FUNDAMENTALS OF CRYSTALLOGRAPHY AND MINERALOGY

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The manual outlines the terms, concepts, basic principles and laws of crystallography, the mechanisms for describing the symmetry of crystals, the algorithm for determining and forming the names of simple shapes. A general idea of the origin, growth of crystals and processes of mineral formation is given. The main physical and morphological properties of minerals are considered. Descriptive mineralogy includes a list of about 100 of the most common minerals.

The manual is intended for students-geologists studying in the direction of 21.05.02 specialty "Applied Geology".

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CONTENT

INTRODUCTION

The presented manual outlines the key concepts of crystallography and mineralogy. The motivation for writing this textbook was to systematically outline the basic information considered within the course "Fundamentals of crystallography and mineralogy". It describes the basic laws of crystallography, mechanisms for describing the symmetry of crystals, and an algorithm for determining the names of simple crystal shapes. Within the framework of this course, the student will learn how to describe the forms of simple and complex crystals using examples of ideal models. The second part of the textbook is dedicated to mineralogy, and allows the reader to get an idea about the characteristics of different minerals, including crystal morphology, chemistry, physical properties, and the processes by which they form.

The textbook includes a series of descriptive tables that highlight the diagnostic features of the most common minerals found on Earth, providing the students with a resource to support their learning of the visual characteristics of these minerals. The text is accompanied by images to facilitate understanding and assimilation of the material.

I am very grateful Matthew Brzozovski for a significantly revised draft of the manual, which allowed improving it. I thank E.Yu. Nadezhdina and E.M. Asochakova for their valuable reviews. I am grateful Adel Shirazy for his idea, which led to the writing of this manual. In addition, of course, special thanks to my family: my mother, two daughters and sun, who allowed me to devote time for my favorite work…

PART 1. CRYSTALLOGRAPHY

In a faceted crystal
A natural phenomenon itself
As if, he puts the finished one,
A well-formulated problem
The solution of which is impossible
Without in-depth geometric
Research…

I.I. Shafranovsky

Crystallography is the science of crystals. The crystalline state is determined by the way, in which a substance is constructed. Crystals reflect the ordered regular arrangement of elementary particles (atoms, ions, molecules) of which they are composed, and determines their regular geometric shape. Modern crystallography includes principles on the external form of crystals (geometric crystallography), the atomic–molecular structure of crystals determined via different analytical methods, such as X-ray diffraction, electron diffraction, and neutron diffraction (structural crystallography), the physical properties of crystals (physical crystallography), the composition of crystalline substances (crystal chemistry), and the theory of crystallogenesis (i.e., the formation of crystal).

The origin of crystallography as a science dates back to the 17th century. One of the first scientific interpretations on the shapes of crystals was the book by Johannes Kepler "On Hexagonal Snowflakes" (1611) [1].

Information: *J. Kepler (1571–1630) expressed the opinion that the shape of snowflakes (ice crystals) is a consequence of the general arrangement of their constituent particles. From Johannes Kepler's book "Since every time it starts to snow, the first snowflakes are in the shape of a hexagonal star, there must be a reason. For if this is an accident, then why are there no pentagonal or heptagonal snowflakes, why do hexagonal snowflakes always fall, if only they do not lose their shape from collisions, do not stick together in a multitude, but rarely and separately? When I recently discussed this topic with someone, we agreed, first of all, that the reason should be sought not in the substance, but the active principle ... " [1].*

> *In 1783, the French scientist Rene Just Hauy (1743–1822) discovered that crystals cleaved along straight planes that met at constant angles. R.J. Hauy dropped a calcite crystal, and, seeing how it crumbled into regular rhombohedrons, exclaimed, "Everything is found." He began to split all of the crystals that he received, earning the nickname "crystalloclast – a crusher of minerals" from his acquaintances. The shapes that the minerals were split into (cube, rhombohedron, octahedron, rhombododecahedron) allowed him to assume, in 1783, that minerals comprised a "multifaceted" shape of atoms. Fundamental to his theory were the laws of decrement and of constancy of angles, whereby the cleavage forms of crystals were related geometrically to their primary forms or nuclei.*

A further step in the development of the atomistic idea of crystals occurred in 1813 when William Hyde Wollaston (1766–1828), an English physicist and chemist, replaced atoms in a crystal with mathematical dots, introducing the concept of crystal lattices.

Thus, from the three-dimensional arrangement of the particles that constitute a crystal, an abstract geometric image arose – a *space lattice*. In other words, a *space lattice* is a three-dimensional system of points located in sites that are environmentally equivalent.

Each space lattice comprises a repeating element of a crystal structure – a *primitive unit cell*. A *primitive unit cell* is the smallest unit cell by which an entire crystal can be built. A crystal is built by combining spatial (i.e., volumetric) *primitive unit cells* together in space.

I. A *primitive unit cell* is an elementary parallelepiped, the regular repetition of which forms a *space lattice* (Fig. 1, *a*). To define the geometry of the unit cell in three dimensions we choose a right-handed set of crystallographic coordinate axes (X, Y, Z), which point along the edges of the unit cell. The origin of coordinate system is at one of the lattice points. The length of the unit cell along the x, y, and z direction are defined as a, b, and c. Alternatively, we can think of the sides of the unit cell in terms of vectors $\boldsymbol{a}$, $\boldsymbol{b}$, and $\boldsymbol{c}$. The angles between the crystallographic axes are defined by:
   - ✓ $\boldsymbol{\alpha}$ = the angle between b and c;
   - ✓ $\boldsymbol{\beta}$ = the angle between a and c;
   - ✓ $\boldsymbol{\gamma}$ = the angle between a and b,

   where a, b, c, α, β, γ are collectively known as the ***lattice parameters*** (often also called 'unit cell parameters') (Fig. 1, *a*).

II. *Lattice vectors* – a set of nodes located along a straight line and repeated at regular intervals. The *vectors* correspond to the *edges* of the crystals and are identified by the convergence of lines of two *plane grids* (Fig. 1, *b*, *c*).

III. *Plane grid* – a set of *nodes* located in the same plane and ordered at the vertices (*points*) of parallelograms. This element of the space lattice corresponds to the crystal *faces* (Fig. 1, *c*). It should be noted that crystal faces correspond to flat networks of nodes that have the highest *reticular density*. The *reticular density* is the number of nodes per unit area of a flat grid or the unit length of a row of a space lattice.

IV. *Nodes* are particles corresponding to the *points* of polyhedra. In other words, these are the points of convergence of several lattice vectors (Fig. 1, *b*, A_0–A_n).

V. The *space lattice* is a regular, indefinitely repeated array of points in three dimensions in which the points lie at the intersections of three sets of parallel equidistant plane (Fig. 1, *d*).

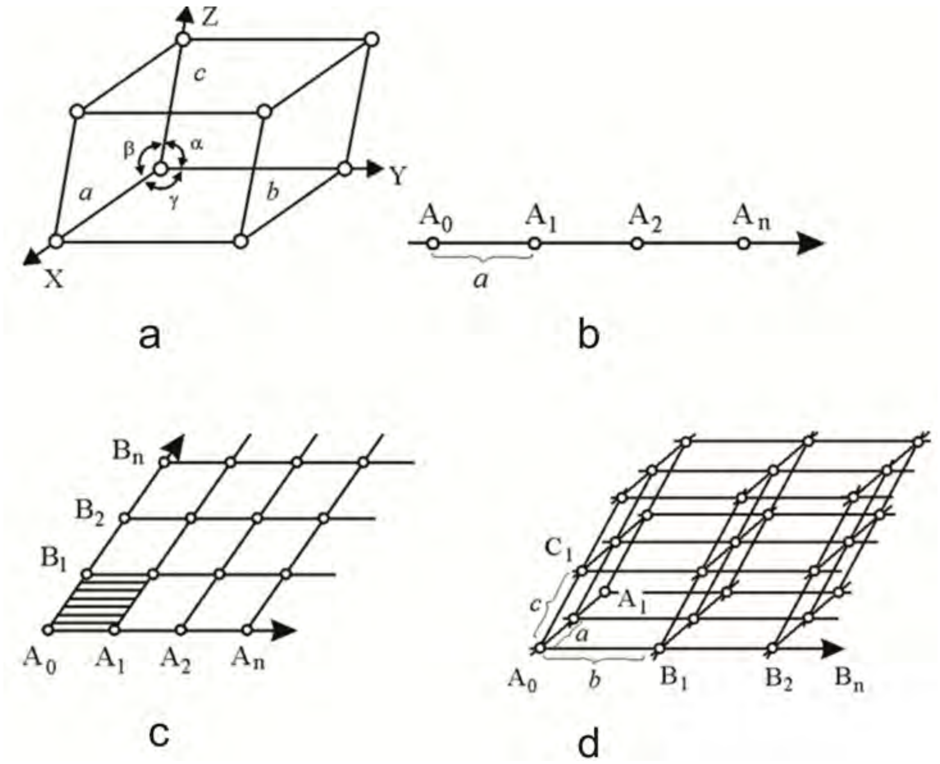

Fig. 1. A primitive unit cell (a); a row of the space lattice (rows A_0-A_n) (b); a plane gride (c); a space lattice (d)

Putting this all together, a *crystal* is a solid body in the form of a polyhedron, in which particles of matter (atoms, ions, and molecules) are arranged regularly in the form of a space lattice.

> ***Information:*** *In 1912, German physicist Max von Laue (1879–1960) discovered the phenomenon of X-ray diffraction when X-rays pass through crystals. This was the main experimental support regarding the theory of a lattice structure for crystalline solids.*

Thus, it was confirmed that all crystals consist of particles that are regularly arranged about each other, like the nodes of a space lattice. Following the experiments carried out by M. Laue, the theory of a lattice structure for crystalline solids ceased to be just a speculative conclusion and became a law [2].

Therefore, all crystals of the same substance are equivalent in structure, meaning that the mutual arrangement of layers (plane grids) relative to each other is the same. The size of the crystal increases by building up several new faces in parallel layers, but the angles between these faces will not change regardless of the crystal size. Hence follows the basic law of crystallography – the Law of constancy of interfacial angles (Fig. 2).

Information: *In 1669, Nicolas Steno (1638–1686), while studying quartz and hematite, made an important observation – even though crystals of one mineral can have different shapes, the angles between their respective faces are the same. In the next century, the Frenchman Jean-Baptiste Louis Romé de l'Isle (1736–1790) found this property to be inherent in all crystalline substances. This property of crystals received the name "The law of constancy of interfacial angles" (Fig. 2) [3].*

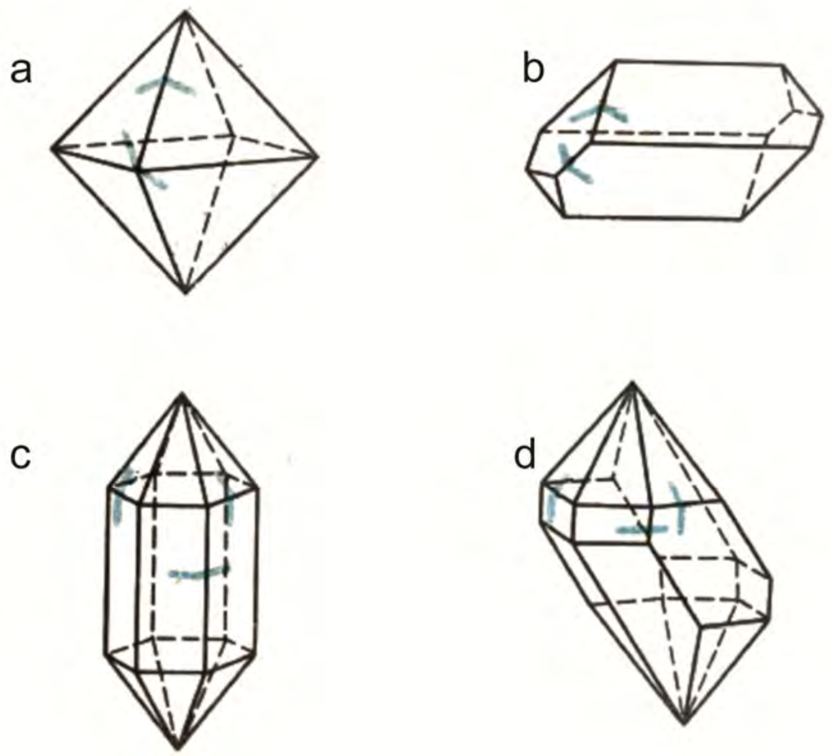

Fig. 2. Law of constancy of interfacial angles. The corresponding faces of the crystals of magnetite (a, b) and quartz (c, d) form the same angles with each other; a, c – ideal crystals; b, d – distorted crystals

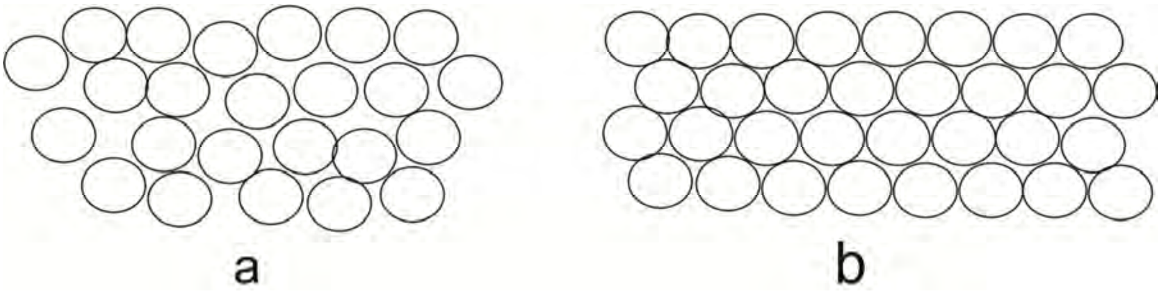

Fig. 3. The nature of the arrangement of material particles in amorphous (a) and crystalline (b) bodies

In addition to *crystalline* substances, in which the space lattice "controls" the placement of particles, there are solid bodies in which particles are arranged in a less ordered manner (i.e., there is no three-dimensional periodicity in the arrangement of particles). Such bodies are called *amorphous* (Fig. 3, *a*). Amorphous bodies are similar in structure to liquids or gases. Their strength, as a rule, is lower than crystalline substances. Examples of amorphous bodies include glasses, resins, and opal (SiO_2*nH_2O). Crystalline solids have the most stable internal structure (Fig. 3, *b*), which reflects the equilibrium state of the substance. Therefore, while glasses can turn into a crystalline state, the opposite is not observed (at the same temperature).

The difference between crystalline and amorphous bodies is particularly evident in their behavior during heating. A *crystalline* substance melts at a strictly defined temperature and, during cooling, will transition from liquid to solid (i.e., crystallize) at that same temperature. *Amorphous* bodies, however, do not have a definite melting or crystallization temperature.

The natural, ordered internal structure of crystalline substances determines their three main *properties*:

1. *Homogeneity* – the same properties of the crystal in parallel directions.

A crystal is a system of particles (atoms, ions, and molecules) ordered in space. They are positioned in specific locations and most often fill the volume of space as tightly as possible. Substance in which, at finite distances from any of its points, there are others equivalent to it not only in physical terms, but also geometrically, can be considered *homogeneous*. In other words, the same arrangement of particles is observed in parallel directions.

2. *Anisotropy* – different properties of the crystal in non-parallel directions.

This property is manifested in monocrystals (single crystals). If *anisotropy* reflects the ability of a substance to exhibit different properties (thermal conductivity, hardness, elasticity, refractive index, etc.) in different directions ($a \neq b \neq c$), then isotropy is the opposite. If the properties of a substance are constant in all directions, the substance is considered *isotropic*. This is another fundamental difference between *amorphous* and *crystalline* substances – the former is isotropic and the latter is anisotropic. The exception to this are crystals in the isometric system, which have the same properties in all three directions. Minerals crystallizing in the isometric system are, therefore, also homogeneous in all three directions of the space lattice ($a = b = c$).

