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## Hyalophane twins from Zagradski potok in Central Bosnia

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### Abstract

The location Zagradski potok near Busovača in Bosnia and Hercegovina has yielded numerous hyalophane specimens. Unique Karlsbad twins and different types of Manebach-Baveno combination twins were found there. The most interesting are double Manebach-Baveno combination twins. The mineral paragenesis present at this location is typical for alpine-type veins. The morphology of these minerals is described as a result of the active tectonic environment that caused the formation of so-called fadens (threads) and correlated secondary and tertiary morphological structures that feature in the Karlsbad twins and Manebach-Baveno combination twins. The different twinnings observed in the hyalophane crystals at this location are therefore the result of the mechanical process. Different combinations of Karlsbad twins are mentioned and described: (001)- and (010)-Manebach-Baveno combination twins as well as (010)-(010)-Manebach-Baveno- and (001)-(010)-Manebach-Baveno combination twins. Similar adularia morphological structures can be described with the theory proposed.

### Introduction

Among the minerals occurring in alpine-type fissures, those of the feldspar group are quite common. Adularia, a hydrothermal form of orthoclase, is reported to have been found at numerous sites. Hyalophane, on the contrary, which represents a link between orthoclase and celsiane and is similar to adularia, is much more rare and is reported only from few locations by Smith (1974), Gramaccioli (1975), Ramdohr and Strunz (1978), Zebec (1984), Weibel (1990) and Strübel and Zimmer (1992). They both have similar habitus and crystal forms. The most frequent are (110), {001},  $\{\bar{1}01\}$ ,  $\{\bar{2}01\}$  and (010) forms as described by Philipsborn (1967), Barić (1972), Smith (1974), Gramaccioli (1975), Ramdohr and Strunz (1978) and Roesler (1980). Twins, according to Karlsbad, Manebach, Baveno and the Cunnorsdorf law as well as the Manebach-Baveno combination twins (hereinafter called fourlings) are also reported for both minerals from numerous locations by Barić (1972), Smith (1974), Gramaccioli (1975), Schwarzmann (1977), Ramdohr and Strunz (1978), Roesler (1980), Zebec and Šoufek (1986), Zebec (1987/88) and Weibel (1990). Among these locations, the one at Zagradski potok near Busovača in Bosnia and Hercegovina seems to have been the source of the best hyalophane specimens known.

Divljan mentioned this location for the first time in 1954. The location and its mineral paragenesis were subsequently thoroughly described by Ilić (1954), Barić (1955, 1961 and 1972), Varićak (1971), Trubelja and Barić (1979), Zebec (1980/81 and 1987/88), Zebec and Zagorščak (1983), Zebec and Bermanec (1985), Zebec and Šoufek (1986) and Bermanec and Zebec (1987). The location has many incompletely filled veins in the paleozoic sericitic-phyllitic schists with some ore mineralisation. According to Ilić (1954), the veins are the remnants of the sulphide ore body swept away by erosion. Barić (1972), on the contrary, was of the opinion that these veins were of the alpine type. Water from Zagradski creek had cut its way through schists and thus revealed some veins incompletely filled with quartz and hyalophane crystals. The veins intersect the schists perpendicular to their strata, which is typical of alpine-type veins.

In the fifties, mining activities in search of crystallized quartz with piezoelectric properties, opened a series of more than 70 parallel veins up to one meter wide with some over 50 m long. More than 500 kg of quartz as well as hyalophane crystals are reported to have been mined during this period. Unfortunately, the examinations of this material were conducted improperly. Consequently, the material was lost and the results were of almost no significant scientific value; Varićak (1971). Some specimens were recovered later.

Divljan (1954) mentioned some typical crystallographic forms he had observed in these crystals. He also reported that the crystals were often twinned according to the Manebach-Baveno law and their pagoda-like form. More data on hyalophane crystallographic forms were published by Barić (1972) who mentioned 13 different crystallographic forms. He also reported Manebach and Baveno twins as well as one type of Baveno-Manebach fourlings. The results of chemical analyses of the hyalophane from this location, given by Barić (1972), show that it is composed of 35–41 mole % celsiane, 38–49 mole % orthoclase, 14–21 mole % albite and 1–2 mole % anorthite. As hyalophane is by definition orthoclase with more than 5 mole % of celsiane component, it can be concluded that in this case a true intermediate link between orthoclase and celsiane is present.

Zebec and Šoufek (1986) and Zebec (1987/88) reported some other hyalophane forms with higher  $\{hkl\}$  indexes and mentioned twins according to Karlsbad and the Cunnersdorf law. He described hyalophane fourlings as compositions where one Manebach twin is placed upon another so that both are then twinned according to the Baveno law. The uppermost Manebach twin is the youngest. More than two Manebach twins can thus be combined, forming up to five "stories" which really resemble a pagoda because the higher the "story", the smaller the Manebach twin combined with another in a Manebach-Baveno fourling. In rare cases this process is repeated symmetrically with regard to the lowermost "story". He published figures of the two types of Manebach-Baveno fourlings and also mentioned the parallel growth of hyalophane crystals. Zebec (1987/88) also mentioned regular succession of particular crystal growths as follows: Karlsbad twins – Manebach-Baveno fourlings – parallel growths – single crystals, where Karlsbad twins are the oldest and singles the youngest appearances.

Despite the abundance of hyalophane, no other Ba-minerals have been found.

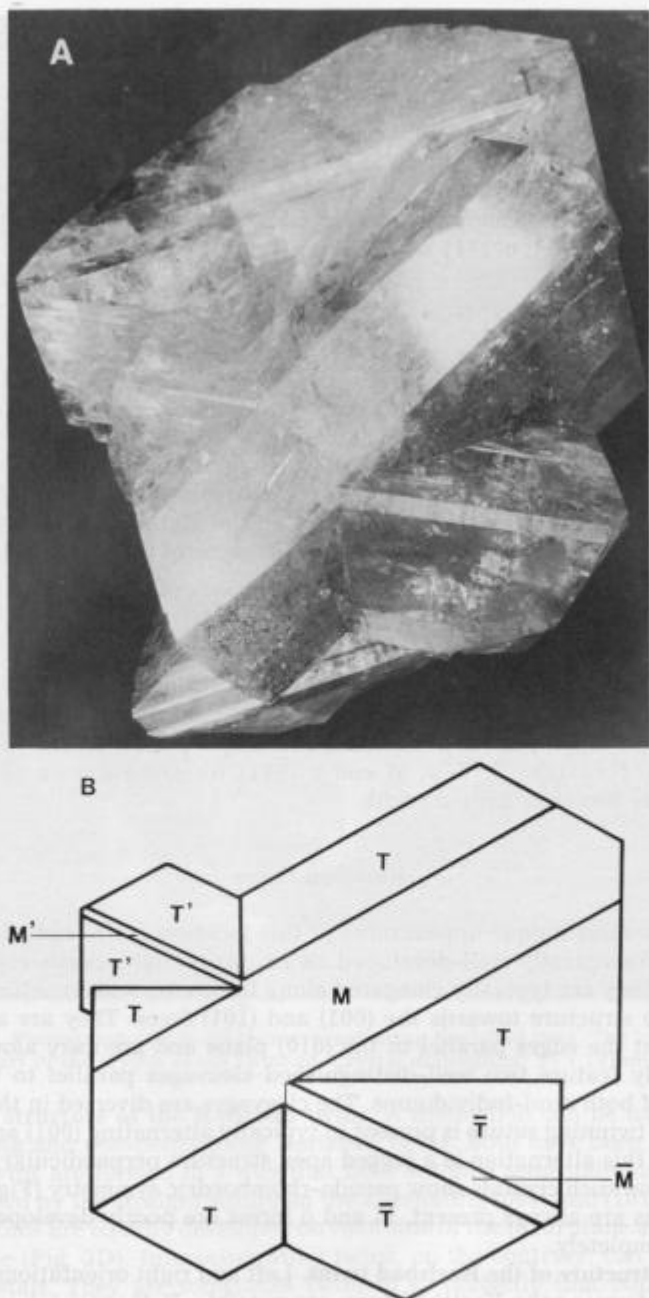


Fig. 1. Photograph of a  $(010)\text{-}\overline{(010)}$ -Manebach-Baveno combination twin with distinct secondary Manebach twin inversion (A) and its redrawing (B).  $M(010)$ ,  $T(110)$ . Specimen dimensions:  $50 \times 50$  mm

## Observations on hyalophane twins and combination twins from Zagradski potok

### *Baveno twins*

These are extremely rare as independent growths. Only few have been found. The (001) faces of one semi-individuum and (010) of the other are almost parallel. The angle between (001) and (021) is  $44^{\circ}50'$ ; Barić (1972). This twinning plays an important role in the composition of the Manebach-Baveno combination twins.  $P\{001\}$ ,  $T\{110\}$ ,  $x\{\bar{1}01\}$ ,  $o\{\bar{1}11\}$  and  $M\{010\}$  forms are usually present.

