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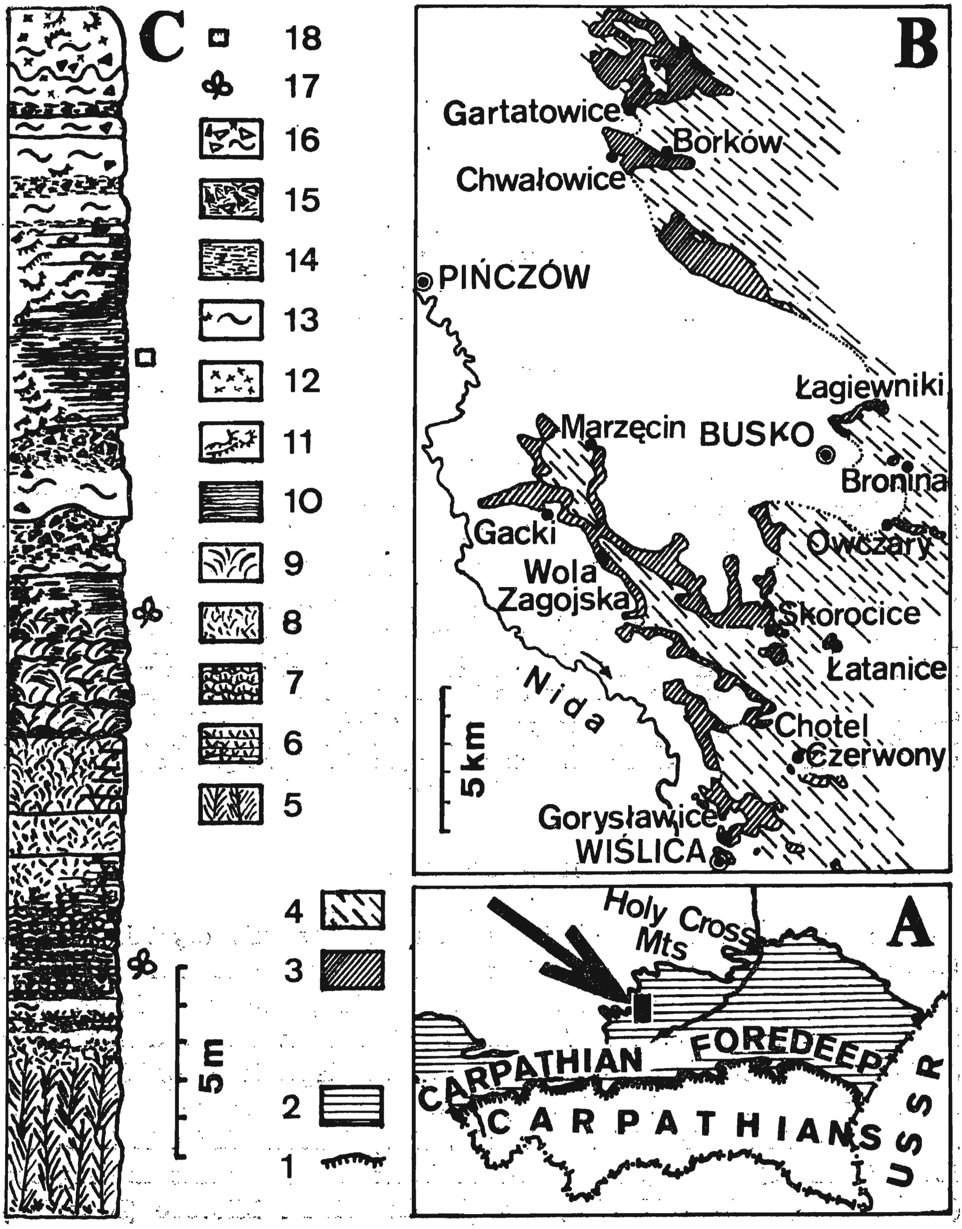
Giant gypsum intergrowths from the Middle Miocene evaporites of southern Poland

ABSTRACT: Sediments called the *glassy gypsum*, built of giant, up to 3.5 m high, juxtaposed skeletal crystals occur in the Middle Miocene (Badenian) evaporites of southern Poland, the best exposed along the southern slopes of the Holy Cross Mts. The gypsum crystals form giant intergrowths similar to the contact $\bar{1}01$ twins. These are not the true twins because any crystallographic symmetry between the crystals does not exist. The intergrowths grew upward on the bottom of the evaporitic basin in competition for free space, and revealing unusual skeletal structures. The upper surface of the giant crystals is built of many parallel lens-shaped subcrystals having their sharp edges pointed obliquely upward. The clay impurities, gathered in concavites of the crystals surface, were incorporated into the crystal bodies preferently along the boundaries between the lens-shaped subcrystals. The sedimentary structures in the glassy-gypsum layer, especially abraded and corroded gypsum crystals, load structures of the crystals growing on the muddy bottom, indicate all the synsedimentary growth of the giant crystals in the glassy gypsum.

INTRODUCTION

The growth of large, vertically arranged gypsum crystals on the bottom of the evaporitic basin is one of the most spectacular ways of gypsum precipitation in nature. Such crystals, usually twinned, can reach the great sizes up to 7 m in height as it is observed in Cyprus (SCHREIBER 1978). This variety of gypsum deposits is widely spread in the Late Miocene (Messinian) gypsum of the Mediterranean (SCHREIBER 1978, ORTI CABO & SHEARMAN 1977, SHEARMAN & ORTI CABO 1978), in the Quaternary sediments of Australian salt lakes and lagoons (GOTO 1968, WARREN 1982), and in the Middle Miocene (Badenian) gypsum deposits of southern Poland as well (KREUTZ 1925; RADWAŃSKI 1969, 1985; BĄBEL 1984). The large Mediterranean and Australian gypsum crystals commonly form twins having the 100 face as a twin plane. However, both crystallography, morphology of crystals, and textures of many of those fascinating deposits have not yet been described and understood (except of some occurrences in Alicante, south-



eastern Spain; *see* ORTI CABO & SHEARMAN 1977, SHEARMAN & ORTI CABO 1978).

This paper presents a consideration upon the coarse-crystalline gypsum deposits from southern Poland called the *glassy gypsum* (in Polish literature *szklica*; *see* KWIATKOWSKI 1972), in which the crystals have a unique skeletal appearance (SCHREIBER 1978) and, contrary to the Mediterranean ones, form not the twins but peculiar intergrowths (*see* WALA 1973; BĄBEL 1984, 1985).

GEOLOGIC SETTING

The glassy gypsum in the Middle Miocene (Badenian) evaporites of southern Poland have formed at finishing stages of development of the marine sedimentary basin which existed in the Middle Miocene as a part of the Paratethys northwards from the Carpathians (*see* Text-fig. 1). The sedimentary basin then occupied mainly the Carpathian Foredeep, *i.e.* the Fore-Carpathian Depression, and evolved together with tectonic movements of the Carpathians (*see* NOWAK 1938; RADWAŃSKI 1969, 1973, 1985). The evaporites mostly consist of gypsum and anhydrite, and they rarely exceed more than 60 m in thickness (*see* PAWŁOWSKI, PAWŁOWSKA & KUBICA 1985). The best outcrops are situated along the southern slopes of the Holy Cross Mts, just along the Nida river in the vicinity of towns Pińczów, Busko and Wiślica (Text-fig. 1). The evaporites of this region are known as the *Nida Gypsum* (*see* FLIS 1954). The paleogeography and stratigraphic setting of the associated Miocene

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Fig. 1. Location of the Nida Gypsum deposits (Middle Miocene, Badenian) in southern Poland

A — Extent of the Middle Miocene (Badenian) deposits in the Fore-Carpathian Depression

1 — Carpathian overthrust, 2 — Middle Miocene deposits

B — Extent of the Nida Gypsum deposits, southern slopes of the Holy Cross Mts (*after* FLIS 1954; simplified)

3 — gypsum on the surface, 4 — gypsum under the surface

C — Profile of the gypsum deposits exposed at the Gacki quarry

5 — large crystal intergrowths in the glassy gypsum, 6 — rows of gypsum crystals having a grass-like appearance, 7 — gypsum stromatolite domes, 8 — rod-like gypsum crystals (less than 15 cm long), 9 — sabre-like gypsum crystals (over 15 cm long), 10 — laminated gypsum, 11 — arcuate and elliptical recrystallizational forms, 12 — translucent and honey gypsum crystals (below 3 cm in size), 13 — alabaster-like gypsum, 14 — clay, 15 — breccias with clay cement, 16 — breccias with "alabaster" cement, 17 — plant remains, 18 — gypsum pseudomorphoses after halite

deposits were precisely recognized by RADWAŃSKI (1969). The best profile of the Nida Gypsum, cropping out at the Gacki quarry, is about 32 m thick (BĄBEL 1984). It begins from the extremely coarse-crystalline layer of the glassy gypsum. It is overlain by layers with the smaller gypsum crystals of the grass-like appearance (*cf.* RICHTER-BERNBURG 1973) and containing stromatolite gypsum domes (KWIATKOWSKI 1970, 1972; SCHREIBER, ROTH & HELMAN 1982). Higher in the profile, a variety composed of long, curved gypsum crystals of the sabre-like shapes occurs (*see* PAWŁOWSKI, PAWŁOWSKA & KUBICA 1985; BĄBEL 1986), and it gradually passes upwardly into thin-grained laminated gypsum with numerous intraformational breccias and layers of "alabasters" (KWIATKOWSKI 1970, 1972; *see also* OSMÓLSKI 1972).

The giant crystals of the glassy gypsum form the layer which usually attains about 4 m in thickness. This layer, never exceeding 10 m in thickness, is recognizable in many boreholes situated in the wide area along the northern extent of the Badenian gypsum deposits within the Fore-Carpathian Depression (*see* KUBICA 1984; PAWŁOWSKI, PAWŁOWSKA & KUBICA 1985).

CRYSTALLOGRAPHY

The glassy gypsum is built of vertical, juxtaposed giant crystals, up to 3.5 m in height, joined together in pairs along flat surfaces oriented perpendicularly to the depositional surface (Pl. 1). The surfaces closely resemble the twin junctions, because the crystals on both sides of these surfaces show palmate structures which at first sight are symmetrical. Since crystallographic axes *c* are placed (*see* Text-fig. 2) obliquely to this junction the crystal pair looks like the contact $\bar{1}01$ twin (Text-fig. 3a—b and Pl. 4, Fig. 2; *see also* KREUTZ 1925; BĄBEL 1984, 1985). However, the planes of the 010 perfect cleavage belonging to the both crystals are not strictly parallel (Text-fig. 3a—b and Pl. 1, Fig. 1) as it should be in true gypsum twins. Moreover, the situation of both the 010 planes and the axes *c* and *a* in one crystal pair is always less or more different than in the other. It seems that each crystal pair realizes its own crystallographic orientation and there is no simple low of orientation common for all crystal pairs. A more close examination shows that there is no crystallographic symmetry in particular pairs, and neither a twin plane nor a twin axis is recognizable (BĄBEL 1984). Since the most popular definitions of the twins require that between the twinned crystals some elements of symmetry must exist (*see* LÖFFLER 1934 for older definitions; *and* FRIEDEL 1926, BUERGER 1945, CAHN 1954, HARTMAN 1956, KERN 1961, MOKYEVSKY 1983), the investigated forms should not be called the twins. They are peculiarly oriented

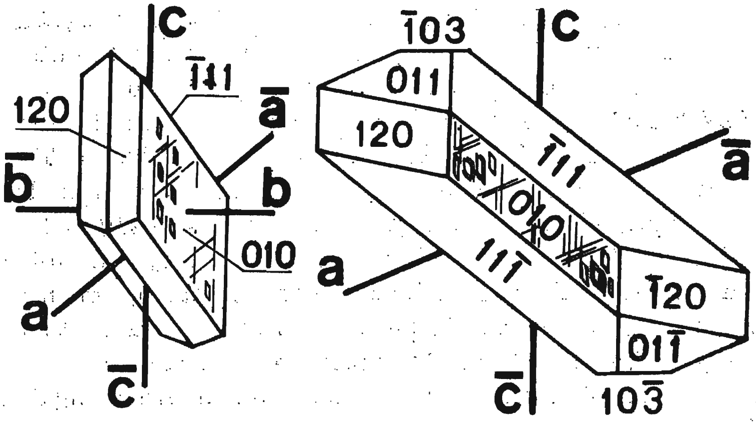

Fig. 2. Crystallographic orientation of two gypsum crystals, having a typical morphology, *according to* PALACHE, BERMAN & FRONDEL (1951); crystallographic axis *b* of the right crystal is oriented perpendicularly to the drawing

On 010 faces the traces of cleavage planes (100 parallel to the crystallographic axis c, and 011 parallel to the axis *a*) and etch pits (natural, or artificially produced in running water) are marked

intergrowths of gypsum crystals, only similar to the $1\bar{0}1$ twins. The vertical surface that joins the crystals is herein named the *composition surface* as it is an interface of the individuals of the oriented intergrowth of crystals (*see* BISHOP 1967, p. 270; CAHN 1954; CURIEN & KERN 1958).

