalactites (chandeliers) and stalagmites derived from reworked material (Fig. 35: p. 150). The caves of Crimea (Ukraine) are typical of limestone caves fed by meteoric water, and are abundantly decorated by speleothems showing the following sequence: tuffaceous stalactite-stalagmite kora, crystalline calcite stalactite-stalagmite kora, coralite kora, antholite kora (Stepanov 1971).

An ensemble is, therefore, very different from other MMBs. It is an expression of the mineralogic landscape of a cave or cave passage. Because of differences in the chemistry of the host rock or the mineralizing solution, a great many possible ensembles can be found in caves. However, within any one cave, or within a small karst region, they are relatively few in number. One weakness of the ensemble concept is that it is not transitive; i.e., in different cave regions the crystallization products and their evolution are different. A stalactite is much the same in all caves, as is a multicorallite or an antholite kora. Ensembles rarely repeat themselves exactly.

Ontogeny is concerned only with minerals deposited during a single crystallization cycle. Very old speleothems, formed during several cycles of deposition, have no "through" regularities and are not MMBs. The separate phases of deposition can be studied using ontogeny techniques (e.g., Stepanov 1971), but such speleothems as a whole must be classed as *rocks* and studied by petrographic techniques.

CONCLUSION

In this paper, we have shown how crystal individuals combine together to form aggregates, and how associations of aggregates build the higher levels of the minor mineral body hierarchy—koras and ensembles. These more complex MMBs are best understood by building parallels to regular mineralogy. Multiaggregates may be viewed as the MMB equivalent of paragenesis, koras of associations, and ensembles of sequences.

Curiously, the higher levels of the MMB hierarchy are readily understood by non-mineralogists. Most members of the general public know that stalactites and stalagmites "go together", which (with textural considerations) is the kora concept. Experienced cavers will describe stalagmites covered with popcorn corallites as "old-looking", this being the ensemble concept of one kora replacing another as a crystallization cycle progresses. The historical problem for cave scientists has been how to deconstruct the mineralogical landscape, to break

it down into simpler units. But without the concepts of ontogeny, any studies of MMB texture suffer greatly, as was the case for the first thorough study of speleothems (Prinz 1908).

Another apparent problem for studies of ontogeny is that the detailed structure and texture of speleothems can only be seen by microscopic examination of cut sections. However, once this determination has been made and described, the specific form of many common speleothems can be recognized simply by eye. Cavers with a small amount of mineralogic experience are, therefore, able to accurately identify the stage in a development cycle of the mineral growth in any newly discovered cave passage.

Ontogeny of minerals is not simply a new classification system for minerals. It is a method by which past crystallization environments can be interpreted from the mineral bodies that were deposited. The structure and texture of minor mineral bodies can be directly related to environmental factors, and speleothems are ideal subjects for this type of study.

ACKNOWLEDGMENTS

The conceptual framework of this paper belongs to our colleague Vladimir Maltsev, who worked with us on an earlier version of the text. The ideas presented here have been developed from the (largely unpublished) work of the late Victor Stepanov. We would like to acknowledge Donald Davis, Paolo Forti, George Moore, Bogdan Onac, Victor Polyak, and William White for their helpful reviews during the preparation of this paper, and to thank the many who contributed photographs and drawings.