### *Manebach twins*

Independent twins of this type are considerably rare. Typical formations are parallel (001) and (010) faces of both semi-individuums. The (010) faces are always striated or etched and well developed. A twinning suture on the (010) face parallel to the (001) face is easily distinguishable. They can reach up to five centimeters in size.  $P$ ,  $T$ ,  $x$ ,  $M$ ,  $o$  forms and those with higher  $\{hkl\}$  indexes are present. This twinning plays a most important role in the formation of the Manebach-Baveno combination twins, as well as their secondary and tertiary structures (Figs. 1A and 1B).

### *Cunnersdorf twins*

They are extremely rare; only four are known to have been found. Typical are parallel  $(\bar{2}01)$  and (010) faces of the two semi-individuums. In one case a Karlsbad twin is twinned simultaneously with another single crystal to form a Cunnersdorf twin; Zebec (1987/88).  $P$ ,  $T$ ,  $x$ ,  $M$  and  $y$   $(\bar{2}01)$  forms have been observed. Their dimensions are less than 2 cm in width.

### *Karlsbad twins*

One of the most unique appearances at this location are Karlsbad twins. About twenty, macroscopically well-developed twins, up to eight centimeters long, have been found. They are typically elongated along the  $c$ -axis and sometimes narrowing in a step-like structure towards the (001) and  $(\bar{1}01)$  faces. They are almost always transparent at the edges parallel to the (010) plane and are hazy along the  $c$ -axis. They typically feature two well-distinguished cleavages parallel to the (001) and (001)' faces of both semi-individuums. The cleavages are diverted in the (010) plane. A significant twinning suture is present in typically alternating (001) and  $(\bar{1}01)$  faces. The result of this alternation is a jagged apex structure perpendicular to the  $c$ -axis. For that reason such crystals show pseudo-rhomboedric symmetry (Figs. 2 and 3).  $P$ ,  $T$  and  $x$  forms are always present.  $M$  and  $o$  forms are poorly developed or, in some cases, fail completely.

**Primary structure of the Karlsbad twins.** Left and right orientations of two semi-individuums forming the Karlsbad twin are possible. Both orientations are equally present on the Zagradski potok Karlsbad twins. They can be easily recognised because of the two distinctive cleavages running in opposite directions from the (010) plane and typical orientations of  $(\bar{1}11)$  faces (Figs. 2 and 3).

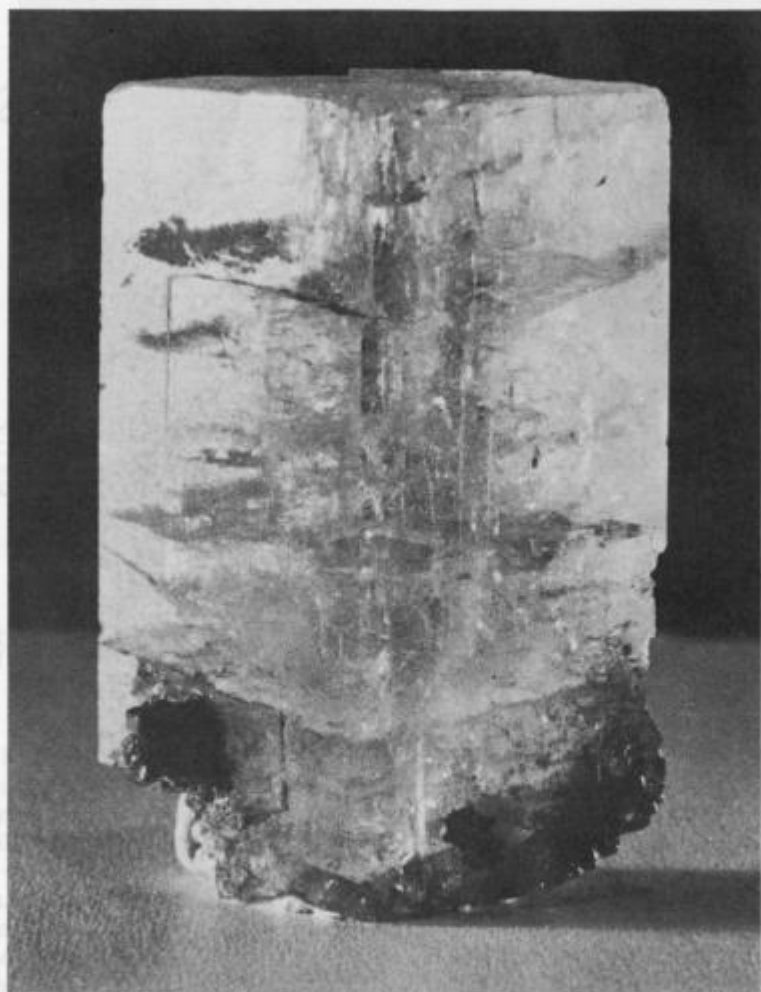


Fig. 2. Photograph of a R-(001)-interpenetrating Karlsbad twin. The lower part of the crystal is not twinned. Crystal dimensions:  $27 \times 19$  mm

**Secondary structure of the Karlsbad twins.** A distinction can be made between interpenetrating and non-penetrating Karlsbad twins. Both have been found. Non-penetrating twins are formed in a way that both twinned semi-individuums can be easily recognised by the straight suture on the alternating (001) and  $(\bar{1}01)$  faces. Both semi-individuums are equally developed on each side of the (010) plane and are easily distinguishable (Fig. 3D). Interpenetrating twins, on the contrary, can be mistaken for single crystals. They are sometimes twinned so perfectly that both semi-individuums together make a perfectly developed single crystal. The most distinguishable facing cleavages as well as the uneven twinning suture on alternating (001) and  $(\bar{1}01)$  faces are diagnostic. The positions of  $(\bar{1}11)$  faces are also characteristic (Figs. 2, 3B and 3C).

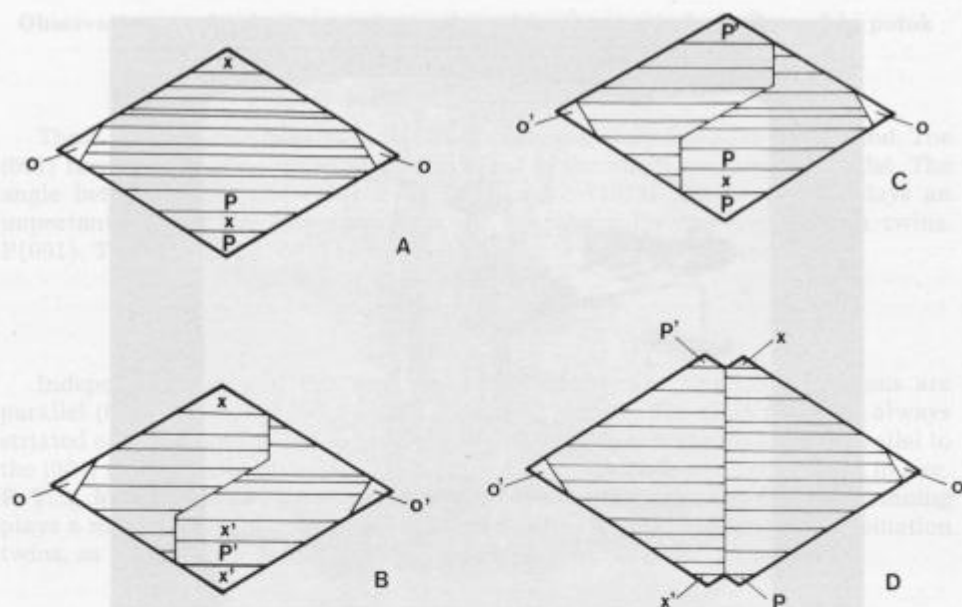


Fig. 3. Terminations of different Karlsbad twin types. Single crystal (A), R- $(\bar{1}01)'$ -interpenetrating (B), L- $(001)$ -interpenetrating (C) and L-non-penetrating Karlsbad twin (D). P $\{001\}$ , x $\{\bar{1}01\}$ , o $\{111\}$

**Tertiary structure of Karlsbad twins.** This structure is characterised by the appearance and positions of  $(001)$  and  $(\bar{1}01)$  faces on both semi-individuums. These faces are present in both semi-individuums only in the case of non-penetrating twins. Left and right combinations are possible (Fig. 3D). The situation is different in interpenetrating twins. Twinned crystals develop in a way that only  $(001)$  or  $(\bar{1}01)$  faces of the twinned semi-individuums are present. This fact increases the number of possible combinations by four, i.e. L- $(001)$  and L- $(\bar{1}01)'$  as well as their right analogues (Figs. 3B and 3C). Six combinations are possible in single Karlsbad twins. A complete description of a Karlsbad twin from the Zagradski potok location should read: L-interpenetrating- $(\bar{1}01)'$ -single Karlsbad twin or shortly L- $(\bar{1}01)'$ -Karlsbad twin and R-non-penetrating-single Karlsbad twin or shortly R-Karlsbad twin. All these combinations were found and are evenly distributed.

