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SULPHATE FILAMENTARY CRYSTALS AND THEIR AGGREGATES IN CAVES

by

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ABSTRACT

This paper is based on observations made in the Cupp-Coutunn cave system of Turkmenistan. Genetic models for sulphate filamentary crystals in caves are often based on solutions seeping through porous substrates under some external hydrostatic pressure. The physical models of such seeping are examined and the seepage hypotheses found to be implausible for natural environments. The main genetic mechanism is shown to be only local feeding, exclusively due to capillary pressure together with a short-period (seasonal) humidity cycle. In some cases there is also a major role for sulphate reduction processes. Some new aggregates, based on filamentary crystal growth, are described.

INTRODUCTION

Filamentary and acicular gypsum crystals (in some cases formed with other minerals) and their aggregates (antholites or "flowers", "hair", "beards", "cotton", etc.) are fairly com mon in caves. Three major papers (Maleev, 1971; Malishevsky, *in prep*; Stepanov, 1971) suggest mechanisms for filamentary crystal growth in the near-surface zone of porous substrates, for the cases of both oversaturated and undersaturated solutions. The feeding mechanisms, described as seepage through the substrate under some external pressure, seem to be wrong for most of the aggregates studied by the author.

This paper examines genetic mechanisms for filamentary crystal aggregates, generated on the phase boundary between porous carbonate substrates and the air. All the examples come from the Cupp-Coutunn cave system, located in the Kugitangta mountains of Turkmenistan, but similar aggregates are found in many other caves (Hill and Forti, 1986). A comparison is made with two types of filamentary gypsum growth in the surface zone of clay substrates. Some new aggregate types are described.

As a number of technical terms used in this paper are either new to or used differently in the West, these are explained in an appendix.

CRYSTALLIZATION IN THE SURFACE ZONE OF SOLID SUBSTRATES.

A typical gypsum antholite from Cupp-Coutunn, according to Malishevsky (*op cit.*), is formed from filamentary crystals 0.002-0.1 mm in diameter (disregarding crystals specific for clay substrates, which are thicker). "Hair" and "spiderwork" consist of even thinner crystals. This would mean crystallization in pores of corresponding diameter. It is important to understand the physics of seepage through such substrates. If one considers some permanent flow (when the supply is external), there are two possible situations.

In the first situation, the water level in the substrate is far enough from the surface to have "full-profile" solution meniscuses in the pores. Knowing the pore diameters:

$$0.002mm \le d \le 0.1mm$$

the surface tension of the water in contact with vapour or air:

$$\sigma_{1,2} = 73erg/cm^2$$

and the wetting angle:

$$\theta \approx 10$$

the range of capillary pressure in the pores can be estimated:

$$28800g/cm^2 \le \frac{4\sigma_{1,2}\times\cos\theta}{d} \le 1440000g/cm^2$$

(for hair this would be even greater),

with an error of about 25% caused by local features of the solution and the substrate. This means that in this case, if there is seepage through the substrate as a result of external pressure, this pressure must be higher than the capillary pressure. The capillary pressure may be regarded as an hydrodynamic analogue of friction at rest. As the calculated capillary pressure is 1440 at. for the finer crystals and as such hydrostatic pressures in a karst cave are impossible there is no need for further examination of this situation.

In the second situation, when the substrate is completely water-filled, meniscuses are absent and there can only be external causes as a source of excess pressure. The capillary pressure is self-compensating. Rather than considering general physics, it is simpler to take a typical example and carry out calculations for that alone. The result will be precise enough for most typical observations. Gypsum antholites in the Dvukhetazhnyi chamber grow on the roof of a small dead-end passage, with another passage only 1m above. It is possible to calculate the expenditure of solution in the pores. One must imagine some water in the upper passage, but with the lower passage dry, although this may seem improbable it is quite a common situation in caves. So, the length of the pores:

$$l = 1m$$

and the excess pressure:

$$P - P_o = 100g/cm^2$$

The filamentary crystals here have diameters:

$$d = 0.01mm$$

The water viscosity for 20°C:

$$\mu = 1.005$$

This gives everything necessary to apply Poiseuille's equation:

$$Q = \frac{\pi}{128} \times \frac{p-p_0}{l} \times \frac{d^4}{\mu}$$

Calculating the equation for this data obtains the water expenditure in a pore:

$$Q = 2.44 \times 10^{-14} cm^3/\sec$$

corresponding to a linear seeping speed of about 40 cm/year. This is a maximum estimation because the geometry of the pores will be more complicated than the cylinder modelled in the equation. Considering the solution as saturated, or there would be crystalization outside the substrate, one can re-calculate for a maximum possible gypsum growth speed of 0.4 mm/year. This maximum estimate does not contradict other observations, such as a comparison of antholite size with the possible duration of a stable microclimate. Estimates based on the growth speeds of fast-growing speleothems differ by no more than a factor of 3 or 4. But one conflict still remains. The model presented above is true for a single pore, or for substrates with equal-sized pores which would be impossible in a real cave. Pore dimensions always have a log normal distribution and the limestone always has fractures. It is quite impossible, in the several square metres of the antholite growth area, not to have a lot of pores and fractures with their diameters 2 or more orders larger than the mean value. From the same Poiseuille's equation it