3. *The ability to self-facet* – the ability to acquire the shape of a regular polyhedron under favorable growth conditions.

As the acute reader has already understood, the ability to *self-facet* is the result of a regular and ordered internal structure of a crystalline substance. The visible boundaries of crystals are a complete external reflection of strict internal ordering space lattice bounded by planes (faces). It is appropriate to emphasize that the ability of a crystalline substance to self-facet depends on the crystallization strength of the substance and does not always manifest itself. Only under especially favorable conditions when the external environment does not interfere with the formation and free growth of crystals will they self-facet (e.g., in a vug or some other void space). If, for some reason, these conditions are not met, either xenomorphic or partially deformed crystals will form. Regardless of the external form of crystals, however, their internal structure remains ordered.

4. *The symmetry* of crystals is also a result of their regular internal structure. Symmetry or proportionality is manifested not only in crystallography, but also in the diversity of our world.

Information: *René Just Hauy (1743–1822) was one of the first to note the importance of symmetry.*

For example, a bird needs two wings to fly, a person needs two legs to walk, and a fish needs two fins to swim. Symmetry is balance and stability, beauty and harmony.

The *symmetry* of crystals is the regular repetition of the same faces, edges, and vertices concerning some auxiliary geometric images.

Information: *Auguste Bravet (1811–1863), one of the great French founders of geometric crystallography, formulated the concepts of symmetry elements.*

There are three *elements of crystal symmetry*:

1. The axis of symmetry (L) is a straight *line* (Fig. 4) through a crystal around which the crystal can be rotated 360° several times and remain

aligned with its original position. In other words, when rotating a symmetrical figure by a certain angle around a virtual line (the axis of symmetry), it will occupy the same position in space that it occupied before the rotation.

The axis of symmetry is the spine of the crystal. The smallest angle of rotation around the axis at which the figure is aligned with itself is called the *elementary angle of rotation*. In this case, we are talking about *rotational* symmetry. The number of times the crystal aligns with its original position during a 360° rotation determines the order of the symmetry axis.

In crystals, it is customary to draw the symmetry axes of the second (180°), third (120°), fourth (90°) (Fig. 4), and sixth (60°) orders. The named axes of symmetry are usually denoted by the following symbols: L_2, L_3, L_4, and L_6, respectively. Symmetry axes with orders greater than 2 are called *higher-order symmetry axes*.

A crystal can have one or several axes of symmetry of the same or different orders, or it can have no axis. The number of axes of the same order is indicated by a factor in front of the symmetry axis symbol. For example, $6L_2$ reads six axes of the second-order [4].

The first-order axis in crystals is not indicated as it can be drawn in any polyhedron. Symmetry axes greater than the sixth-order have not been found in crystals. As a reminder to the reader, the property of symmetry in crystals is manifested due to the regularly ordered structure of crystals. A space lattice consisting of an infinite set of elementary cells, or bricks controls this regularity. A crystal is built by combining these bricks in space. The bricks should be the same size and shape, and be laid in the same way, filling the space without gaps. The bricks can be three-, four-, and six-sided prisms, but not five- and seven-sided prisms, as the latter will not permit all of the space to be filled without gaps. Thus, five- and seven-sided prisms are not suitable for the construction of crystals, and so L_5 and L_7 symmetry axes are impossible [3].

> ***Information:*** *For inanimate substances, symmetry is prevalent. Asymmetry predominates in living matter, however, down to the micron scale. Interestingly, in flowers, rotational symmetry of the fifth order is most common, which is fundamentally impossible in periodic crystal structures.*

The *axes* of symmetry can pass through the *centers of the faces* (planes bounding the polyhedron), the *midpoints of the edges* (straight lines along which the crystal faces converge), and the *vertices* (points of intersection of the edges) of the *polyhedra*.

Let us analyze, using a *cube* (i.e., hexahedron; six faces) as an example, how symmetry axes are drawn in crystals. The L_4 axis can be drawn through the midpoints of the cube faces since, when rotated by 90°, all points of the cube will return to their original position (Fig. 4). The axis of symmetry is a straight line passing through 2 points, that is, through two faces. It follows from this statement that there are three mutually perpendicular L_4 axes in the cube since there are six faces. Three L_4 axes can, therefore, be drawn through each pair of parallel faces (Fig. 4). It is important to note that if higher-order axes are drawn in the crystal, L_4 in this case, then the lower-order axes are no longer drawn in these directions.

The next possible passage of symmetry axes in the cube can be the midpoints of the edges (lines of intersection of the faces). The minimum angle of rotation during which all points of the hexahedron will coincide with themselves is 180° (L_2) (Fig. 4). We count the number of edges in the cube – there are 12 of them, so we draw $6L_2$ axes through every two of the mutually parallel edges. The axes of symmetry can also be passed through the vertices of the cube. When rotated at 120° (L_3), all points of the figure coincide with the original position. Accordingly, $4L_3$ axes can be drawn through the opposite vertices of the hexahedron since there are eight vertices. Thus, the set of symmetry axes for the hexahedron can be written as $3L_44L_36L_2$. The notation for writing the axes of symmetry is carried out in one line, without punctuation marks, in decreasing order of symemtry. The coefficients in front of the axes indicate the number of each of the axes in a crystal.

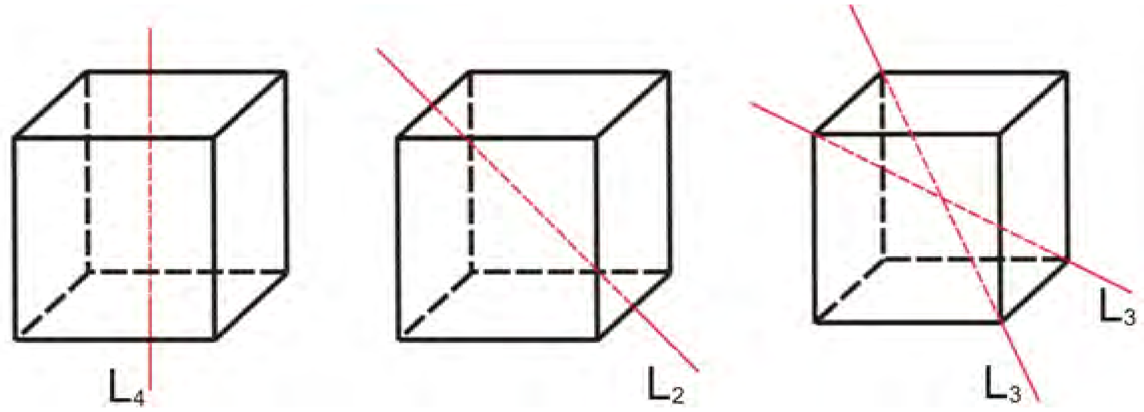

Fig. 4. Axes of symmetry passing through the centers of faces, edges, and vertices. The axis order determines the minimum rotation angle that returns all points of the shape to their original position when rotated. The set of axes of symmetry for a cube is $3L_44L_36L_2$

It is important to note that in addition to the symmetry axes L_2, L_3, L_4, and L_6 in crystals, one should also be able to identify *inversion symmetry* *axes*. Within the framework of this textbook, it is necessary to be able to determine the inversion axes of the fourth L_{i4} and sixth L_{i6} orders.

The inversion axis is a mirror-like rotary axis, which manifests itself in the three forms – tetragonal tetrahedron, tetragonal scalenohedron (L_{i4}), and rhombohedron (L_{i6}). The L_{i4} inversion axis in crystals coincides with L_2, and L_{i6} with L_3. Inversion axes are determined by combining all points of the figure not in the direct position, but the opposite of the mirror position. Thus, in the tetragonal tetrahedron and scalenohedron (Fig. 5), L_2 (180°) passes through the opposite centers of the edges and a reverse, or mirrored, set of faces is observed after 90° of rotation. Hence, L_{i4} passes in this direction. A similar picture is established for the rhombohedron, in which the sixth-order inversion axis (L_{i6}) coincides with L_3 since the opposite arrangement of the upper faces is observed at a rotation of 60°.

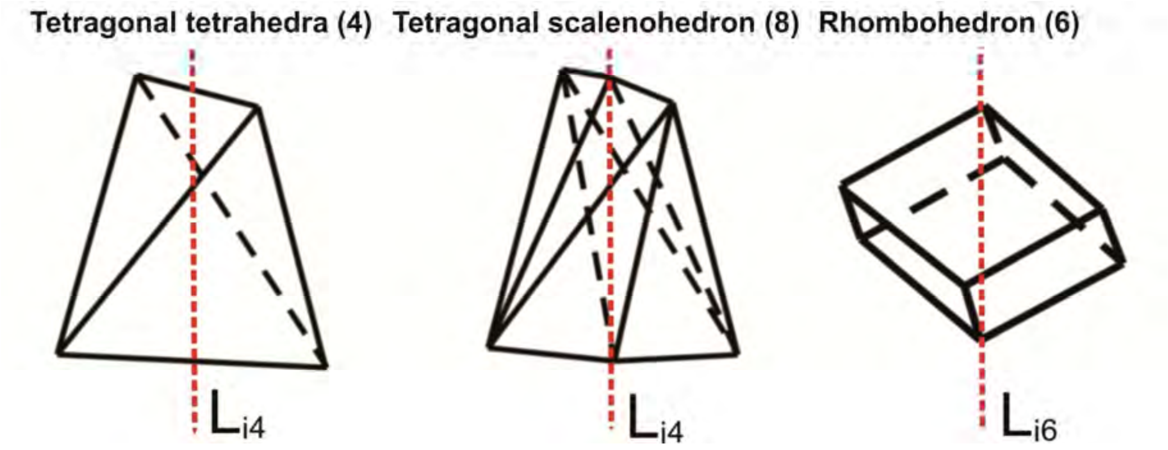

Fig. 5. Inversion axes of the fourth (Li_4) and sixth (Li_6) orders in crystals of the medium category

2. The *plane of symmetry (P)* is a *plane* that divides the crystal into two mirorred parts (Fig. 6). As a result of this virtual division, a figure is an object and its mirror image. If you put two palms together, then the plane separating them will be the plane of symmetry. This element of symmetry is *reflective*. The maximum number of symmetry planes that can be drawn in crystals is nine (Fig. 6). *The planes of symmetry are drawn through the midpoints of the faces, along the edges, and along the diagonals of the faces*.
3. The *center of symmetry (C)* is an imaginary point inside the crystal at which the symmetry lines intersect and bisect, connecting opposite identical faces, edges, and vertices of the crystal. If a crystal has a center of symmetry, then each face of the crystal must have an equal parallel and reverse-directed face. If in a crystal at least one of the faces does not have an equal, parallel, and reverse-directed face, then the crystal has no center of

symmetry. A practical way to determine the presence of a center of symmetry in a crystal is to lay a polyhedron on a flat surface (for example, on a table). A center of symmetry is present if every face of the polyhedron that is aligned with the plane of the table has an equal and parallel opposite face, not a vertex or protruding edge.

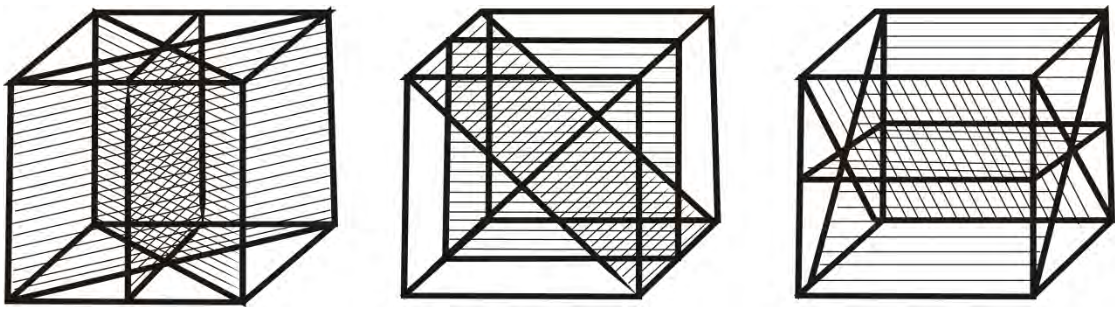

Fig. 6. Planes of symmetry of the hexahedron (the number of planes is nine)

The totality of all available symmetry elements (axes, planes, and center) in a crystal must be written in one line, without punctuation marks between them, starting with the higher-order axes, then indicating the number of symmetry planes and, last of all, the presence of a center, if any. For example, the symmetry elements of a tetragonal prism are written as $L_4 4L_2 5PC$ [4].

To correctly identify the symmetry elements of a crystal, there are several *rules*:

1. If the crystal has an axis of symmetry of the n-th order and the axes of the second-order pass perpendicularly to this axis, then in total there are "n" axes of the second order, perpendicular to the axis of the n-th order. Example: $L_3 3L_2$; $L_4 4L_2$; $L_6 6L_2$.
2. If the crystal has an n-th order symmetry axis, and the asymmetry plane passes along it, then "n" such planes will pass through this axis in total.
3. The line of intersection of two planes of symmetry is the axis of symmetry, and the angle of rotation around this axis is twice the angle between the planes.

All symmetry elements interact with each other. As a result, some of their combinations are impossible in crystals and some are required. Therefore, the third order axes (L_3) can be one, 4 or none, 4th order (L_4) can be 1, 3, or none, and 6th order (L_6) can 1 or none numers of axis. All axes of symmetry intersect at one point [3].

According to all of the elements of symmetry in crystallography, it is customary to distinguish *three symmetry categories* and *seven syngonies (systems) of crystals*. The *category* reflects the most essential properties and relationships of objects of the objective world. In other words, a category is a group or class of homogeneous crystals that have common features. *Syngony* (gr. Syn together + gonia angle) is a system that unites crystals with the same set of angles between the faces.

> ***Information:*** *The German scientist Christian Samuel Weiss (1780–1856) and the Carl Friedrich Christian Mohs (1773–1839), known for this Mohs hardness scale, formulated the foundations of the doctrine of syngonies [3].*

Crystals of each system are characterized by the same angles and relative values of segments (unit cell parameters: a, b, c) along three coordinate axes, and have a similar set of symmetry elements – axes and planes of symmetry. In addition, in each crystal system, crystals have the same number of unit directions. A *single direction* is a direction that is not repeated in a crystal.

HIGHEST CATEGORY

- *Isometric system* (obligatory presence of $4L_3$, several axes above the second-order), *unit cell parameters*: $a = b = c$; $\alpha = \beta = \gamma = 90°$.

MEDIUM CATEGORY

- *Hexagonal system* (obligatory presence of one L_6 axis), *unit cell parameters:* $a = b \neq c$; $\alpha = \beta = 90°, \gamma = 60°$.
- *Tetragonal system* (obligatory presence of one L_4 axis), *unit cell parameters:* $a = b \neq c$; $\alpha = \beta = \gamma = 90°$.
- *Trigonal system* (obligatory presence of one L_3 axis), *unit cell parameters:* $a = b \neq c$; $\alpha = \beta = 90°, \gamma = 120°$.

LOWEST CATEGORY

- *Orthorhombic system (*the sum of the axes of symmetry of the second-order and the planes of symmetry is six or three – $3L_23P$ or L_22P. No axes of symmetry higher than second-order, *unit cell parameters:* $a \neq b \neq c$; $\alpha = \beta = \gamma = 90°$.
- *Monoclinic system* (the sum of the symmetry axes of the second-order and the planes of symmetry is equal to two or one – L_2PC or L_2. There are no axes of symmetry higher than the second-order), *unit cell parameters:* $a \neq b \neq c$; $\alpha = \beta = 90°, \gamma \neq 90°$.
- *Triclinic system* (the presence of a center of symmetry (C), or the complete absence of symmetry elements), *unit cell parameters:* $a \neq b \neq c$; $\alpha \neq \beta \neq \gamma \neq 90°$.

In total, 32 *types of symmetry* occur because of various combinations of symmetry elements in crystals (Table 1).