#### *Manebach-Baveno combination twins*

Fourlings represent the largest part of the whole mass of hyalophane found at this site. Their dimensions range from less than one millimeter up to 20 centimeters. They are well developed and are found on the walls of clefts as well as in the form of floaters. Broken and rehealed fourlings are also frequent. Etchings and striations on  $(010)$  faces, and etchings on  $(001)$  and  $(\bar{1}01)$  faces are characteristic and only rarely absent (Fig. 5). The presence of the Manebach twins around the fourlings and their gradual narrowing in the direction of a common fourfold twinning a-axis really



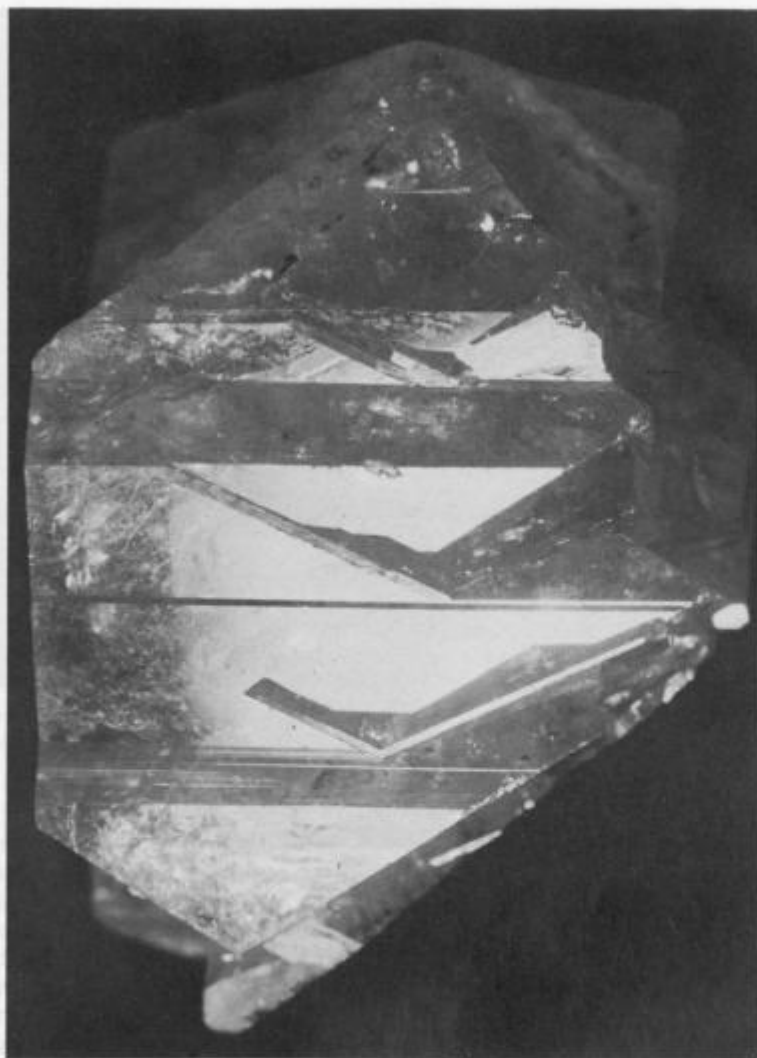


Fig. 4. Photograph of a (010)-Manebach-Baveno combination twin. Some secondary Manebach twins and alternating (001) and (101) faces can be seen. Secondary Manebach (001) twinning planes are aligned with the fourling (010) plane of symmetry. Note the non-alignment (bottom left) of the secondary Manebach twin (010) plane of symmetry with the fourling (010) symmetry plane. Crystal dimensions: 30 × 20 mm

resemble a pagoda (Figs. 4 and 5). Complex double fourlings, a most unique phenomenon, have been found strictly in the form of floaters or lying on a matrix (Figs. 6 and 7).

**Primary structure of Manebach-Baveno combination twins.** Adularia fourlings are mentioned in literature among others by Grammaccioli (1975) Ramdohr-

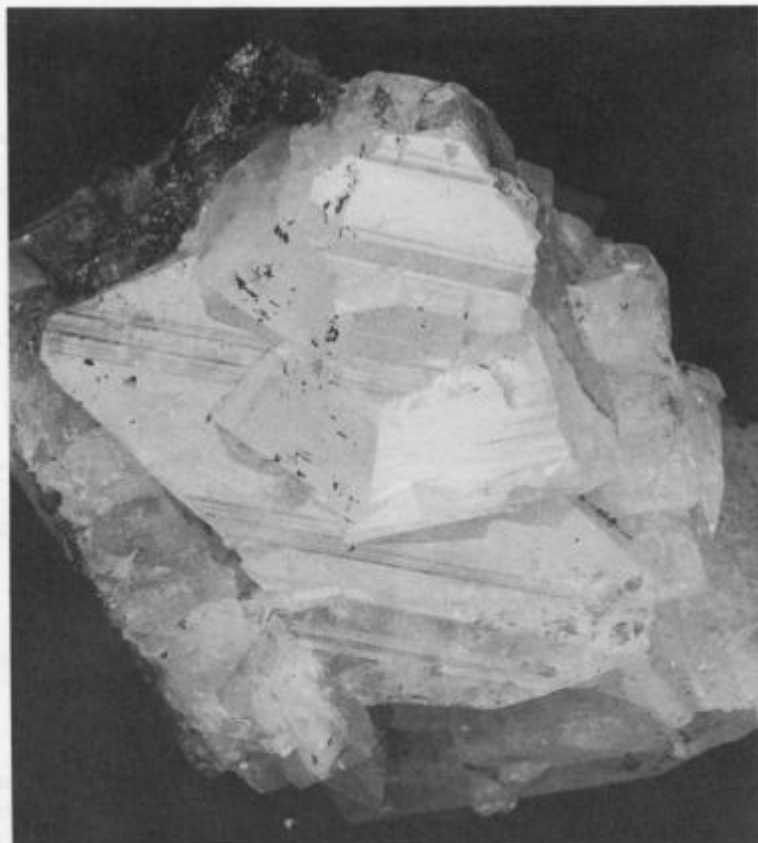


Fig. 5. Photograph of a (001)-Manebach-Baveno combination twin with visible etchings on the alternating (001) and  $(\bar{1}01)$  faces. Some secondary Manebach twins as well as a concave termination can be seen. Note the distance between the (001) twinning planes of the secondary Manebach twins and the hollow diameter. Specimen dimensions:  $102 \times 120$  mm

Strunz (1978), Weibel (1990) as well as hyalophane furlings by Barić (1972) Zebec and Šoufek (1986), and Zebec (1987/88). Grammaccioli (1975) mentioned explicitly two types of furlings where one type is Manebach-Baveno twinned and the other Baveno-Baveno. In fact there are two types of Manebach-Baveno furlings that cannot be distinguished with these terms only. They can be described as follows: two Manebach twins can be twinned according to the Baveno law thus producing a structure where both twinning  $a$ -axes coincide in a common fourfold  $a$ -axis. Normals to (001) and (021) hyalophane faces thus close an angle of  $44^\circ 50'$ , and normals to (010) and (021) faces, an angle of  $45^\circ 10'$ ; Barić (1972). Two orientations of two Manebach twins are possible at the moment of their twinning to a Manebach-Baveno furling according to the Baveno law (Fig. 8). Besides other characteristics, these two furlings are distinguished by the faces whose normals are perpendicular to the common fourfold twinning  $a$ -axis, i.e. (010) and (001) (Fig. 9). Let the first type