REFERENCES

- Broughton, P.L., 1983a, Lattice deformation and curvature in stalactitic carbonate: *International Journal of Speleology*, v. 13, n. 1-4, p. 19-30.
- Broughton, P.L., 1983b, Environmental implications of competitive growth fabrics in stalactitic carbonate: *International Journal of Speleology*, v. 13, n. 1-4, p. 31-42.
- Broughton, P.L., 1983c, Secondary origin of the radial fabric in stalactitic carbonate: *International Journal of Speleology*, v. 13, n. 1-4, p. 43-66.
- Dana, J.D., 1837, *A system of mineralogy* (1st ed.): Durrie & Peck, New Haven, 452 p.
- Fersman, A.E., 1935, Achievements of Soviet mineralogy and geochemistry during recent years, 1929-1934: Moscow-Leningrad, Izdatel'stvo A.N. SSSR. In Russian.
- Fersman, A.E., & Shcherbakov, D.I., 1925, The Tyuya-Muyun deposit of radium ore in Fergana: Moscow. In Russian.
- Folk, R.L., 1965, Some aspects of recrystallization in ancient limestones, in Pray, L. C., & Murray, R. C. (eds.), *Dolomitization and limestone diagenesis*: Society of Economic Paleontologists and Mineralogists Special Publication 13, p. 14-48.
- Folk, R.L., & Assereto, R., 1976, Comparative fabrics of length-slow and length-fast calcite and calcitized aragonite in a Holocene speleothem, Carlsbad Caverns, New Mexico: *Journal of Sedimentary Petrology*, v. 46, n. 3, p. 486-496.
- Godovikov, A.A., Ripenen, O.I., & Stepanov, V.I., 1989, Spherulites, spherocrystals and spheroidalites: New data on minerals: *Nauka, Moscow*, v. 36, p. 82-89. In Russian.