> ***Information:*** *The first conclusion regarding symmetry groups was made in 1826. German crystallographer Moritz Ludwig Frankenheim (1801–1869). The idea was then corroborated in 1830 by the German mineralogist Johann Friedrich Christian Hessel (1796–1872), who geometrically shown that the external shape of crystals is described by only 32 types of symmetry. At the same time, he developed a complete theory of the symmetry of finite figures and deduced an infinite number of types of their symmetry. However, this work went unnoticed. The same 32 types of symmetry were discovered again, albeit differently, in 1867 by Russian scientist Axel Vilgemovich Gadolin (1828–1892). These 32 types of symmetry encompass all artificial crystalline substances, and all mineral species and varieties, without exception.*

Table 1

Types of crystal symmetry (32)

Symmetry Category	Syngony/ System	Symmetry type						
		Primitive	Central	Axial	Planar	Planaxial	Inversion-primitive	Inversion-planar
Lowest	Triclinic	–	C					
	Monoclinic			L_2	P	L_2PC		
	Orthorhombic			$3L_2$	L_22P	$3L_23PC$		
Medium	Trigonal	L_3	L_3C	L_33L_2	L_33P	L_33L_23PC		
	Tetrahonal	L_4	L_4PC	L_44L_2	L_44P	L_44L_25PC	Li_4 (=L_2)	$Li_4 = 2L_22P$
	Hexagonal	L_6	L_6PC	L_66L_2	L_66P	L_66L_27PC	Li_6 (=L_33P)	Li_63L_23P (=L_33L_24P)
Highest	Isometric	$3L_24L_3$	$3L_24L_3$ 3PC	$3L_44L_3$ $6L_2$	$3Li_4$ $4L_36P$	$3L_44L_3$ $6L_29PC$		

Exercise 1. ***Answer the following questions:***

1. What elements of symmetry do you know?
2. In which category are there no single directions?
3. How many categories are there?
4. What inversion axes of symmetry do you know?

Exercise 2. ***Choose and explain why true or false the following statements:***

1. The center of symmetry (C) is a real point outside the crystal at which the symmetry lines intersect and bisect, connecting opposite identical faces, edges, and vertices of the crystal.

2. The first conclusion regarding symmetry groups was made in 1926.

3. The natural, ordered internal structure of crystalline substances determines their three main properties: homogeneity, anisotropy, and the ability to self-facet.

Exercise 3. ***Choose and underline the correct presence of axes.***

1. *Isometric system* (obligatory presence of $\mathbf{3L_2/4L_3}$, several axes above the second-order), *unit cell parameters*: $a = b = c$; $\alpha = \beta = \gamma = 90°$.

2. *Tetragonal system* (obligatory presence of $\mathbf{4L_2/L_4}$ axis), *unit cell parameters:* $a = b \neq c$; $\alpha = \beta = \gamma = 90°$.

3. *Monoclinic system* (the sum of the symmetry axes of the second-order and the planes of symmetry is equal to two or one – $\mathbf{L_2PC/L_2}$. There are no axes of symmetry higher than the second-order), *unit cell parameters:* $a \neq b \neq c$; $\alpha = \beta = 90°$, $\gamma \neq 90°$.

Exercise 4. ***A primitive unit cell is an…***

A. elementary triangle.
B. elementary parallelepiped.
C. elementary tetrahedron.

Exercise 5. ***The reticular density is…***

A. the number of lines per unit area.
B. the number of vectors per unit area.
C. the number of nodes per unit area.

1.1. Shape of crystals

> *"The crystal invariably bears on itself*
> *Traces of previous moments*
> *In its existence, and in its form,*
> *By the sculpture of its faces, trifles*
> *And details of its surface*
> *We can read his past …"*
>
> *A.E. Fersman*

The shape of crystals is not accidental; in nature, shape reflects the conditions of formation of minerals.

A *simple* ideal *crystal shape* is called a polyhedron, all the faces of which can be obtained from one face using transformations of a certain group of symmetry elements. If the space is closed, then a convex polyhedron is formed, which is a *closed simple shape.* All simple shapes of the highest category of crystals are closed (Fig. 7), that is, the edges of these simple forms limit and close the final volume of the shape. *Open simple shapes* do not enclose a space; they always occur in combination with other simple shapes, the result of which is considered a complex shape.

So, among crystals, two groups of shapes are distinguished: i) simple shapes and ii) complex shapes (a combination of simple shapes). A simple shape is called a crystal, which consists of faces of the same size and shape, having a symmetrical arrangement.

A complex shape is a crystal consisting of faces of various sizes and shapes. The *number* of different faces determines the *number* of simple shapes in the combination. That is, the number of simple shapes that participate in the combination is equivalent to the number of varieties of faces visible in the polyhedron.

To date, *47 simple shapes* have been discovered, the names of which reflect the shape of the cross-section, the number of faces, and the outline of the faces. The following terms are used in the nomenclature of simple crystal forms:

- Mono – one
- Di, bi – two
- Three – three
- Tetra – four
- Penta – five
- Hexa – six
- Okta – eight
- Dodeca – twelve
- Hedron – facet
- Gonio – angle
- Sin – similar
- Pinacos – table
- Cline – slope
- Poly – numerous

The isometric system includes 15 simple, closed crystallographic forms (Fig. 7).

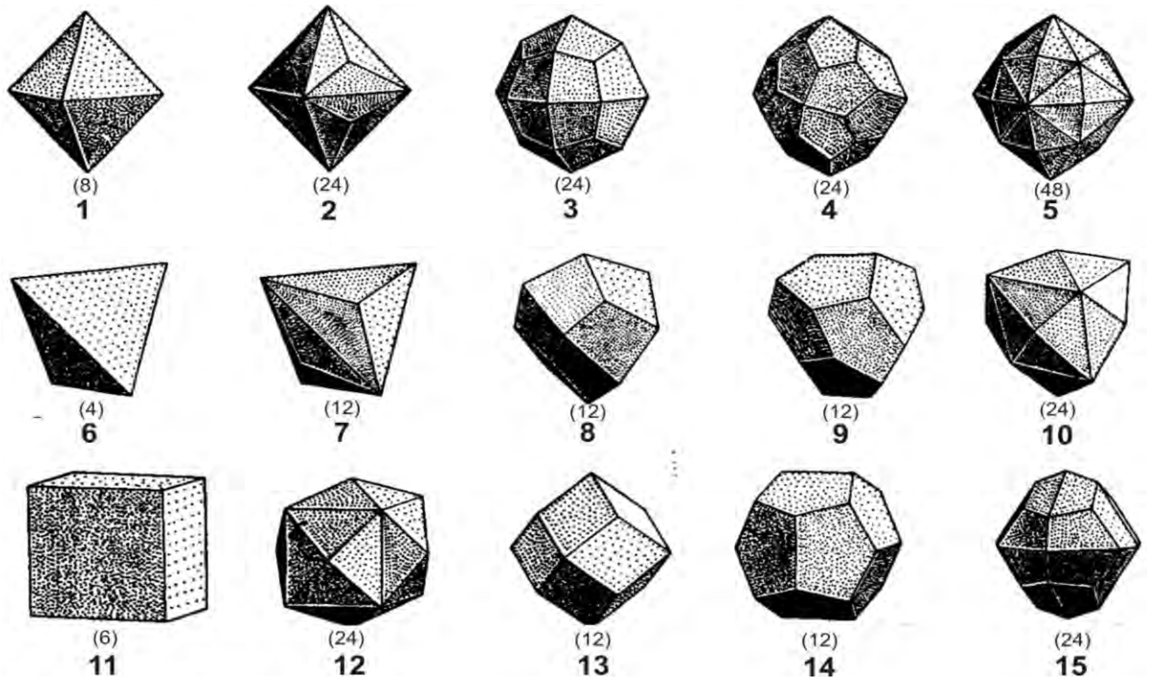

Fig. 7. Simple shapes are the highest category of the cubic system.
The number of faces is indicated in brackets. Legend:
1 – Octahedron (8); 2 – Trigontrioctahedron (24); 3 – Tetragontrioctahedron (24);
4 – Pentagontrioctahedron (24); 5 – Hexaocahedron (24); 6 – Tetrahedron (4);
7 – Trigontritetrahedron (12); 8 – Tetragontetrahedron (12);
9 – Pentagontetrahedron (12); 10 – Hexatetrahedron (24); 11 – Hexahedron (6);
12 – Tetrahexahedron (24); 13 – Rhombododecahedron (12);
14 – Pentagondodecahedron (12); 15 – Didodecahedron (24)

In the *medium category (trigonal, tetragonal, hexagonal systems)* (see Table 1), there are several types of crystal shapes. Prisms are crystals in which all faces of a simple shape are located parallel to each other and relative to the axis of symmetry of a high order. Pyramids (when all faces converge at one point – a vertex), bipyramids a trapezohedra (in this case, a face is simply the shapes represent a quadrangle, not a triangle, as in bipyramids; in trapezohedrons, the belt of edge faces does not lie on one straight line, unlike bipyramids), two scalenohedra (ditrigonal and tetragonal), rhombohedron (Fig. 8). Since prisms and pyramids are open simple shapes (i.e., they do not enclose a space), they occur in combination with pinacoids and monohedron. It must be remembered, however, that the pinakoid and monohedron are characteristic simple forms of the lowest category (Table 1).

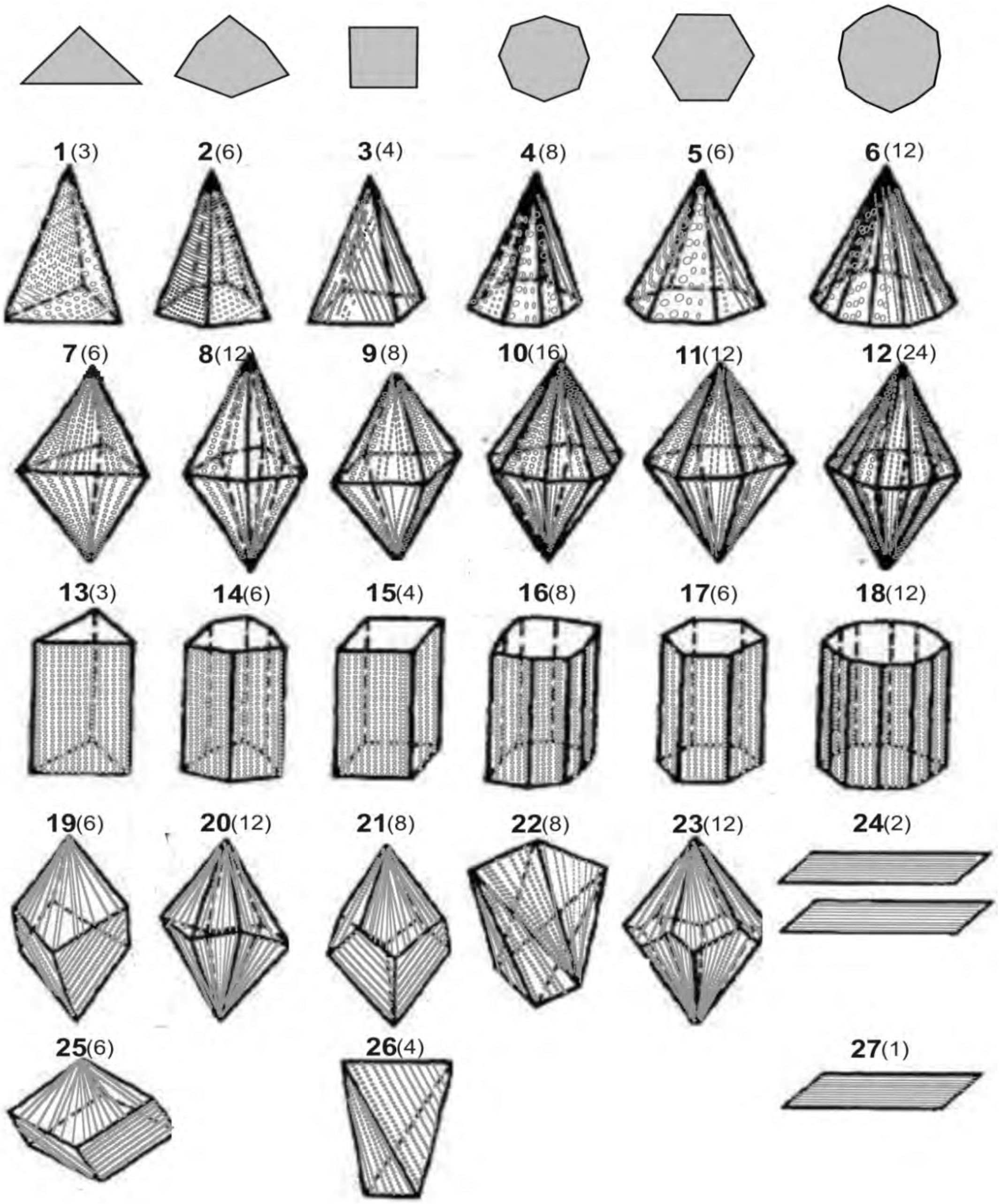

Fig. 8. Simple shapes of the medium category of crystal symmetry. The number of faces is indicated in brackets. Legend: 1 – Trigonal pyramid (3); 2 – Ditrigonal pyramid (6); 3 – Tetragonal pyramid (4); 4 – Ditetragonal pyramid (8); 5 – Hexagonal pyramid (6); 6 – Dihexagonal pyramid (12); 7 – Trigonal dipyramid (6); 8 – Ditrigonal dipyramid (12); 9 – Tetragonal dipyramid (8); 10 – Di-tetragonal dipyramid (16); 11 – Hexagonal dipyramid (12); 12 – Dihexagonal dipyramid (24); 13 – Trigonal prism (3); 14 – Ditrigonal prism (6); 15 – Tetragonal prism (4); 16 – Ditetragonal prism (8); 17 – Hexagonal prism (6); 18 – Dihexagonal prism (12); 19 – Trigonal trapezohedron (6); 20 – Ditrigonal scalenohedron (12); 21 – Tetragonal trapezohedron (8); 22 – Tetragonal scalenohedron (8); 23 – Hexagonal trapezohedron (12); 24 – Pinacoid (2); 25 – Rhombohedron (6); 26 – Tetragonal tetrahedron (4); 27 – Monohedron (1)

In the *lowest category (triclinic, monoclinic,* orthorhombic system) (Table 1) a rhombic prism, rhombic pyramid, rhombic dipyramid, and rhombic tetrahedron (i.e., the rhombic system) are possible, as well as a dihedron, monohedron, and pinacoid (Fig. 9).

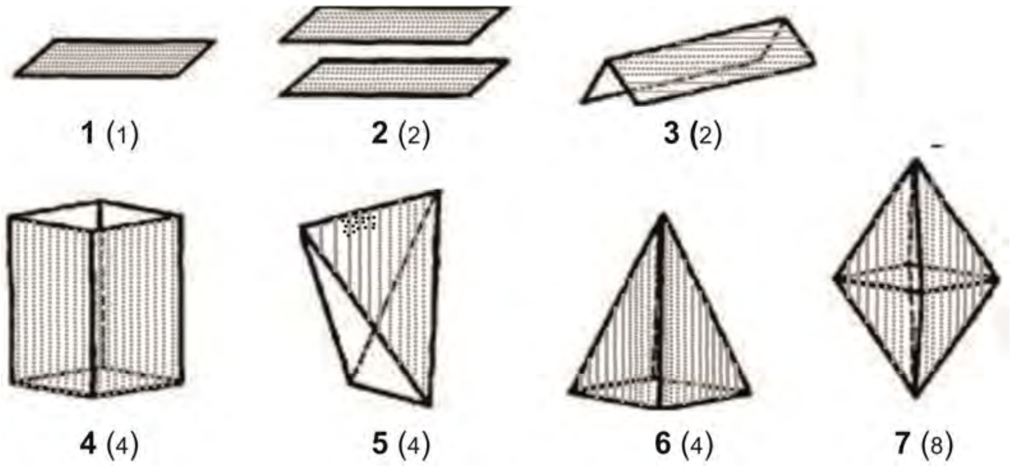

Fig. 9. Simple shapes of the lowest category.
The number of faces is indicated in brackets. Legend:
1 – Monohedron (1); 2 – Pinacoid (2); 3 – Dihedron (2); 4 – Rhombic prism (4);
5 – Rhombic tetrahedron (4); 6 – Rhombic pyramid (4); 7 – Rhombic bipyramid (8)

Rules for working with complex crystals

To correctly describe complex crystals, you need to know the exact algorithm for working with them.