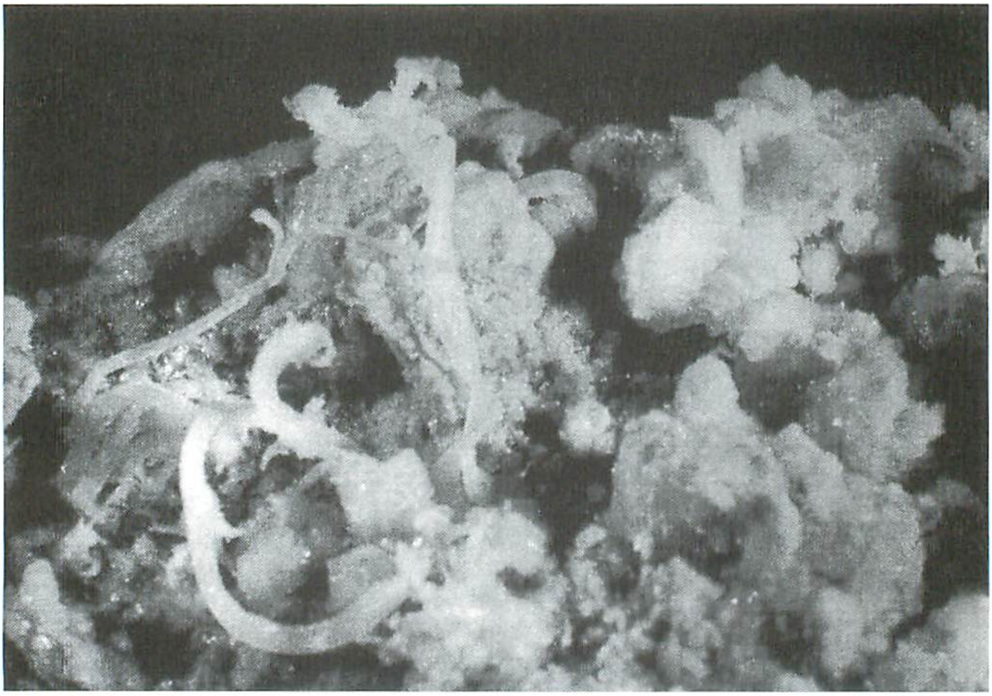

Figure 1. *Gypsum antholites up to 3cm long, growing on an isolated limestone block 15cm large. Cupp-Coutunn cave, Nadezhda chamber. Photo: V.Maltsev.*

can be seen that the water expenditure is proportional to the fourth order of the pore diameter, while the linear flow speed is proportional to the second order of the diameter. If one considers the mean estimated speed together with the existence of pores two orders larger, it can be see that there is no theoretical possibility of complete evaporation from these larger pore openings. There must be excessive flows from them and stalactites growing from these flows. However stalactites are never syngenetic to antholites. Moreover, this generic view strongly contradicts the statistics of observation. Antholites grow only in very dry cave areas free from any water flows (Hill and Forti, 1986, Stepanov, 1971).

It is easy to see from these estimations that any mixed case, derived from these two situations, is similarly impossible. So one can conclude that any external feeding hypothesis for sulphate filamentary crystal growth on solid substrates cannot be accepted. This does not, however, contradict Maleev's work (1971). In his chapter on experiments it is explained that filamentary crystal growth is obtained only with optimum pressure, combined with optimum pore dimensions. This last point means high regularity of the substrate, such as in the artificial substrates used by Maleev. His mechanisms really work, but for real cave conditions with less regular substrates some other feeding mechanisms must be found.

If external supply is impossible, then local feeding mechanisms must be considered. This means that all the moistening of the substrate and all the seepage through it, are caused by capillary pressure itself. In this case capillary pressure functions not as an obstacle, but as the main driving force. There are again two such mechanisms possible. The first is a seeping through mechanism, when one side of the substrate is in contact with some solution reservoir and the other side is in a dry place. In this case evaporation from one side makes the solution inside the substrate move. This mechanism does not contradict any theory, but if it works there must be filamentary crystal growth on the bank of any permanent pool of near-saturated gypsum solution. All the observations, both by the author and from literature (Hill and Forti, 1986; Sletov, 1985) show that filamentary crystals are never found near pools. Perhaps dry enough conditions are simply impossible near water reservoirs, or maybe there is some other cause. The second possible mechanism is when the substrate functions like a buffer, being moistened and dried during short-period humidity changes, like the seasonal cycle described by the author (Maltsev, 1989). This mechanism may also include seepage because it is possible to have condensation mainly on one side of the substrate and evaporation mainly from some other side. Anyway, the symmetry of the antholite crust texture will be controlled by evaporation/condensation physics.