- Grigor'ev, D.P., 1961, Ontogeny of minerals: Lvov, Izdatel'stvo L'vovskogo Univ. In Russian. English translation 1965, Israel Program for Scientific Translations, 250 p.
- Grigor'ev, D.P., & Zhabin, A.G., 1975, Ontogeny of minerals. Individuals: Nauka, Moscow, 200 p. In Russian.
- Hill, C.A., & Forti, P., 1997, Cave minerals of the world (2nd ed.): National Speleological Society, Huntsville, Alabama, 463 p.
- Jones, B., & Kahle, C.F., 1993, Morphology, relationship, and origin of fiber and dendrite calcite crystals: *Journal of Sedimentary Petrology*, v. 63, n. 6, p. 1018-1031.
- Jushkin, N.P., 1973, The theory of micro-blocked crystal growth in natural heterogenic environments: Syktyvkar NC, 74 p. In Russian.
- Kantor, B.Z., 1997, Besedi o mineralakh (Discussions about minerals): Nazran, Astrel, 136 p. In Russian. Republished in English 2003, as Crystal growth and development interpreted from a mineral's present form: *Mineralogical Almanac*, v. 6.
- Kendall, A.C., 1977, Fascicular-optic calcite: a replacement of bundled acicular carbonate cements: *Journal of Sedimentary Petrology*, v. 47, n. 3, p. 1056-1062.
- Kendall, A.C., 1985, Radiaxial fibrous calcite: A reappraisal, *in* Schneiderman, N., and Harris, P.M. (eds.); *Carbonate Cements*, Society of Economic Petrologists and Mineralogists Special Publication no. 36, p. 59-77.
- Kendall, A.C., 1993, Discussion: Columnar calcite in speleothems: *Journal of Sedimentary Petrology*, v. 63, n. 3, p. 550-552.
- Kendall, A.C., & Broughton, P.L., 1977, Discussion: Calcite and aragonite fabrics, Carlsbad Caverns: *Journal of Sedimentary Petrology*, v. 47, n. 3, p. 1397-1400.
- Kendall, A.C., & Broughton, P.L., 1978, Origin of fabrics in speleothems composed of columnar calcite crystals: *Journal of Sedimentary Petrology*, v. 48, n. 2, p. 519-538.
- Korshunov, V.V., & Shavrina, E.V., 1998, Gypsum speleothems of freezing origin: *Journal of Cave and Karst Studies*, v. 60, n. 3, p. 146-150.
- Maleev, M.N., 1971, Properties and genesis of natural filamentary crystals and their aggregates: Nauka, Moscow, 180 p. In Russian.
- Maleev, M.N., 1972, Diagnostic features of spherulites formed by splitting of a single crystal nucleus. Growth mechanism of chalcedony: *Tschermaks Mineralogische und Petrographische Mitteilungen*, v. 18, p. 1-16.
- Maltsev, V.A., 1989, The influence of season changes of the cave microclimate to the gypsum genesis: *Proceedings of the 10th International Congress of Speleology*, Budapest, v. 3, p. 813-814.
- Maltsev, V.A., 1993, Minerals of the Cupp Coutunn karst cave system, south-east Turkmenistan: *World of Stones*, Moscow, v. 1, p. 5-30.
- Maltsev, V.A., 1996a, Filamentary gypsum crystals from the Cupp-Coutunn Cave: *Journal of Cave and Karst Studies*, v. 58, n. 3, p. 204.
- Maltsev, V.A., 1996b, New levels in the minor mineral bodies hierarchy: *Journal of Cave and Karst Studies*, v. 58, n. 3, p. 204-205.
- Maltsev, V.A., 1996c, Sulphate filamentary crystals and their aggregates in caves: *Proceedings of the University of Bristol Speleological Society*, v. 20, n. 3, p. 171-186.
- Maltsev, V.A., 1997a, A model of structure and genesis for the gypsum "nest" found in the Geophysicheskaya Cave (Kugitangtou Mountains, Turkmenistan): *Journal of Cave and Karst Studies*, v. 59, n. 2, p. 87-90.
- Maltsev, V.N., 1997b, Overview of cave minerals onthogeny: *Proceedings of the 12th International Congress of Speleology*, La Chaux-de-Fonds, Switzerland, v. 1, p. 219-222.
- Maltsev, V.A., 1997c, Stalactites, crustalactites, corlactites, tuflactites – 4 types of "stalactite-like" formations, generated from crystallization environments with different physical properties: *Proceedings of the 12th International Congress of Speleology*, La Chaux-de-Fonds, Switzerland, v. 1, p. 267-270.
- Maltsev, V.A., 1998, Stalactites with "internal" and "external" feeding: *Proceedings of the University of Bristol Speleological Society*, v. 21, n. 2, p.149-158.
- Moore, G.W., 1952, Speleothem – A new cave term: *National Speleological Society News*, v. 10, n. 6, p. 2.
- Moore, G.W., 1954, The origin of helictites: *National Speleological Society, Occasional Papers*, n. 1, 16 p.
- Moore, G.W., 1999, Discussion: Helictites, *in* V. A. Slyotov, *Cave Geology*, v. 2, n. 4, p. 196.
- Moroshkin, V.V., 1976, On genesis of crystallite types of aggregates: *Nauka, Novye Dannye o Mineralakh SSSR*, v. 25, Moscow. In Russian.
- Moroshkin, V.V., 1986, Karstotypic mineralization: *Mineralogicheskii Journal*, Kiev, v. 8, no. 5, p. 10-20. In Russian.
- Polyak, V.J., 1992, The mineralogy, petrography, and diagenesis of carbonate speleothems from caves in the Guadalupe Mountains, New Mexico: Unpublished MS thesis, Texas Tech University, Lubbock, 165 p.
- Prinz, W., 1908, Les cristallisations des grottes de Belgique: *Nouveau Memoire de la Societe Belge de Geologie*, ser. 4, n. 2, 90 p. In French. English translation 1980, *Cave Geology*, v. 1, n. 7, p. 191-258.
- Serban, M., Viehmann, I., & Coman, D., 1961, *Caves of Romania: Meridiane, Bucharest*. In Romanian, Russian, French, and German editions.
- ShafraNovskiy, I.I., 1961, Crystals of minerals: Curved-faced, skeletal and granular forms: *Gosgeoltekhizdr*, Moscow, 230 p. In Russian.
- Shubnikov, A.V., 1935, *How crystals grow*: Izdatel'stvo AN SSSR, Moscow-Leningrad. In Russian.
- Slyotov (Sletov), V.A., 1985, Concerning the ontogeny of crystallite and helictite aggregates of calcite and aragonite from the karst caves of southern Fergana: *Novye Dannye o Mineralakh CCCP (New Data on Minerals)*, Nauka, Moscow, v. 32, p. 119-127. In Russian. English translation 1999, *Cave Geology*, v. 2, no. 4, p. 196-208.
- Stepanov, V.I., 1965, Exploration de la succession de crystallisation des agregats mineraux comme l'une des facon d'etude de l'histoire de la formation des grottes a concrections calcaires (abst.): *4th International Congress of Speleology*, Ljubljana, Yugoslavia. Summaries of lectures, p. 54-55. In French.
- Stepanov, V.I., 1970, On the genesis of so-named "collomorphic" mineral aggregates, *in* *Ontogenetic methods of studying minerals*: Nauka, Moscow, p. 198-206. In Russian.
- Stepanov, V.I., 1971, Crystallization processes periodicity in karst caves: *Trudy Mineralogicheskogo Muzeya imini A.E. Fersmana*, Moscow, n. 20, p. 198-206. In Russian. English translation, 1999, *Cave Geology*, v. 2, no. 4, p. 209-220.
- Stepanov, V.I., 1973, On aims and methods when studying crystallization sequences in ore mineral aggregates; *in* *Issledovaniya voblasty prikladney mineralogii i kristalokimii*: Institute of Geology, Geochemistry, and Crystallography of Rare Elements, Moscow, p. 3-10. In Russian.
- Stepanov, V.I., 1997, Notes on mineral growth from the archive of V. I. Stepanov (1924-1988): *Proceedings of the University of Bristol Speleological Society*, v. 21, n. 1, p. 25-42.
- Zhabin, A.G., 1979, *Ontogeny of minerals. Aggregates*: Nauka, Moscow, 300 p. In Russian.