1. Initially, it is necessary to determine the symmetry elements (axes, planes, and center) for the entire crystal.
2. Once the set of symmetry elements is characterized, the syngony of the complex crystal can be determined (see Table 1).
3. Narrowing down the possible simple shapes present in a combination based on the syngony, one can proceed to count the number of simple shapes that occur in the complex crystal. To do this, it is necessary to count the number of faces that are different in size and shape. The number of unique faces is equivalent to the number of simple shapes present in the combination.
4. Further, for each type of face (i.e., a separate simple shape), its total number must be calculated and its relative position to the elements of symmetry must be characterized. The name of the simple shape can then be determined.
5. As a result of the description of a complex crystal, a record should appear from a set of symmetry elements and an enumeration of simple forms participating in the formation of a complex crystal.

Example: Figure 10 illustrates three complex shapes in the cubic system with different faces.

1. Firstly, symmetry elements for the entire crystal must be determined, after which the syngony can be established. In this case, the set of symmetry elements is $3L_44L_36L_29PC$. Such a set is typical for crystals of the cubic system (see Table 1).

2. Next, we count the number of simple forms participating in the combination. To do this, we determine visually how many different types of faces are present in the crystals – there are two.

3. We determine the simple shapes based on the number of identical faces and their position relative to the elements of crystal symmetry. One type of face has six identical faces, the other has eight. Note that the arrangement of the faces in each of the examples, regardless of their development relative to the elements of crystal symmetry, remains unchanged (Fig. 10, a–c). In this case, one type of face is located perpendicular to the crystallographic axes of the fourth-order (L_4) and the second is perpendicular to the axes of the third order (L_3).

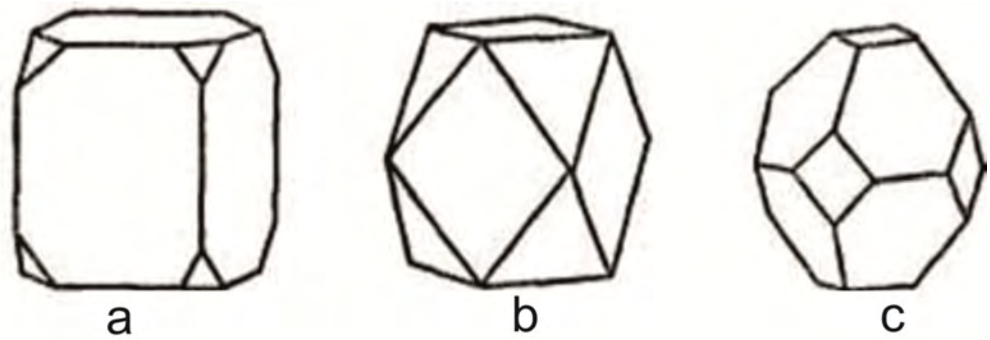

Fig. 10. A combination of two simple forms of the cubic system – hexahedron and octahedron. Developed faces of the hexahedron (a); equally developed faces of hexahedron and octahedron (b); predominance of the development of octahedron faces (c)

Thus, the first simple form, in terms of the number of faces and their position in space relative to the elements of symmetry of the cubic system, represents a hexahedron, and the second, an octahedron. The resulting description of the crystal can be written as: *The crystal has a set of symmetry elements* $3L_44L_36L_29PC$ *and represents a combination of two simple shapes of the cubic system – a hexahedron and an octahedron.*

Exercise 6. ***Answer the following questions:***

1. Can simple forms of the tetragonal system occur in a combination of a cubic system?
2. An octahedron is a simple form of what crystal system, how many faces does it have?
3. Rhombic prism is a simple shape of which category?
4. What scalenohedra do you know?
5. How many axes of the second-order and how are they drawn in a hexagonal prism?
6. Name the symmetry elements of the trigonal trapezohedron.
7. In what system does the rhombododecahedron occur, what figure does its facet represent?
8. Which figure is located in the cross-section of the rhombic prism?
9. Does the pinacoid have a center?
10. In which category are there higher order unit axes?
11. What is a monohedron?
12. In which category does the rhombohedron occur?
13. In which category does the tetrahedron occur, which polygon does its faces form?

Exercise 7. ***Answer the following questions choosing the correct letter:***

1. Dihedrons, monohedrons, pinacoids are more typical for which category?

A. Highest
B. Medium
C. Lowest

2. The hexagonal bipyramid has a single axis of what order?

A. L_4
B. L_6
C. L_3

3. In which category are there no single directions?

A. Highest
B. Medium
C. Lowest

4. ***In what category in crystals do not have axes of symmetry higher than L_2?***

A. Highest
B. Medium
C. Lowest

5. ***What order has the main axis in the rhombohedron?***

A. L_4
B. L_6
C. L_3

Exercise 8. ***Choose and underline the correct words.***

1. Prisms are crystals in which all faces of a simple shape are located **parallel/perpendicular** to each other and relative to the axis of symmetry of a high order.
2. In bipyramids, the belt of edge faces does **not lie/lie** on one straight line.
3. A complex shape is a crystal consisting of faces of **various/equal** sizes and shapes.
4. A **simple/complex** shape is called a polyhedron, all the faces of which can be obtained from one face using transformations of a certain group of symmetry elements.

1.2. Natural shapes and crystal growth

The beauty and shine of crystals
Everyone understands.
They enchant a glance
Their forms are entertaining to their minds.
Sophisticated observer
Will see their secrets of life,
And put it on the shelves
Anything that seems random …

Author unknown

The shapes of natural crystals are not limited only to the forms determined by their internal structure. Ultimately, a crystal form is the result of interaction between the symmetry of its internal structure and the symmetry of the crystallization medium.

A one-sided or inhomogenous inflow of components required for the growth of crystals or the physicochemical inhomogeneity of the crystallization medium can lead to distortions of the external shape of the crystal. Perfectly developed crystals with obvious geometric outlines are not common in nature.

Information: *One of the founders of the taxonomy and nomenclature of forms of natural crystals is the famous Saxon mineralogist Abraham Gottlob Werner (1750–1817). In the second half of the 19th century, Russian academicians Nikolai Ivanovich Koksharov (1818–1892) and Pavel Vladimirovich Eremeev (1830–1899) jointly created works devoted to the study of crystal shapes. The summaries compiled by them gave science a powerful descriptive basis, a kind of morphological standard of mineral species, earning the highest assessment of contemporaries and followers. Vladimir Ivanovich Vernadsky, evaluating the scientific activity of N.I. Koksharov wrote: "We can say that only thanks to N.I. Koksharov we have an accurate knowledge of the geometric shape of the main groups of minerals, and only after his works were correct generalizations and comparisons of those phenomena possible for the cognition of which the form is the main and decisive one."*
Until now, the thorough work of the German crystallographer Victor Moritz Goldschmidt (1853–1933) – the multivolume Atlas of Crystallographic Forms, which collected all the images of mineral crystals published by that time, has retained its significance and popularity.

> *Such outstanding scientists as Evgraf Stepanovich Fedorov (1853–1919) devoted their lives to the study of the forms of natural crystals, their greatest achievement being the rigorous deduction of all possible space groups.*
>
> *Anatoly Kapitonovich Boldyrev (1883–1946) created a large compilation called "Identifier of Crystals". At the Leningrad Mining Institute, A.K. Boldyrev founded one of the first X-ray laboratories in the USSR, the first and only crystal-modeling workshop in the USSR, two goniometric laboratories, and a crystallization laboratory for educational and scientific purposes. The successor of this school and promoter for ontogeny in the study of natural crystals was Dmitry Pavlovich Grigoriev (1909–2003) [3].*
>
> *Vladimir Ivanovich Vernadsky (1863–1945) and Alexander Evgenievich Fersman (1883–1945) also made large contributions to the study of natural forms of crystals.*

However, geometric crystallography cannot provide all the answers to many questions concerning the shapes of real crystals. For example, why are the edges of natural crystals not perfectly smooth? What causes distortion of crystal shapes? Only an in-depth study of the origin and history of crystals can provide definite answers to these questions.

The process of formation and growth of crystals is called crystallization. It is the transition of a substance into a crystalline state by stacking atoms, ions, and molecules into a crystal lattice.

Crystals grow when a substance passes from any state of aggregation to a solid-state. Crystallization can occur from melts, solutions, and gases. No more than 20 % of mineral species crystallize from melts, but they account for over 90 % of the mass of the Earth's crust.

These primarily include light- and dark-colored rock-forming minerals. Crystallization from aqueous solutions covers approximately 90 % of mineral species. These include most of the ore minerals. Not more than 2.5 % of mineral species crystallize from gases and vapors.

Crystallization of a substance is initiated by the development of crystallization centers, or germs, and their achievement of a critical value after which the addition of the particles would make their growth energetically more favorable than their destruction. Most often, such germs disintegrate as a result of either natural oscillations or their bombardment with free particles.

For most substances, nucleation of crystals occurs as a result of two processes – decreasing temperature or increasing concentration of a substance. Decreasing temperature decreases the motion of particles (atoms and ions), allowing them to be grouped into a space lattice, and hence, leading to the development of germs. Increasing the concentration of a substance in a solution or gas leads to an increase in the probability of particle collisions, and hence, to the development of germs [5].

Thus, crystal growth can be considered the process by which the smallest crystalline particles – germs – reach macroscopic dimensions. It should be noted that crystallization does not take place in the entire volume of space, but only proximal to germs.

The factors influencing the development of germs are not limited to cooling and an increase in the concentration of a substance in solution or viscosity of a melt. Germ development is also influenced by the presence of extraneous crystal fragments or dust grains on which particles can be collected, thereby simplifying the onset of crystallization. At some point, a change in external conditions stops crystallization, and sometimes even causes dissolution (melting) of the crystals. Following the crystallization of one mineral, the formation of others may begin. These later-formed minerals will occupy the space interstitial to the initially formed crystals.

Crystallization occurs spontaneously because it reduces the free energy of the system. In other words, the crystallization process is energetically beneficial [3].

> ***Information:*** *The main energy laws governing the processes of nucleation and growth of crystals were established at the end of the last century by Josiah Willard Gibbs (1839–1903), an outstanding American physicist and one of the founders of the theory of thermodynamics.*
> *In 1927–1928. German physicist Walther Kossel (1888–1956) and I.N. Stranski jointly proposed a molecular kinetic theory of perfect crystal growth.*

According to the theory of Kossel-Stranski, the growth of crystals occurs by the addition new layers of matter onto a crystal in a manner such that new faces grow parallel to themselves (Fig. 11). The growth of a face per unit of time in a direction perpendicular to its plane is called the *face rise rate*. Due to the growth of the faces parallel to themselves, the angles between any two faces of the growing crystal remain constant [3].

Thus, during the growth of a crystal, a competition takes place, with some facets growing and displacing other facets. The main thing to remember is that it is those edges that grow slowly that increase in size (Fig. 11).

The layer-by-layer growth model explains the flatness of crystal faces, but does not provide answers to many other questions – for example, why do crystals having flat facets continue to grow? After all, as calculations demonstrate, for the continued growth of an ideal flat-faceted crystal, enormous supersaturation of a substance is necessary. This contradiction is explained by another aspect of crystal growth, which is the importance structural defects to the growth of real crystals.

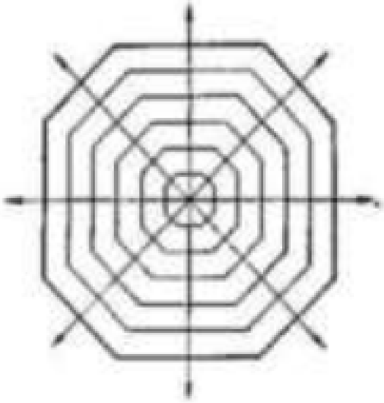

Fig. 11. Arrows show the speed and direction of face growth

> ***Information:*** *In 1949, two Nobel Prize laureates, the German-American physicist James Frank (1882–1995) and the English chemist Derek Harold Richard Burton (1918–1998) proposed a model of dislocation growth rather than layer-by-layer crystal growth (Fig. 12). The essence of this idea is that on the edge of the growing crystal there is a non-vanishing step that grows over itself in spiral, rather than flat, layers. The existence of such a step is explained by defects in the regularity of the structure of real crystals, or by a helical dislocation.*

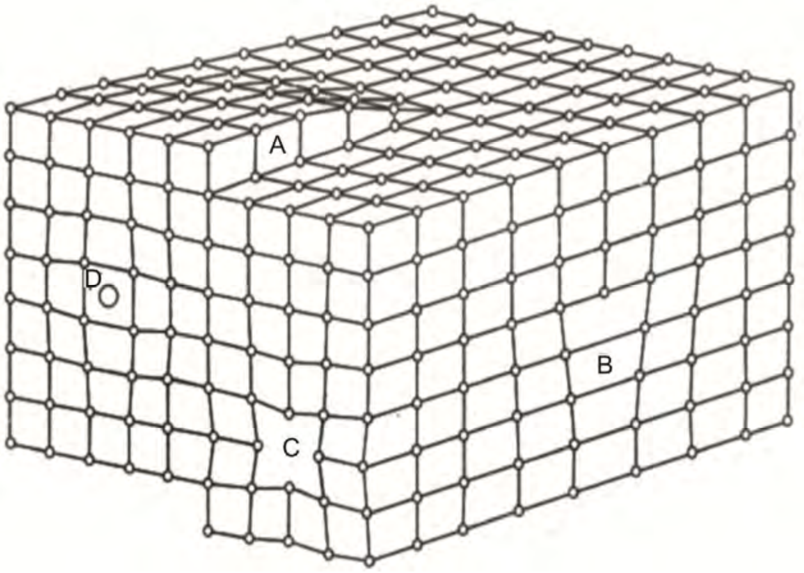

Fig. 12. Diagram of the structure of a crystal lattice with various types of point defects that promote the growth of crystals. Screw dislocation (A), edge dislocation (B), vacancy (C), and the insertion of an atom into an intervening space (D)

Defects are capable of moving and, at temperatures close to the melting point of a crystal, the rate of movement of vacancies can be several meters per second. However, this movement is chaotic and more reminiscent of treading in place (i.e., at any given moment a vacancy is displaced by only a few micrometers). Yet, this movement allows atoms to diffuse within crystals, making recrystallization in the solid-state possible [3].

The growth rates of different edges of a crystal structure vary. The growth rate is often determined by the rate of heat and mass transfer, the presence of dislocations (i.e., structural defects), impurities, solution supersaturation, and concentration fluxes. All other things being equal, where a depleted solution is quickly replaced with a fresh solution, the edges will grow faster. The directed influx of a solution causes deposition of a substance on the crystal faces facing the direction opposite to the flow. For example, when a crystal grows in a foliated rock (e.g., shale), it will become elongated in the direction of the foliation since the permeability of the rock is at its maximum in this direction and the solution is renewed faster. The gravitational force, which is always directed vertically, also has a noticeable impact on crystal habit. A depleted solution, which has a lower density than a concentrated solution, moves upwards, forming a so-called concentration flux, which causes the outstripping growth of the "leeward" upper side of the crystal.

