AN INTRODUCTION TO GENETIC MINERALOGY AND THE CONCEPT OF "ONTOGENY OF CAVE MINERALS"

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ABSTRACT
The "ontogeny of minerals" is the study of individual crystals and their aggregates as physical bodies rather than as mineral species. The genetic approach to mineralogy has been developed in Russia over the last 80 years, but is poorly understood (if at all) in the West. Although ontogeny as a subject had its origins in the Russian mining industry, caves prove to be ideal settings for ontogeny studies because, while there are few common mineral species in caves (mainly calcite, aragonite, and gypsum), there is a great variety in the speleothem forms that these minerals can take. This paper introduces the basic principles of minerals ontogeny and explains a hierarchy classification scheme whereby mineral bodies can be studied as crystal *individuals*, *aggregates* of individuals, association of aggregates (termed *koras* by the Russians), and as sequences of koras (*ensembles*). The importance of minerals ontogeny is that, just by looking at the physical organization of a simple minieral body, its environment of deposition can often be deduced.

INTRODUCTION
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), and by the 1950s Grigor'ev (1961) had divided genetic mineralogy into two 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 ("minor mineral 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. However, this line of study has become a well-established science in Russia.

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, such as *Cave Minerals of the World* (Hill and Forti, 1997). It is now necessary to study cave mineralogy from a *genetic* perspective. Ontogeny explains not only *how* speleothems grow, but *why* different speleothem types exist.

HIERARCHY OF MINOR MINERAL BODIES
Minor mineral bodies (MMBs) are simple enough to be studied purely by mineralogic techniques. They are classified according to their complexity of structure and texture. However, the hierarchy scheme of MMBs is *not* the same as the classification of speleothems into types and subtypes as was done by Hill and Forti (1997). "Speleothem" is a descriptive term and can only be used to indicate the morphology of a MMB. The hierarchy scheme for MMBs is outlined in Table 1. Only the most important of these MMBs are discussed herein; for a more detailed discussion of this topic refer to Self and Hill (2003). In Table 1, the term *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.

(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. 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.

(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. An example in a cave would be an individual calcite spar (non-druse) crystal.

(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. 1). Second-order individuals grow in response to certain environmental conditions, particularly oversaturation – a common occurrence in caves due both to CO_2 loss and evaporation of thin films.

(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. 2). Different minerals have a different "splitting ability" depending on their crystal structure. 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 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.

(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; if nucleated on a substrate, they grow as hemispheres. Spherulites are composed of straight subindividuals, but often the subindividuals themselves continue to split. If part of the growth surface becomes mechanically blocked, the unobstructed "rays" will continue their growth in the form of a new spherulite. This composite body is still a mineral individual, not an aggregate. Spherulites are widespread in caves as components from which many speleothems are built.

(1.2.1B) Spherulite Bunches. Spherulite bunches are composed of subindividuals that grow from a single nucleus to 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 frostwork. 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.

(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 and supersaturation allows for split growth.

(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. Most coralloids display spheroidalitic growth.

(1.2.1E) Spherocrystals. Spherocrystals 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.3). Although spherocrystals are composed of subindividuals, the separate fibers are not visible even under microscopic examination. However under crossed nicols (polarizers), spherocrystals display a "Maltese cross" extinction.

(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.

Most aggregates form where growing individuals compete for space by physically contacting one another. In such a situation, contact faces develop between neighboring individuals, leaving a group growth front comprised of the crystallographic terminations of many individuals. 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 CO_2 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 most influential process during the early stages of crystal growth is *geometric selection*. The crucial elements of geometric selection are (Fig. 4): (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. 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).

(2.1) First-Order Aggregates. In ontogeny, first-order aggregates are simply termed *aggregates*, while second-order aggregates are termed *multiaggregates*. 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. Texture is the distinctive pattern of crystal boundaries that is produced by competitive growth. Aggregates are subdivided according to their texture.

(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. 4). Each druse crystal has had to compete with other individuals, and is a survivor of geometric selection at the aggregate druse growth front.

(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. Cave pearls are a common type of spherulitic (core) aggregate.

(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 (Fig. 5). The change to radial-fibrous texture is due to a decrease in solution supply in a capillary thin-film environment. If the solution supply decreases further, radial-fibrous texture may lead to interruptions in growth and/or contamination of the growth surface.