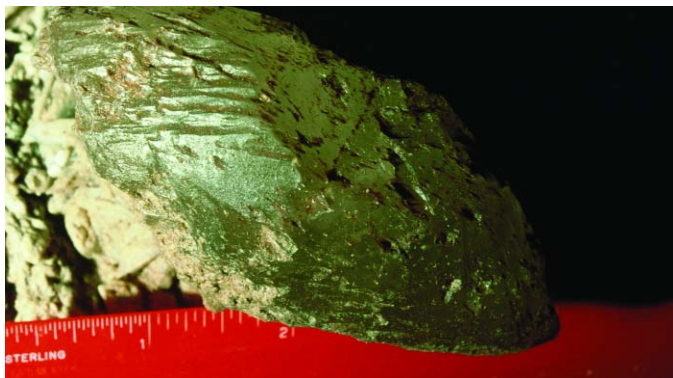


Figure 2. (A - top) A single spar crystal of hydrothermal calcite on a passage wall, Carlsbad Cavern, New Mexico. Photo by Cyndi Mosch. (B - bottom) Gypsum individuals on the side of a pseudohelictite, Cupp-Coutunn Cave, Turkmenistan. Photo by Vladimir Maltsev.

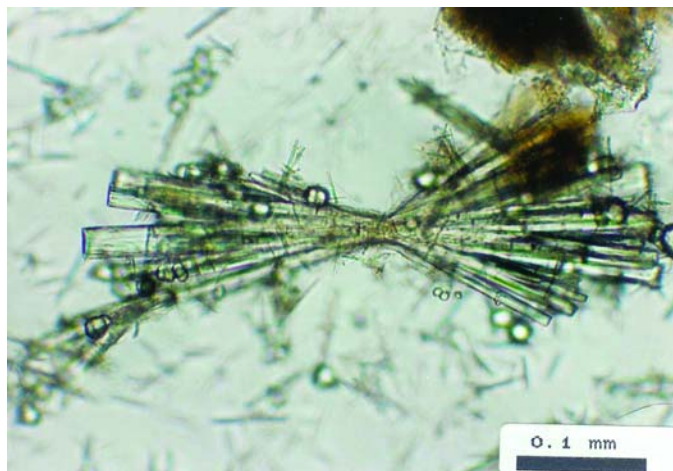


Figure 3. Thin-section photomicrograph of a split crystal of aragonite growing from a single nucleus (the small round structures in the photo are spherules of monohydrocalcite). Precipitation was achieved under laboratory conditions. From Polyak (1992).



Figure 6. Spherulites of wavellite, an aluminium phosphate mineral (non-cave photo). From Kantor (1997).