When you have eliminated the impossible, whatever remains, however improbable, must be the truth (Conan Doyle, 1903). So one must examine closely the one variant left, moistening and drying processes caused by seasonal cave wind inversions. The boundary conditions are simple:

a) moistening cannot be complete, the maximum water level must stay deep enough in the pores, otherwise seasonal dissolution or re-crystallization is inevitable. This means that the solution capacity of the substrate must exceed the full-year condensation on its surface and the full-year condensation must not exceed the full-year evaporation. Such conditions are quite possible in some caves.

b) the substrate must contain enough gypsum or other sulphate. This condition is not trivial and at first sight contradicts a lot of observations. For example, the limestone blocks in a large collapse in Nadezhda Chamber are covered with gypsum antholites on all sides. If one

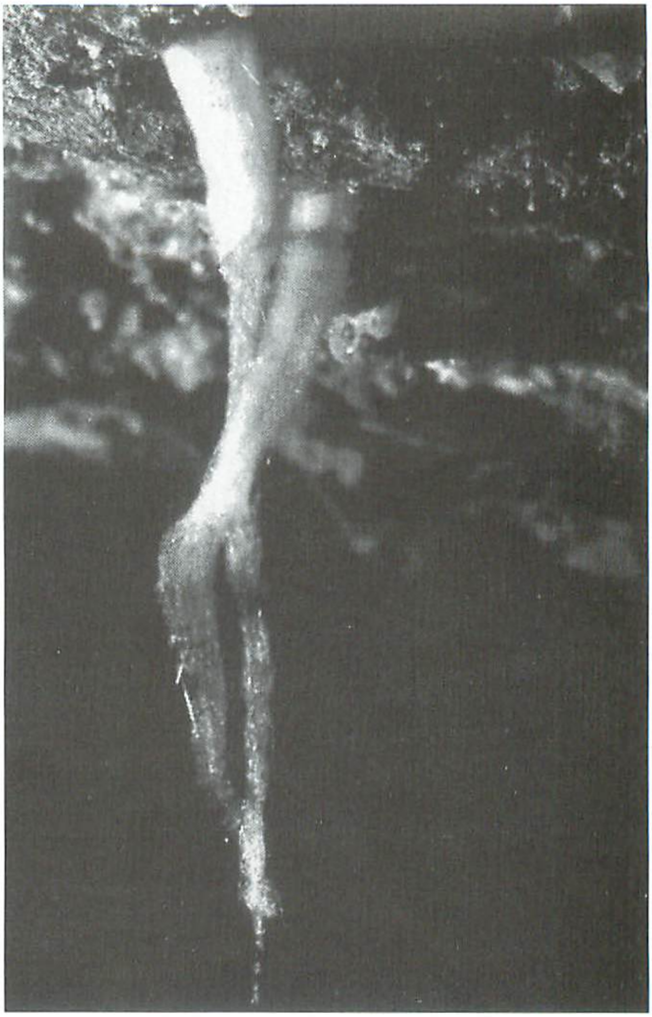

Figure 2. *Gypsum beard, 12cm long. Cupp-Coutunn cave, Pautinny maze. Photo: V.Maltsev.*

considers such a block of about 15 cm size, with a regular covering of antholites 2-4 cm long and 3-6 mm wide on its surface (Figure 1), and the block itself is in contact with surrounding blocks only at four points, each about 0.5 cm^2 in area, no evident feeding possibility can be seen. If the supply comes from surrounding blocks, the covering must have a visible disymmetry. If the feeding is strictly local, there is no possibility of having such quantities of sulphate either as solution in the pores or in the limestone itself. The variant of periodical flooding is also excluded because one can see no traces of dissolution or re-crystallization, necessary for such a soluble mineral as gypsum. The only possible explanation is permanent gypsum generation inside the blocks. Bacterial sulphate reduction and sulphur oxidation are known in Cupp-Coutunn (Korshunov, *et al*, 1994). Acidic gases are present in the cave air and acid forms on limestone surfaces. In moist periods both penetrate into the pores with the condensing water and both take part in gypsum generation. This process is evident in places like Nadezhda Chamber, but is important throughout the Cupp-Coutunn system, there is a strong correlation between the intensity of sulphuric acid corrosion and the intensity of gypsum and epsomite filamentary crystal aggregates growth. One can note that gypsum antholite finds in other limestone caves are also often reported together with sulphate reduction.