(2.1.4) Branching Aggregates. A great variety of 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. 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 CO_2) 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. 6). 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, and aggregates situated there develop rapidly.

Less favorably situated aggregates find it increasingly difficult to lose solvent molecules, and their growth is suppressed or distorted away from nearby large bushes.

(2.1.4A) Corallites. Corallites 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 and 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. A full range of intermediate forms exists between corallites and crystallictites, where different degrees of crystal splitting are displayed. Aragonite frostwork is a prime example of a crystallictite (Fig. 6).

(2.1.5) Fibrous Aggregates. Fibrous aggregates are built from filamentary individuals 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). 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. 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 so as to form “cotton”. 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.

(2.2) Multiaggregates. *Multiaggregates* are an intergrowth or co-growth of different types of aggregates that form simultaneously and syngenetically in the same crystallization environment. They can be either polymineral or polytextural, as compared to simple aggregates, which are always monomineral and texturally homogeneous. A common polymineral multiaggregate found in many caves is calcite popcorn from which grows aragonite frostwork that is often tipped with a magnesium-rich mineral such as hydromagnesite. All three mineral species form simultaneously from the same capillary solution and in the same crystallization environment. Stalactites are a polytextural multiaggregate comprised of a monocrystalline tube with a crown of skeleton crystals, plus a spherulitic aggregate outer layer.

(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 no “through” structure can exist. For tufaceous deposits and some types of 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.

(3) THIRD LEVEL: Assemblages of Aggregates. 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. A kora is an assemblage of texturally similar aggregates, growing together at the same time and in the same crystallization space, and forming under the same environmental conditions. An example is the “stalactite-stalagmite kora” where different forms of stalactites, stalagmites, draperies and flowstones grow together and simultaneously in a dripping water environment.

(4) FOURTH LEVEL: Assemblages of Koras. On the fourth hierarchy level is an *ensemble*. The ensemble concept is fundamentally different from that of other terms used in MMB hierarchy: it involves a cycle of regular changes through time that takes place in the crystallization environment as a whole (Stepanov, 1971). An ensemble is usually described as a "diagnostic set" of minerals or speleothems or as the “mineralogic landscape” of a cave or cave passage. Each cave or cave system has only a limited number of ensembles.

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Table 1. Hierarchy of Minerals Ontogeny

(0) ZERO LEVEL: Subindividuals	(2.1.2A) Core spherulites
(1) FIRST LEVEL: Mineral individuals	(2.1.2B) Irregular spherulites
(1.1) First-order individuals	(2.1.3) Radial-fibrous aggregates
(1.2) Second-order individuals	(2.1.4) Branching aggregates
(1.2.1) Split crystals	(2.1.4A) Corallites
(1.2.1A) Spherulites	(2.1.4B) Crystallictites
(1.2.1B) Spherulite bunches	(2.1.5) Fibrous aggregates
(1.2.1C) Discospherulites	(2.1.6) Interactive aggregates
(1.2.1D) Spheroidalites	(2.1.7) Other aggregates
(1.2.1E) Spherocrystals	(2.2) Multiaggregates
(1.2.2) Skeleton crystals	(2.2.1) Polymineral multiaggregates
(1.2.3) Twin crystals	(2.2.2) Polytextural multiaggregates
(1.2.4) Screw crystals	(2.2.3) Hybrid multiaggregates
(1.2.5) Block crystals	(2.3) Pseudoaggregates
(1.2.6) Complex	(2.3.1) Tufaceous mineral bodies
(2) SECOND LEVEL: Assemblages of individuals	(2.3.2) Moonmilk
(2.1) Aggregates	(3) THIRD LEVEL: Assemblages of aggregates
(2.1.1) Parallel-columnar aggregates	(3.1) Koras
(2.1.2) Spherulitic aggregates	(4) FOURTH LEVEL: Assemblages of koras
	(4.1) Ensembles