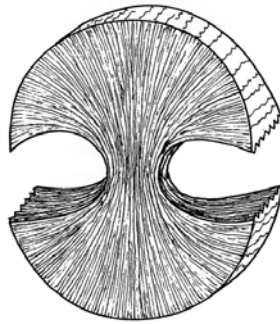
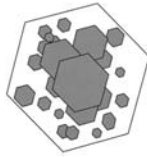
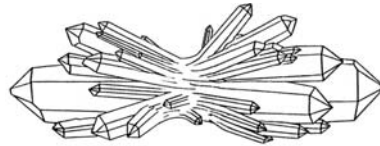
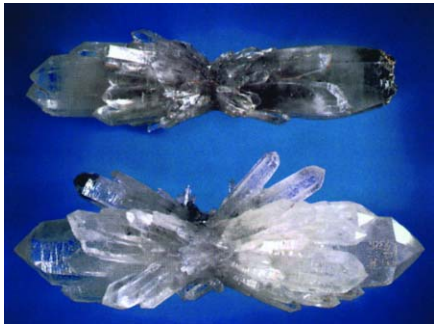
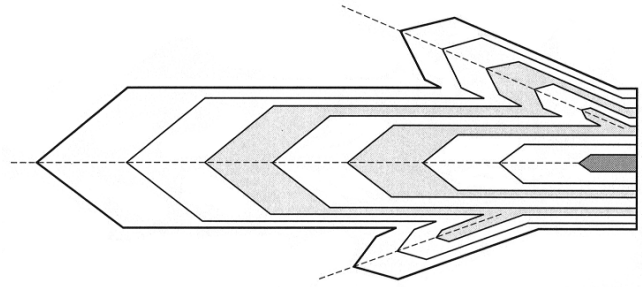
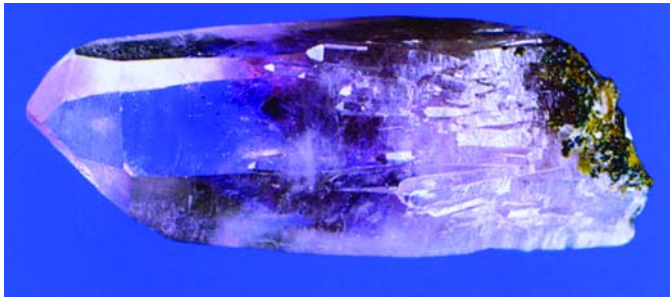


Figure 5.
Photos and representative drawings of :
(A - top) late stage simple splitting of a quartz crystal;
(B - center) early stage “sheaf” splitting of a quartz crystal,
(C - bottom) “twin leaf” continuous splitting of stellerite, a mineral of the zeolite group (non-cave photos).
From Kantor (1997).



Figure 8.
(A - left) Growth of an aragonite beaded helictite, Carlsbad Cavern, New Mexico. Note the tip of the helictite where split crystals are poised to begin a new bead. Photo by Cyndi Mosch.
(B - right) A pseudostalactite (a type of aragonite spathite), Cupp-Coutunn Cave, Turkmenistan. Photo by C. Self, courtesy of University of Bristol Speleological Society.

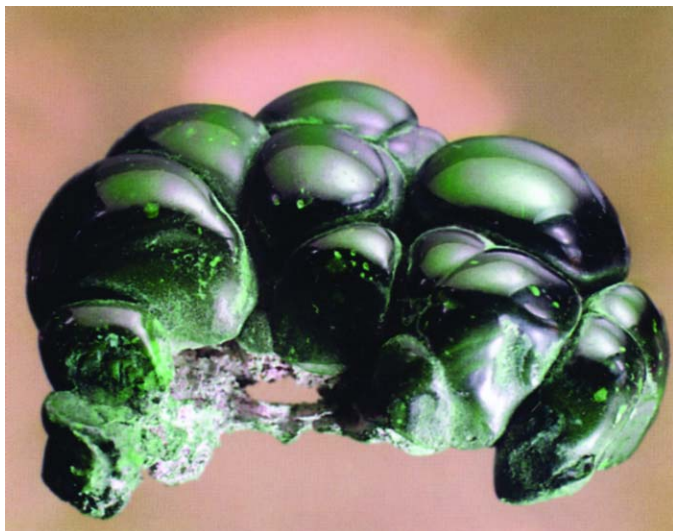


Figure 10. The smooth, bright surface of malachite, which is composed of several spherocrystals (not a cave photo). From Kantor (1997).