Faces, the atomic networks of which are densely covered with material particles, dominate Crystals. That is, they have the highest *reticular density*. On the other hand, the slow growth of faces typically increases their surface area, since fast-growing faces disappear over time (Fig. 13). Therefore, it can be said that *faces that have the lowest growth rate and the highest reticular density cover crystals.*

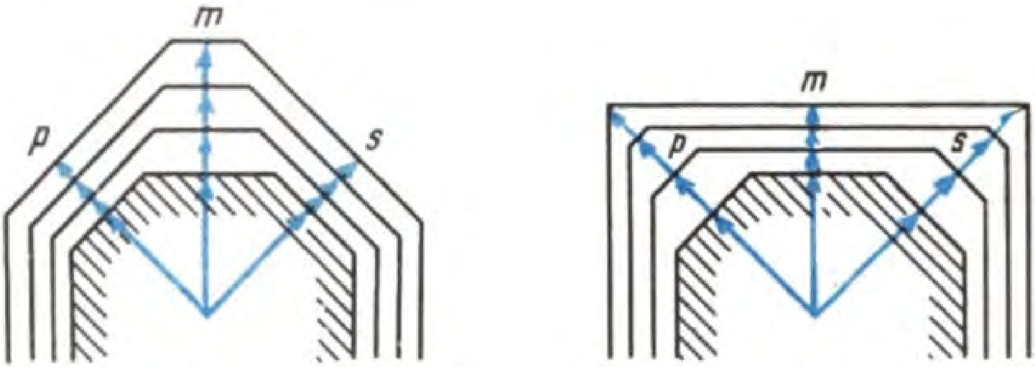

Fig. 13. Effects of different growth rates of faces on crystal shape.
*In the left crystal, face **m** grows faster than faces **p** and **s**. In the right crystal, face **m** grows slower than faces **p** and **s***

The faces of natural crystals often deviate from ideal polyhedra in the form of *vicinal formations, depressions, zones of dissolution,* and *shading*.

Vicinal formations are growths in the form of gentle pimples, slightly deviated from the plane of the main facet. They are specific to each mineral and each simple shape. These formations originate due to the local enhancement of growth resulting from the appearance of some sort of inhomogeneity (i.e., a defect around which the nucleation of new layers is facilitated). Inclusions of other minerals and damages, such as scratches and cracks, can also become sites of nucleation. The growing crystal copes with them on its own – increased growth occurs around the damages as a result of irregularities on the smooth face and a growth scar is formed (similar to a wound healing). This has been termed "scar vicinity" by GG Lemmlein in his book "Morphology and Genesis of Crystals".

Cavities and zones of dissolution in crystals are the result of undersaturation of the solution in which the crystals are growing. Once the solution becomes supersaturated again, the crystals that began to dissolve will begin to grow again. The solubility of a crystal increases markedly due to structural defects and impurities. If the growth of a crystal is accompanied by the appearance of *vicinal formations,* then during dissolution (erosion), *stains* will appear – these are called *etching figures*. The shape and symmetry of the etching figures depend on the crystal structure. Different crystal faces are susceptible to different degrees of dissolution; throughout a period of dissolution, the crystal gradually becomes covered by rapidly dissolving faces (whereas slowly growing faces predominate during growth). In general, the vertices and edges of crystals dissolve quickly, and so dissolution causes a crystal to become more rounded and curved [3].

Combination shading reflects the competition between the faces of various simple shapes in their height. It is presented as narrow strips of edges of adjacent shapes. Combination shading is always parallel to the edge that separates the faces.

As noted above, in nature, crystals do not always have an ideal shape as if we are accustomed to seeing in crystallographic models. Due to the influence of external factors, crystals are often distorted and deviate from the ideal polyhedra of a particular system.

For example, when a solution as the nutrient medium does not mix well and the concentration of solutes is heterogeneous, uneven crystal growth prevails. In this case, the growth of faces begins to lag relative to the growth of vertices and edges, which, in contrast to the faces, are surrounded by a nutrient medium on all sides. This situation arises in supersaturated, immobile solutions in which diffusion is difficult, such that the solution is not able to provide a uniform supply of a substance to the crystal. Crystallization in such a growth medium generates complicated growth figures – *skeletal crystals.* Under certain circumstances, the skeletal shape allows the crystal grow more quickly. Here, it is appropriate to quote the opinion of the prominent Soviet crystallographer NN Sheftall, "a crystal, first of all, seeks to grow, and secondly – to grow most perfectly."

Snowflakes are a classic example of *skeletal crystals*. This type of rapid growth also includes crystalline dendrites. The reasons for their occurrence are the same as for skeletal crystals – uneven nutrient supply and poor heat dissipation. Dendrites are often found in narrow cracks in rocks. Each branch tends to grow in the direction of a saturated solution, away from a competing neighboring branch. Because of this, the dendrite expands continuously sideways. This growth pattern determines the shape of the dendrites, similar to shrubs and trees (Fig. 14). Hence the name – "dendros", the Greek word for tree [3].

Fig. 14. Manganese dioxide dendrites (Germany)

It has long been noted that dendrites form, without exception, in supersaturated solutions and in supercooled melts. An important role is played by impurities inhibiting crystal growth – under the same conditions, dendrites develop in contaminated envinronment, whereas ordinary crystals develop in uncontaminated medium. Why this happens was explained by USSR researcher D.D. Saratovkin in 1950 in his book "Dendritic Crystallization". A growing crystal extracts pure substances from a solution or melt, causing impurities such as Cu, Mn to accumulate; these impurities then act to inhibit the growth of crystal faces. However, near the vertices and edges of crystals, the impurities are pushed aside by adjacent faces, creating regions with less impurites; these gaps ensure the predominant growth of crystal vertices and edges. At the fracture of the contour of the formed appendix, a branch arises; a branch of the second generation of crystals grows on it over time. *Antiskeletons* are much less common in nature – they are crystals with convex faces that grow faster than the edges and vertices of the crystals. A possible prerequisite for their occurrence is less non-equilibrium compared to skeletons (system openness): with the same mass, the antiskeleton has a smaller surface. The development of antiskeletons can be facilitated by the preferential adsorption of inhibitory impurities onto the edges and tops of crystals. The occurrence of antiskeletons is more likely at lower degrees of supersaturation.

A.E. Fersman clearly showed in his sketches, using diamond crystals as an example, how their crystal shape changes from skeletal to antiskeletal depending on changes in external factors in the growth environment (Fig. 15).

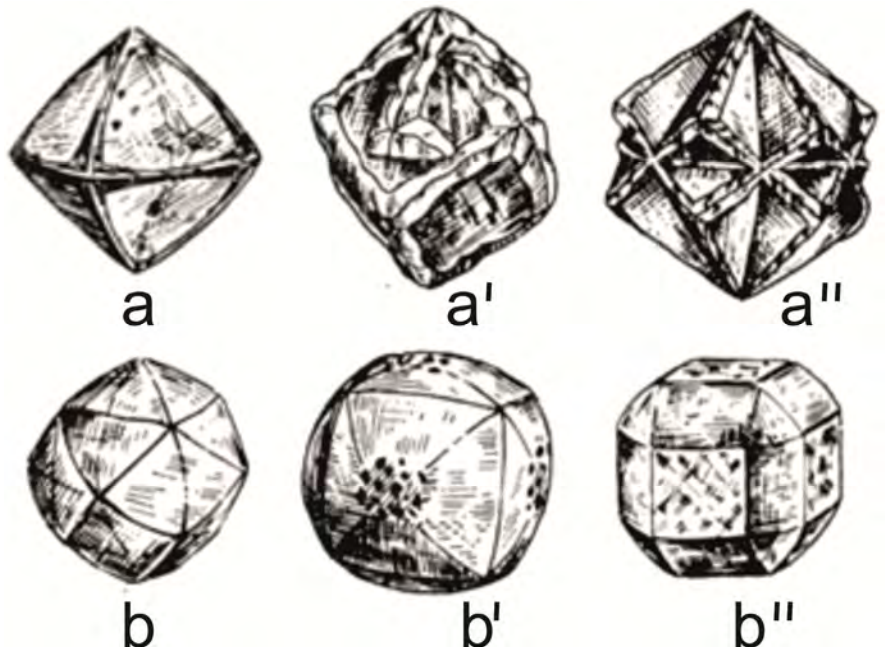

Fig. 15. Various skeletal forms of diamond crystals: Octahedron (a); Typical cruciform growth (twins) of octahedra (a', a''); Anti-skeletal form of diamond crystals (b); Tetrahexahedron (b'); A combination of hexahedron, octahedron, and rhombododecahedron (b'')

Presumably, as kimberlites (the host rock of diamonds) crystallize, high pressure create a condition for solubility, which leads to the formation of skeletal forms – with decreasing pressure, diamond crystals begin to grow more quickly.

Fig. 16. Bissolite crystals – whiskers of actinolite

In addition to skeletal and anti-skeletal crystals, *whiskers,* or hair-like crystals, can also form (Fig. 16). In M.N. Maleev's book "Properties and Genesis of Natural Filamentous Crystals and Their Aggregates", the appearance of elongated crystal shapes is caused by the joint, mutually reinforcing action of several factors, each of which creates a tendency towards elongated crystal growth. Due to some peculiarity in the crystal structure, such as the presence of a screw dislocation, the crystal begins to grow predominantly in one direction from the earliest stages of its growth.

If a solution has a low degree of supersaturation, crystal growth proceeds slowly, and a perfect structure with few dislocations is formed, which are located mainly along with the crystal elongation. When a solution is insufficiently supersaturated for the nucleation of new layers, growth of the side faces ceases, but growth continues at the tip of the crystal, as it is here where the axes of the screw dissolutions exist. The tendency towards filamentous growth is enhanced by selective absorption of impurities by the lateral faces [3].

All of the above discussion referred to the formation of individual crystals. However, in nature, individual, isolated crystals do not commonly form. Rather, crystals commonly occur as *crystalline intergrowths (aggregates)*, which, depending on their mutual orientation in space, can be subdivided into *naturally determined*, *approximately regular,* and *irregular* intergrowths. Irregular intergrowhts include aggregates of variably oriented crystalline grains, in which the mutual orientation is more or less random. An example of *approximately regular crystalline aggregates* are *druses* (mineral brushes) – clusters of crystals having a common substrate and an approximately regular orientation of individual crystals. *Regular intergrowths* include *epitaxy*, *parallel crystal jams*, and *twins*.

Epitaxial intergrowths reflect the regularly oriented growth of one mineral onto another. As a rule, the overgrown crystals are equally oriented on the individual base – the "matrix". It is the equal orientation of both crystals that differentiates epitaxial intergrowths from irregular mineral intergrowths. More than 400 epitaxial pairs are described in the mineralogical literature, however, one should not assume that the discoveries of new epitaxial intergrowths will end there. Epitaxy can manifest itself both at the micro and macro level.

Already in 1908, V.I. Vernadsky noted that the lowest-energy crystal interface arises during epitaxial coalescence. In this regard, epitaxial growth can be advantageous over the formation of separate crystals and random, undirected growth. The surface of the matrix (like any crystal) is a type of structural defect (i.e., a violation of the homogeneity of the structure; a localization of free energy), and epitaxy heals and corrects this defect.

Graphic granite, which represents the natural integrowth of feldspar and quartz, is a good example of epitaxial growth. Such intergrowths occur, according to A.E. Fersman, by the simultaneous crystallization of quartz and feldspar from *eutectic melts*. A *eutectic melt* is one in which a certain combination of two (or more) solid phases simultaneously crystallizes. Due to the rounded, flattened shape of quartz intergrown with feldspar similar to the shape of fish, A.E. Fersman called them "ichthyoglipts"; since the quartz crystals are often parallel to each other, they create a visual effect similar to that of a school of fish [3].

Autoepitaxy is a special case of the formation of parallel intergrowths. *Autoepitaxy* (homoepitaxy) is the oriented growth of a crystalline substance onto a substrate that is similar in structure and chemistry. The difference between the growing crystal and the substrate may lie in the number of impurities that they contain, which makes it possible to form homogeneous electron-hole structures.

An example of autoepitaxy is the commonly encountered autoepitaxic intergrowths of quartz. Oriented nucleation occurs in locations where surface energy is concentrated – at the vertices separating the prism and the rhombohedral facets of the head. The growing crystal of the second generation merges and forms an epitaxial corolla or a thickened head, called a "scepter". The formation of new crystals can be associated with changes in external conditions. This is evidenced by a change in color (e.g., from colorless to violate in quart (Fig. 17).

Fig. 17. Scepter quartz crystal

In autoepitaxy, the crystal structure of the newly formed crystal continues the structure of the susbtrate crystal, such that both constitute essentially one crystal. All of the structural elements of the individual crystals are located in parallel. As a result, the faceting elements – faces, edges, and vertices – are equally oriented. In addition to autoepitaxy, parallel intergrowths of multi-headed crystals also occur.

Both *autoepitaxial* and *multi-headed growth* lead to the same result – parallel intergrowth. However, from a genetic point of view, they are not the same process. Autoepitaxy begins with the formation of a new embryo, while multi-headed growth occurs because of a change in habit or regeneration of an already grown crystal. Parallel intergrowth is a purely morphological term – it simply refers to the growth of parallel-oriented crystals, regardless of the reason for the orientation. Parallel intergrowths can form with several cystals having the same orientation, epitaxially growing on one matrix, or by the separation of crystals along cleavage directions.

Like parallel intergrowths, *twins* refer to regular intergrowths of the same mineral species, in which the intergrowth surface belongs simultaneously to the same flat networks of both individuals. However, if in parallel aggregates the structures of individuals on both sides of the intergrowth surface continue each other and are obtained from one another by a simple parallel transfer, then in twins the structures are connected by axial or mirror symmetry.

Thus, a *twin* is the natural splicing of two homogeneous crystals in which one crystal is a mirror image of the other, or one crystal is removed from the other by rotating 180°. The plane along which the crystals are mirrored is called the *twin plane*. The direction around which one cystal can be rotated 180° to match the other crystal is called the *twin axis* (Fig. 18) [6]. Thus, in *twins*, several characteristic features should be distinguished: 1) enter angles, 2) twin axis, and 3) twin plane.

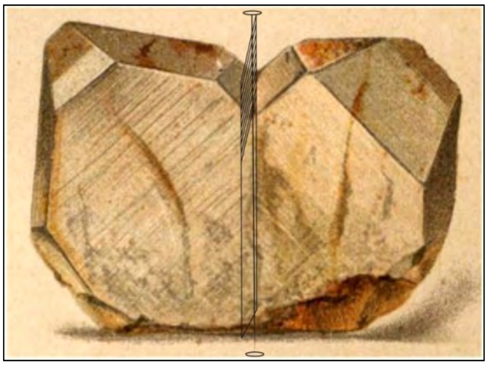

Fig. 18. Twin crystals of quartz

Why do twins form? Largely, the answer lies again in the energy benefit of the formation of such a natural fusion. The recessed corners play the role of the very step at which the deposition of particles is facilitated in comparison with a smooth edge. For growth, the entering angles of twins are even more convenient than in epitaxy, since the structures of individuals are identical. In other words, twinning is one of the ways a crystal can facilitate its growth. Suppose that, during the growth process, a "packing error" occurs – a group of particles was accidentally sited in a position that was asymmetric (or twinned) to their usual site. Due to the appearance of the entering angle, however, such an error is energetically favorable and there is no need to correct it. Growth continues with the twin packing of particles and the deposition of matter occurs predominantly in the entering angles.

The formation of twins is also facilitated by several factors: i) temperature fluctuations causing polymorphic change (e.g., transition from hexagonal β-quartz to trigonal α-quartz), ii) the presence of chemical impurities (e.g., in transformation twins), and iii) mechanical pressure (twinning decreases mechanical stress). It is for this latter reason (iii) that some twins of calcite and dolomite (including complex polysynthetic twins) are formed in marbles (Fig. 19). In some cases, crystals can be aggregated in such a way that every two neighboring crystals are oriented relative to each other in a twin position. Such twins are called *polysynthetic* [6].