The irrational crystal faces meeting on the composition surface always belong to the same restricted crystallographic area situated

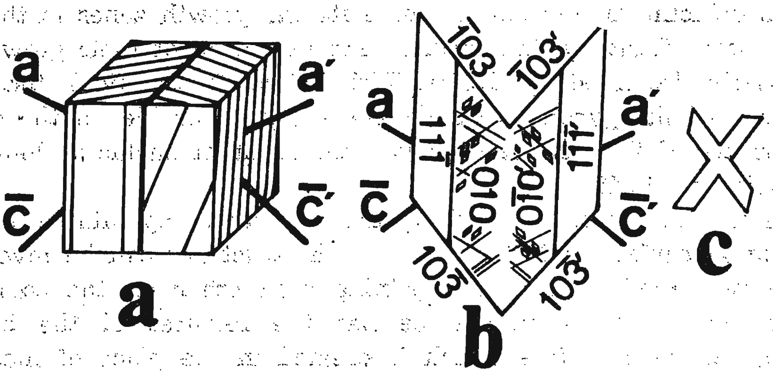

Fig. 3. Orientation of the gypsum crystals in the twins and in the intergrowths

a — The most frequent setting of the gypsum crystals in the intergrowths from the glassy gypsum; the hachure marks the situation of 010 perfect cleavage planes near the composition surface (the angles enlarged)

b — The $1\bar{0}1$ twin of gypsum; on 010 and $0\bar{1}0'$ faces the traces of cleavage planes (100 parallel to the crystallographic axis *c*, and 011 parallel to the axis *a*) and etch pits are marked (*compare* Pl. 4, Fig. 2)

c — An intergrowth of gypsum crystals with parallel 010 planes produced in laboratory by RUSSO & PETROV (1983) between $1^{-}01$, $1^{-}11$, $1^{-}1^{-}1$, $3^{-}02$ faces. The orientation of crystal axes, as traced along the composition surface, is constant but in the others, more external parts of the intergrowth, the axis *c* going out of the composition surface tends to be more and more vertical, up to the parallel position to this surface (Pl. 8, Fig. 2 and Pl. 10, Fig. 3). The crystal lattice is thus distinctly twisted. Macroscopically, the crystals display, noticeable *mosaic, block* or *lineage structure* (*see* ZWICKY 1929 *and* BUERGER 1932, 1934; *fide* CARSTENS 1986), *i.e.* they are built of many smaller and slightly misoriented blocks (= subcrystals), which are easily seen with a naked eye on the 010 perfect cleavage planes by their slightly different light reflection. The subcrystals are observable as a complicated network of rhomboidal fields of mm-sizes which are elongated nearly perpendicular to the axis *c* (Pl. 6, Fig. 2).

GROWTH STRUCTURES AND MORPHOLOGY OF CRYSTALS

The history of the crystal growth can be reconstructed from the analysis of the growth zones, marked by inclusions, which allow to recognize the habit changes of the developing crystal. The growth zones in the crystals of the glassy gypsum were noticed long ago by KREUTZ (1925) who first gave a sedimentological interpretation of such crystals as primarily growing on the see bottom. Unfortunately, KREUTZ did not illustrate these zones and did not describe them in full detail. Because of a rather composed internal structure of the crystals, it now appears difficult to find and to correlate the growth zones in the entire crystal body. Recently, the crystals and the mode of their growth were also briefly described by SCHREIBER (1978). In the field, the growth structures of the gypsum crystals are easily noticeable on the common 010 surfaces of the perfect cleavage and on other surfaces along which the crystals split off.

The crystals of the glassy gypsum are easily separatable along the composition surface and thus the growth structures can be investigated on the two crystal surfaces, adjoining each other on the composition surface. The composition surface has the features of the *induction surface*, *i.e.* the interface which is created in the place of meeting of the two simultaneously growing crystals* or subcrystals (*see* FERSMAN 1922, GRIGORYEV & ZHABIN 1975, PETROV & *al.* 1983, POPOV 1984). Many of such surfaces, visible as discontinuities or cracks of the crystal body, are developed in the external parts of the intergrowths (*e.g.* Pl. 5, Fig. 3; Pls 6—7; Pl. 8, Fig. 2; Pl. 10, Fig. 3). Likely the induction surfaces the composition surface, although generally flat, has a characteristic

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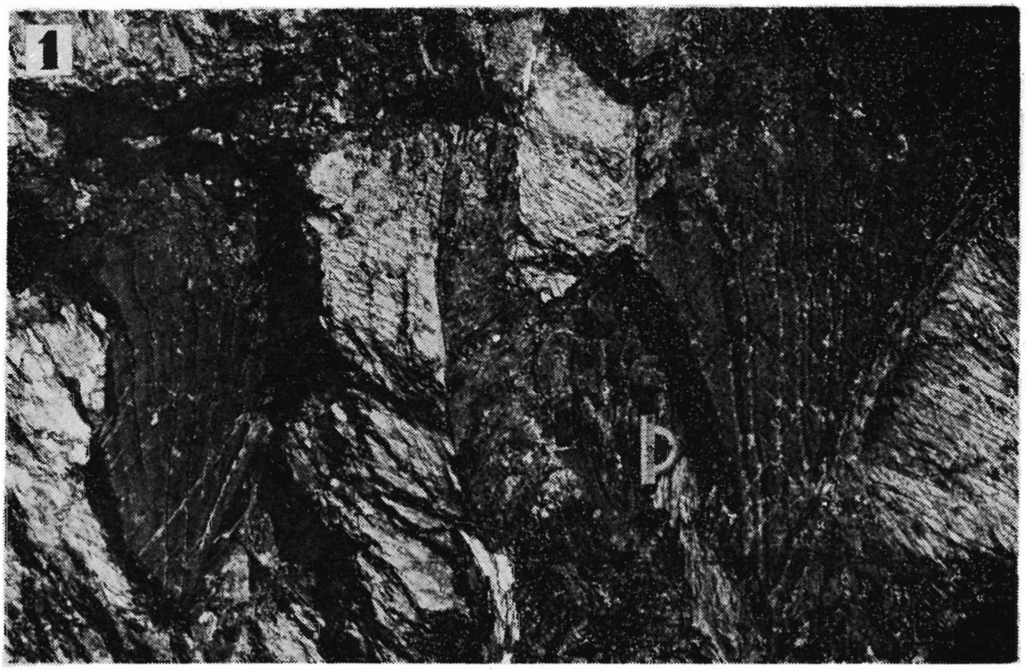
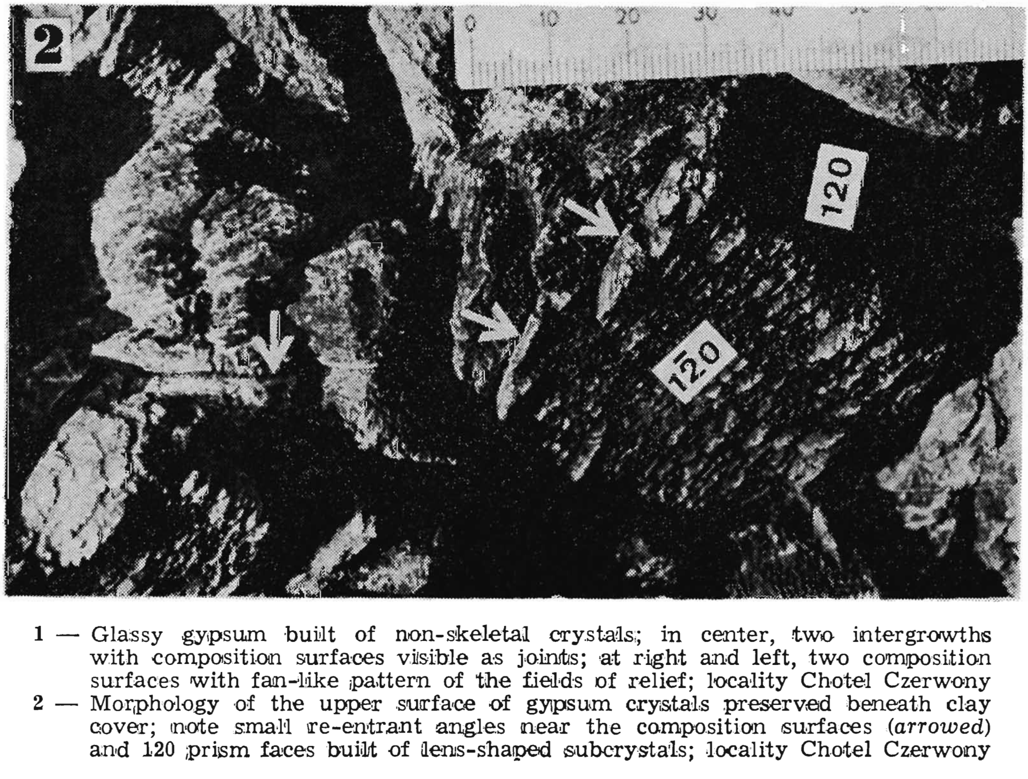
* Such surfaces are also called the *compromise boundaries*; see references in BUCKLEY (1951 p. 125—127) and BATHURST (1975 p. 421).

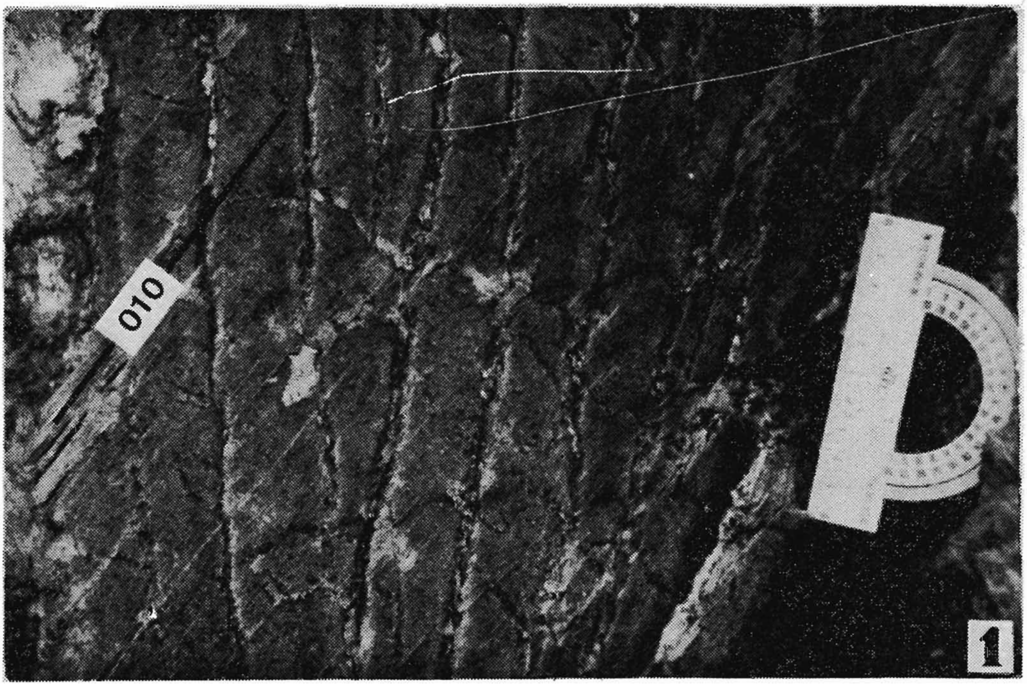
Gypsum intergrowths with composition surfaces visible as vertical joints; note difference in light reflection on 010 cleavage planes on both sides of composition surfaces indicating that 010 planes are not parallel (*see* Pl. 2, Fig. 1); locality Chotel Czerwony

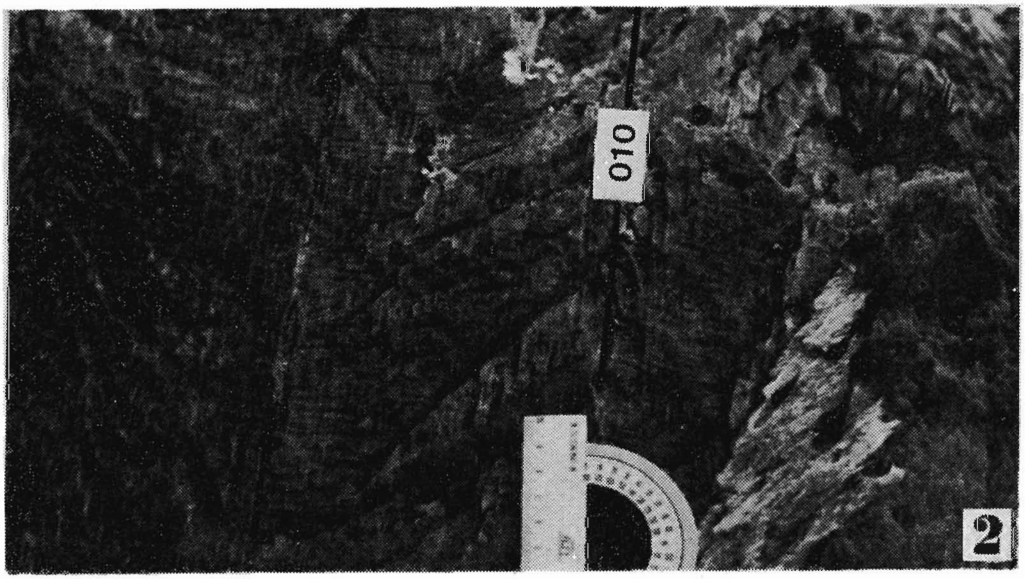




1 — Glassy gypsum built of non-skeletal crystals; in center, two intergrowths with composition surfaces visible as joints; at right and left, two composition surfaces with fan-like pattern of the fields of relief; locality Chotel Czerwony