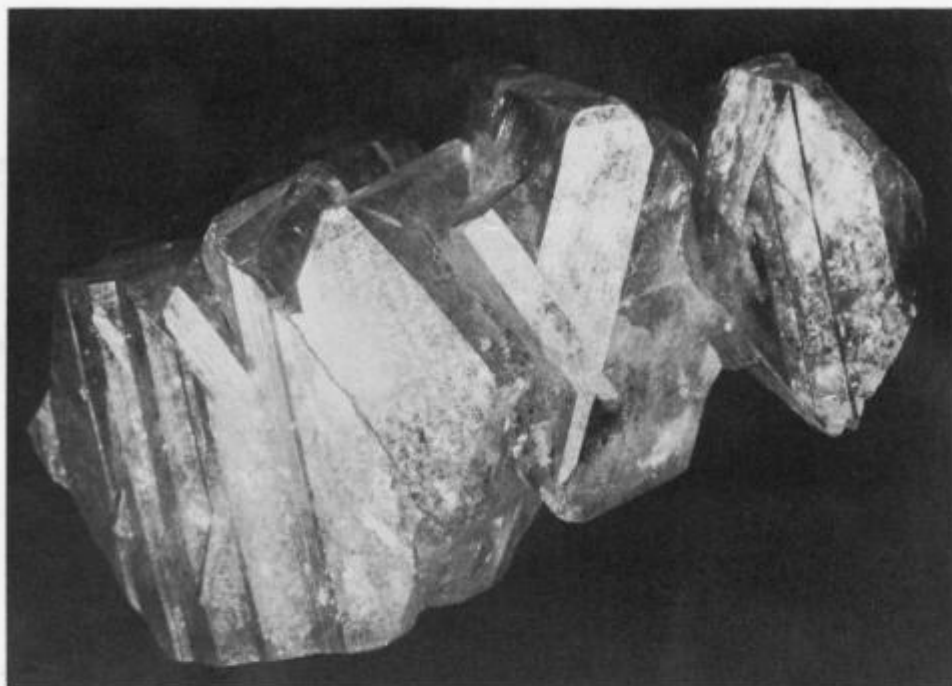


Fig. 6. Photograph of (010)- $\overline{(010)}$ -Manebach-Baveno combination twin. Note the inversion of the secondary Manebach twin. The primary (010)-Manebach-Baveno combination twin is on the left-hand side. Crystal dimensions: 34 × 15 mm

be defined as a (010)-Manebach-Baveno combination twin (fourling) and the second one as a (001)-Manebach-Baveno combination twin (fourling). It is evident that both fourlings are twinned according to both Manebach and Baveno laws, which acted simultaneously. It is evident also that different halves of the two Manebach twins are twinned into a fourling according to the Baveno law. This forms the primary structure of fourlings. The (010) and (001) faces have a most significant influence on the morphology of fourlings.

**Secondary structure of Manebach-Baveno combination twins.** Typical of both fourling type are secondary Manebach twins positioned around these fourlings. These positions are different and are diagnostically important for the determination of particular fourling types.

**1. (010)-Manebach-Baveno combination twins.** This type of Manebach-Baveno fourling is present in crystals up to several centimeters large (Fig. 4). The crystals are combinations of alternating and narrowing M, P, x, d  $\{\overline{221}\}$  and z  $\{130\}$  forms. The (010) faces of secondary Manebach twins are rarely connected to the Baveno twin. They are separated from other secondary Manebach twins with (001) and  $(\overline{101})$  faces which results in a shape where single Manebach twins protrude out of (001) and  $(\overline{101})$  faces. This type of fourling is relatively closed. The distribution of the afore mentioned secondary Manebach twins is uneven on the four fourling sides. All secondary Manebach twins are symmetrically intersected along their twinning (001) planes with

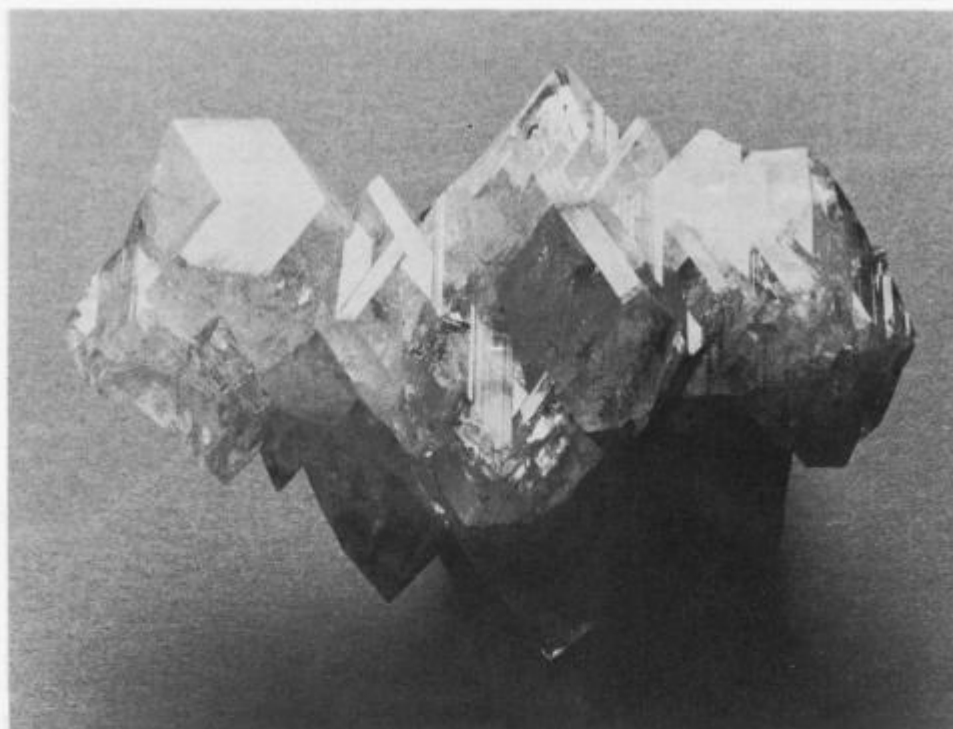


Fig. 7. Photograph of a  $(001)\text{-}\overline{(010)}$ -Manebach-Baveno combination twin. The primary  $(001)$ -Manebach-Baveno combination twin is on the right-hand side. Crystal dimensions:  $66 \times 39$  mm

two fourling planes of symmetry, i.e.  $(010)$  and  $(100)$ . This is clearly visible on the  $(010)$  striated Manebach twin faces whose junctions make a visible twinning suture along their  $(001)$  twinning planes (Fig. 4). This is also the direction of the fourling cleavage. A  $(010)$  face is always well-developed and striated. It sometimes stretches over the entire side of the fourling but never on all sides simultaneously. This type of fourling ends in a conical apex structure as shown in Figures 8C and 9A. The apex is rarely perfectly formed because of the presence of secondary Manebach twins that also contribute to its formation.

**2.  $(001)$ -Manebach-Baveno combination twins.** These fourlings are well developed and have dimensions that can reach more than 20 cm. They are not always square in the section perpendicular to their common fourfold twinning axis and can be more or less rectangular. The observed forms are: T, P, M, x, o, z, y, d and  $k\{100\}$ . Typical etchings are frequently observed on otherwise lustrous  $(001)$  and  $\overline{(101)}$  faces (Figs. 5, 8B and 9B). The  $(010)$  face is characteristically well developed, always striated and sometimes deeply etched. The  $\overline{(221)}$  face is always dull with a more or less pronounced layered surface. A typical concave apex structure is formed on the top of such a fourling. It is rarely perfectly developed (Fig. 5). On all four fourling sides additional secondary Manebach twins are always present which also contribute to the apex structure formation. The form  $k\{100\}$  can frequently be observed in the apex structure. Diameters of the apex hollow depend on the dimensions of the