Some additional evidence of short-period cyclic crystallization also exists. The antholite crust texture has a specific two-directional disymmetry. The antholites are mostly developed on substrate ledges (where evaporation is concentrated) and inside larger grooves, niches,

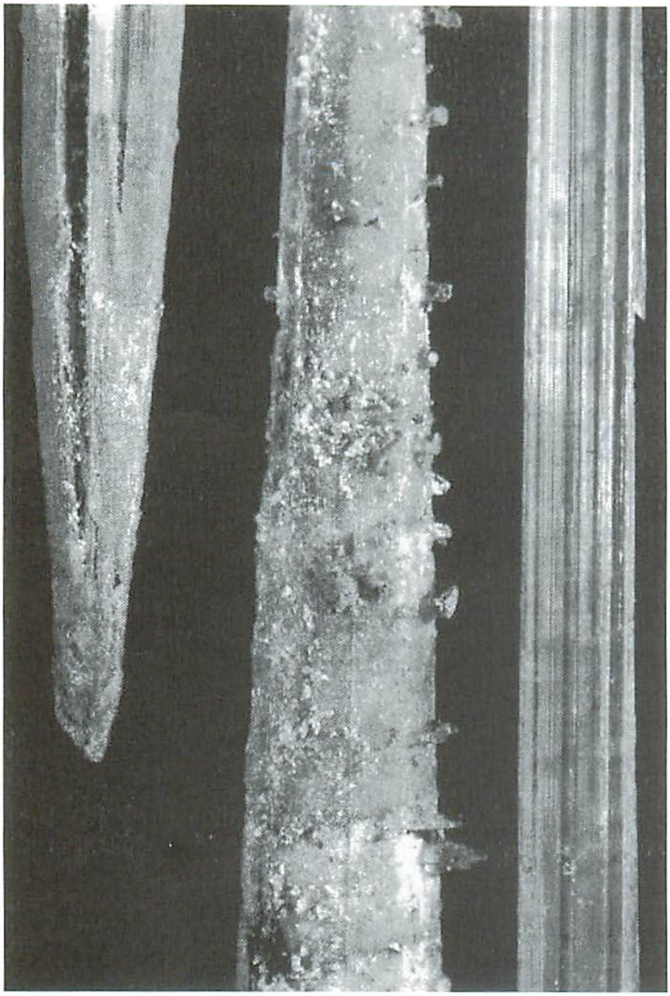

Figure 3. *Gypsum needles. Splitting zone is seen on the left, two types of skeleton growth in the middle and on the right. The left hand needle is 1.5 cm thick. Photo: V. Maltsev.*

fractures, under blocks (where condensation is concentrated). Absence of other disymmetries (for example, the lack of fracture-controlled antholite lines) shows the absence of external pressure. Only in the condensation cycle variant is the growth speed in a pore proportional to the first order of the pore diameter. This corresponds to the observed splitting grade for antholites, and also to the distribution of lengths (which can be seen directly) in beards and hair - they are all within first order statistical models.

It is necessary to examine closely the most critical point of the suggested model: why, if one speaks about a condensation/evaporation cycle, traces of filamentary crystal aggregate corrosion directly by the condensing water cannot be found. In reality such corrosion sometimes occurs, but only for antholites and only weakly. In the case of poorly connected aggregates; beards, hair, spiderwork (Figure 2); it is completely absent, otherwise they would be destroyed every year. There are three main reasons for this, listed in increasing order of importance:

a) the substrate surface curvature is generally less than the aggregate surface curvature, thus setting the evaporation/condensation balance for the aggregate greater than for the substrate;

Figure 4. *Antholite-like packet 2.5 cm long. Cupp-Coutunn cave, Dvukh Kolodtsev chamber. Photo: V.Maltsev.*

b) condensation is not necessarily the direct result of air overmoistening. A more common immediate reason is a change in temperature, which always goes together with humidity jumps in the seasonal cycle. In this case a single filamentary crystal has a very low thermal capacity, thus equalizing its temperature to that of the air quickly (the thermal capacity is proportional to the second order of the diameter, the heat exchange intensity and the condensation area both to the 1st order). So the condensation per unit surface area on the substrate and on the aggregate differs by at least 1 order;

c) rapid sucking in of the condensing water. The capillary pressure, estimated above, now all works for the immediate sucking of water into the pores (except for a 1-2 molecules thick film, having very low mass-capacity). This suction is strong enough to leave no time for corrosion in the near-surface zone, especially just near the pore openings where the crystals under discussion are located. Of course this is only true when full-profile meniscuses are kept in the pores even at the maximum moisture level, but this has already been explained as a boundary condition.

CRYSTALLIZATION IN THE SURFACE ZONE OF PLASTIC SUBSTRATES.

A very different situation appears when discussing crystallization on the surface of massive clay sediments during the period of their drying (Figure 3). The most common aggregates are acicular crystals or twins, 0.5-15mm thick and up to 90 cm long, extruded from the clay. Less common are antholite-like fibrous packets. Inside the clay sediment many more aggregates may be found, displaying a contiguous cycle of transient formations from needles to splitted needles, then to satin spar micro veins, then to linear-blocked crystals, then to euhedral crystals, then back to needles. The best descriptions of such aggregate morphology is presented in Casali and Forti (1969), where about 40 morphological types are described. However some of the aggregates have a poorly described structure, and one has only general genetic ideas. Two types only, extruded needles and antholite-like packets, will be considered.