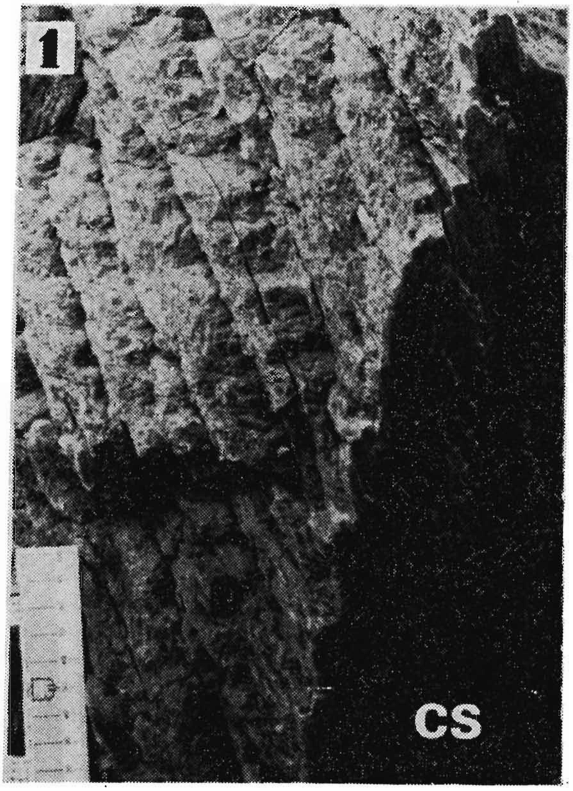
2 — Morphology of the upper surface of gypsum crystals preserved beneath clay cover; note small re-entrant angles near the composition surfaces (*arrowed*) and 120 prism faces built of lens-shaped subcrystals; locality Chotel Czerwony

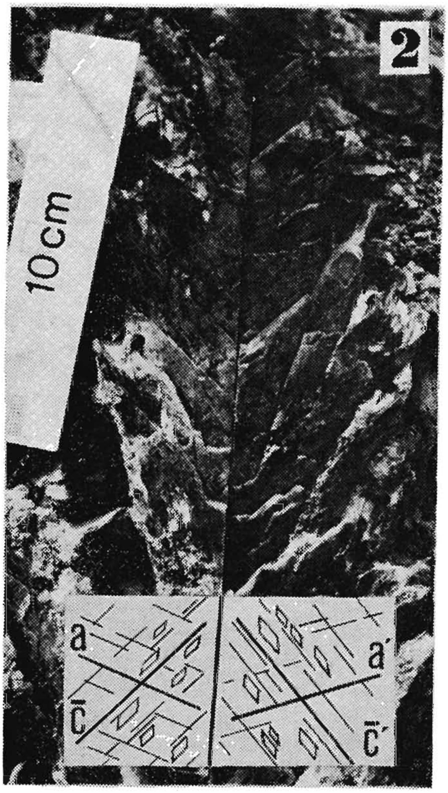




1 — Composition surface with fan-like pattern of the fields of relief (detail of Pl. 2, Fig. 1); horizontal dark streaks of clay inclusions indicate an arrangement of crystal (or subcrystal) apices (*see* Text-fig. 4b); traces of 010 cleavage planes are marked; locality Chotel Czerwony

2 — Composition surface of a gypsum intergrowth corroded by rainfall water; boundaries between slice-like subcrystals (*i.e.* $1\bar{0}3$ faces) are visible perpendicularly to 010 cleavage planes (*see* Pl. 6, Fig. 1; Pl. 7, Figs 1—3; Pl. 8, Fig. 2); locality Łagiewniki

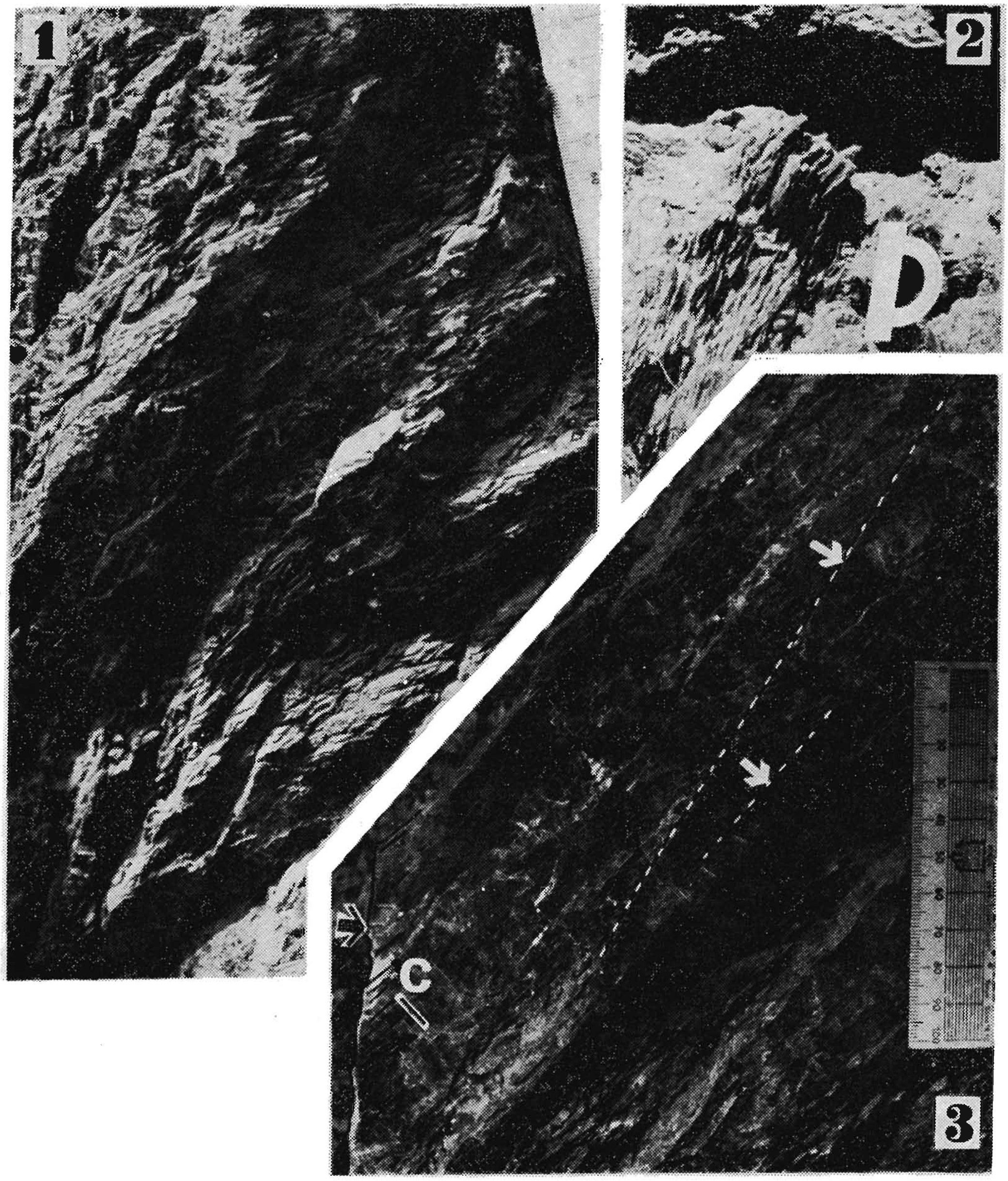




1 — Half on an intergrowth of skeletal gypsum with the fields of relief seen on the composition surface (*cs*), and arcuate aggregates of subcrystals arranged one over the other along these fields; locality Gacki

2 — Orientation of crystallographic axes *a* and *c*, cleavage planes (100 parallel to c, and 011 parallel *a*) and etch pits on 010 cleavage planes of gypsum intergrowth (*see* Text-figs 2 and 3); note the re-entrant angle near the composition surface in the upper part; the top of glassy gypsum at locality Gorysławice

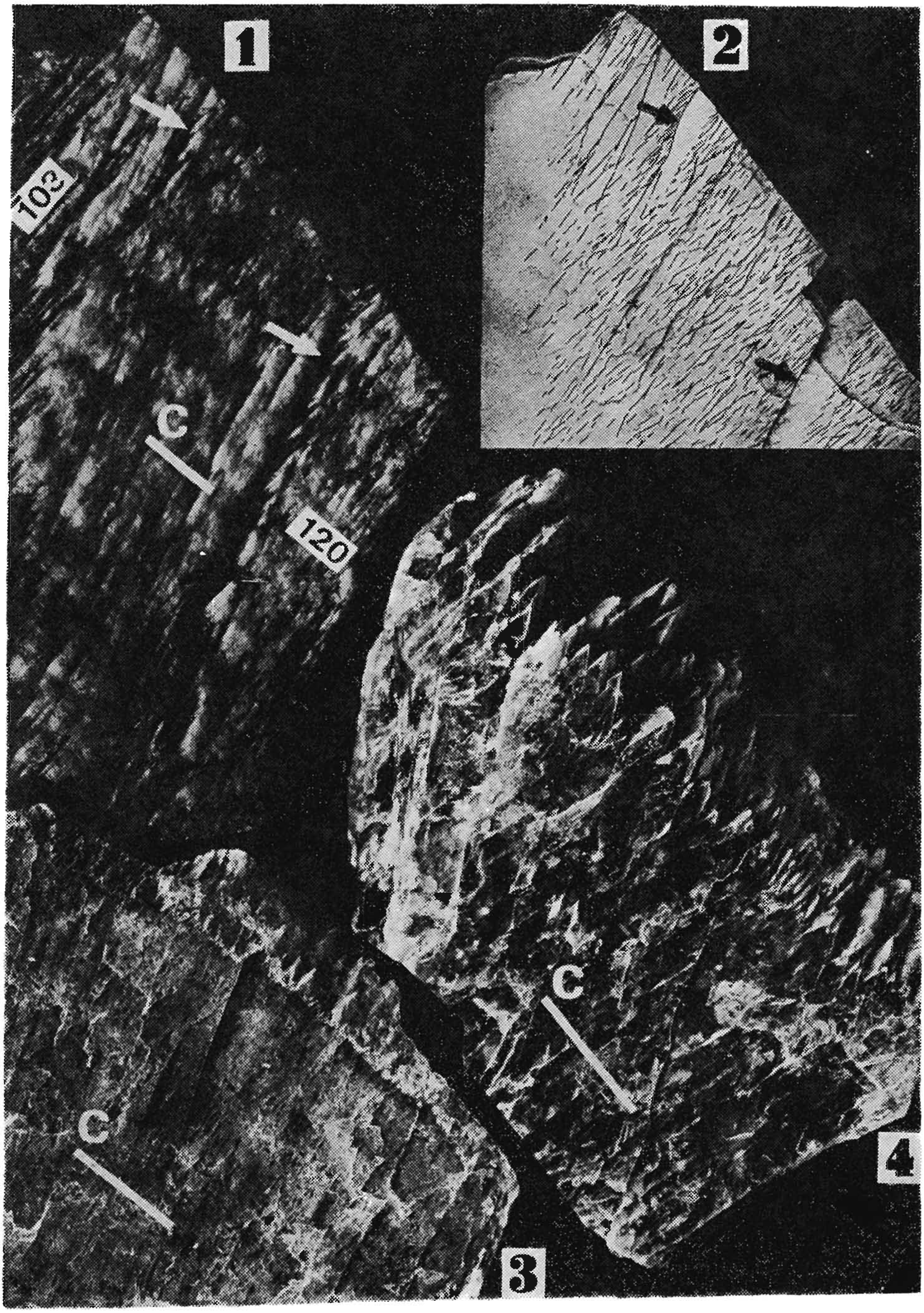
3 — Corrosion surface cross-cutting gypsum intergrowths; at left, a new generation of crystals grown on the corrosion surface; at right, crystals grown syntaxially; locality Chotel Czerwony



1 — External part of a gypsum intergrowth built of aggregates of lens-shaped subcrystals having a skeletal structure; locality Gacki

2 — Parallelly arranged lens-shaped apices of large subcrystals (or aggregates) visible on the top surface of glassy gypsum after removal of the clay cover; locality Sielec Rządowy

3 — View on 010 cleavage planes of a half of the gypsum intergrowth; black arrow indicates composition surface; white arrows indicate induction surfaces with traces of parallel slice-like subcrystals (*see* Text-fig. 4a—c; Pl. 6, Fig. 1; Pl. 7; Pl. 8, Fig. 2); orientation of crystallographic axis *c* is marked; locality Gacki



Growth structures and morphology of crystals from the glassy gypsum

All photos of natural size; taken by K. ZIELIŃSKA (Figs 2—4) and by B. DROZD (Fig. 1)

Explanation on the opposite page

relief and is divided into series of long fields forming a fan-like pattern (Pl. 2, Fig. 1 and Pl. 8, Fig. 1). Sediment impurities, mainly clay inclusions, were successively entrapped along the composition surface during the crystal growth. Hence, on the composition surface or, strictly speaking, on two crystal surfaces meeting on the composition surface, visible is a zonality of inclusions which reflects the growth stages of the adjacent crystals. The zones arrange into series of upwardly bent arcs, all of them being situated inside one of the fields of relief (Text-fig. 4b and Pl. 3, Fig. 1; Pl. 8, Fig. 1). Sometimes, the arcs are replaced by a sharper, saw-toothed pattern. From this it is evident that the fields of relief reflect an arrangement of crystals (subcrystals) apices near the composition surface (*see* Text-fig. 4b and Pl. 8, Fig. 1).

The zonation, seen on the composition surfaces, is invisible in long-existing outcrops because the atmospheric water easily dissolves and removes the thin surficial layer of the gypsum crystals. On such partly corroded surfaces, the parts of the intergrowths, a little more distant from the composition surface, display quite different growth structures noticeable as thin laminae perpendicular to the traces of the 010 cleavage planes (Pl. 3, Fig. 2). These laminae occupy narrow, maximum up several centimeters wide areas on both sides of the composition surfaces and they are very well seen on the 010 perfect cleavage planes (Pl. 5, Fig. 3; Pl. 6, Fig. 1; Pl. 8, Fig. 2). Each lamina belongs to a single slice-like subcrystal which is flattened in the direction perpendicular to the crystallographic axis *c*. Commonly, the subcrystals are about 1 mm thick. Clay impurities, as seen on the 010 cleavage planes, always lie on the upper side of the subcrystals boundary. These boundaries, sometimes slightly convex upwardly, seem to be the traces of the subcrystal upper faces situated nearly perpendicularly to the axis *c*. These faces relate to the irrational faces situated between $1^{-}03$ (and so designated in the following text and in Pl. 6, Fig. 1; Pl. 7; Pl. 8, Fig. 2), 011, 001 and $01^{-}1$ (*see* Text-fig. 2), many of which were recognizable in this area of the gypsum crystals, especially of those having lens-shaped habit. The upper faces of the slice-like subcrystals, *i.e.* the $1^{-}03$ faces, have appearently formed a very small re-entrant angle near the composition surface like in true swallow-tail twins of gypsum (Text-fig. 4a and Pl. 2, Fig. 2; Pl. 4, Fig. 2).