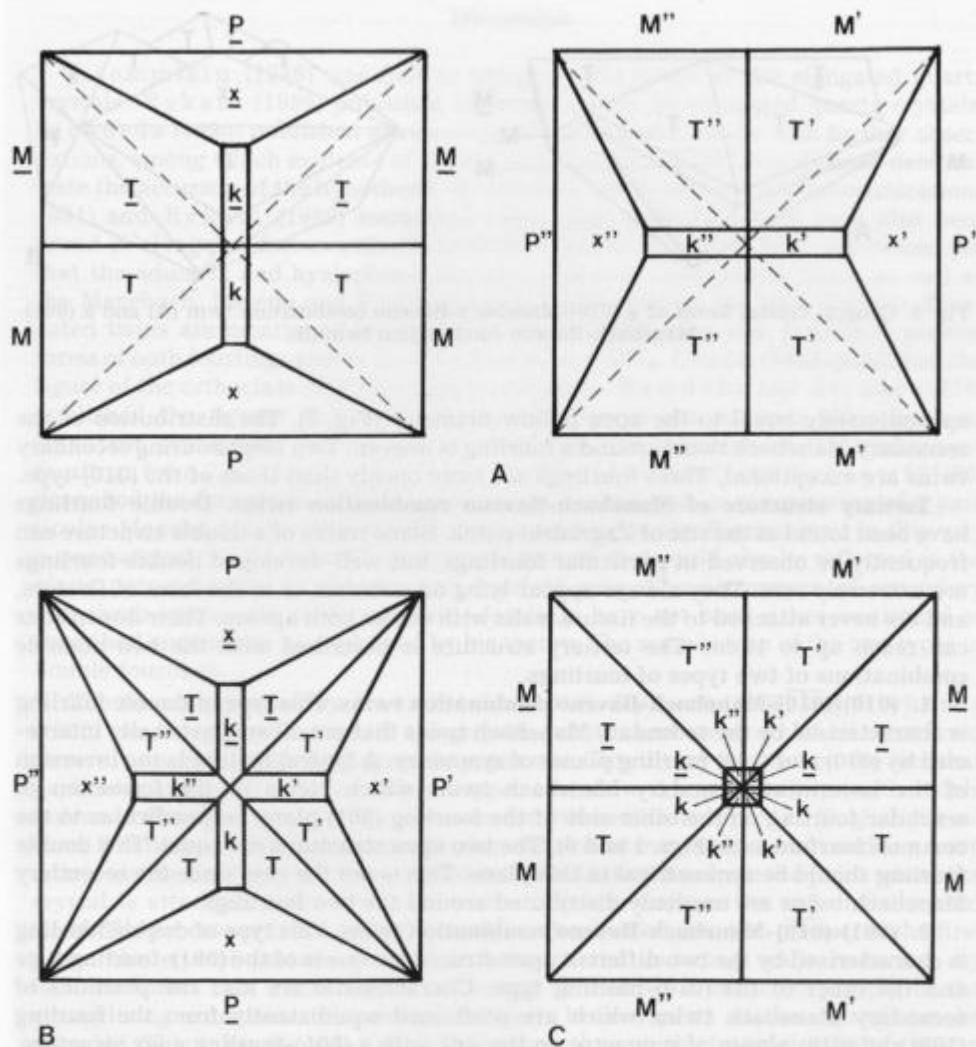


Fig. 8. Positions of particular Manebach twins prior to twinning according to the Baveno law (A). Terminations of the formed (001)-Manebach-Baveno combination twin (B) and (010)-Manebach-Baveno combination twin (C).  $P\{001\}$ ,  $x\{\bar{1}01\}$ ,  $T\{110\}$ ,  $k\{100\}$  and  $M\{010\}$

fourling itself as well as on growth conditions. They can reach up to 8 cm in size. Characteristic compensation faces with higher  $\{hkl\}$  indexes are formed frequently on the (001) and  $(\bar{1}01)$  faces of the fourling. Their center lies at the point where (001) and  $(\bar{1}01)$  faces are protruded by secondary Manebach twins. The most significant feature is the presence of secondary Manebach twins. In comparison with those on a (010)-fourling they are positioned equidistantly to the left and right of the (010) and (100) fourling planes of symmetry (Fig. 5). The distance between the (001) twinning planes of the secondary Manebach twins on one fourling side is more or less constant and is

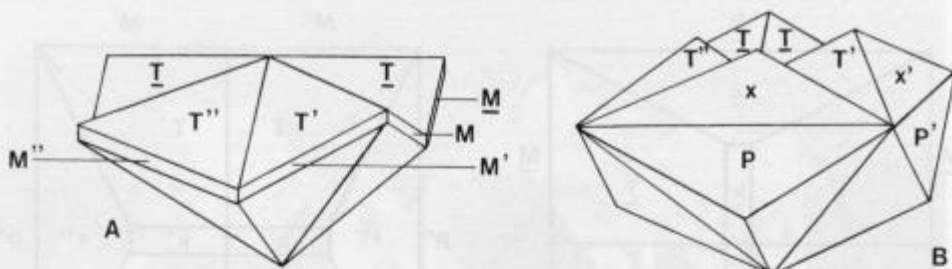


Fig. 9. General crystal forms of a (010)-Manebach-Baveno combination twin (A) and a (001)-Manebach-Baveno combination twin (B)

approximately equal to the apex hollow diameter (Fig. 5). The distribution of the secondary Manebach twins around a fourling is uneven. Two neighbouring secondary twins are exceptional. These fourlings act more openly than those of the (010)-type.

**Tertiary structure of Manebach-Baveno combination twins.** Double fourlings have been found at the site of Zagradoski potok. Some traces of a double structure can frequently be observed in particular fourlings, but well-developed double fourlings are extremely rare. They always appear lying on a matrix or in the form of floaters, and are never attached to the fissure walls with one or both apices. Their dimensions can reach up to 15 cm. The tertiary structure is described with the two possible combinations of two types of fourlings.

**1. (010)-(010)-Manebach-Baveno combination twins.** This type of double fourling is characterised by the secondary Manebach twins that are all symmetrically intersected by (010) and (100) fourling planes of symmetry. A typical feature is the inversion of the lowermost secondary Manebach twins which yields to the formation of a similar fourling on the other side of the fourling (001) plane perpendicular to the common fourfold axis (Figs. 1 and 6). The two apex structures are equal. This double fourling should be symmetrical in this plane. This is not the case since the secondary Manebach twins are unevenly distributed around the two fourlings.

**2. (001)-(010)-Manebach-Baveno combination twins.** This type of double fourling is characterised by the two different apex structures: one is of the (001)-fourling type and the other of the (010)-fourling type. Characteristic are also the positions of secondary Manebach twins which are positioned equidistantly from the fourling (100) and (010) planes of symmetry on the side with a (001)-fourling apex structure. These Manebach twins are intersected with the same planes of symmetry on the side with (010)-fourling apex structure. It is evident that the double fourling composed of both types is present. Significant is the inversion of the lowermost secondary Manebach twins (Fig. 7).

#### *Distribution of Manebach-Baveno combination twins*

All fourlings studied in this paper were classified into the four afore-mentioned groups. Out of more than 350 fourlings examined about 53 % were of (001)-type, 33 % of (010)-type, 7 % of (010)-(010)-type, and 7 % of (001)-(010)-type. If the mass percentage is considered, then the share of (001)-type is well over 95 %.

### Discussion

Laemmlein (1946) was first to report on the origin of the elongated quartz crystals. Rykart (1989) published his observations on elongated quartz crystals. Richards (1990) published a reviewing article on faden quartz with further observations, among which evidence of crystal growth from a faden was given to demonstrate the accuracy of the hypothesis. Richards (1990, and private communications 1991) and Rykart (1989) mentioned some other minerals which have also been found in elongated forms with characteristic fadens. It has not been mentioned yet that the adularia and hyalophane Manebach-Baveno combination twins as well as the Manebach, Baveno and Karlsbad twins could undergo the same process. Elongated twins are mentioned by Gramaccioli (1975) who also published general forms of both fourlings and by Schwarzmänn (1977). Linck (1923) published the figure of the orthoclase (010)-fourling termination. Ramdohr and Strunz (1978) published the figures that show the termination of the adularia (001)-fourling. Divljan (1954) and Barić (1972) mentioned the structure of the hyalophane fourlings from Zagradski potok. Zebec and Šoufek (1986) and Zebec (1987/88) described the formation of such hyalophane structures as an overgrowing of a particular Manebach twin with another one according to the Baveno law. In this way a symmetrical "multi-storied" structure is formed that could also be reflected in the plane perpendicular to the common fourfold axis. The occurrence of secondary Manebach twins with (010)- and (001)-fourlings have not been either mentioned or described and cannot be explained by his theory. The same is true of the two types of double fourlings.

The theory proposed by Laemmlein (1946), Rykart (1989) and Richards (1990) can be applied to explain the growth, habitus and structure of all mentioned mineral appearances at the Zagradski potok site. This theory is based on the fact that particular quartz crystals from alpine-type veins show elongated habitus with visible fadens in their interiors. Faden (German for "thread" is accepted in English literature; Richards, 1990) is the result of an active tectonic environment and is a more or less visible hazy thread in the crystal interior. It stretches from the point where the crystal is attached to the vein wall, to the opposite wall, or the end of the crystal itself. The process of faden crystal growth can be divided into two phases. In the first phase the crystal particle positioned between the widening walls is broken by tectonic forces that cause fissure widening. If there is a sufficient supply of the crystallizing substance, the crevice between broken parts of the crystal can be rehealed. This takes place faster on their edges than on the internal sides of the gap between the ends of the broken crystal. This is due to higher surface energy and ionic transport limited by particular diffusion coefficients. The faden grows as long as the rehealing rate of the crevice is high enough to follow the vein widening. If the rate of faden growth is lower than that of the vein widening, the crystal cannot be rehealed and thus the two parts cannot be connected. At this stage the faden growth is completed and the secondary phase begins. In this phase more substance is crystallized around the faden and finally a crystal with a more or less distorted or elongated habitus is formed. The habitus of a crystal thus formed depends on the position of the primary crystal and the direction of the fissure widening. If a large amount of the substance is deposited around the faden (floaters), then the crystal shows a normal habitus, but with a characteristic faden line in its interior.