Figure 5. *Quasi-epitaxial coatings (gypsum endings). Cupp-Coutunn cave, Dikobrazii chamber. The large crystal is 4.5cm across. Photo: V.Maltsev.*

a) Needles. They are not really acicular crystals, but filamentary crystals transformed into a needle as a result of clay plasticity. The capillary pressure and the crystallization pressure together press the substrate, leaving "alive" only the pores that are optimal in the pair pressure/speed. The other pores collapse. This is a very specific type of selection, not geometrical selection but some other mechanism and not described in the literature. The solution, pressed out from the collapsed pores, appears in the active pores between the crystallization front and the surface, thus providing material to increase the thickness of the growing filamentary crystals. This can be seen in the 1-5cm long transition zone near the roots of the needles (Figure 3), which displays the transformation from a poor geometry controlled filamentary crystal to a faced needle. As a result of this mechanism, several interesting features appear:

i the needles never grow close to each other, distances between each pair of needles vary from 1mm to 1-2cm. This is several orders greater than in the case of crystals grown from a solid substrate;

ii the crust texture has spherical symmetry with no preferences in growth directions;

iii the individual needle parameters are very regular. In each location, the lengths of the needles vary only within half an order, which means almost equal growing speeds. This length distribution may have its explanation in non-simultaneous start of growth. New pores appear while the substrate is drying;

iv the crystallization environment in the transition zone is disbalanced. Strong oversaturations, appearing when the pressed out solution (under high pressure) reaches an active open pore, contrasts with the small quantities of this pressed out solution. This disbalance leads to additional structural features of the transition zone. Close to the root the solution deficit is not too strong. This provides for an increase in thickness mostly through crystal splitting. At some greater distance from the root, where the solution deficit is stronger, features of skeleton growth appear (up to the appearance of hollow "case crystals"). These two effects can be seen in figure 3 and both are in accordance with the theories of crystals splitting and skeleton growth (Grigorjev and Jabin, 1975; Russo, 1981).

b) Antholite-like packets. At first sight, these aggregates are very similar to normal antholites (splitted packets of filamentary crystals), but in reality each such packet is a single splitted filamentary crystal. The genetic mechanism is almost the same as for needles. The difference is in a higher clay plasticity, allowing the pressing out of all the solution from the collapsed pores close to the crystallization front. This leaves the zone of splitted growth, but eliminates the zone of skeleton growth, so faced aggregates are not seen. The screw dislocations typical for gypsum are not suppressed by skeleton growth, as in the previous case, but lead to the whole aggregate curving. Despite the visual similarity to antholites (the delicate splitting zone is usually destroyed when extracting from the clay), there is a method of distinguishing between them. As is noted above, curving in these two cases has different causes. An antholite is curved for mechanical reasons: growth speed differences between the pores. The curvature radius has only a general trend and on the micro level this leads to great internal tensions, with the result that the fibres of an antholite are always broken on the curves. An antholite-like packet has curvature because of screw dislocation, balanced between the micro- and macro- levels, and so has no such breaks of fibres. This difference may always be seen under a 20x-50x lens or a microscope.