The parts of the intergrowths more distant from the composition surface are built of many irregular subcrystals of various sizes and, generally, of a lens-shaped habit. This area is usually 15—30 cm (sometimes up to 50 cm) wide. The sub-

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1 — View on 010 surface of a cleaved fragment of the crystal taken nearby the composition surface (*at left*). Note: 1 — clay inclusions (*dark*) forming stripes perpendicular to *c* and placed on $1^{-}03$ faces of slice-like subcrystals (*see* Pl. 7, Figs 1—3), along the upper sides of induction surfaces and along boundaries between smaller subcrystals; 2 — the same inclusions groupped into streaks, roughly parallel to *c*, and marking growth stages of the faces approximate to 120 prism; locality Gacki

2 — The same fragment, covered with ammonium chloride; lines marking boundaries between larger subcrystals (or induction surfaces, when arrowed) are visible because of slightly different light reflection on 010 cleavage planes

3-4 — View on 010 cleavage planes of gypsum crystals from external parts of the intergrowths; upper surfaces of crystals are built of lens-shaped subcrystals; induction surfaces visible as cracks on 010, crystallographic axes *c* are marked; locality Chotel Czerwony (Fig. 4 from Czernica, Upper Silesia) crystals in the external parts of an intergrowth produce the composed aggregates which have the shapes of arcs or curved rods forming palmate structures (*see* Pl. 1; Pl. 4, Fig. 1; Pl. 9; Pl. 10, Figs 1 and 3; Pl. 11, Fig. 1; Pl. 12, Figs. 1—2). The aggregates are separated by large and more distinct induction surfaces, curved or flat (Pl. 5, Fig. 3; Pls 6—7; Pl. 8, Fig. 2; Pl. 10, Fig. 3) or, in the case of the skeletal crystals, typical of the glassy gypsum (SCHREIBER 1978), by free spaces filled only by small amounts of clay or marly clay (Pl. 5, Fig. 1; Pl. 10, Fig. 1; Pl. 12, Figs 1—2). In the skeletal crystals it is visible that the arcuate aggregates are bound along the areas creating the fields of relief on the composition surface. In such situations the aggregates form separate groups in which they are arranged one over the other (Pl. 4, Fig. 1). In other intergrowths, the aggregates of subcrystals create more complicated spatial patterns difficult to a detailed recognition. It is very characteristic that beneath some large induction surfaces the series of the slice-like subcrystals are developed in the same manner as nearby the composition surfaces (Pl. 5, Fig. 3; Pl. 6, Fig. 1; Pl. 7 and Text-fig. 4a).

In many places the top surface of the glassy gypsum is covered with a thick layer of clay and thus the morphology of the crystal apices is well preserved (Pl. 5, Fig. 2). The pattern of this surface gives an imagination how the bottom of the evaporitic basin looked like at the time of the glassy gypsum growth (*see* Pl. 2, Fig. 2; Pl. 4, Fig. 2; Pl. 6, Figs 3—4; Pl. 7, Figs 1 and 3). It is appearent that the upper surface of the crystals is built of many parallel lens-shaped acute subcrystals. Sometimes, on the crystal surface the faces of the 120 prism appear; however, they also have a distinct relief and are composed of many tiny lens-shaped subcrystals (Text-fig. 4b and Pl. 2, Fig. 2). The 120 prism faces are characteristic of non-skeletal crystals, while the lens-shaped habit of the subcrystal apices is typical of skeletal crystals.

Sediment impurities, mainly clay inclusions but also aggregates of calcite crystals, diatoms, and seen with a naked eye ghosts of algal filaments (*see* SCHREIBER 1978, KASPRZYK & BĄBEL 1986), form two spatial systems recognizable on the 010 perfect cleavage surfaces (Pl. 6, Fig. 1; Pl. 7, Fig. 2; Pl. 8, Fig. 2). Firstly, they are distributed as patches and thin streaks lying concordantly with elongation of subcrystals, *i.e.* almost perpendicularly to the crystallographic axis *c*. The impurities lie along the upper sides of the boundaries between the slice-like subcrystals from the vicinity of the composition surface and along upper

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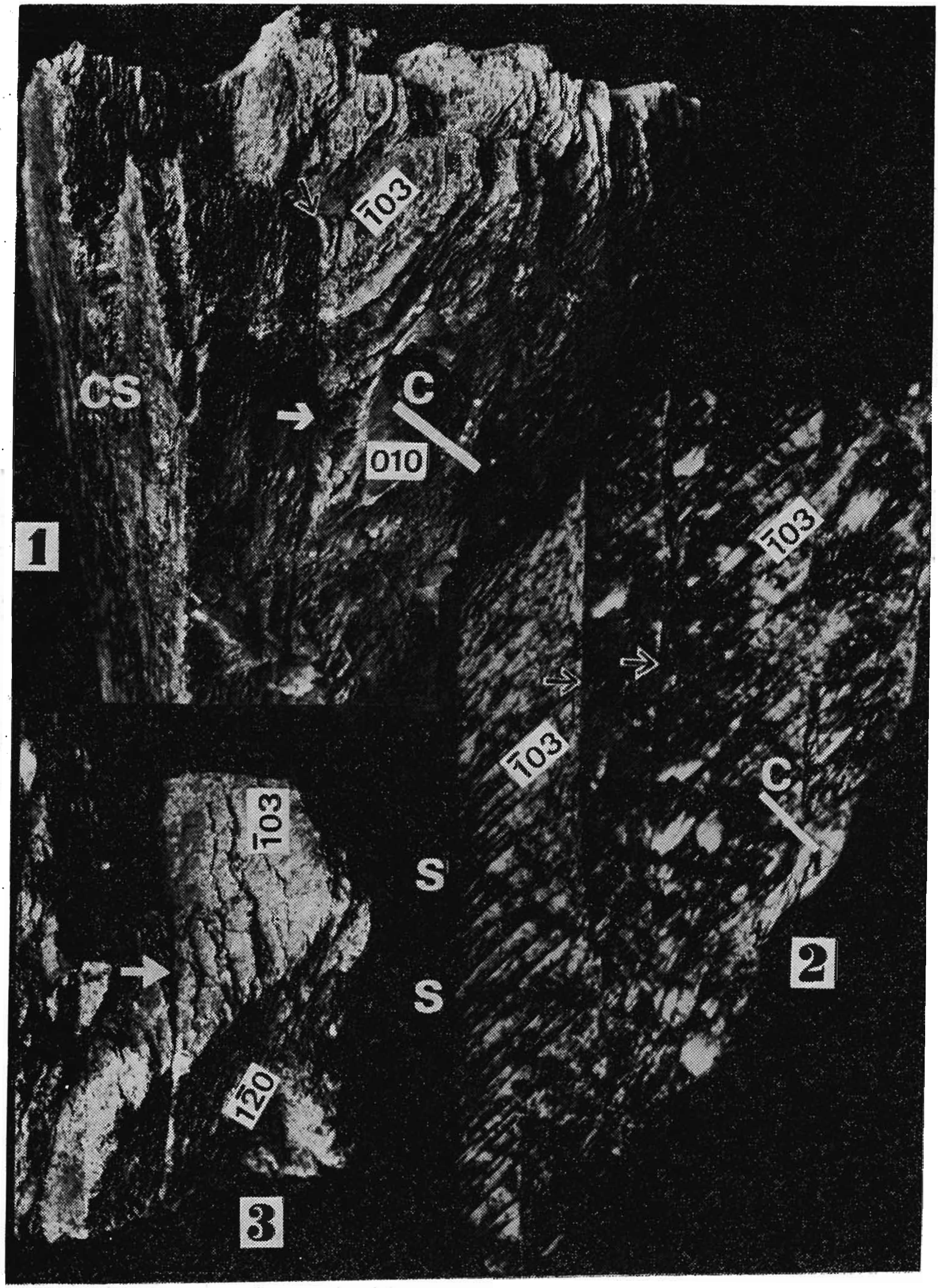
1 and 3 — Upper surfaces of crystals from external parts of the intergrowths; arrowed are traces of large induction surfaces near which parallel slice-like subcrystals (terminated by $1\bar{0}3$ faces) are developed; note the re-entrant angles, near the induction surfaces, in which subcrystals originated and grew perpendicularly to crystallographic axis *c* (marked on 010 cleavage plane), successively one over the other; in Fig. 3, the induction surface cross-cuts $12\bar{0}$ face built of tiny lens-shaped subcrystals; locality Chotel Czerwony

2 — View on 010 plane of a cleaved fragment taken nearby the composition surface (*at left*); arrowed are large induction surfaces near which parallel slice-like subcrystals (terminated by $1\bar{0}3$ faces) are developed; clay inclusions (*dark*) are placed on $1\bar{0}3$ faces, along other subcrystal boundaries and induction surfaces and, additionally, in horizontal streaks (*s*) cross-cutting the subcrystals (crystallographic axis *c* is marked); the growth structures are similar to those shown in Fig. 1; locality Małoszów, Miechów Upland



Morphology and growth structures of crystals from the glassy gypsum

All photos of natural size; taken by K. ZIELIŃSKA (Fig. 1 and 3) and by B. DROZD (Fig. 2)

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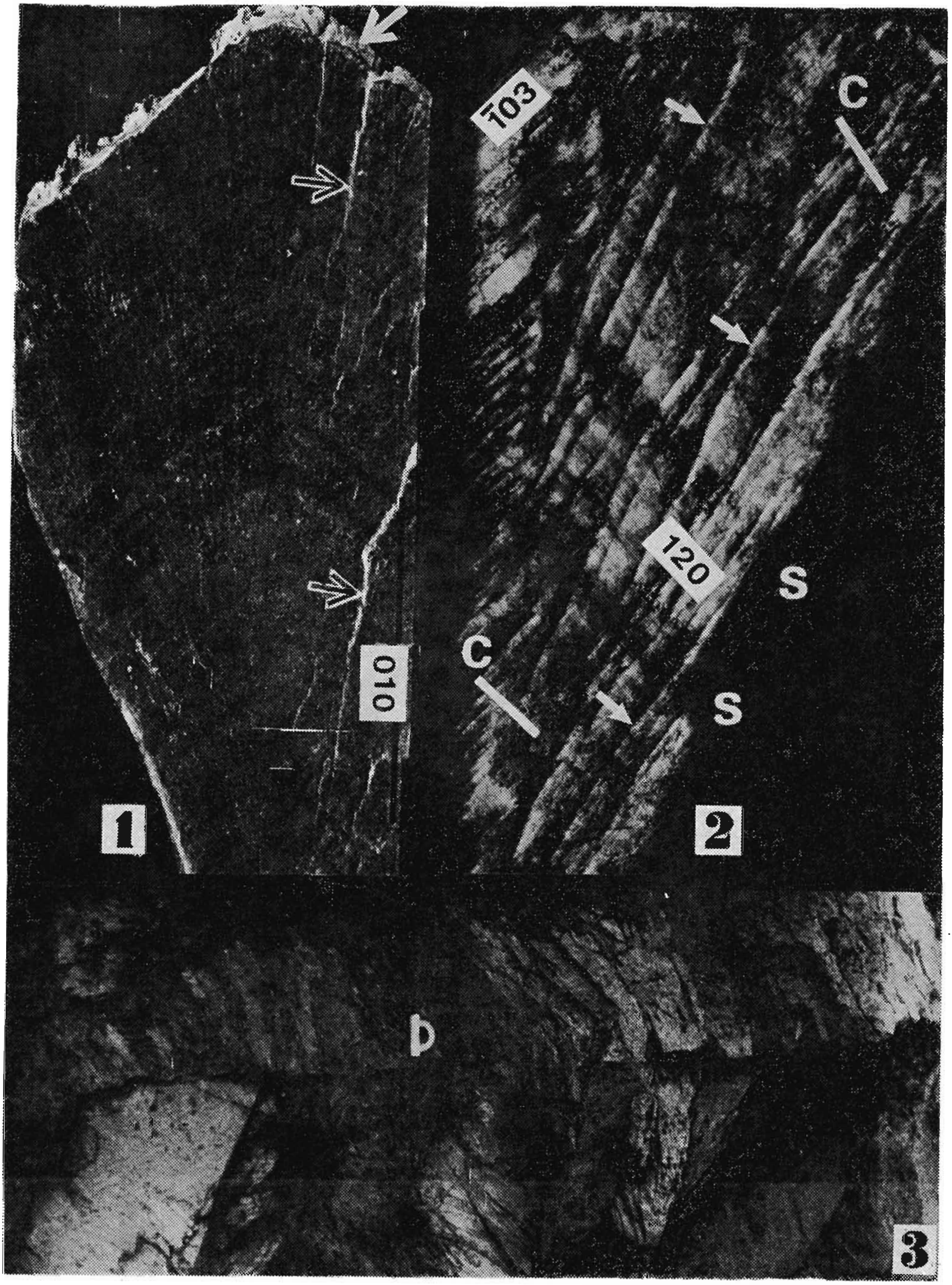

Growth structures of the glassy gypsum
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sides of the large induction surfaces. The large induction surfaces are curved and hence they strongly resemble the traces of the characteristic curved surfaces of gypsum crystals (*see* SHEARMAN & ORTI CABO 1978). However, contrary to the large Mediterranean twins of gypsum (*see* SHEARMAN & ORTI CABO 1978) the growth zones of the curved surfaces are not developed. It seems that the growth of the investigated crystals on these surfaces, in direction of their convexities, was drastically inhibited. The traces of the $\bar{1}03$ faces of the slice-like subcrystals near the composition surface, as it is evident from the crystals morphology (*see* Pl. 7), are not the growth zones of the $\bar{1}03$ faces. The traces of the $\bar{1}03$, although very similar to the growth zones of the curved surfaces (SHEARMAN & ORTI CABO 1978, ORTI CABO & SHEARMAN 1977; *see also* SCHREIBER 1978, who described in the glassy gypsum the aberrant splitting of the curved surfaces into lens-shaped subcrystals), have in fact a diachronic nature. The subcrystals originated nearby the composition surface or nearby some other induction surfaces and grew only in direction perpendicular to the axis *c*, while the growth on the upper $\bar{1}03$ faces was strongly inhibited (*see* Text-fig. 4a). The same growth structures occur in single larger crystals of gypsum from the layers overlying the glassy gypsum. The relations between morphology of such single crystals and their internal structure are well readable to reconstruct the growth mode of these crystals and of the glassy gypsum (*see* Text-fig. 4c). Since clay material in the glassy gypsum was deposited from suspension on the $\bar{1}03$ faces of the subcrystals, each of the subcrystals, when grew, enclosed poikilitically impurities gathered on the upper $\bar{1}03$ face of the underlying subcrystal. Thus, the clay inclusions are always found on the upper side of the boundary between the slice-like subcrystals and, because of this, on the upper sides of the large curved induction surfaces. Similar growth structures of parallel subcrystals in gypsum twins were reported from Australia by WARREN (1982) who, however, did not give their crystallographic description. When the subcrystal boundaries or induction surfaces in the glassy gypsum were oriented more vertically, as in the case of the composition surface, the impurities were placed on both sides of such boundaries or surfaces.