Almost every quartz crystal from the Zagradski potok site is deformed in a par-



ticular direction with a visible faden in its interior. The Dauphiné twinning of quartz crystals is also characteristic of this site. Elongated ankerite as well as apatite crystals are present, too. The mineral paragenesis at this site is about 60 million years old (Barić, 1972). It can be concluded that the mineral paragenesis at the Zagradski potok site could grow longer. The formation of faden crystals could occur since the process of vein widening was slow.

Hyalophane, the most abundant mineral at this site besides quartz, shows some morphological properties which can be explained by the stretching process and faden formation. Hyalophane possesses excellent cleavage parallel to the (001) face and less pronounced parallel to the (010) face. For that reason hyalophane crystals are interwoven with visible cleavage planes, which make the fadens invisible. Only few specimens with visible fadens have been found.

The elongation direction of a hyalophane crystal can be described as a vector:  $E = xa + yb + zc$ , where  $xa$  is the component of the vector in the a-axis direction which is similar to the other two components. If two components are equal to zero, the elongation leads in the direction of one crystallographic axis. If one component equals zero, the translation of a particular plane occurs, which yields in parallel growth.

Some extreme elongation examples are:

$E = xa, yb = zc = 0$ , translation in the direction of a-axis; formation of elongated crystals with Fibbia habitus, formation and inversion of Manebach twins (Figs. 1A and 1B),

$E = zc, xa = yb = 0$ , translation in the direction of c-axis; formation of elongated crystals, formation of Karlsbad twins (Fig. 2) and

$E = yb, xa = zc = 0$ , translation in b-axis direction – parallel growth.

If component  $xa$  is equal to zero, then the (010) face is narrow or missing. The typical parallel striations on the (010) faces are thus the result of infinitesimal stretching, i.e. breaking and rehealing of the crystal between fissure walls. These faces are therefore prone to etching and are frequently deeply etched. All orientations of the vector  $E$  are possible and thus also all elongated structures. The rotation of this vector results in the twisted and curved structures which are frequently found at the Zagradski potok site.

#### *Manebach twins*

Translation in the a-axis direction yields Fibbia habitus. This habitus is extremely rare at this site. More probable is Manebach twinning, where a crystal is broken along the (001) plane. The (001) face is thus exposed. Such a crystal can be twinned with another two crystal semi-individuums. In this way a "penetration" Manebach twin is formed, but in fact it consists of one connecting individuum and two semi-individuums. This process is well manifested on (010) surfaces which have typical striations and twinning sutures (Figs. 1A and 1B). Translation of a single hyalophane crystal in the a-axis direction yields to the formation of a Manebach twin on one side. A twinning suture is formed. Further translation of the crystal in the opposite a-axis direction results in Fibbia habitus with a more or less developed and striated (010) face without a twinning suture and can be ended with another Manebach twin. The formation of the twinning suture begins on the (010) face. This is the inversion of the Manebach twin which plays an important role in the formation of



double fourlings. The onset of the Manebach twin formation depends on growth conditions in the translation process. Sometimes it takes a relatively long time. In this case the (010) face of the primary individuum is broad (Figs. 1A and 1B).

### *Karlsbad twins*

Translation in the *c*-axis direction yields to elongation of the crystal in this direction or formation of a Karlsbad twin. In this case the hyalophane crystal is broken along the (010) plane. The (010) face is exposed and a Karlsbad twin can be formed (Fig. 2.). This is actually the process that is diametrically opposite to the Synneusis mechanism of orthoclase twinning in magmatic milieu where two single floating orthoclase crystals are preferably oriented to form a Karlsbad twin (Smith 1974). The proof of such a Karlsbad twin formation is the specimen that is not twinned in its lower part, but at a particular point of the crystal the Karlsbad twinning begins to form. This is demonstrated by a cleavage that runs throughout the lower part of the crystal and is reversed in its upper part, where two reversed cleavages are observed (Fig. 2). It is quite possible that such a process can be repeated on the other side of a single crystal, as occurs in the case of double fourlings, and therefore double Karlsbad twins can be formed. The ends of these twins have different primary structures, i. e. one end would show the left structure and the other right one. Taking into consideration secondary and tertiary structures, nine combinations would be possible. Out of these, six would be penetrating, two mixed and one non-penetrating. The nomenclature of such twins would be for example: R-interpenetrating-L-(101)' -non- penetrating double Karlsbad twin, or shortly, R-L-(101)' - Karlsbad twin. The probability of a Karlsbad twin formation is low at the Zagradoski potok site and therefore formation of a double twin even lower. No double Karlsbad twin has been found.

### *Manebach-Baveno combination twins and double combination twins*

The most interesting elongated structures are Manebach-Baveno fourlings. They are oriented with their common fourfold axis perpendicular to the cleft wall in the nucleation phase. As the vein widens they break and are rehealed again, thus forming a faden.

**(010)-Manebach-Baveno combination twins.** The first phase is the translation of this fourling type in the direction of its common fourfold axis. This would result in the formation of a simple crystal structure where an elongated fourling would be formed with even, extremely developed (010) faces and a termination structure as shown of Figures 8C and 9A. It can be seen from Figure 10A that two (001) Manebach twinning planes intersect the fourling parallel to its common fourfold *a*-axis and these two planes, i. e. the (001) and (010), are at the same time two out of the four planes of fourling symmetry. The secondary Manebach twin is formed at the point where the crystal is broken in the (001) twinning plane (Fig. 11). This secondary Manebach twin grows outwards from that point in the secondary phase. It becomes more and more developed with (001) and (101) faces that could not be present in the case of a pure (010)-fourling. These faces are then developed to the extent where they completely overgrow the faden, thus producing such a fourling with well developed

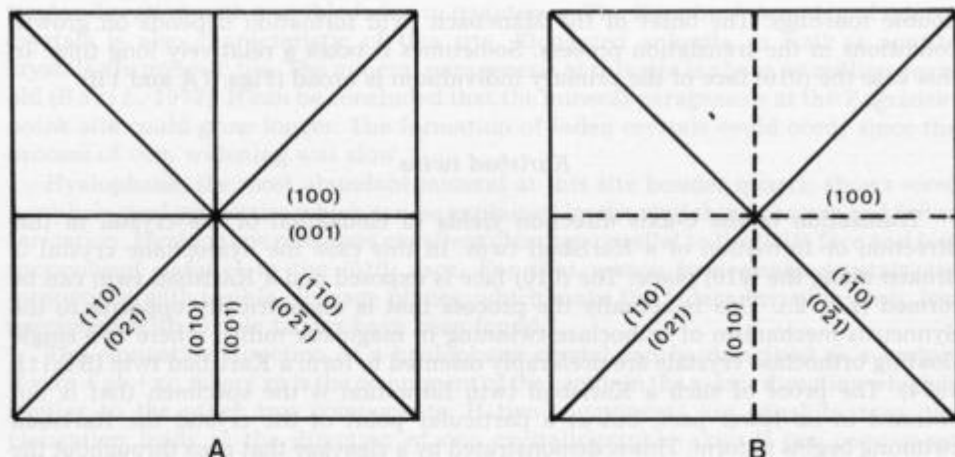


Fig. 10. Drawings of the faden (001)-cross-sections of the (010)-Manebach-Baveno combination twin where the fourling (010) and (100) planes are at the same time (001) Manebach twinning planes (A) and a (001)-Manebach-Baveno combination twin, and where these planes are not Manebach twinning planes (B)

(001) and  $(\bar{1}01)$  faces that are protruded here and there with a primary (010)-fourling faden structure, i.e. (010) faces (Fig. 4).

Such a fourling could be described as a superposition of many particular Manebach twins that are also twinned according to the Baveno law; Zebec and Šoufek (1986) and Zebec (1987/88). The problem of such an explanation is the non-alignment of the (010) planes of secondary Manebach twins with the fourling (001) and (010) planes of symmetry. They should be in this planes if only a single (010)-fourling were formed.