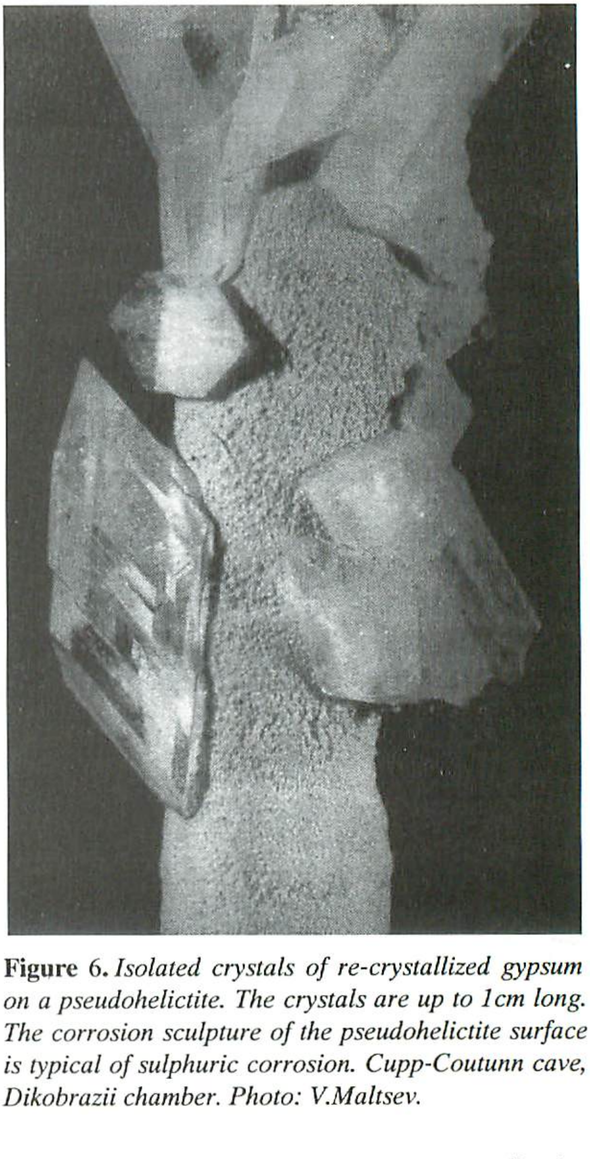

Figure 6. *Isolated crystals of re-crystallized gypsum on a pseudohelictite. The crystals are up to 1cm long. The corrosion sculpture of the pseudohelictite surface is typical of sulphuric corrosion. Cupp-Coutunn cave, Dikobrazii chamber. Photo: V.Maltsev.*

It should be explained that these two types of formations were called "aggregates" only for ease of understanding. In strict onthogenetic terminology they are individuals rather than aggregates, as they grow from a single embryo and crystallization was a single-act process,

Figure 7. *Intermediate type of gypsum coating, displaying the crystals morphology as in figure 6, and the coating morphology as in figure 5. The crystals are up to 1.5cm in size. Cupp-Coutunn cave, Dikobrazii chamber. Photo: V.Maltsev.*

evidence of which is corroded roots of the needles and occasionally observed zonality, but these are of secondary importance. The main crystallization process is contiguous. In conditions suitable for the growth of filamentary crystals, massive clay sediments are in a state of general drying (see above) and their capacity for sulphates and water is enough for them to need no solution supply.

A SPECIAL CASE: GYPSUM ENDINGS.

Filamentary crystals, transformed into something with a morphology far from filamentary or fibrous, are not specific for plastic substrates and may form not only individuals but real aggregates also. The following discusses one such speleothem known as "gypsum endings", though they may be structurally described as quasi-epitaxial coatings.

These rare formations, known only from two chambers in Cupp-Coutunn cave, Dikobrazii and Nizkii, at first sight display nothing filamentary or fibrous. They have an extremely simple structure, a calcite-aragonite pseudo-helictite (also known as a quill anthodite) (Hill and Forti, 1986, Maltsev and Self, 1992) has an oriented macrocrystalline gypsum overgrowth on its surface. The very end of the pseudohelictite is completely inside one of the gypsum crystals. The gypsum crystals are aligned with L2 perpendicular to the pseudohelictite axis (Figure 5). Gypsum epitaxy upon polycrystalline calcite surfaces is nonsense, so one must try to find some explanation of such growth through mass-transportation symmetry features.

The most evident mass-transportation factor is the moving and evaporating capillary film on the surface. On the macro level the texture symmetry of the coating corresponds to the mass-transportation symmetry in such a film, the coating becomes thicker close to the pseudohelictite end (Figure 5), thus displaying cone symmetry (Stepanov, 1971). On deeper examination level the picture changes. Each sharp crystal edge or top, when outstanding from its surroundings, must generate an aggregate also having cone symmetry. Such aggregates are known as crystallictites (Moroshkin, 1976) and are well-studied. Here features typical for crystallictites cannot be seen. The growth is not dendritic, there is no specific geometrical selection, the crystals are not enlongated, the faces are not curved. On the individuals level the coating texture shows spherical symmetry, excluding growth from capillary film evaporation as well as growth from gravitation-controlled solution flows.

So one must search for some local features of mass-transportation through the capillary film providing a) oriented crystal embryo generation and b) spherical symmetry of growth on the individuals level. There are few possible local effects, only chemical composition and feeding distributions, both with many variants of changes and frequency.