The second system of the clay-inclusion arrangement is much harder to be noticed. The impurities enclosed in the crystals are arranged into discontinuous and obscured wavy streaks cross-cutting the crystals nearly horizontally and being raised upwardly in the vicinity of the composition surface in the middle part of each intergrowth (Pl. 6, Fig. 1; Pl. 7, Fig. 2; Pl. 8, Fig. 2). This system is crosswise to the first one. The streaks pass into the zonation of clay inclusions on the splitted composition surfaces (*see* Text-fig. 4a—b and Pl. 3, Fig. 1) and also into a similar zonation visible on the splitted induction surfaces from the

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1 — Composition surface of the gypsum intergrowth (similar to that illustrated in Pl. 2, Fig. 2); note small steps forming the relief (*black arrows*), zonality of clay inclusions, similar to growth zones of 120 prism faces, and a small face (*white arrow*) producing the re-entrant angle near the composition surface (*cf.* Text-fig. 4b); traces of 010 cleavage planes are marked; locality Chotel Czerwony (natural size; photo by K. ZIELIŃSKA)

2 — View on 010 plane of a cleaved fragment, taken nearby the composition surface (*at left*); clay inclusions (*dark*) lay along the upper sides of large induction surfaces (*arrowed*), on the upper sides of boundaries between slice-like subcrystals (*i. e.* on their $\bar{1}03$ faces) and, additionally, they create streaks (s) marking the growth stages of faces approximate to 120 prism; note slightly different position of crystallographic axis *c*; locality Gacki (natural size; photo by B. DROZD)

3 — Horizontal corrosion surface which locally disappears (*see* middle part of the photo) because of the syntaxial upward growth of large crystals of the glassy gypsum; locality Chotel Czerwony

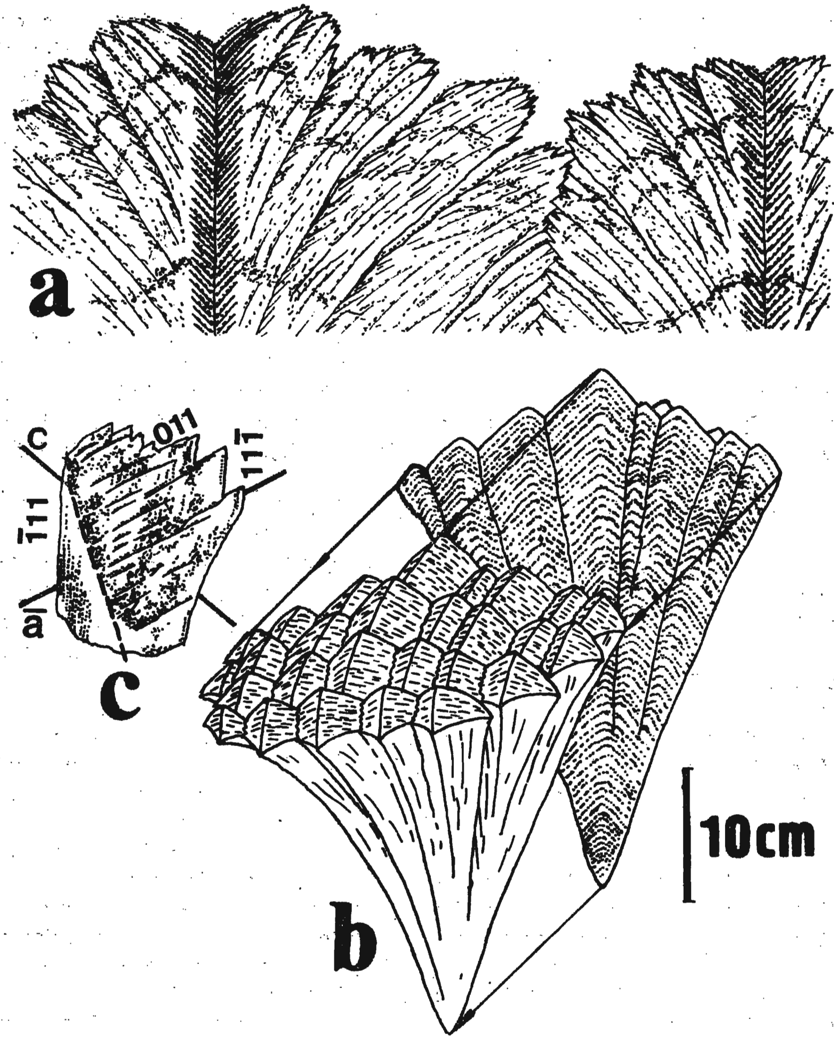


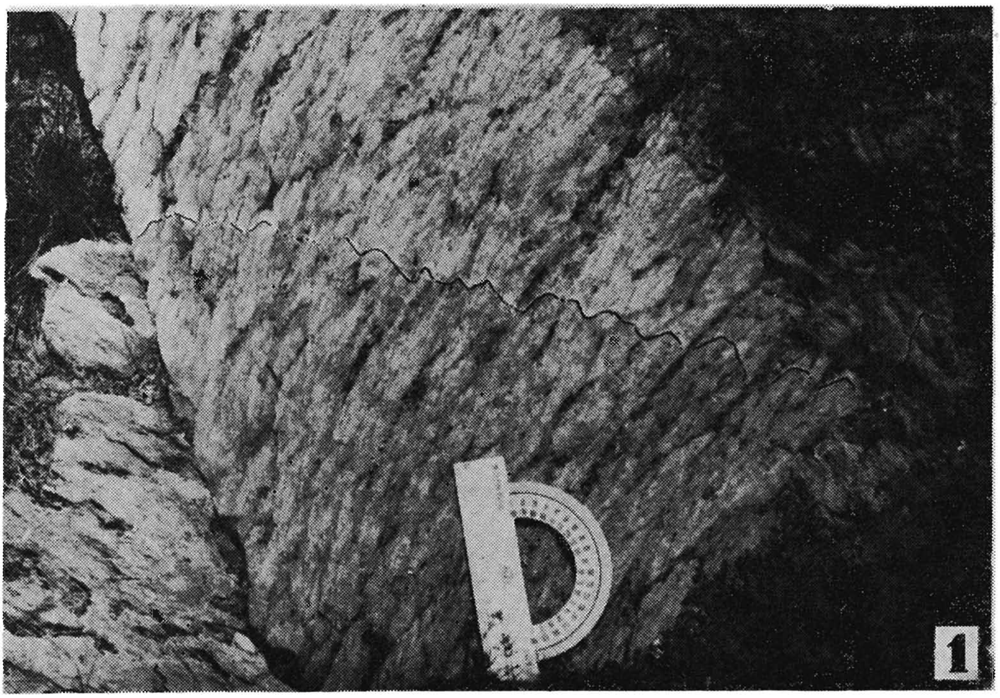
Fig. 4. Reconstruction of the morphology of crystals in the glassy gypsum

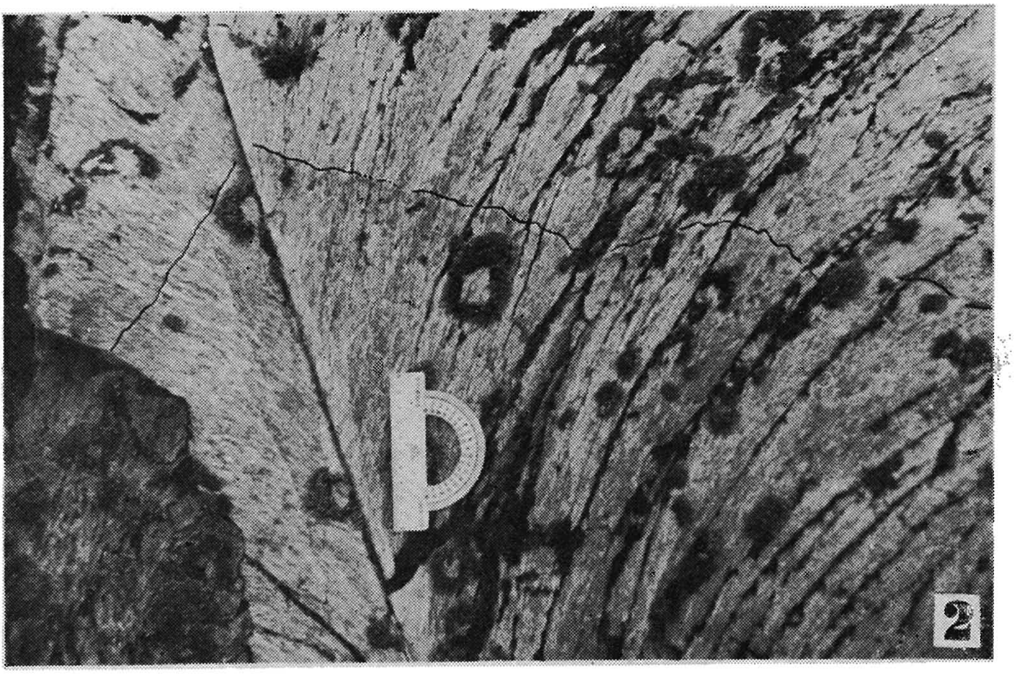
a — Scheme showing the development of the crystal intergrowths and the growth structures, as visible on the surfaces of 010 perfect cleavage in the glassy gypsum
b — An idealized free-growing intergrowth of gypsum crystals, splitted along the composition surface; note a fan-like pattern of the fields of relief and zonation of clay inclusions on the composition surface; upper surfaces of the crystals are built of 120 prism faces

c — An apex of the single gypsum crystal (given in natural size) from the layers overlying the glassy gypsum; view on 010 perfect cleavage plane

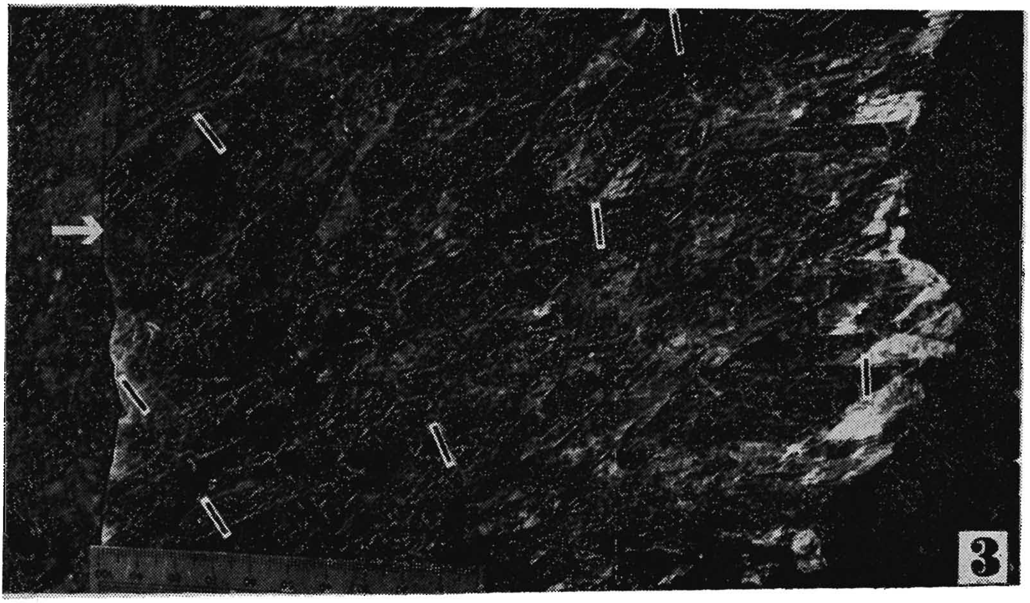
The dashed line separates the growth sector of 1-11 face and the sector of the blocky growth (blocks are terminated by 011 and 111- faces; *see* Text-fig. 2); the boundaries between the blocks are produced mainly by 011 faces, the growth of which was strongly restricted; the clay inclusions are placed along the upper sides of these boundaries

In the glassy gypsum there are similar growth structures, in which the growth sector related to 1-11 face is extremely narrow and the analogous blocks (slice-like subcrystals having 1-03 faces as their boundaries) are very regular (*see* Pl. 4, Fig. 2; Pl. 5, Fig. 3; Pl. 6, Fig. 1; Pl. 7; Pl. 8, Fig. 2)





1-2 — View on 010 cleavage planes of gypsum intergrowths; composition surface is visible as a vertical joint; black horizontal line marks laminae of white-colored inclusions entrapped along the former growth surfaces of crystals, *i. e.* along the crystals/water interface; locality Owczary (Fig. 1) and Łagiewniki (Fig. 2)



1 — Intergrowth of skeletal gypsum crystals; note primary free spaces between aggregates of the lens-shaped subcrystals elongated obliquely to the composition surface (*arrowed*), and area of the competitive growth of crystals (*at right*); locality Gacki

2 — A zig-zag boundary of gypsum crystals growing competitively; composition surface is arrowed; locality Owczary

3 — View on 010 cleavage plane of a half of the gypsum intergrowth (non-skeletal structure); induction surfaces are visible as cracks, composition surface is arrowed; bars mark orientation of crystallographic axis c; locality Gacki

external parts of the intergrowths. The most distinct streaks reach the thickness up to 0.5 cm, and they are correlatable in many adjacent intergrowths. This arrangement of impurities corresponds to the synchronous growth zones of the crystals, and hence to the sediment/brine interface. The obliterated and obscured character of these zones results from the morphology of the crystal which was built of the lens-shaped subcrystals (*see* Text-fig. 4a). The clay material was gathered in the concavities of the crystal surfaces and trapped favorably along the boundaries between the lens-shaped subcrystals. In such a way, the clay inclusions did not form continuous horizons in the glassy gypsum. However, there are several thick streaks of black clay which are precisely correlatable over a distance of 20 km (BĄBEL 1984). These probably mark episodes in which a greater amount of clay was supplied into evaporitic basin and/or the rate of the crystal growth, related to the salinity of brine, was relatively slower.