The Manebach twinning around a broken faden can begin at any time. This does not occur necessarily on all four sides simultaneously. Then the secondary Manebach twins grow outwards from the faden. Figure 11 shows that two neighbouring secondary Manebach twins in the Baveno twinning position at the same time form a secondary (010)-fourling. Further stretching yields in the translation of secondary Manebach twins which causes wide (010) and (001) faces. The translation of secondary Manebach twins can be completed and again continued after a period of translation during which no secondary Manebach twin is formed. As the faden grows further, more and more secondary Manebach twins are formed. The lower and older secondary Manebach twins have more time to develop than the upper and younger ones, therefore a structure with a conical pagoda-like form is developed. This structure can be compared to that of a pine cone where particular scales grow from a common kernel. The same situation is present in this structure because certain secondary Manebach twins do not make a uniform crystal. They have only a common kernel (faden), from which they grow outwards as independent individuals which are otherwise unconnected. The growth of each secondary Manebach twin as well as outward growth of the faden is spatially limited as all of them grow simultaneously outwards around the faden, thus encountering each other sooner or later. The whole structure of such a crystal is held together by a common faden as well as a penetration of certain secondary Manebach twins. If there were sufficient material to be

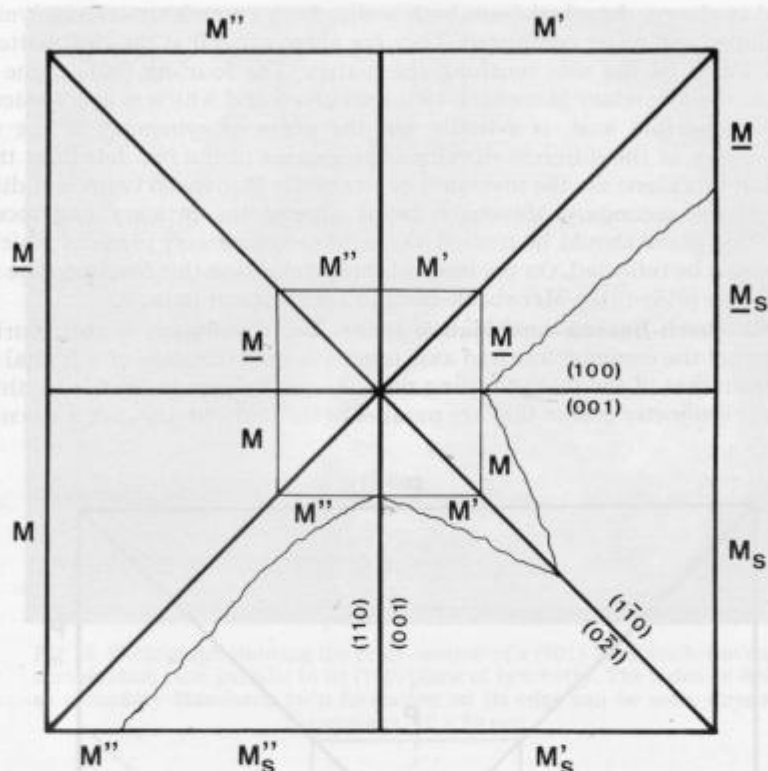


Fig. 11. Drawing of (010)-Manebach-Baveno combination twin (001)-cross-section with the formation of secondary Manebach twins. Index *s* denotes secondary faces

deposited around the faden in the secondary phase, a ripe fourling with aligned parallel (010) and (001) faces would be formed (Fig. 4). This would be the final stage of fourling growth unless another stretching process took place where a double fourling develops.

**(010)-(010)-Manebach-Baveno combination twins.** A faden is normally formed so that one end of the crystal always remains connected to the wall whereas the other one is repeatedly broken and rehealed. Assuming that a crystal could be broken alternatively on both sides and rehealed, a fourling with a double conical form would develop. All secondary Manebach twins on all four sides should have the same direction. Such a crystal has not been found. However, double conical fourlings with secondary Manebach twins leading in opposite directions, i.e. reversed in the double fourling pseudosymmetry (001) plane have been found (Figs. 1 and 6). The reason is the inversion of the lowermost secondary Manebach twins. The (010)-fourling is formed again with their inversion (Figs. 1, 6 and 11). Further translation results in the formation of the same structure as on the primary side, but in the opposite direction. Because this type of crystal becomes heavy during secondary growth, the connection points cannot resist its own weight under tectonic stresses. Consequently

the crystal is always detached from both walls. Such crystals are rarely symmetrically developed and never completed. They are always found at the cleft bottom and are undeveloped on the side touching the matrix. The fourling (001) plane where inversion of the secondary Manebach twins occurred and which is perpendicular to the common fourfold axis, is actually not the plane of symmetry of the double fourling because of the different development degrees of the two fourlings that are connected in this plane via the inversion of secondary Manebach twins and different positions of the secondary Manebach twins around the primary and secondary fourlings. This plane should be treated as the pseudosymmetry plane in which both fourlings could be reflected. On the basis of this proposition this fourling type should be defined as a (010)-(010)-Manebach-Baveno combination twin.

**(001)-Manebach-Baveno combination twins.** The translation of this fourling in the direction of the common fourfold axis results in the formation of a crystal that is different from that of the (010)-fourling type. As can be seen in Figure 10, this type also has four symmetry planes that are parallel to the fourfold axis, yet it has no (001)

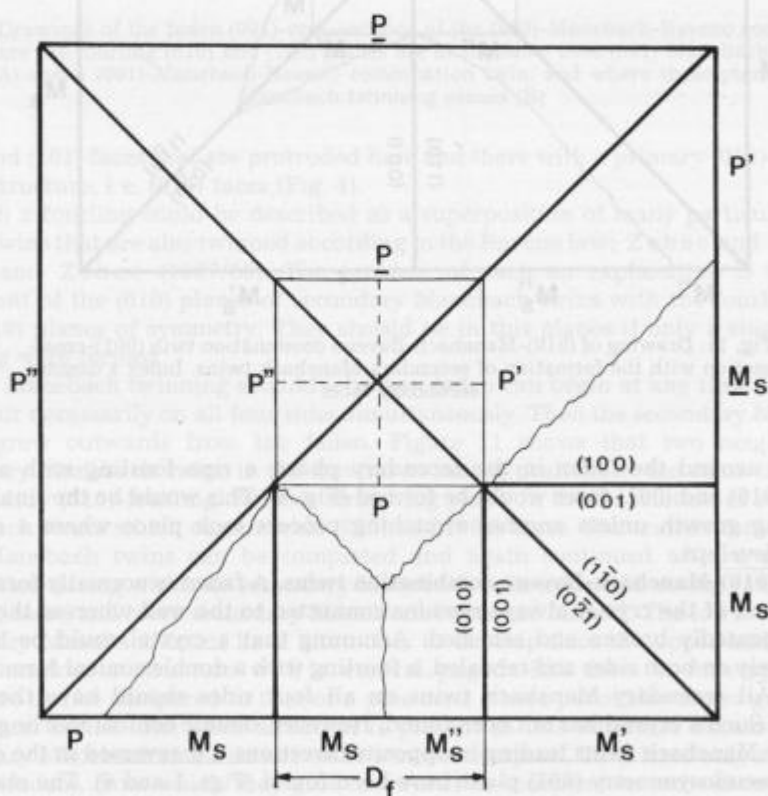


Fig. 12. Drawing of a (001)-Manebach-Baveno combination twin (001)-cross-section with the formation of secondary Manebach twins and their inversion to a (010)-Manebach-Baveno combination twin.  $D_f$  is the distance between the secondary Manebach (001) twinning planes and the diameter of the faden at that point. Index  $s$  denotes secondary faces



Fig 13. Photograph showing the cross-section of a (001)-Manebach-Baveno combination twin parallel to its (100) plane of symmetry. The faden as well as secondary Manebach twin formation on its edge can be seen. Crystal dimensions: 70 × 80 mm

Manebach twinning plane. In this case, this plane is contracted to a line identical to the fourfold axis. If a (001)-fourling were translated in the direction of its common fourfold axis, then an elongated crystal with extremely developed (001) faces and with a termination as shown in Figures 8B and 9B would result. No such crystal has been found at the Zagradoski potok site, whereas crystals with secondary Manebach twins protruding out of (001) and (101) faces, that are equidistantly positioned on both sides of the (100) and (010) planes of fourling symmetry on all four sides of the crystal, have been found (Fig. 5).

This is explained by the translation of this fourling where two secondary Manebach twins can be formed at the points where the fourling is broken in the (021) twinning plane. The (001) face of each twinned sub-individuum is exposed. At that point the crystal can be twinned into a Manebach twin. As two such points exist on each fourling side, two parallel secondary Manebach twins can be formed simultaneously on each fourling side (Fig. 12). The distance between the (001) twinning planes of both secondary Manebach twins is exactly the diameter ( $D_f$ ) of the faden at that point. Due to the growth conditions and spatial limitations, parallel secondary Manebach twins are rarely formed. More frequent are the alternating secondary Manebach twins on both sides of the (001) fourling symmetry plane (Fig. 5).

Confirmation of this hypothesis can be seen in Figure 13, where the cross-section of the (001)-fourling parallel to the (100) plane of its symmetry can be seen. It is evident that secondary Manebach twins are formed on the edge of the faden. It can also be seen that the faden itself has only (001) and (101) faces. If the faden growth



were not the cause of development of such a crystal, secondary Manebach twins would grow from any point of the fourling. The result would be a fourling with randomly scattered secondary Manebach twins around it. The cross-section of a fourling made in a (001) fourling plane is shown in Figure 14. It can be seen that the secondary Manebach twin is formed exactly at the point where the crystal was broken in the (021) twinning plane and grew from that point outwards.