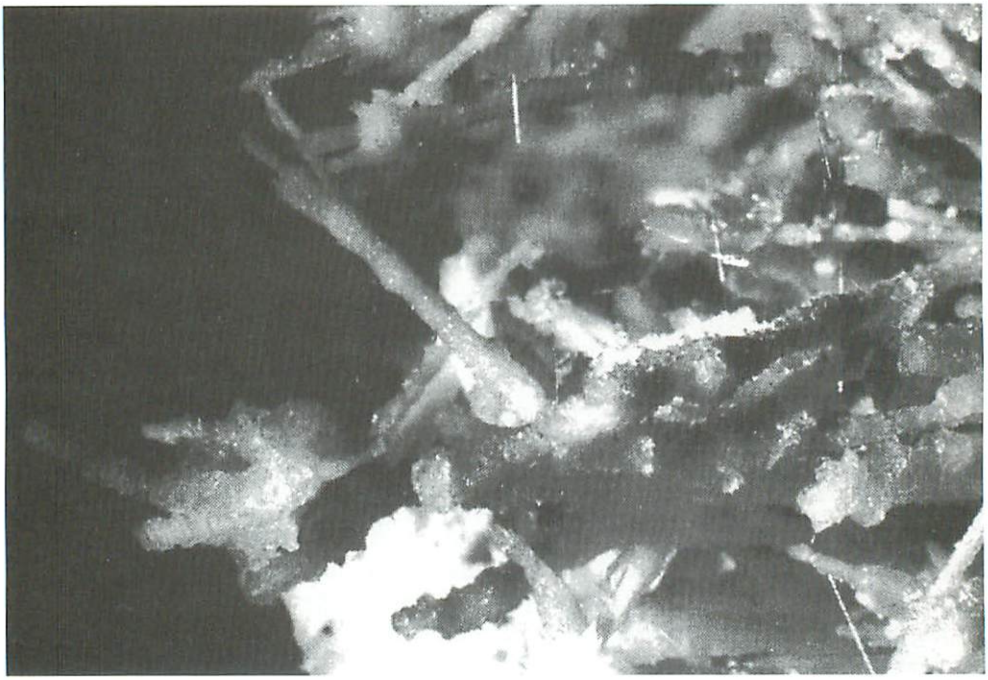

Figure 8. *Filamentary gypsum crystals, growing on pseudohelictites. Crystal lengths up to 4cm. Cupp-Coutunn cave, Dikobrazii chamber. Photo: V.Maltsev.*

To begin, note that sundry gypsum coatings on carbonate speleothems are very typical for Cupp-Coutunn, here only their unusual shape is discussed, but that is the reason to look for these two features separately, searching for each of them in other types of gypsum coatings.

With such a soluble material as gypsum, any change in the chemical composition of a solution may lead to some re-crystallization. Mostly it results in a decrease in the number of crystals, with an increase in dimension of the survivors. Moroshkin's (1976) idea that the capillary film environment has a mass-capacity too low for any re-crystallization is probably true only for carbonates. For sulphates, a 0.1mm film has a rather high mass-capacity and is already gravitation independent. The gypsum crystals shown in figure 6 (also growing on a pseudohelictite) are a result of re-crystallization, certainly in the capillary film environment. The evidence is: a) growth/dissolution directions are controlled only by crystallography, not by any mass-transportation symmetry; b) few crystal embryos; c) quite unlike geometrical selection; d) no gravitation control; e) a corroded pseudohelictite surface; f) no possibility of flooding.

Quasi-epitaxial coatings have several similarities with this clear case (one can even find some formations intermediate between them, such as are seen in figure 7), so they also may be considered as something that has re-crystallized. But this something must have a property of oriented crystal embryos, which makes a difference from the cases seen in figures 6 and 7. Moroshkin (1976) writes that the property of oriented embryos and suppressed geometrical selection may appear in crystallictites, and that he obtained it in one of his experiments. Sletov (1985) disproves this possibility. Stepanov's explanation (*pers.comm.*) is that in this experiment Moroshkin used a porous substrate and so received not clear crystallictites, but crystallictites growing upon filamentary efflorescences having a less dispersed distribution of embryo orientations.

This last idea is the key for understanding these coatings. The surface layer of a pseudohelictite is an enlongated calcite corespherolite (in terminology from Godovikov *et al*, 1989). If one imagines that its individuals are poorly connected as they grow, with pores left between them, these pores must be isometric in cross-section and strictly perpendicular to the surface. If a long dry period occurs in the cave, and if bacterial sulphur processes are active during this period then, as described in the section on solid substrates, it is possible to obtain filamentary crystal growth in these pores oriented in all cases like the crystals from the quasi-epitaxial coatings. Of course there are many "ifs" in this concept, but studies were carried out near the areas where quasi-epitaxial coatings are found. In several places where there is a continuing dry period, modern filamentary crystal growth from pseudohelictite surfaces was observed (Figure 8). Now it is possible to build a complete genetic model for these coatings:

i Firstly a pseudohelictite develops with abnormally poor connection between individuals of the outer layer.

ii Next, as the microclimate becomes much drier, the pseudohelictite itself stops developing and filamentary gypsum crystals start growing from the pores.

iii Finally, the microclimate becomes humid again and a moving capillary film reappears. Filamentary gypsum crystals partially dissolve and partially act as embryos for isometric gypsum crystal growth. Additional quantities of gypsum (it is evident that filamentary crystals do not contain enough material for a coating such as in figure 5) are brought in by several processes, for example with the capillary water film.

FURTHER DISCUSSION.