As seen on the 010 perfect cleavage planes the wavy streaks pass in places into delicate growth zones which are strictly parallel to the crystallographic axis *c* (Pl. 6, Fig. 1 and Pl. 8, Fig. 2). These zones originated from the growth of the 120 prism faces (*see* Text-fig. 4b and Pl. 2, Fig. 2); they are also obliterated and obscured because the 120 prism faces have not been precisely flat but composed of the tiny lens-shaped subcrystals.

Sometimes, colorful white or brown inclusions (the last ones being possibly the remains of the weathered tuffaceous material; *cf.* KUBICA 1984) create very distinct continuous laminae parallel to the clay streaks described above (Pl. 9). They are also correlatable in the whole area of the Nida Gypsum.

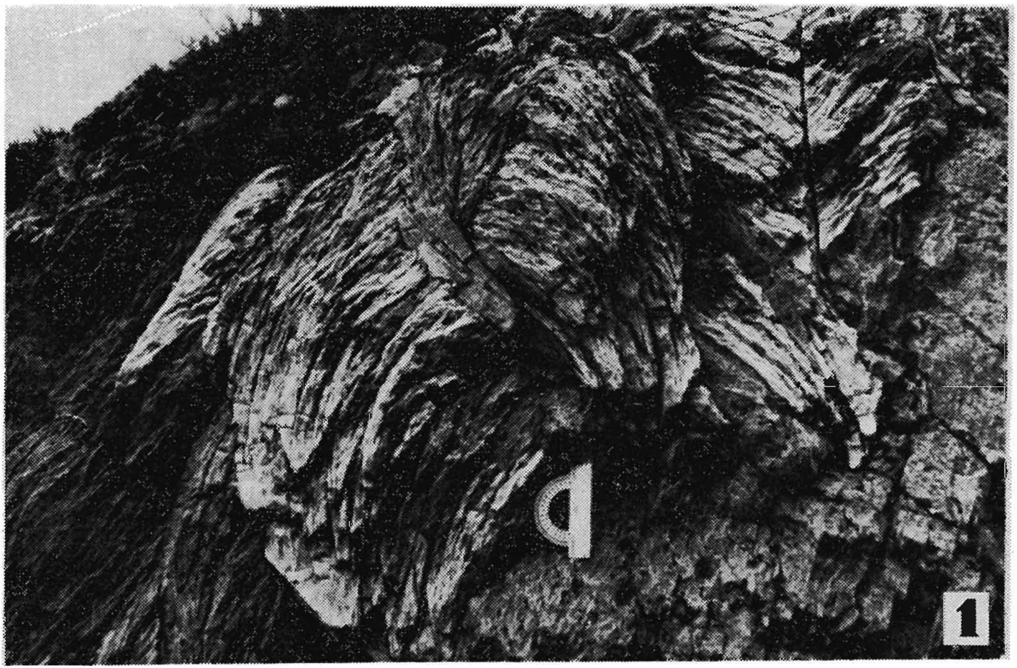
The crystals of the neighboring intergrowths evidently competed one with another for free space and formed characteristic zig-zag boundaries (Pl. 10, Fig. 2). The contact of the crystals along such a boundary, contrary to the contact along the composition surface, is not crystallographically oriented. In the area of the contact the crystals very often reveal the skeletal structure (Pl. 10, Fig. 1). In free spaces, small lens-shaped crystals have grown on the surfaces of the larger ones in a drusy manner.

The textures of the glassy gypsum vary in dependence on the morphology of crystals and on their spatial orientation. In a great number of outcrops the intergrowths are set up vertically with their composition surfaces perpendicular to the depositional surface (Pl. 1; Pl. 2, Fig. 1; Pl. 12, Fig. 1). Such oriented intergrowths attain the greatest height. In another variety of the glassy gypsum the composition surfaces are oriented obliquely to the depositional surface and the intergrowths are smaller, rarely attaining more than 1 m in height (Pl. 11). Some of the intergrowths, especially at the base and at the top of the glassy gypsum, have their upper parts developed to enormous sizes (*see* Pl. 11, Fig. 1). Similar textures occur within the Mediterranean twins in which the "twin plane" is placed horizontally (ORTI CABO & SHEARMAN 1977; SHEARMAN & ORTI CABO 1978; LO CICERO & CATALANO 1978; DRONKERT 1978, 1985).

REGULARITIES OF THE CRYSTAL GROWTH

Gypsum does often form very well known and popular 100, 1¯01 and rarely 2¯09 twins (PALACHE, BERMAN & FRONDEL 1951). Many other twins and regular intergrowths of gypsum have recently been produced in experiments by RUSSO & PETROV (1983). Some of the intergrowths exhibit neither a twin plane nor a two-fold twin axis (*see* Text-fig. 3c). However 010 planes of both individuals are parallel and it is possible to transform one crystal into another by one rotation according to the coinciding lattice row normal to the 010 plane about some non-rational angle. In contrary to the forms described by RUSSO & PETROV (1983), the intergrowths from the glassy gypsum present more curious features. Detailed crystallographic investigations show that in purpose to coincide one crystal with the other it is necessary to use, in general case, not one but two operations of symmetry according to some irrational lattice planes or rows strictly like as in the case of accidentally groupped crystals. However, some laws of the crystals orientation occur and perhaps they realize in a statistical way, since the crystals in the great number of the intergrowths achieve a similar mutual orientation (as given in Text-fig. 3a). This orientation exists only near the composition surface where the irrational faces lying in the area between 1¯01, 1¯11, 3¯02 and 1¯1¯1 are joined together. The other external parts of the intergrowth loose this orientation because of the blocky growth and the crystal lattice twisting (GRIGORYEV & ZHABIN 1975). The forms similar to the described intergrowths of gypsum, as far as the author knows, have not been noticed in the world of oriented intergrowths of the same substance (for example compare with regular intergrowths, which belonging to the twins is questionable, described by DRUGMAN 1928 *and* SHASKOLSKY & SHUBNIKOV 1933 *fide* FRIEDEL 1933, LEMMLEIN 1926, GLISZCZYNSKI 1948 *fide* CAHN 1954, KOBAYASHI & FURUKAWA 1978, RUSSO & PETROV 1983, KNIGHT & DEVRIES 1985). The crystallographic nature and laws of orientation of those peculiar intergrowths of gypsum require further detailed investigations.

The macroscopic observations testify that the composition surface has been created on the earliest stages of the crystal growth and it played a very important role in the further development of the entire intergrowth. Just from the vicinity of the newly created composition surface the subcrystals began to grow in a direction perpendicular to the crystallographic axes *c*, upwardly and obliquely to the composition surface. Firstly, a series of parallel thin slice-like subcrystals had formed and then the more composed aggregates of subcrystals developed on them producing the palmate structures of the external parts of the intergrowths (*see* Text-fig. 4a—b). The blocky growth of crystals was connected with the splitting of the crystal bodies. Such a splitting began from the origination of initial discontinuities, perhaps of the dislocation type, and then the more distinct induction surfaces developed which divided the slightly differently oriented parts of the gypsum crystals. The splitting and the blocky growth led to the anomalous twist-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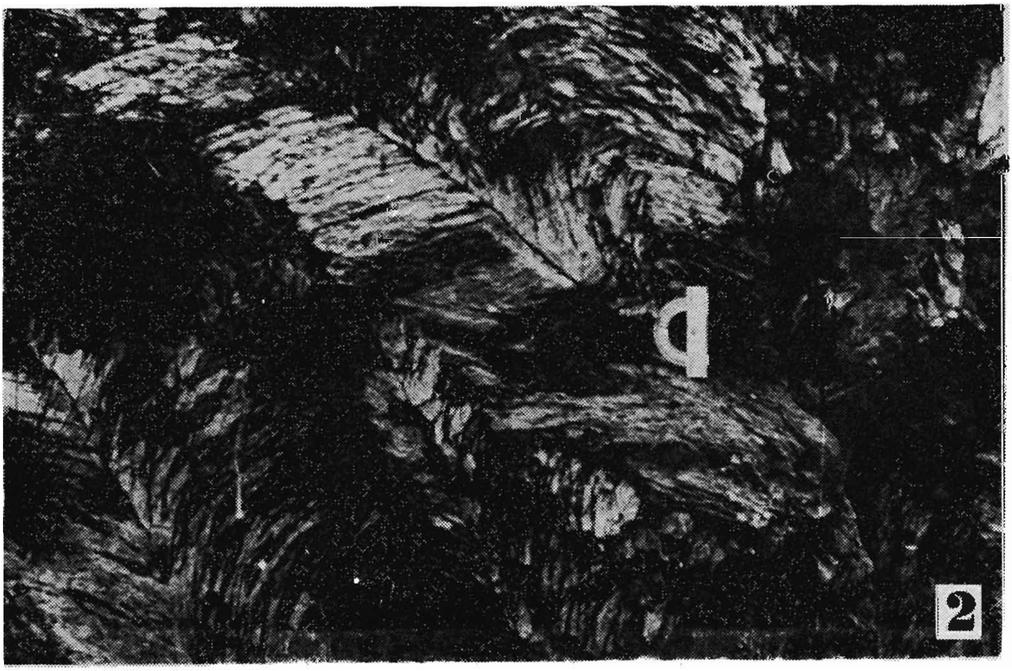
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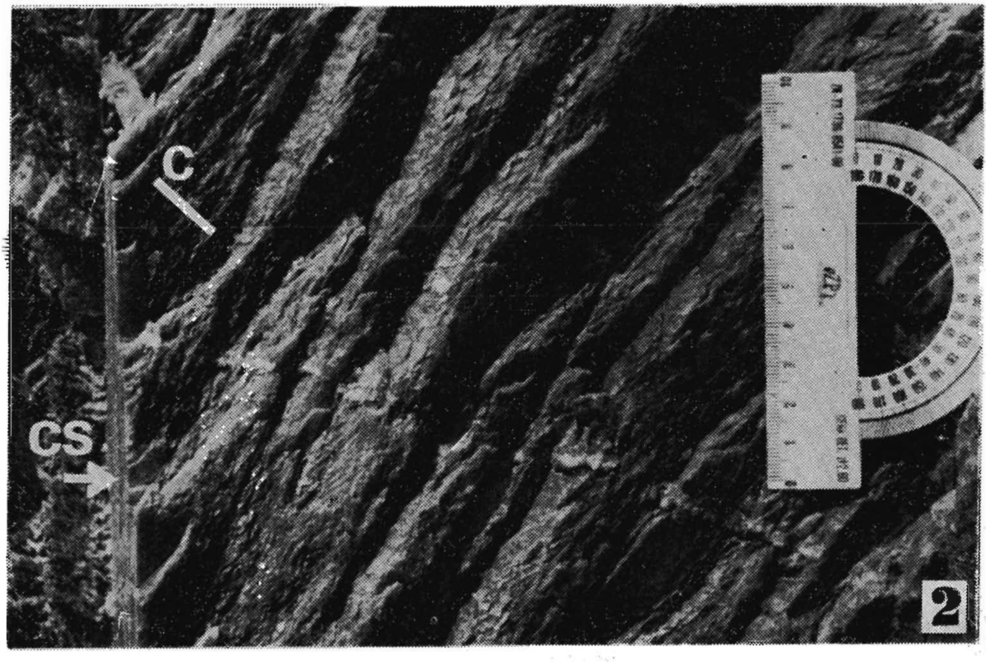
1-2 — Gypsum intergrowths with composition surfaces oriented obliquely to the depositional surface; locality Łagiewniki



1 — Glassy gypsum built of skeletal crystals; locality Gacki

2 — Laminae of thin-grained gypsum enclosed into skeletal crystal (detail of Fig. 1); the crystal was corroded prior to deposition of detrital gypsum grains; composition surface (*cs*) and crystallographic axis *c* are indicated ing of the crystal lattice in one direction. From the growth structures and from the lens-shaped habit of the subcrystals it is evident that the growth of crystals in direction of the axis *c* was extremely restricted. Since the subcrystals practically grew only in a direction perpendicular to the axis *c* it was mainly the composition surface which enabled the intergrowths to spread upwardly and to reach their height up to 3.5 m. The lens-shaped, flattened and perpendicular to the axis *c* habit of the gypsum crystals could result from the presence of organic compounds and the alkalinity of the environment (*see* CODY 1979; KIROV 1980, 1982).