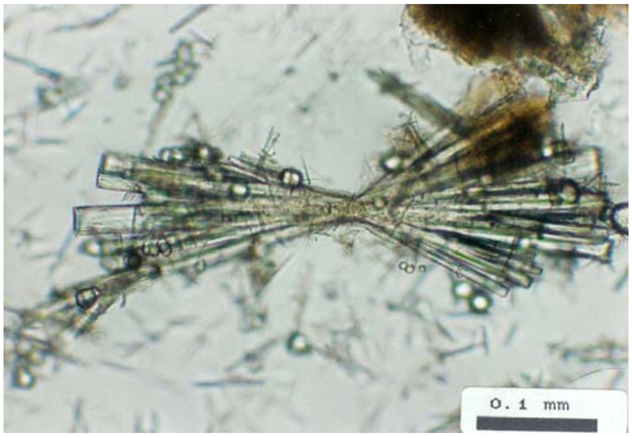

Figure 1. Thin-section photomicrograph of a split crystal of aragonite grown from a single nucleus under laboratory conditions. From Polyak (1992).

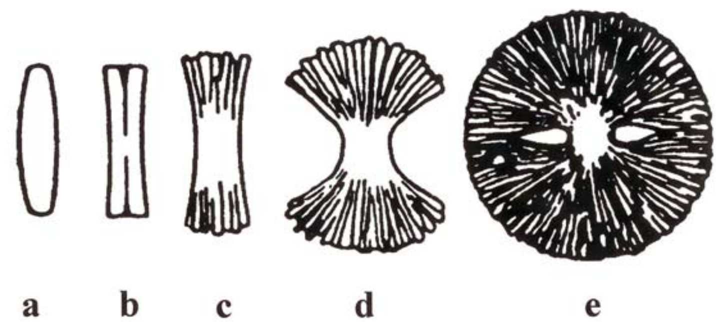

Figure 2. Drawing of successive stages of splitting during crystal growth: a = no splitting, b and c = simple splitting, d = “sheaf” structure, e = spherulite. From Grigor’ev (1961).

Figure 3. The smooth, bright surface of malachite, which is composed of several spherocrystals (not a cave photo). From Kantor (1997).

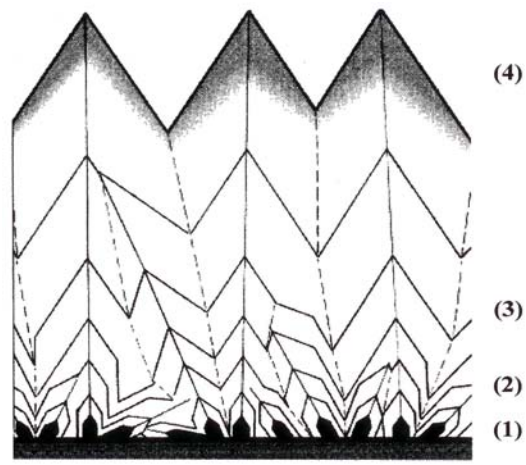

Figure 4. Geometric selection on a flat growth surface showing competition between crystals and selection. Numbers correspond to those in the text. From Kantor (1997).

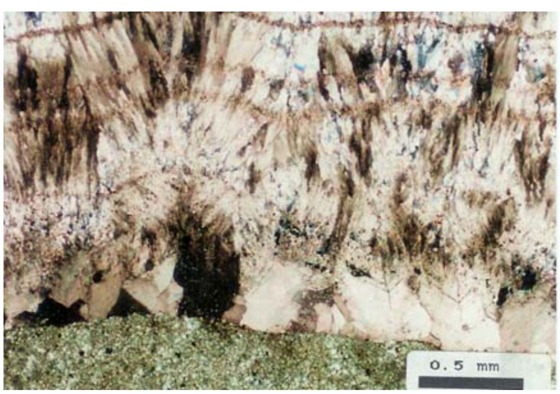

Figure 5. Thin-section photomicrograph of parallel-columnar texture (spar crystals at growth surface) changing to radial-fibrous texture (“felted” or “coconut-meat” crystals overlying spar). The “lines” may be due to interruptions of growth or contamination of the growth surface. From Polyak (1992).

Figure 6. Aragonite frostwork growing from a stalagmitic floor crust, Cueva del Nacimiento, Spain. Note that the separate branches of the crystallictite do not touch each other. Also note that when competition is indirect, as in this case due to interaction by convection of water vapor and CO_2, true crystal faces (but no contact surfaces) are displayed. Photo by C. Self.