Figure 11. A sublimation ice crystal aggregate, Eiskogelhöhle, Tennengebirge, Austria. Note the skeletal nature of these crystals. The largest crystal on the left is ~9 cm in diameter. Photo by W. Hartman.

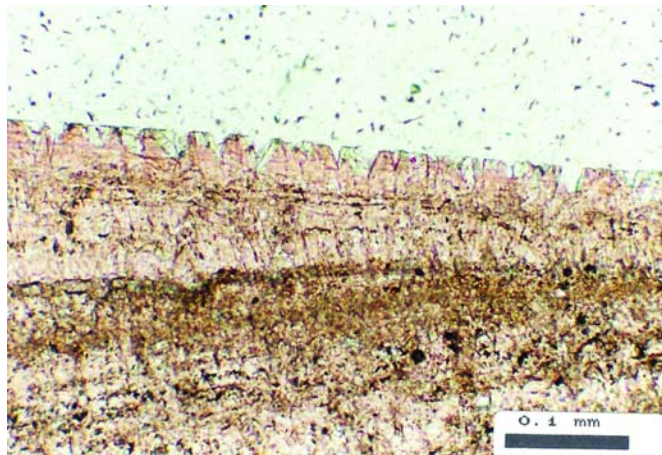


Figure 16. Thin-section photomicrograph showing crystal terminations on the surface of a stalactite, ABC Cave, New Mexico. From Polyak (1992).

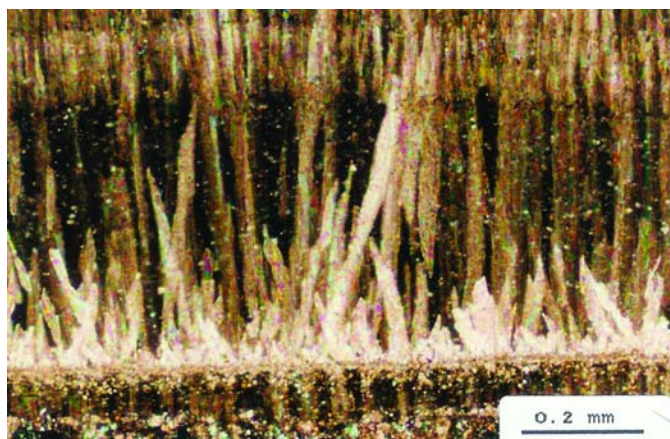


Figure 18. Thin-section photomicrograph showing competitive growth of calcite and a transition from randomly oriented to parallel-columnar texture, from a cave in New Mexico. From Polyak (1992).

Figure 12 (left). A twin crystal of selenite (gypsum) from Fort Stanton Cave, New Mexico. Note the symmetrical growth around the “twin plane” (central line along the crystal). The crystal is ~4 cm long. Photo by Alan Hill.

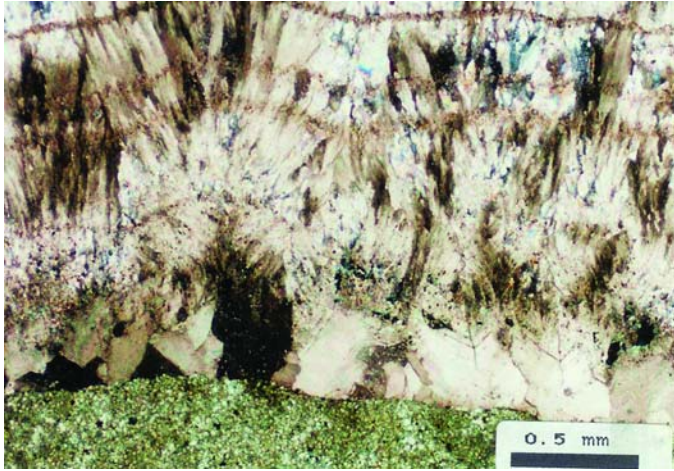


Figure 22. Thin-section photomicrograph of parallel-columnar texture (spar crystals at growth surface) changing to radial-fibrous texture (“felted” or “coconut-meat” crystals overlying spar), from Endless Cave, New Mexico. The horizontal “lines” may be due to interruptions of growth where “dirt” accumulated on the surface of the growing speleothem. From Polyak (1992).