The suggested model of feeding the aggregates from the antholite crust has one interesting consequence. Probably, good estimations for growth speeds and aggregate ages may be obtained in a significant number of cases without isotope studies. In most cases the buffering zone of the substrate is only several centimetres thick. Both overdrying and overmoistening will cause visible crystallization breaks. For aggregates without such breaks, year-to-year irregularities of the range of water level in the substrate must generally be within half an order (with statistical compensation during the long period). So the growth speed for such aggregates is almost constant and can be measured for one or several years (according to the precision needed) in an indirect manner, by measuring the total evaporation/condensation balance with its re-calculation into growth speed through pore dimensions and mineral solubility.

Finally, one must list the filamentary crystal and fibrous aggregate types for which the modelling above cannot be applied:

a) growing on sulphate substrates – because of different pore structure and different chemistry of the buffering zone;

b) growing deep inside the substrate – because of different feeding physics;

c) non-sulphate – because of different chemistry and sometimes different physics (for example, ice has different crystallization physics);

d) growing outside caves – because of different microclimatic conditions, mostly with a shorter cyclicity.

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APPENDIX - TECHNICAL TERMS USED IN TEXT

Screw Dislocations: This is a well-known effect, whereby molecular layers in a crystal have regular small rotations between them, thus providing the appearance of a screw-dislocated crystallographic network. For some minerals (such as quartz), screw dislocations are always present; for some they appear occasionally. In rare cases, this results in a crystal with screw faces. Screw-dislocated networks have a more dense packing and the crystal is more strongly built, a feature that is used in certain technologies.

Skeleton Crystals: In the American school, skeleton crystals are taken together with dendrites; in Russian science, dendrites are splitted (see below) skeleton crystals, the next organisation level for mineral bodies. By definition, a skeleton crystal is a crystal with well-developed edges or faces but with a poorly-developed body. It can take the form of a crystal that is empty inside (Goblet Crystal or Case Crystal), or of a crystal constructed from needles along the edges with nothing between them. It can appear as a needle with regular branches, ending on the "proposed faces" of the whole crystal. The branches keep strictly to the crystallographic directions and do not have separate embryos.

Skeleton crystals appear in peculiar environments, but their growth mechanisms are very simple. The environment must be sufficiently oversaturated for very rapid growth, but with a deficit in material due to slow supply or poor mixing of the solution. This conflict results in growth which is concentrated in points or lines, but not planes.

Splitted Crystals and Spherocrystals: The following types of mineral individuals are distinguished by an increase in Splitting Grade, (which may best be defined as the degree of loss of boundaries between sub-individuals).

a) The simple case with a low splitting grade. In any museum you can see several "crystals" which start from a single point, then as they grow further they bend apart from each other. Some minerals (such as stilbite) almost always appear this way. In terms of minerals onthogeny they are not separate crystals, as they start from the same embryo (nucleus) and carry the physical properties of that embryo. If the mineral is quartz, they are all "left" orall "right", never mixed. Such crystals are considered as "mineralindividuals", just like ordinary crystals and skeleton crystals. Splitting can be caused by two mechanisms. In most of the simple cases, where the splitting grade is low, splitting may be regarded as a mechanical process. The crystal regularly receives extra molecules in the molecular layers, so the splitting is physical. The other mechanism is chemical, where ions in the crystal fabric are replaced by ions of higher radius (for example Mg replacing Ca in calcite). We rarely meet chemical splitting in the simple case, in spherolites we meet both chemical and mechanical splitting, while in the case of spherocrystals we only find chemical splitting. The splitting grade is defined by the regularity of the appearance of extra molecules or replacement ions, their density, and the ability of the crystallographic network to "heal" these defects. Splitting is controlled by both physical and chemical conditions, and much has been written about it.

b) Spherolites. At a higher splitting grade, the crystal loses anything like faces and its internal structure is visible only from radial fibres. Spherolites are fully three dimensional, discospherolites have a two dimensional radial structure, while spherolite bunches are 3-d sectors. Spherolites should not be confused with core spherolites, which are aggregates not individuals, having a central core and growing from multiple embryos by geometric selection.

c) Spheroidolites. These are spherolites with asymmetric growth, characterised by bent fibres. The best examples are certain corallites.

d) Spherocrystals. This is the top grade of crystal splitting and the physical properties become generalised across the crystal. Fibres disappear at any examination level and a spherical cleavage appears. Malachite provides some of the best examples of these features.

Antholites: This term roughly corresonds to "flowers", but in the sense of complete aggregates not single branches. The term was suggested by Stepanov in 1971.

Crystallictites: Thin film generated varieties of frostwork. The term was proposed in Shcherban *et al* (1961) and defined by Stepanov (1971).

Corallites: Thin film generated varieties of coralloids and popcorn. The term was proposed in Shcherban *et al* (1961) and defined by Stepanov (1971).

Pseudohelictites: From photographs, these appear to be similar to speleothems known as Quill Anthodites in the west, but Quill Anthodite structure and texture has never been described.

ADDITIONAL REFERENCE

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