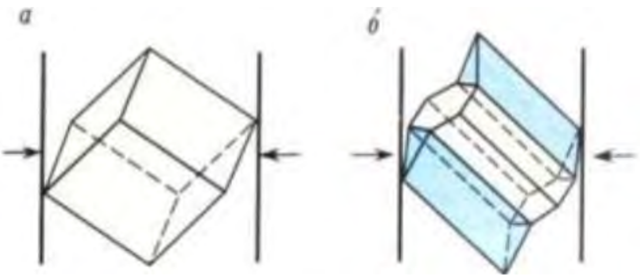

Fig. 19. Mechanical twinning: Rhombohedron of calcite before twinning (a); polysynthetic twin of calcite (b)

Polysynthetic twins can impart pseudochromatic (false) coloration to plagioclase crystrals (rock-forming framework silicates). Plates of polysynthetically twinned plagioclase crystals often have a microscopic thickness; it is for this very reason that a characteristic optical effect, *iridescence*, is associated with the planes of their intergrowths.

In the above disscussion, we were talking about twin crystals, or contact twins, when individual crystals are located on opposite sides of the twin plane (Fig. 20, *a*). In contrast to this, in *penetration twins*, crystals seem to penetrate each other (Fig. 20, *b*). In such twins, the crystals seem to overgrow each other, or penetrate through one another, touching along a complex, winding (stepped) surface [7].

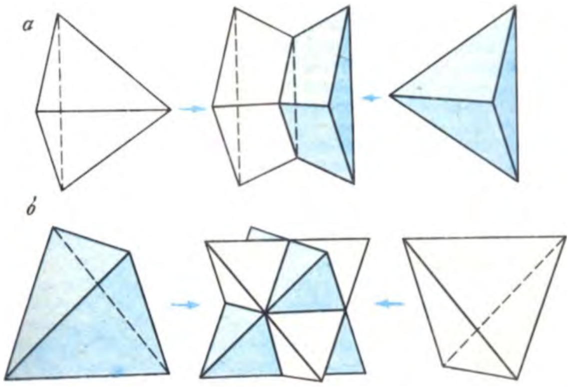

Fig. 20. Contact twins (a) and penetration twins of tetrahedra (b)

More than two crystals can participate in twinning – this is then terms *Trillings*, *fourling*, etc depending on the number of crystals involved [3]. There are several laws of twinning, which are determined by the directions in which crystals grow together. For example, in the *Spinel Law*, twins grow together along the face of an octahedron. In the *Aragonite Law*, the twin plane is the face of a rhombic prism. An example of a trilling in the Aragonite Law is the intergrowth between aragonite and cerussite, which has a pseudohexagonal symmetry.

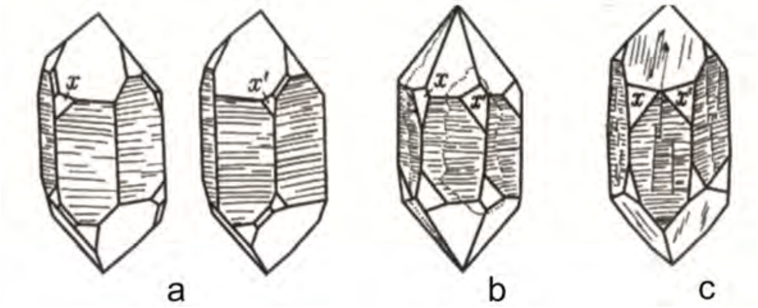

Fig. 21. Quartz twinning:
Left and right crystals (a); Dauphiné twin (b); Brazil twin (c)

With respect to quartz, about 18 laws of twinning have been described, the most common being twins aligned with the L_3 axis; these are called Dauphiné and Brazil twins. The peculiarities of quartz twinning are associated with the fact that its structure allows the existence of left and right crystals, which differ in the arrangement of small x faces (Fig. 21, *a*). In Dauphiné twins, two identical individuals sprout into each other (Fig. 21, *b*), whereas in Brazil twins – left and right (Fig. 22, *c*).

Exercise 9. ***Answer the following questions:***

1. What are the deviations of the shapes of real crystals from ideal ones?
2. What are the main causes distortion of crystal shapes?
3. Define what is a scepter?
4. Why are the edges of natural crystals not perfectly smooth?
5. What twins are named polysynthetic?

Exercise 10. ***Name the mineral by the picture***

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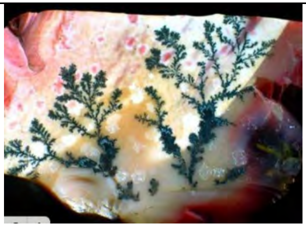
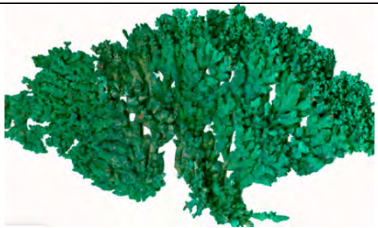
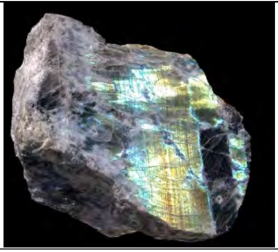
2		5	
3		6	

Exercise 11. ***Choose and explain why true or false the following statements:***

1. Crystallization can occur from melts and solutions;
2. Snowflakes are a classic example of antiskeletal crystals;
3. Epitaxial intergrowths reflect the regularly oriented growth of one mineral onto another.

PART 2. MINERALOGY

> *Thoughts are silent.*
> *Words do not convey their essence.*
> *Only a stone will tell you about everything*
> *Lying silently before my eyes...*
>
> *Vietnamese wisdom*

Knowledge of the mineral world occurred mainly in connection with the practical needs of mankind. Moreover, regardless of how prosaic it may sound, minerals were used primarily to extract valuable components from them – noble, non-ferrous, ferrous, and rare metals and non-metals, trace elements, and various chemical compounds.

Mineralogy is the science of minerals. It is a study focusing on the crystal structure, chemical composition, physico-chemical properties, morphology, and formation and change of minerals, as well as the patterns of their occurrence in nature. It also focuses on the conditions and methods of artificial production (synthesis) of minerals and their application. The objects of study in mineralogy are *minerals* – physically and chemically homogeneous crystalline substances formed by natural physico-chemical processes.

2.1. Crystal habit and aggregate morphology

Crystal habit the appearance of crystals, called crystal habit, is determined by the predominance of certain simple shapes. The morphology of individual mineral is expressed in different ratios of their length, width, and thickness. Depending on these parameters, it is customary to distinguish the following morphological types of crystal habits:

1. *Isometric* crystals are characterized by the same length, width, and thickness values. Typically, the *isometric* appearance of crystals is characteristic of minerals crystallizing in the isometric system. Examples of isometric minerals are *diamond, magnetite, garnet, sphalerite, and pyrite.*
2. *Elongated* crystals are those in which the length is significantly greater than the width and thickness. Elongated crystals include *columnar*, *needle*, *prismatic*, *fibrous*, and *filamentous* crystals. The elongated habit of crystals is characteristic of minerals crystallizing in the lowest/predominantly

medium category or symmetry (i.e., hexagonal, tetragonal, and trigonal systems). Examples of elongated minerals are *tourmaline, beryl, and asbestos*.

3. *Flattened (tabular/lamellar)* crystals are those in which the length and width are significantly greater than the thickness. This habit is typical of minerals crystallizing in the predominantly category or symmetry (rhombic, monoclinic, and triclinic systems). Examples of minerals with a flattened habit are *mica, molybdenite, and graphite*.

Aggregate morphology the main difference between crystal aggregates and individual crystals is that the latter arises from many growth centers, in which individual crystals begin to grow independently of each other. In aggregate growth, individual crystals unite in an aggregate and grow together, obeying the general laws of development. Mineral individuals are very often found in monomineral (composed of one mineral) or polymineral (composed of several minerals) intergrowths.

An *aggregate* is a set of interrelated and, as a rule, of the same type of crystals. The minerals included in aggregates may, however, different in appearace (e.g., size and habit). Nevertheless, the same minerals can be combined into different aggregates depending on environmental circumstances. To understand these environmental circumstances, we study aggregates to try to characterize the ways in which they form and then classify them into an ordered system. Several types of mineral intergrowths exist.

Granular aggregates can be subdivided based on grain size into *coarse-grained* (>5 mm), *medium-grained* (1…5 mm), *and fine-grained* (<1 mm). Based on the distribution of grain sizes within a mineral aggregate, the aggregate can be classified as either *equigranular* or *non-equigranular*.

Druses are aggregates of regular, well-formed crystals that have grown in cavities (voids) of rocks on any surface (Fig. 22). They are densely aggregated crystals bounded by the heads and faces of the crystals that make it up on one end, and the substrate on which they have grown on the other. Druses are characterized by two main qualities – the geometric shape of the individual crystals and the chaotic arrangement of the crystals.

Idiomorphic crystal faceting of individual crystals in a druse is indicative of growth in free space. Each individual crystal also has areas of induction surfaces where a crystal jointly grew with neighboring crystals and an imprint of the substrate on which the druse grew. The idiomorphic portion of individual crystals carries information about the growing environment, including nutrient supply and orientation in space. It happens that a druse is composed of crystals of different ages. Which of them are older and which are younger can be judged by their mutual arrangement – crystals of the younger generation are nucleated and grow on older crystals, and fill the space between the older crystals.

Fig. 22. A druse of amethyst quartz crystals

Why do we see approximately parallel groups of individual crystals oriented perpendicular to a common substrate since crystallization centers are initially oriented chaotically/randomly? The reasons lie in the growth and joint crystallization process of the aggregate. As the ensemble of crystals is forming, the crystals, one by one, begin to touch and grow together, with only the successful minerals surviving. For example, crystals growing obliquely to the substrate will eventually bump into their neighbors and their growth will stop (Fig. 23, *a*, *b*); at this point, they will be overgrown by the larger crystals (Fig. 23, *c*). As a result, only those crystals that grow perpendicular to the substrate and, hence, do not interfere with each other will continue to grow (Fig. 23, *c*, *d*). Such organization of growth is not uncommon.

This growth process can be qualitatively illustrated using a graph of number of crystals growing vs. distance from a substrate (Fig. 23, *e*). Within a short distance of the substrate, the number of crystals does not change and all the nucleated crystals grow. With increasing distance from the substrate, crystal growth enters a stage of geometric selection in which the number of growing crystals gradually decreases. Eventually, crystal growth enters a stage of parallel-columnar growth; at this stage, the number of crystals does not change as geometric selection ceases to function. As is evident in the graph, there is no sharp transition between the stages; rather, they gradually change from one to another.

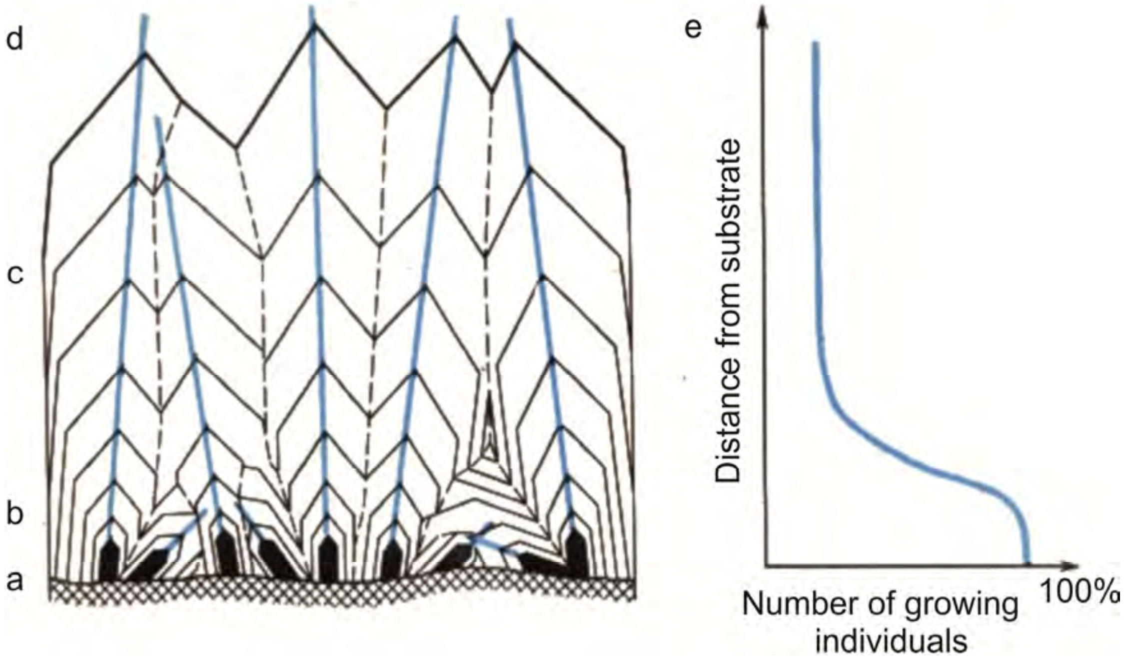


Fig. 23. The process of druse formation: Initial growth of separate crystals (a); A Druse congeries (b); Parallel-columnar congeries (c); A Druze (d); Graph of geometric selection (e)

> ***Information:*** *In the 1920, the USSR Soviet physicist and crystallographer Alexander Vasilyevich Shubnikov (1887–1970) introduced the concept of geometric selection. In 1949, Academician Andrei Nikolaevich Kolmogorov (1903–1987) developed its mathematical theory.*

Druses are formed not only because of geometric selection in free growth conditions, but they can also grow in more confined spaces, such as a narrow gap or fracture. In this case, the crystals grow towards the opposite wall of the fracture and rest against it. Growth stops at this point resulting in the final form of the druse congeries. If the fracture gradually opens, however, then the growth of the aggregate can continue and its structure will depend on the rate of opening. If the fracture opens quickly and the growing crystals cannot catch up to the opposite wall, geometric selection arises, leading to the formation of an aggregate of the first type.

The fracture can be also pushed apart by the crystallization pressure of the growing aggregate due to the release of a solid substance from the solution (i.e., it develops due to the energy released during crystallization). In this case, parallel-columnar aggregates of the third type are formed – so-called "grooved veins". Chrysotile, amphibole asbestos, and selenite (a fine-fiber variety of gypsum) can occur as such veins (Fig. 24).

Fig. 24. Parallel-columnar intergrowth of fine-fiber crystals of gypsum with a silky sheen (selenite), as example of "grooved vein"

In a parallel-columnar aggregate, mineral fibers are stretched parallel to each other and perpendicular to the walls of a fracture containing the vein; in the middle portion of the aggregate, there is a thin "hole" where the vein mineral occurs in the form of a druse, usually containing small foreign inclusions.

> ***Information:*** *The well-known mineralogist Arkady Grigorievich Zhabin (1934–2007) demonstrated in 1967 that autoepitaxy plays an important role in the formation of such parallel-columnar aggregates containing a hole.*

The growth history of the parallel-columnar aggregate begins with the formation of a hole – a thin druse crystallizing in a narrow fracture. Having grown from one wall to the other, the minerals begin to exert crystallization pressure on the walls of up to 200 N/cm^2 or more. This means that over every square meter of vein area, a force of 200 tons can act in both directions. For comparison, the floor of a modern house reinforced with concrete is stable for loads 1000 times less than the crystallization pressure exerted by growing parallel-columnar aggregates. The resulting force exerted by the growing crystals is, in many cases, sufficient to slightly expand the fracture due to the compaction of the rock.

In the tight space of the fracture, geometric selection takes place. It is accompanied by the growth of new crystals, which, at their inception, are epitaxially oriented along the dominant direction of the crystals, that is, perpendicular to the wall of the fracture. It should also be noted that under conditions where the walls resist the growth of the crystal aggregate, geometric selection could be regulated by the fact that the maximum crystallization pressure develops in the direction of greatest crystal growth. If resistance from the fracture walls is great enough, then growth of the aggregate is inhibited, ending at the stage of geometric selection. If, however, crystallization pressure exceeds the resistance of the fracture walls, then crystals oriented perpendicular to the fracture continue to grow, whereas crystals oriented obliquely to the walls are suppressed. Geometric selection and self-ordering of the druse are completed more quickly than in a druse forming in an unconstrained environment druse. After complete formation of the druse, columnar crystals grow from both of the fracture walls, oriented morphologically and crystallographically parallel to each other and perpendicular to the fracture [3].