From one such point two secondary Manebach twins can grow outwards simultaneously. It is evident that they are both in the Baveno twinning position at the same time (Fig. 12). The result is a secondary (010)-Manebach-Bavento fourling which is the inversion of the (001)-to (010)-fourling that plays an important role in the formation of a (001)-(010)-Manebach-Bavento combination twin. The apex structure is rarely theoretical. It is normally more complex because of the secondary Manebach twins that also contribute to its formation. The apex is concave and if the faden building process were the reason for crystal growth, a hollow faden would be possible. Crystals with a channel in the center of the faden have been found. If much substance had been deposited around the faden in the secondary phase, a ripe crystal with aligned (001) and (010) faces resulted.

As it has been mentioned previously, these crystals are most abundant at this locality. It seems that the nucleation of (001)-fourlings was more favoured in comparison to that of (010)-fourlings and single crystals. The largest crystal of this type found has a diameter of 23 cm and the longest one about 15 cm. The diameters of the fadens range from tenths of a millimeter to eight centimeters. If the faden is narrow, these two types are difficult to distinguish because with a (001)-fourling type secondary Manebach twins are almost aligned, thus imitating the secondary Manebach twins of a (010)-fourling, where they are aligned. The difference lies in the apex structure.

**(001)-(010)-Manebach-Bavento combination twins.** The existence of double fourlings where one side is composed of a (001)-fourling and the other of a (010)-fourling confirms that two inversions of secondary Manebach twins took place. It has been pointed out that two neighbouring secondary Manebach twins on a (001)-fourling form a secondary (010)-fourling. If it is assumed that the lowermost secondary (010)-fourling can be translated in the opposite direction, as mentioned in the case of a (010)-(010)-fourling, the inversion of secondary Manebach twins occurs. The result is a (010)-fourling translated in the opposite direction. The double fourling thus formed has a primary side of a (001)-fourling type with non-aligned secondary Manebach twins and a secondary side of a (010)-fourling type with aligned secondary Manebach twins in the opposite direction (Fig. 7). Both semi-fourlings are connected via secondary Manebach twins that are inverted in the common (001) plane of both fourlings. This is neither the symmetry nor the pseudosymmetry plane, but only the plane where the inversion of secondary Manebach twins occurs. The full nomenclature of such a fourling is a (001)-(010)-Manebach-Bavento combination twin.

If the (001)-fourling were translated and secondary Manebach twinning did not take place, a double conical structure would be formed, but this would be a (001)-fourling again. No such crystals have been found at this site. It can be concluded that the formation of a (001)-(001)-Manebach-Bavento combination twin is not possible.

As has been mentioned, about 7% of all fourling structures are of this type. They can reach up to 15 cm in size. This is probably the most complex twinning the crystal world has ever observed.



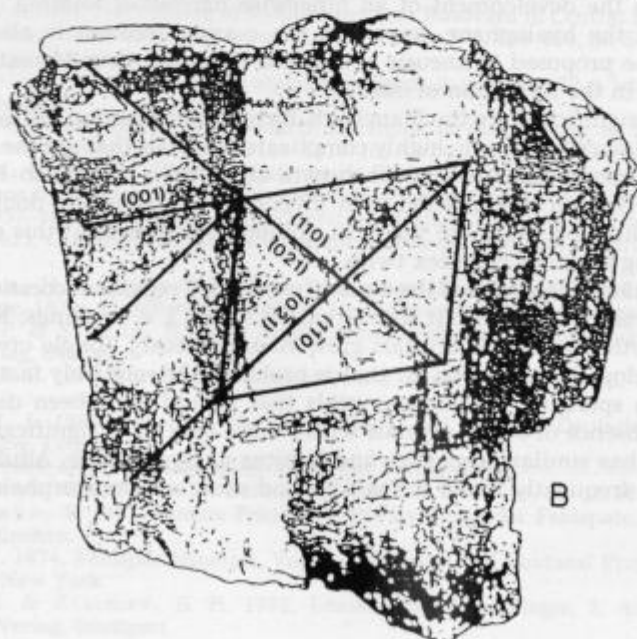
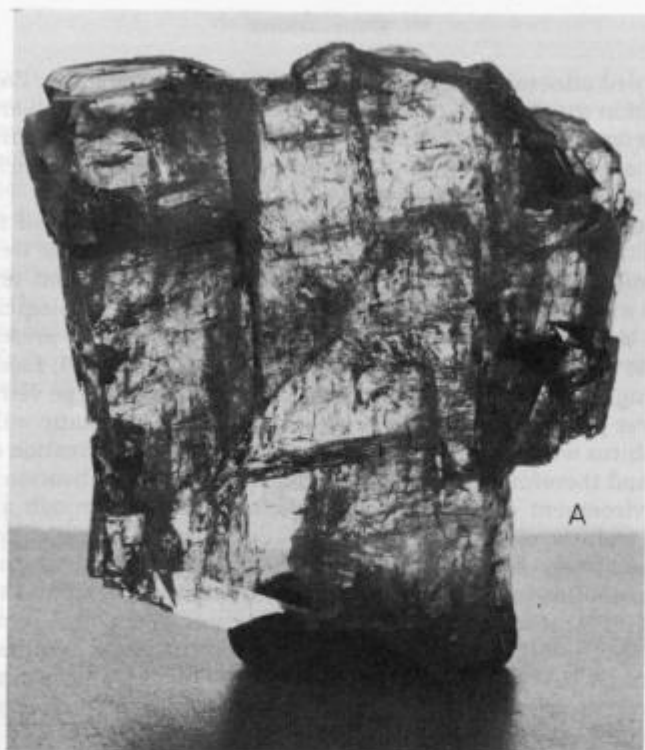


Fig. 14. Photograph (A) and its drawing (B) of the (001)-cross-section of a (001)-Manebach-Baveno combination twin. Section dimensions: 37 × 37 mm

## Conclusions

The variety of minerals with elongated habitus appearing at the Zagradski potok site confirms that the described veins, in the paleozoic schists which are perpendicular to their strike, are not the remnant of a sulphide ore body as mentioned by Ilić (1954). They are alpine-type veins with mineral paragenesis which is normally associated with such veins, as asserted by Barić (1972).

The numerous parallel and relatively long veins are the result of tectonic forces which caused them to open. Different minerals present at that time were broken and rehealed, forming elongated faden crystals. The most significant are hyalophane crystal forms with their primary, secondary and tertiary morphological structures.

A typical adularia habitus of the hyalophane crystals is present. It can be concluded that the adularia habitus, with narrow or missing (010) faces, is the result of relatively high pressure and low temperature in the alpine-type vein, compared to relatively lower pressure and higher temperature in the magmatic milieu, where an orthoclase habitus with wide (010) faces is formed. The crystallization causes a lower energy state and therefore the heat released during the crystallization process in the magmatic environment can be more effectively dissipated through a wider crystal habitus with well-developed (010) faces. Adularia habitus, on the contrary, is the outcome of relatively high pressure and its slow decrease. For that reason the crystallization equilibrium is achieved with contraction of the crystal volume, resulting in missing (010) faces. Crystals from the pegmatites have a more pronounced (010) form but are not as wide as those from magma, which is also in accordance with their growth conditions that are more moderate than the two aforementioned ones.

Stretching of the crystal with adularia habitus is thus exactly the opposite process to crystal volume contraction. The crystal is continuously broken and rehealed, which causes the development of an otherwise narrow or missing (010) face. The stretching of the hyalophane crystal in the c-axis direction is also the opposite process of the proposed Synneusis orthoclase Karlsbad twin formation and sometimes results in the formation of one.

The most significant are the Manebach-Baveno combination twins. Their elongation yields to morphologically highly complicated crystals that are the outcome of the two possible inversions, i. e. Manebach twin and (001) – Manebach-Baveno to (010) – Manebach-Baveno combination twin inversion. The resulting double Manebach-Baveno combination twins are the most unique appearances at this site and can be ranked among the most complex twins.

Zebec (1987/88) proposed the already mentioned regular succession of growth of particular hyalophane forms. It seems that all forms, i. e. fourlings, Karlsbad twins, parallel growths and single crystals grew simultaneously. Single crystals are small and less developed. The reason for that is probably the relatively fast growth rate of the fourlings sponging on single crystals that should have been dissolved in this phase. The absence of single crystals with Fibbia habitus is significant.

Adularia has similar properties and habitus as hyalophane. Adularia twins and fourlings are frequently found in the Alps and show similar morphological features.

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