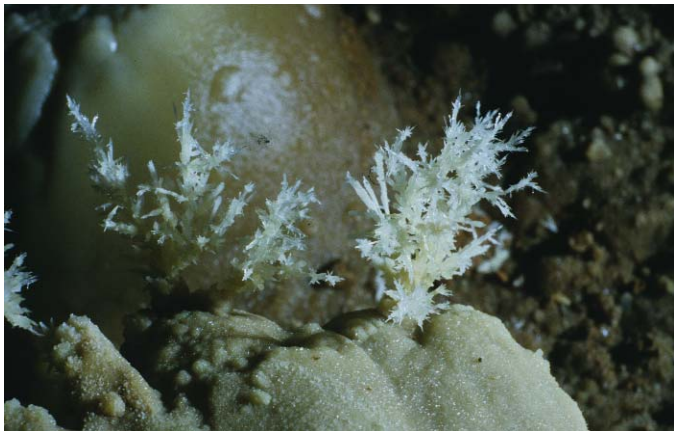


Figure 24. Aragonite crystallictites growing from a stalagmitic floor crust, Cueva del Nacimiento, Spain. Note that the separate branches never touch each other. Photo by C. Self.



Figure 26 (above). A calcite crystallictite overgrowth on a stalactite, Cueva del Nacimiento, Spain. The curved crystal faces are probably due to chemical splitting at the molecular level (in a similar manner to that of spherocrystals). Photo by C. Self.

Figure 25 (left). Corallites growing on a bear's skull, Piatra Altarului Cave, Romania. Note that the strongest growth is on the more convex surface at the back of the head. Photo by Cristian Lascu.



Figure 28. Gypsum cotton (on ceiling) and hair (on and over ledge) in a Grand Canyon cave, Arizona. Photo by Alan Hill.

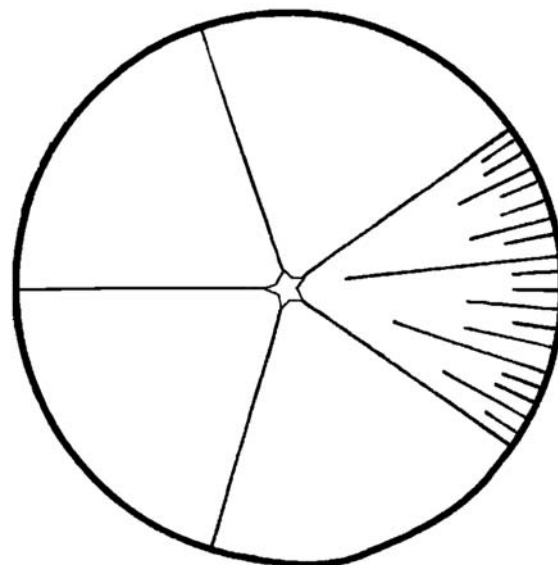


Figure 30. (A - top) Aragonite "cut" helictites, The Blue Cave (a Roman copper mine), France, showing parallel co-growth of 4 spherulite bunches. Photo by Patrick Cabrol. From *Cave Minerals of the World, Second Edition* Copyright 1997, National Speleological Society, Inc. Used with permission. (B - bottom) Sketch cross section of a helictite built from 5 spherulite bunches (for clarity, subindividuals are shown in only 1 of the 5 spherulite sectors).



Figure 29. Epsomite (left) and gypsum (right) flowers in Torgac Cave, New Mexico. Note the shard of rock (in center of photo directly below caliper) that has been pushed outward from the wall by mineral growth. Photo by Alan Hill.