The solution that feeds the growing crystal aggregate enters through both contacts of the rock, but typically moreso from one contact than the other. For example, with the growth of selenite in veins, gravity improves the supply of the solution to the upper contact of the vein and weakens the supply to the lower contact.

1. Radial fibrous aggregates and nodules are spherical, sometimes irregular, concretions with a radial fibrous or shell structure. The difference between *radial fibrous aggregates* and *nodules* lies in the mechanism by which matter is deposited. Radial fibrous aggregates grow similarly to parallel-columnar aggregates, with the only difference being that crystals grow on a closed convex surface, such as a grain of sand or rock, rather than a flat surface. A zone of geometrical selection exists in the central part of the radial fibrous aggregate. These aggregates can appear similar to spherulite. If radial fibrous aggregates are genetically similar to parallel-columnar aggregates of the first type, then nodules are similar to the third type. In nodules, crystals are also located around a central axis similar to the radial fibrous aggregates. The space for crystal growth is freed up by crystallization pressure. Aggregates in the form of nodules grows in loose, pliable environments, such as clays and sands. Sometimes organic residue can serve as the seed for crystal growth. The growth of nodules occurs from the center towards the edges. As a rule, nodules are characteristic of minerals formed by sedimentary (surficial) processes. If growth takes place in a fracture or the membrane of a solution, a flattened aggregate forms – a "sun" (Fig. 25). Typical minerals that form nodules are siderite, marcasite, and pyrite (Fig. 25) [3].

2. Concretions are minerals that form in rock cavities. Here the growth of crystals is directed inwards from the edges of the cavity towards the center. *Geodes* and *amygdules* are types of secretions, the former being >2 cm in diameter and the latter being <2 cm in diameter. This type of mineral aggregate has a dense population of crystals along the edges of the cavity, but an empty center.

Fig. 25. A flat disc-shaped radial fibrous nodule of (8.5 x 0.6 cm).
(Sparta, Randolph, Illinois, USA)

3. Ooides are aggregates consisting of small crystalline balls, the size of which can reach up 2 cm in diameter. Similar rounded concretions that are >2 mm in diameter are called *pisoides*. In cross section, these crystalline balls have a predominantly concentric/zonal structure. Ooides form in aqueous environments when a substance in the solution is grouped around grains of sand or air bubbles. With the growth of ooides and pisoides, a grain of sand or other foreign body is enveloped in layers of a mineral, forming a rounded body. Bauxite (a mixture of hydroxides of aluminum, iron, and clay minerals), some iron ores, and calcite and aragonite deposits from spring waters can all form as ooides aggregates.

4. Stalactites and stalagmites. Stalactite means "leaked drop by drop" in Greek. Imagine that a drop of rain remained on the ceiling of a cave for several hundreds of years. After the water evaporated, a tiny ring of limestone would have crystallized on the ceiling. If more and more drops of rain went through the same process, they would all leave behind limestone in the same place. Over time, the rings of limestone would develop into an icicle-like form, which will eventually grow into a *stalactite* (Fig. 26). If thousands of drops of water fell on the floor of the cave over the course of hundreds of years and left behind limestone after evaporation, the result would be a "*candle*" or stalagmite.

Fig. 26. Stalactite cave formations

Stalagmites are usually thicker than stalactites resulting from the water splashing as it hits cave floor. Both stalactites and stalagmites grow at different rates, but overall, their growth is rather slow (relative to the lifetime of humans) – hundreds to thousands of years. If the cave is not very tall, then stalagmites and stalactites will eventually grow together and fuse.

5. Reniform/botryoidal aggregates and "collomorphic" masses. Many authors do not consider it necessary to distinguish between "dripstone" (stalactites and stalagmites) and "collomorphic" masses, referring to them as the same type of aggregate.

> ***Information:*** *In the first half of the last century, the idea arose that agates form through layer-by-layer deposition of chalcedony from a solution entering a cavity. In 1915, the German chemist Raphael Eduard Liesegang came up with a completely different point of view – he associated the origin of agates with rhythmic diffusion. According to Liesegang, a cavity is first filled with a colloidal clot, or silica gel. The gel consists of microscopic (no more than* 10^{-5} *cm) silica particles, weakly bound to each other and immersed in an aqueous medium. Then, other substances seep and diffuse into the gel from the walls of the cavity, forming "Liesegang rings". As a result, the silica gel becomes stained and separated into concentric layers. In the final stage, the gel crystallizes into chalcedony, which inherits the concentric layered structure of the gel. In 1934, the famous USSR mineralogist P.P. Pilipenko, relying on natural material, criticized the rhythmic diffusion hypothesis. He pointed out; in particular, that rhythmic diffusion causes the formation of blurred stripes, whereas the layers in agates are sharply demarcated. The ordered structure of agates*

> *indicates a certain sequence of crystallization. Since the centers of spherulites are located on the surface of an adjacent layer, it must be concluded that this layer crystallized earlier. Hence, it follows that crystallization proceeded layer-by-layer from the walls of the cavity towards the center. The gel would crystallize simultaneously throughout the entire volume. In this case, water would separate from the gel, resulting in a decrease in volume of the gel, causing voids to inevitably remain in the cavity. Meanwhile, agates without voids are quite common. On the other hand, it is not clear where the mass of the gel could have gone in the formation of a thin-walled geode, in which a thin layer of chalcedony on the walls occupies only a small portion of the total volume. Thus, the rhythmic diffusion hypothesis is internally contradictory and at odds with geological observations. It seems that after the works of P.P. Pilipenko, the accept mechanism of agate formation is by secretion, that is, by sequential growth of chalcedony from the periphery to the center of a cavity.*

In 1970, the mineralogist V.I. Stepanov, using an example of chalcedony near Moscow, demonstrated the problems with a gel origin of "collomorphic" aggregates. The high viscosity of the gel would prevent the deposition of crystalline nuclei on the substrate. As a result, crystallization would not be limited to one "front" of the gel, but would inevitably occur throughout the entire mass of the gel as it contains many seeds in the form of colloidal particles. Therefore, during crystallization of the gel, an ordered spherulite crust would not form, but rather a granular aggregate with crystals more or less evenly distributed in space would be obtained. This is how the crystallization of viscous liquids always occurs. For example, in the case of a sugar syrup or honey, a homogeneous mass is obtained upon crystallization rather than separate layers.

In the discussion about "collomorphic" aggregates, another question of interest is the idea of so-called "drip forms". Drip aggregates are aggregates that arise during the flow of a mineral-forming liquid over a substrate onto which the mineral grows. The deposition of silica gel, which results in the formation of a hollow geode of "collomorphic" chalcedony, was approximately the same. Although the hypothesis of the collomorphic origin of agate and chalcedony geodes turned out to be erroneous, the expression "drip forms" out of habit is still used regarding the formation of chalcedony crusts in geodes (i.e., they form when a solution runs down the walls of a geode). Even R. Liesegang gave such formations the name "pseudo-stalactites" since the "icicle" crystals look similar to cave stalactites. In the mineralogical literature, pseudo-stalactites are a common example of "drip forms". However, the universal Curie principle puts everything in its place and convincingly proves the fallacy of ingrained opinion. Let us assume that a fresh solution drained from protrusions out of the roof of the cavity. The fresh solution would migrate down the "pseudo-stalactite" and continuously precipitate minerals; as a result, the concentration of the solute in the solution would decrease from the roof towards the tip of the "pseudo-stalactite". The "pseudo-stalactite" is, therefore, thicker at its base where it contacts the roof. Another option is possible whereby minerals are precipitated mainly at the lower end (tip) of the "pseudo-stalactite" where the solution is retainied as drops. Accordingly, "pseudo-stalactites" generally have a cone shape corresponding to the symmetry of mass transfer from the flowing solution. In addition, the growth of "pseudo-stalactite" in length would occur by deposition of layers mainly at the lower end across its longitudinal axis. However, none of these characteristics are observed. The diameter of "pseudo-stalactites" does not change along its entire length, and its layers have approximately the same thickness and are located concentrically around the axis (Fig. 27). In other words, the shape of "pseudo-stalactites" are similar to a cylinder. Each layer is a continuation of the corresponding layer of the chalcedony wall of the geode, meaning that the layers grew simultaneously on the "pseudo-stalactites" and the geode walls. Further, it is impossible to imagine how and why the "drip" "pseudo-stalactites" could branch and bend, sometimes by up to 180°.

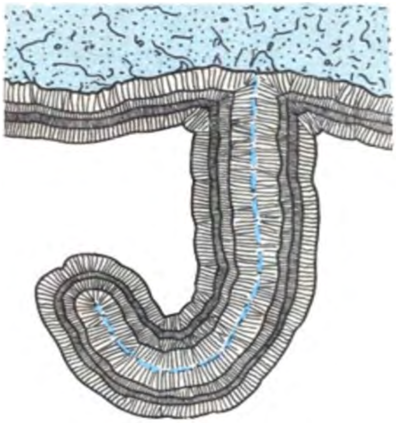


Fig. 27. The crystalline structure of "pseudo-stalactite"

According to Paul Ramdohr, at first, a cavity is filled with a silica solution, most likely in the form of alkali metal silicates. Then, through pores in the walls, solutions containing salts of heavy metals (e.g., iron, manganese) begin to seep into the cavity. This is probably due to some changes in the geochemical environment. At the mouth of the pores, the external solution slowly come into contact with the silica solution contained in the cavity, resulting in the walls of the cavity being covered with a membrane film. Because of osmotic pressure, the membrane is peeled of the walls and is ruptured, resulting in the formation of membrane tubes with bends and branches. Since the membrane is heavier than the solution, the force of gravity causes the tubes that formed at the top of the cavity to hang vertically, whereas those that formed at the bottom of the cavity fall flat and merge with the membrane lining. Therefore, only a few of tubes survive their formation process. After some time, the membrane hardens and turns into a thin substrate, onto which chalcedony layer-by-layer [3].

6. Minerals can also form as *incrustations, powdery coatings,* or *efflorescences*. They are thin films of primary minerals that cover the surface of objects, such as rocks, and typically form in surficial environments. Examples include limonite films on rock and malachite powdery coatings or patina on native copper or chalcocite.

7. Mottles are crystal formations that appear periodically in dry weather and disappear when it rains. They are loose crusts or films that appear fluffy or mossy. These formations typically comprise readily soluble salts, such as chlorides and sulfates.

8. Earthy masses are loose, soft, and mealy aggregates of amorphous or cryptocrystalline material. They most often form as a result of chemical weathering of rocks or where ores are oxidized (e.g., manganese ores).

9. Pseudomorphs are minerals that take the form of another mineral that they have replaced. Limonite pseudomorphs after pyrite is a classic example. The formation of this pseudomorph occurs when pyrite (FeS_2) is oxidized, breaks down, and is transformed to iron hydroxide ($Fe_2O_3*nH_2O$), or limonite, which fills the pyrite form.

10. Paramorph is the same as a pseudomorph, but both the original mineral and the mineral replacing it have the same chemical composition.

Exercise 1. *Match the crystal habit in column "A" with example of minerals in column "B"*

"**A**"	"**B**"
Isometric	**A** Beryl
Flattened	**B** Graphite
Elongated	**C** Asbestos
lammelar	**D** Garnet
Prismatic	**E** Tourmaline
Needle	**F** Mica
Tabular	**G** Emerald
Fibrous	**H** Actinolite

Exercise 2. ***Match the English terms in column "A" with their Russian definition equivalents in column "B".***

"A"	"B"
Pseudomorphs	**A.** Группа кристаллов, имеющая общую подложку
Powdery coatings	**B.** Хемогенные отложения в карстовых пещерах
Druse	**C.** Примазки
Stalactites	**D.** Образование одного минерала по другому с сохранением формы первого

Exercise 3. ***Describe the following types of aggregate morphology in English and translate these terms in Russian:***

- Mottles –
- Botryoidal aggregates –
- Geodes –
- Ooides –
- Paramorph –

2.2. Chemical composition of minerals

The chemical formula of a mineral describes *its chemical composition* in the form of a sequence of elements and subscripts, the latter of which indicating the relative numbers of atoms of each element (i.e., stoichiometry). *To write a mineral formula:*

First, *cations* (*positively charged particles*) are written in the order of increasing valence and quantitative content. Cations are usually represented by metals such as Mn, Fe, Ca, Ti and indicate *isomorphic substitutions*, parentheses are used, in which the substituting cations are separated by commas.

Anions (*negatively charged particles*), including simple anions, anionic groups, complex anions, and radicals, are written next.

Finally, The anions O^{2-}, $(OH)^{1-}$, F^{1-} are written after the radicals in order of decreasing valence.

Example: $Ca_5[PO_4]_3\,(F,Cl,OH)$ *– apatite.*

There are no chemically pure substances among minerals. Their structure includes various chemical impurities. In some minerals, the amount of such impurities is insignificant – these are called minerals of constant composition. Examples of such minerals include quartz SiO_2 (the amount of impurities does not exceed 0.01 %) and halite NaCl (purity > 99.9 %). Most minerals, however, contain impurities, and are termed minerals of variable composition. For example, sphalerite (ZnS) can have variable amounts of iron (Fe) ranging from 0 to 20 at. %. The main reason for the existence of such minerals is ionic substitution.

Ionic substitution, which was introduced into the literature in 1819 by E. Mitcherlich, is the formation of a homogeneous crystal of variable composition by the replacement of one element by another in the crystal lattice of a mineral. In other words, *ionic substitution* involves a *change in the chemical composition of a mineral, while maintaining its crystalline structure*. A necessary condition for such substitutions is the similarity in the chemical properties (e.g., size and charge) of the atoms replacing each other.

Several types of ionic substitution exist:

1. Isovalent – the atoms replacing each other have the same valence. An example of such substitution is that of Mg^{2+} for Fe^{2+} in olivine $(Mg,Fe)_2[SiO_4]$, in which all intermediate compositions of the mineral exist from pure $Mg_2[SiO_4]$ (fayalite) to pure $Fe_2[SiO_4]$ (forsterite). In this example, forsterite and fayalite act as end members of a continuum. Such isomorphism is considered *unbounded*. With *limited isomorphism*, the replacement of one element by another occurs within a limited range [7].

2. Heterovalent isomorphism is more complicated. One of the most important conditions for such isomorphism is the preservation of electroneutrality of the mineral. This requirement is fulfilled through paired substitution. An example of paired substitution occurs in plagioclase (albite $Na[AlSi_3O_8]$ to anorthite $Ca[Al_2Si_2O_8]$) in which one cation (Ca^{2+}) is replaced by a cation with a lower valence (Na^{1+}) and, at the same time, another cation (Al^{3+}) is replaced by a cation with a higher valence (Si^{4+}). In this case, the total charge is conserved. This paired substitution can be expressed as $Ca^{2+} + Al^{3+} = Na^{+} + Si^{4+}$.

Minerals that have variable composition formed as a result of isomorphism are called *solid solutions*. Depending on the mechanism of formation, solid solutions can occur via *substitution, insertion,* or *subtraction* [8].

Exercise 4. ***Choose and explain why true or false the following statements:***

1. Anions (positively charged particles), including simple anions, anionic groups, complex anions, and radicals, are written next.