The composition surface reveals peculiar features. The crystals grew on both sides of this surface in the spatial connection and having the constant crystallographically oriented contact along the whole composition surface. It suggests that between the crystals, similarly as between the twinned individuals, the structural connection must exist (*see* BUERGER 1945). On the other hand, the crystals are very easily split off along the composition surface which has a nature of the induction surface. It can lead to a quite opposite supposition that the structural connection of the crystals on the composition surface, as in the case of an ordinary induction surface, does not exist at all or it is very weak. However, it was observed in some twins that the composition surface ("twin plane") is developed as the induction surface (GRIGORYEV & ZHABIN 1975). This situation is especially common in the twins of gypsum (CAHN 1954), as for example in the large Mediterranean ones in which the composition surfaces ("twin junctions") are visible as the distinct joints (ORTI CABO & SHEARMAN 1977, SHEARMAN & ORTI CABO 1978).

The intergrowths grew and spread faster both upwardly and laterally along the composition surface reaching the habit appearently flattened parallelly to it. Such behavior is quite similar to that observed in many contact twins flattened parallelly to their twin planes, *i.e.* to their composition surfaces (BECKE 1911; *fide* HARTMAN 1956). These regularities can be explained by acting of the re-entrant angles which are placed near the composition surface of some contact twins, as for example in the classical swallow-tail twins of gypsum (*see* GRIGORYEV & ZHABIN 1975). Some of these angles are the sources of the growth layers on the crystals faces forming a re-entrant angle (*see e.g.* SEAGER 1953, p. 21). This is because at the edge of such an angle the molecules are bound into a crystal lattice easier than on the flat crystal face (HARTMAN 1956, GRIGORYEV & ZHABIN 1975; *see also* GOTO 1968). Thus, such twins and similarly the investigated intergrowths, which have the re-entrant angles near the composition surface, grew favorably faster in direction of this angle.

The re-entrant angles both of the swallow-tail twins of gypsum and of the investigated intergrowths are always opened upwardly from the depositional surface. This behavior of gypsum twins is known as the *rule of Mottura* (*see* SHEARMAN & ORTI CABO 1978; for exception of this rule, FLETCHER 1911). This rule can be explained similarly as the regularities noticed in druses in which particular crystals are usually set up nearly parallelly and with their longest dimension perpendicular to the surface of growth. Such an orientation of the crystals results from their competition for free space. The crystals growing faster in the direction perpendicular to the depositional surface forerun the by-chance oriented individuals and, at the end, attain mutually parallel orientation (*see* BUCKLEY 1951, GOTO 1968, GRIGORYEV & ZHABIN 1975, SHEARMAN & ORTI CABO 1978, POPOV 1984). It was testified above that the re-entrant angle of the gypsum intergrowths and swallow-tail twins is opened in the direction of their quickest growth.

TIME OF ORIGIN OF THE GLASSY GYPSUM

Rare occurrences of sedimentary structures in the glassy gypsum, some of which have already been reported (*see* GAWEŁ 1955, SCHREIBER 1978, BĄBEL 1984), allow to discuss the time of origin of those giant crystals. The most impressive of such structures are presented hereafter.

In the layer of the glassy gypsum, especially near its top, flat or slightly wavy horizontal fissures occur (Pl. 4, Fig. 3; Pl. 8, Fig. 3; Pl. 13, Fig. 1). Their wavy shape is in accordance with the surfaces of the simultaneous growth of the crystals. These fissures, filled with clay, are interpreted as the corrosion surfaces which mark the episodes of synsedimentary dissolution of the crystal apices (*see* SCHREIBER 1978; DRONKERT 1985, p. 202). Most frequently, the crystals grew up from the corrosion surfaces in a crystallographic continuity (syntaxially), but sporadically a new generation of the crystals developed. A syntaxial growth easily obliterated the corrosion surfaces, and thus these surfaces do not form continuous horizons. A synsedimentary dissolution of the glassy gypsum was postulated earlier by GAWEŁ (1955) who assumed

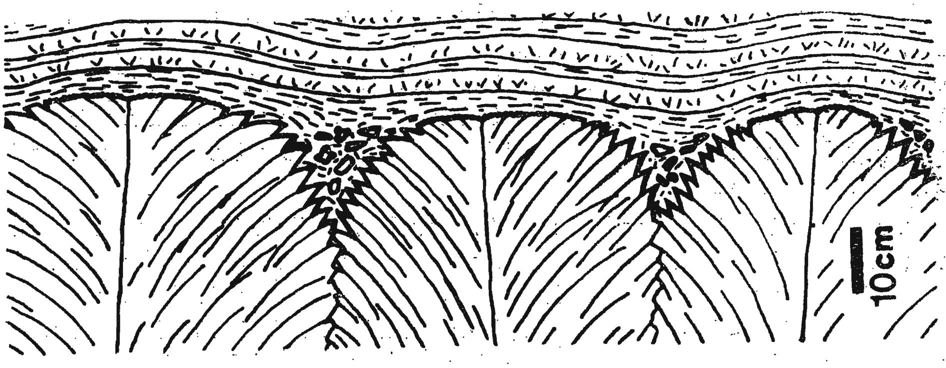
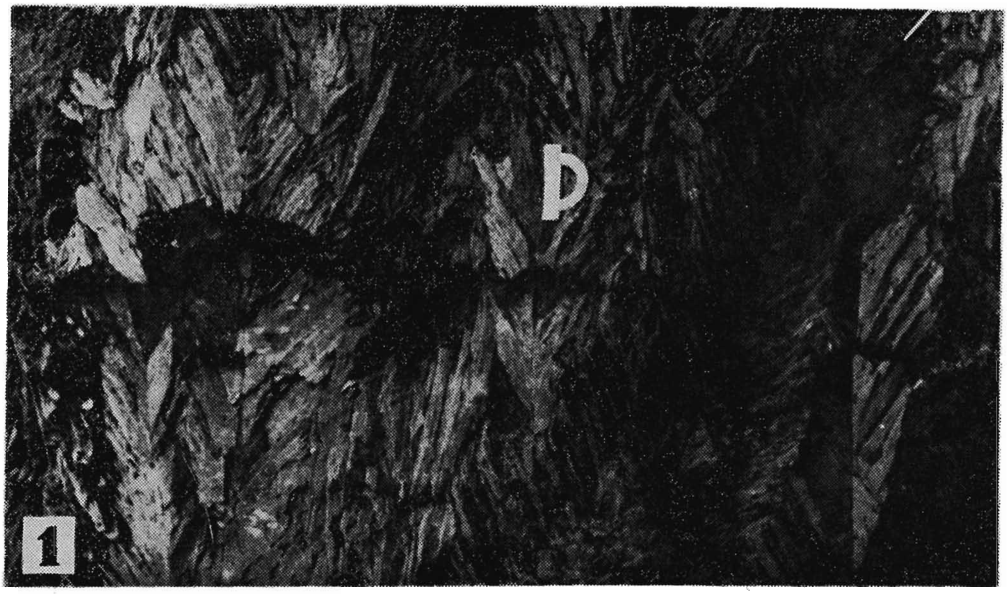
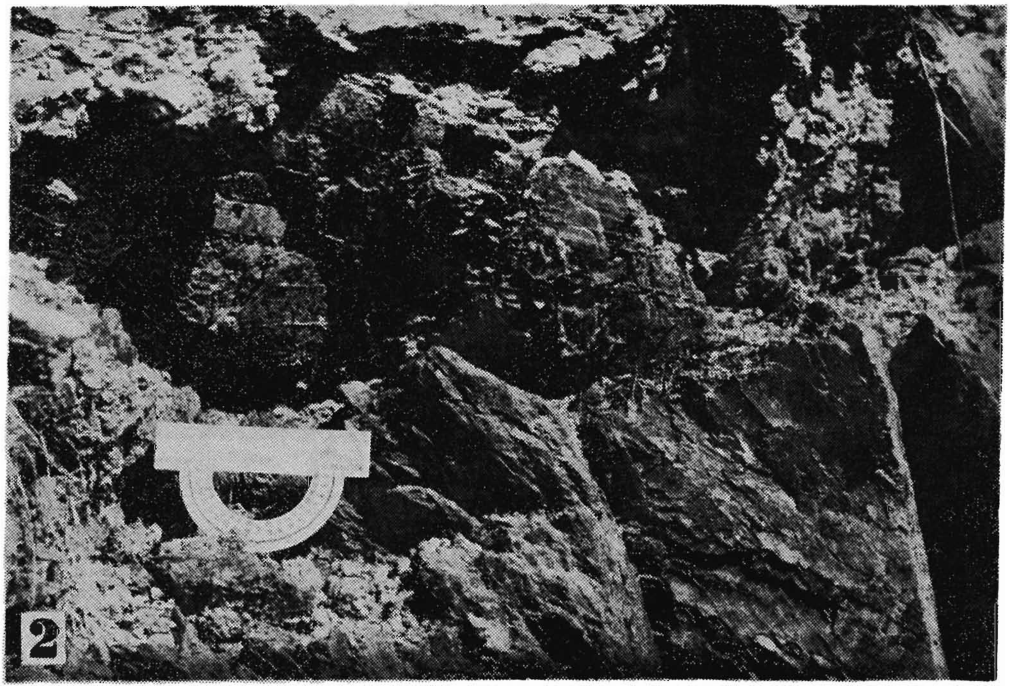


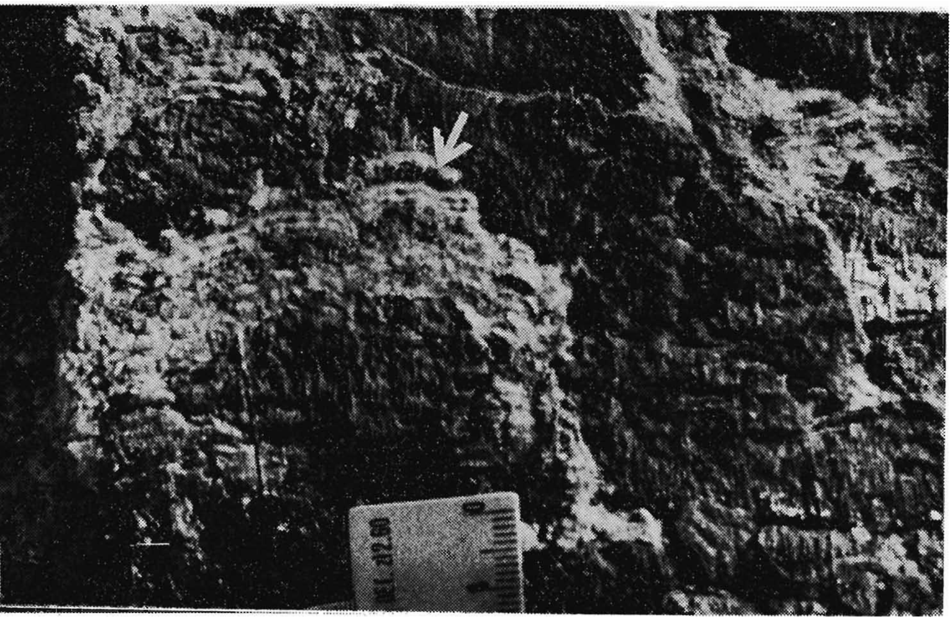
Fig. 5. Typical hollows between erroded and corroded apices of the gypsum crystal intergrowths, which are filled with clay and fragments of broken and corroded gypsum crystals at the top of the glassy gypsum (*see* Pl. 13, Fig. 2)





1 — Horizontal corrosion surface cross-cutting crystals of glassy gypsum; locality Marzęcin

2 — Eroded and corroded top surface of glassy gypsum on which large, broken and reworked gypsum crystals lay being redeposited by storm agitation; locality Sielec Rządowy



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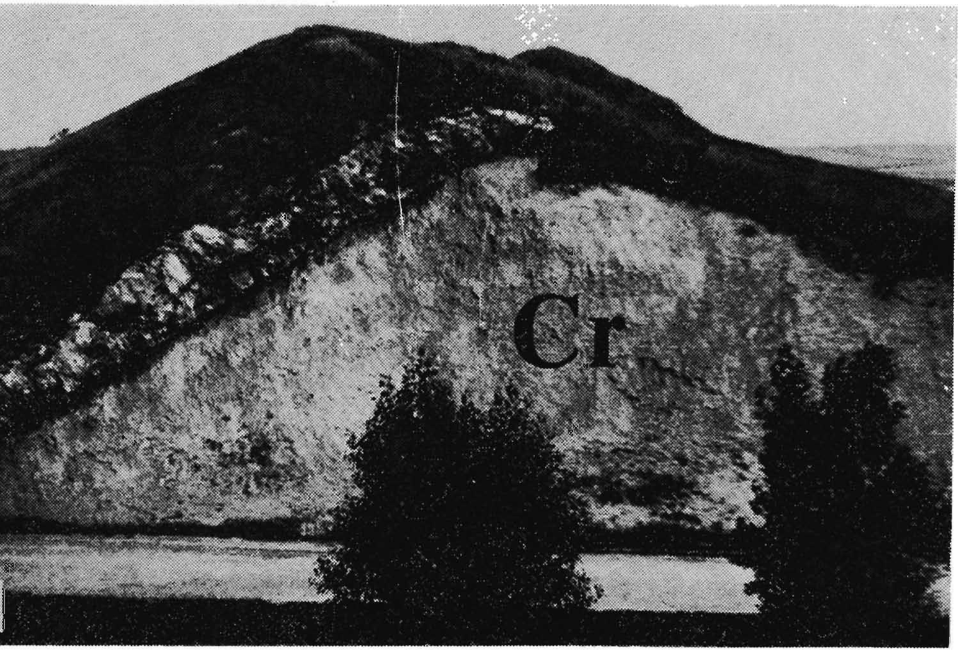

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1 — Thin-grained laminated gypsum (*white*) filling internal spaces of one large skeletal crystal (*dark*); on some gypsum laminae new generations of crystals (*arrowed*) grew upward from earlier detrital precursors; locality Gacki

2 — Base surface of glassy gypsum lying almost directly on hard substrate of Upper Cretaceous marls (*Cr*); locality Wola Zagojska

that the highly concentrated brine with a greater amount of NaCl in time of the successive evaporation became a corrosive agent for the earlier precipitated gypsum. Similar corrosion surfaces in recent salt lakes originate from dilution of brine, for example due to increasing rainfalls (*see* WARREN 1982), or from the existence of very thick algal mats corroding the underlying gypsum crystals (*see* FERSMAN 1919).