Figure 33. Pseudohelictites with partial overgrowth of gypsum crystals, Cupp-Coutunn Cave, Turkmenistan. Photo by C. Self.



Figure 34. The growth tip of a calcite stalactite from Moravia, Czech Republic, showing skeleton crystals. Photo by Igor Audy.



Figure 35. Gypsum chandeliers, Lechuguilla Cave, New Mexico. Because gypsum is precipitated by evaporation, not as a result of CO_2 loss during dripping, it is normal for crystallites to form rather than regular stalactites. Photo by Urs Widmer.



Figure 36. Tufaceous calcite soda straws in the cellar of a house in Bristol, England. Photo by Geoff Wood.



Figure 37. A flowstone "river" of hydromagnesite moonmilk, Pink Dragon Cave, New Mexico. Photo by Alan Hill.

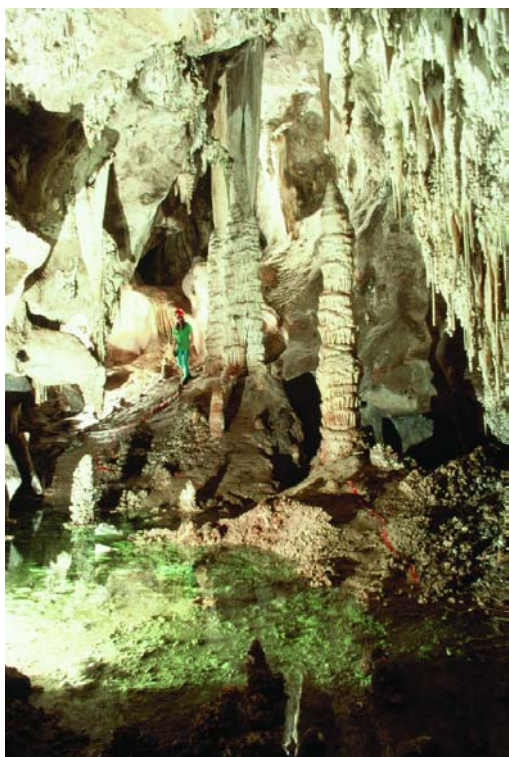


Figure 38. A "stalactite-stalagmite kora of calcite", Carlsbad Cavern, New Mexico. Photo by Urs Widmer.

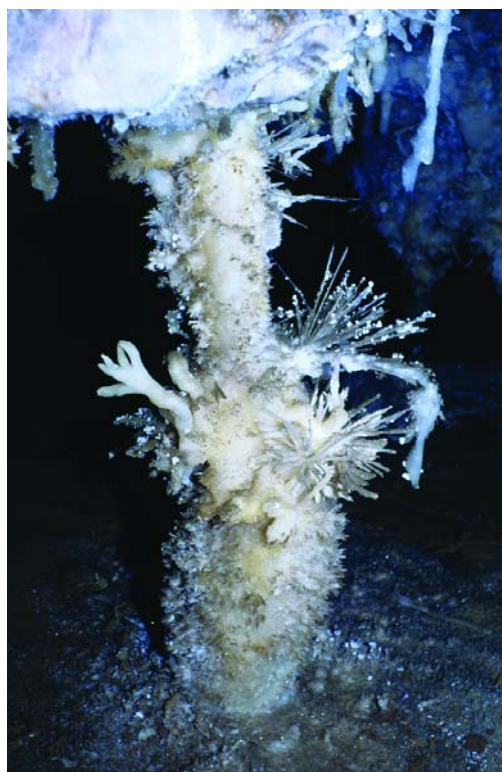


Figure 39. An ensemble of a stalactite-stalagmite kora overgrown by a corallite kora, Cupp-Coutunn Cave, Turkmenistan. Also present in the overgrowth are multicoralites, a branching aragonite helictite (left), and a multicoralite/pseudostalactite hybrid (right).

The presence of pseudostalactites (a type of spathite) growing independently on the cave roof suggests that the progression from a gravitational to a capillary film environment is not yet complete. Photo by C. Self.