The evidences of corrosion are especially numerous near the top of the glassy-gypsum layer. In some places, on the top surface between the corroded and/or eroded apices of the intergrowths, there appear some hollows filled with clay and fragments of broken and corroded gypsum crystals (Text-fig. 5). These hollows, noted by SCHREIBER (1978), evidently indicate the primary nature of the glassy gypsum (*see* HARDIE & EUGSTER 1971). The broken crystals, usually cm-sizes, but sometimes even up to 30 cm (*see* Pl. 13, Fig. 2), seem to be torn out of the bottom and transported at a short distance probably by storm agitation. The crushing of the crystals was facilitated by the existence of numerous corrosion surfaces near the top surface of the glassy-gypsum layer.

Sporadically, there are some intercalations of the thin-grained gypsum in the glassy gypsum (*see* Pl. 12, Fig. 2). The thin-gypsum crystals fill free spaces in the skeletally developed intergrowths. In these fillings thin, newly generated horizons of the gypsum crystals grew upward (*see* Pl. 14, Fig. 1), being created from the earlier ooze.

The layer of the glassy gypsum covers various kinds of the substrate. Where the underlying deposits were compact and lithified, the base of the glassy gypsum is smooth (Pl. 14, Fig. 2). In places where the glassy gypsum lie on the soft marly and glauconitic clay, large convexities separated by hollows filled with strongly deformed and folded clay often occur at the base (Pl. 15; *see also* BĄBEL 1984). The convexities having the flattened top parts reach sometimes 3 m in width. They originated from the sinking of the patch-like groups of the crystals into underlying soft and unconsolidated clay. The sinking was evidently associated with a diapiric squeezing of the clay (Text-fig. 6). Similar load structures, although different in shapes and sizes, occur numerously in the Mediterranean gypsum (*mamelloni* of VAI & RICCI LUCCHI 1977; *nucleation cones* of DRONKERT 1978, 1985; LO CICERO & CATALANO 1978; *super-cones* of DRONKERT 1985; *stellate gypsum clusters* of SCHREIBER 1978) and in the layers of the Nida Gypsum built of the sabre-like crystals (*see* BĄBEL 1985, 1986).

Finally, it is to note that any horizontal lamination within the glassy gypsum, and reflecting the zones of simultaneous growth of the crystals, except of some sporadical situations (*see* Pl. 3, Fig. 1 and Pl. 9, Figs 1—2), is practically invisible.

The lack of any distinct lamination gave even a reason to the opinions that the glassy gypsum was secondary, and it had been formed by diagenetic recrystallization of the primary gypsum ooze (*see* review *in* BĄBEL 1984). As evidenced in this paper, the lack of any lamination results from the morphology of the crystal apices which led to the distribution of clay inclusions not along synchronous growth zones but along the induction surfaces and the boundaries between the subcrystals.

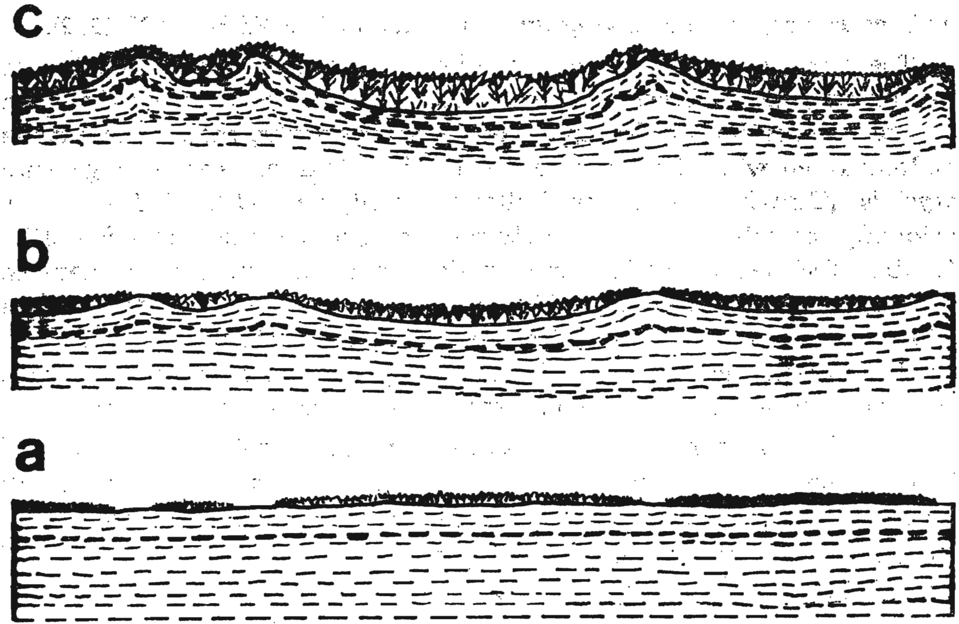

Fig. 6. Interpreted stages of the sinking of gypsum crystals, growing as groups or patches, into muddy substrate with associated diapiric squeezing of clay (*see* Pl. 15, Figs 1—2)

Summarizing, it is to emphasize that the giant gypsum crystals in the Middle Miocene (Badenian) evaporitic sequence of southern Poland grew on the bottom, directly from the basin brine without any ooze-grained precursors. Such direct crystallization of the glassy gypsum was properly recognized long ago by KREUTZ (1925) and his interpretation, advanced by GAWEŁ (1955), RADWAŃSKI (1969, 1985), SCHREIBER (1978) and others (*see* BĄBEL 1984, 1985), is now in accordance with observations of many Recent evaporitic environments (*see* HARDIE & EUGSTER 1971, SCHREIBER 1978, WARREN 1982).

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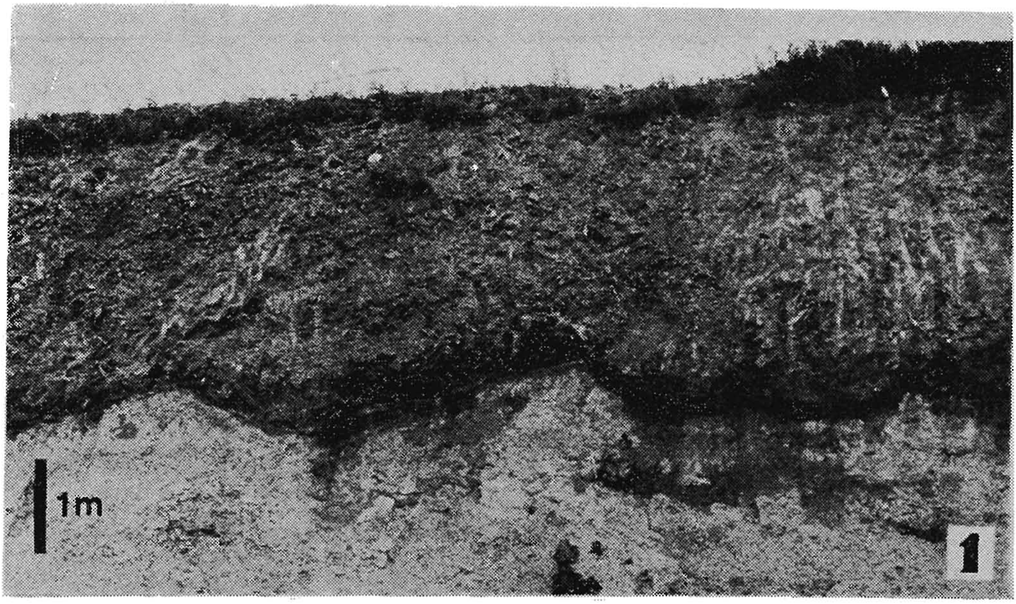

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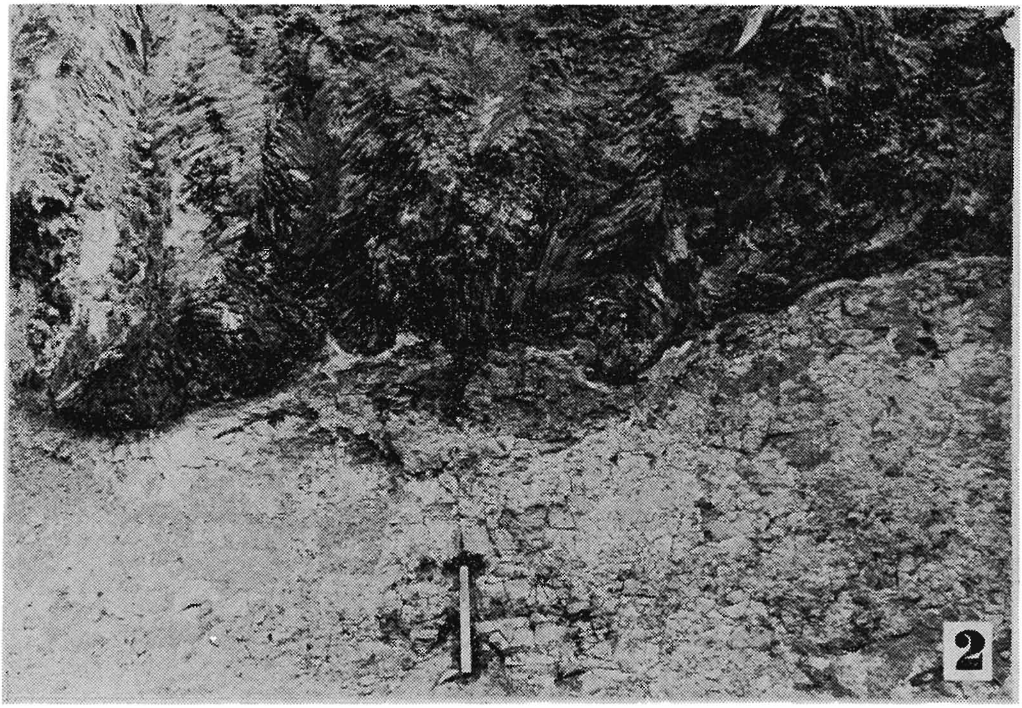

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1-2 — Wavy base surface of glassy gypsum lying on soft Middle Miocene (Badenian) glauconitic marly clay; the knobs and convexities result from the sinking of crystals into muddy bottom (*see* Text-fig. 6); locality Borków

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GENEZA WIELKICH KRYSZTAŁÓW GIPSU W OSADACH MIOCEŃSKICH ZAPADLISKA PRZEDKARPACKIEGO

(Streszczenie)

Przedmiotem pracy jest analiza sposobu wzrostu oraz czasu powstawania wielkich (osiągających 3,5 m wysokości) kryształów gipsu tworzących pokład tzw. *gipsów szklicowych* w spągu mioceńskiej formacji ewaporatowej wykształconej wzdłuż północnych rubieży Zapadliska Przedkarpackiego. Gipsy te, będące unikalnym zjawiskiem przyrodniczym (*por.* KREUTZ 1925; GAWEŁ 1955; RADWAŃSKI 1969, 1985; BĄBEL 1984, 1985), uznawano zwykle za kryształy zbliźniaczone typu „jaskółczych ogonów". Szczegółowa analiza krystalograficzna okazów pochodzących głównie z odsłonięć na południowych stokach Gór Świętokrzyskich (*patrz* fig. 1—6 oraz pl. 1—15) wskazuje jednak, iż kryształy te nie tworzą prawdziwych bliźniaków, lecz jedynie specyficzne zrosty podobne do bliźniaków kontaktowych według ściany $\bar{1}01$. Na podstawie wewnętrznych struktur wzrostu oraz zachowanej gdzieniegdzie morfologii kryształów odtworzono sposób przestrzennego rozwoju tych zrostów. Górna powierzchnia kryształów w poszczególnych zrostach zbudowana była z wielu równoległych soczewkowatych subkryształów, które miały swoje ostre krawędzie skierowane skośnie ku górze. Opadający z toni ił, gromadzący się w zagłębieniach powierzchni kryształów, był preferencyjnie przechwytywany wzdłuż granic pomiędzy soczewkowatymi subkryształami i tworzył smugi usytuowane skośnie do powierzchni warstwowania. Rozmaite struktury sedymentacyjne, choć rozpoznawalne w niektórych tylko odsłonięciach, świadczą o pierwotnej genezie rozważanych zrostów. Są to m.in.: powierzchnie korozyjne, nagromadzenia skorodowanych i redeponowanych kryształów, oraz struktury obciążeniowe związane z pogrzęzaniem kryształów rosnących na mulistym dnie. Analiza wszystkich cech strukturalnych tych wielkich kryształów gipsu wskazuje, iż wzrastały one bezpośrednio na dnie zbiornika podlegającego ewaporacji. Ich rozwój odbywał się poprzez szkieletowy rozrost kryształów, których wierzchołki wystawały ponad przeciętną powierzchnię dna, bez udziału precypitatu w postaci mułu gipsowego.