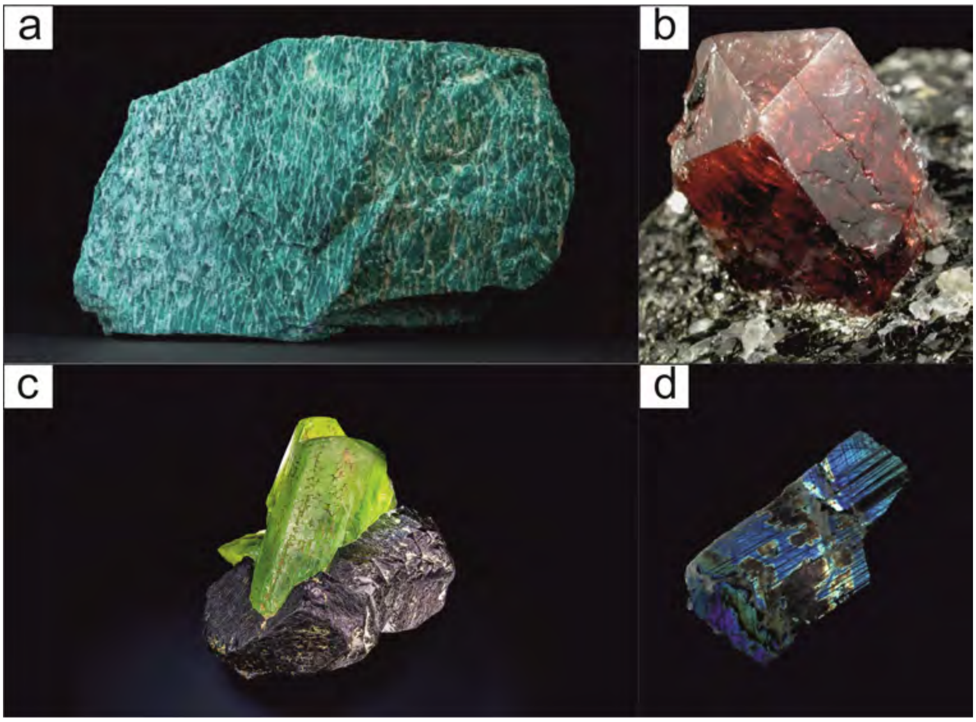
2. Ionic substitution is the formation of a heterogeneous crystal of variable composition by the replacement of one element by another in the crystal lattice of a mineral.

3. Minerals that have variable composition formed as a result of isomorphism are called solid solutions.

Exercise 5. ***Answer the following questions*:**

1. What type of ionic substitution do you know?
2. In what place in the chemical formula of a mineral are cations placed?
3. Name minerals an example of paired substitution.

Exercise 6. ***Indicate what are minerals in the photo from a to d and what type of isomorphism they have?***



2.3. Mineral water

Water can occur in various forms in minerals – *constitutional, crystallization, zeolite,* and *adsorption* water.

Constitutional water occurs in the crystal lattice of the mineral in the form of OH^{1-} ions and less often as less as often H^{1+}. This water converts to a molecular state only when the mineral is destroyed. Removal of water from the mineral occurs through heating in the temperature range of 300…1300 °C; this is accompanied by the destruction of the mineral's structure, and a change in its chemical and physical properties. For example, mineral – *actinolite* $Ca_2(Mg,Fe)_5[Si4O11]_2(\mathbf{OH})_2$.

Crystallization water is in the lattice of the crystal in the form of neutral H_2O molecules (For example: gypsum, $CaSO_4*2H_2O$). The bond strength of this water in the structure of the mineral is insignificant. Most often, this water is removed from the mineral by heating at temperatures of 300…400 °C, rarely at 600 °C, and sometimes even at room temperature.

Zeolite water can be released in a wide temperature range without destruction of the mineral and reabsorbed when conditions change. It is removed from the mineral's structure by heating in the temperature range of 400…800 ºC (typical for zeolites).

Adsorption water are molecules of water adsorbed onto the surface of minerals and are easily removed when heated to temperatures of 105…110 °C without modifying the mineral's structure. This type of water includes *interplanar water*, which is adsorbed on the surface of individual layers of a mineral, *water of solid colloids* (hardened gels, for example, opal (SiO_2*nH_2O), and *hygroscopic water*, which is retained in fine cracks, pores, and powdery masses by surface tension (i.e., mechanically mixed with the mineral). Clays are an example of a group of minerals that contain adsorption water. Removal of water through heating is accompanied by heat absorption. The corresponding endothermic effect obtained on heating curves serves as a diagnostic clue for identifying the nature of the mineral under study.

Exercise 7. ***Choose and explain why true or false the following statements:***

1. Constitutional water occurs in the crystal lattice of neutral H_2O molecules.
2. Zeolite water can be released in a wide temperature range with destruction of the mineral and reabsorbed when conditions change.
3. Clays are an example of a group of minerals that contain crystallization water.

Exercise 8. ***Indicate what water type is in the following minerals?***

- Tremolite
- Opal
- Heulandite
- Kaolinite

2.4. Physical properties of minerals

The physical properties of minerals can be grouped into three categories – *optical*, *mechanical*, and *other*.

Optical properties include *transparency, mineral color, streak*, and *luster*.

Transparency is the ability of a substance to transmit light. Depending on the degree of transparency, minerals can be divided into three groups: *i) transparent* (e.g., quartz, topaz), ii) *translucent* (e.g., sphalerite, cinnabar), and iii) *opaque* (e.g., pyrite, magnetite, graphite). Many minerals that appear opaque as large crystals are translucent as thin chips or along the edges of grains.

The color of a mineral (coloration) is one of its most diagnostic features; it is a manifestation of a mineral's ability to reflect and refract light, creating certain colors. When describing the color of minerals, well-known descriptors taken from the natural world are often used. For example, *cherry red, grass green, pistachio green, and mud green*. When describing ore minerals, the color of metals and alloys are often used. For example, *tin white, silver white, steel gray, lead gray, brass yellow, straw yellow, and bronze yellow* [9].

Conventionally, the color of a mineral can be grouped into three types based on the mechanism imparting the color.

1. *Idiochromatic (native) color* is due to the inclusion of chromophore elements (e.g., Fe, Cr, Mn, Ni, Co, Ti) in a mineral's composition. For example, the presence of Cr determines the herbal-green color of uvarovite ($Ca_3\mathbf{Cr}_2$ $[SiO_4]_3$) and gives the same color to emerald ($Be_3(Al,\mathbf{Cr})_2[Si_6O_{18}]$. The presence of Mn, on the other hand, causes a pink color in rhodonite ($\mathbf{Mn}_3[Si_3O_9]$.

2. *Allochromatic color* is caused by the presence of a fine dispersal of other colored minerals in the host mineral (i.e., mechanical inclusions), disruption in the structure of the mineral's crystal lattice, or the presence of various crystal defects. For example, a fine dust of inclusions of cherry-red hematite and rusty-brown goethite give quartz a reddish and brown tint, respectively. The allochromatic coloration of minerals is also associated with defects in the crystal structure.

3. *Pseudochromatic coloration* is due to optical effects, such as iridescence and tarnishing.

Iridescence is a colored sheen on the edges or cleavage planes of some minerals, most often the plagioclase group (e.g., labradorite). It is caused by their polysynthetic structure, which causes interference of light rays.

Tarnish – a colored film on the oxidized surface of a mineral (e.g., chalcopyrite and bornite).

The streak of a mineral is its color in powdered form. A streak of a mineral can be obtained by scratching the test sample over the matte, unglazed surface of a porcelain plate. This trait is often more diagnostic than the color. Sometimes the color of the streak is the same as the color of the mineral itself, but this is not always the case. For example, steel-gray hematite leaves a cherry-red streak and straw-yellow pyrite leaves a black streak. Being able to create a streak correctly and then recognize its color is an art. Often, students interpret the same color in different ways, and so it is necessary to check the streak of minerals often and remember their characteristic shade. A certain complexity of this feature also lies in the fact that light perception is different for different people. Therefore, only practical independent work can help a student learn how to accurately characterize this feature of a mineral.

Luster depends on the refractive index of a mineral. In other words, it depends on the difference in the speed of light as it passes from air to the crystalline medium. Minerals with a refractive index of 1.3–1.9 are characterized by *glassy* luster (e.g., quartz, fluorite, calcite, corundum, and garnet), whereas those with an index of 1.9–2.6 have *adamantine* luster (e.g., zircon, sphalerite, diamond, and rutile). *Semi-metallic* luster corresponds to minerals with a refractive index of 2.6–3.0 (e.g., cuprite, cinnabar, and hematite), whereas minerals characterized by a metallic luster have an index greater than 3 (e.g., pyrite, antimonite, molybdenite, galena, and arsenopyrite). *The luster* of a mineral can depend on the nature of the surface. For example, minerals with a fibrous structure have a delicate *silky tint* (e.g., asbestos andselenite), whereas minerals with a perfect cleavage have a *pearlescent tint* on their cleavage planes (e.g., mica).

Mechanical properties include *cleavage, parting, fracture, hardness, brittleness, malleability, and elasticity*.

Cleavage is the property of mineral to split along specific crystallographic directions, forming smooth and shiny surfaces. As noted earlier, calcite crystals, regardless of their morphology, split along their cleavage into rhombohedrons, whereas fluorite crystals split into octahedrons. The degree of cleavage perfection can be grouped into four categories:

Very perfect – the crystal is easily split into thin sheets (e.g., mica, talc, chlorite, and molybdenite)

Perfect – with mechanical action on the mineral, it splits along crystallographic directions, forming smooth surface. It is difficult to break the mineral in other directions (e.g., galena, calcite, and fluorite).

Good – there are few shiny surfaces. The mineral can be fractured in all directions (e.g., pyroxenes).

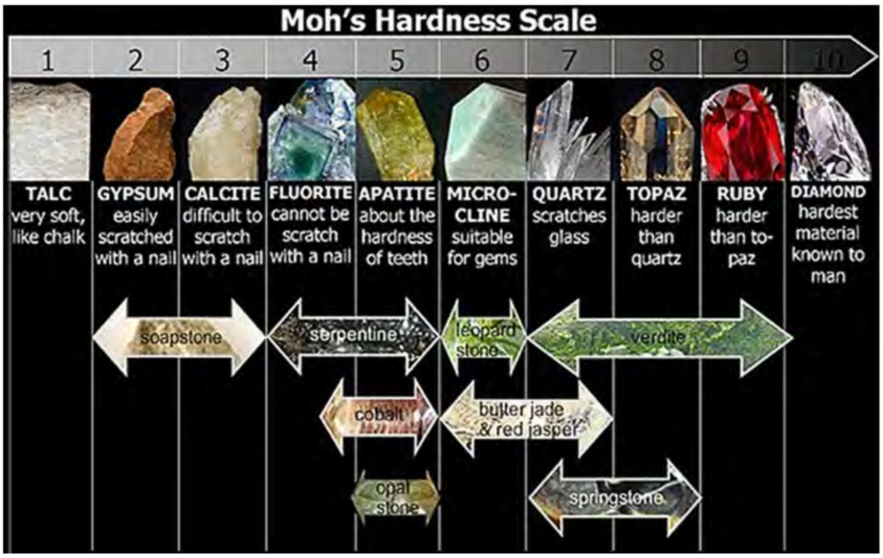
Imperfect or absent – The mineral is easily fractures and does not exhibit smooth shiny surfaces.

It is not uncommon for cleavage oriented in different crystallographic directions of a mineral to differ in the degree of perfection. For example, gypsum has three cleavage directions, one of which is perfect, the second is average, and the third is imprefect.

Parting, in contrast to cleavage, is manifested as coarse cracks that are not related to the crystal structure of a mineral. They are typically associated with regular inclusions at specific positions in minerals and often oriented across the long axis of the crystal (e.g., corundum, pyroxenes).

A *fracture* and its character play a significant role, especially for minerals with imperfect cleavage. It can be *conchoidal (e.g., quartz) and splintery (e.g., amphiboles).*

Hardness determines the degree of resistance of a mineral to external mechanical stress. To determine a mineral's hardness, it is scratched against another mineral of known hardness. The Mohs scale, which comprises 10 reference minerals of known hardness, was adopted as a means of consistently characterizing hardness. The following minerals are used as refereces in the scale: talc – 1 (hardness), gypsum – 2, calcite – 3, fluorite – 4, apatite – 5, orthoclase – 6, quartz – 7, topaz – 8, corundum – 9, and diamond – 10. Standards are not always available, however, so there also exists a household scale for determining hardness. For example, a copper needle (3–3.5), a steel knife (5.5–6), and glass (~5). Soft minerals can be scratched with a fingernail (2.5).



Fragility in mineralogy refers to the property of a mineral to crumble when a line is drawn through it with a knife or needle. If a smooth, shiny trace is left behind in a mineral after, being scratched with a needle or knife, then the mineral deforms plastically. Malleable minerals are flattened under the blow of a hammer into a thin plate, whereas elastic minerals restore their shape after the load is removed (e.g., mica and asbestos) [9].

Other properties include *density, magnetism, radioactivity, taste, odor, and hygroscopicity*.

The *specific gravity* or *density* of a mineral (ρ) is its mass per unit volume and is measured in g/cm^3. Specific gravity is usually proportional to the chemical composition of a mineral. With knowledge of a mineral's chemical formula, the specific gravity can be predicted. For example, galena ($\mathbf{Pb}S$), cobaltite ($\mathbf{Co}AsS$), and wolframite $(Fe,Mn)[\mathbf{W}O_4]$ should be classified as heavy minerals (high specific gravity) since they contain heavy elements (they are shown in bold).

Within the studied course, we will determine the approximate specific gravity of minerals by weighing them in our hands. It is correct to apply this property if the sample is completely or largely composed of one mineral. However, this method cannot accurately quantify a mineral's specific gravity. Minerals are usually divided into three groups based on specific gravity:

Light – specific gravity less than 3 (e.g., quartz, feldspar, halite, and gypsum).

Medium – specific gravity of 3–5 (e.g., sphalerite, chalcopyrite, corundum, and pyrite).

Heavy – specific gravity greater than 5 (e.g., cinnabar, galena, and gold).

Magnetism (i.e., the presence of magnetic properties) occurs in some Fe-bearing minerals with uncompensated Fe charges. For the purposes of this textbook, the number of minerals with magnetic properties is limited to *pyrrhotite* (some, but not all pyrrhotite) and *magnetite*. This feature is, therefore, an important diagnostic feature in identifying these minerals.

Radioactivity occurs in minerals that contain radioactive elements, such as uranium and thorium. They are characterized by the ability to spontaneously emit alpha, beta, and gamma radiation. In rocks, radioactive minerals are often surrounded by red or brown edges. When radioactive minerals occur in other minerals, such as quartz and feldspar, fractures develop in the host mineral that radiate outwards from the radioactive mineral [9].

Other properties. Some minerals dissolve in water (e.g., halite) or hydrochloric acid (5 % HCl) (e.g., sphalerite and carbonates). Some give off a smell when hit (e.g., arsenopyrite gives off a smell similar to garlic). Some minerals have specific feel to them when touched (e.g., talc feels greasy to the touch). Other minerals have a specific taste, such as halite, which is salty.

Exercise 9. ***Choose and explain why true or false the following statements*:**

1. The color of a mineral (coloration) is one of its diagnostic features; it is a manifestation of a mineral's ability to absorb light.
2. Idiochromatic (native) color is due to the inclusion of a fine dispersal of other colored minerals in the host mineral.
3. Streak is often less diagnostic than the color.

Exercise 10. ***Answer the following questions:***

1. What is a mineral's hardness?
2. What tools are used to test a mineral's hardness?
3. This property is the least useful in identifying a mineral.
4. This property describes a mineral's resistance to scratching.
5. This property describes the way a mineral reflects light.
6. The property of a mineral that describes the way it breaks in-to flat surfaces.
8. What is a streak test?
9. This property is measured on a scale of 1 to 10.
10. When measuring hardness on a scale of 1 to 10, _____ is the softest.
11. Shiny, dull, earthy, metallic, glassy, and waxy all describe this property of mineral?
12. These two properties of a mineral must be tested to be ob-served. One uses a nail and another uses a special plate.

Exercise 11. ***Match the questions from 1 to 10 with the right answers from a to i. You can use the same answer several times.***

1. What state of matter are all minerals?
2. What is a mineral's hardness?
3. What tools are used to test a mineral's hardness?
4. This property is the least useful in identifying a mineral.
5. This property describes the way a mineral reflects light.
6. The property of a mineral that describes the way it breaks into flat surfaces.
7. What is a streak test?
8. This property is measured on a scale of 1 to 10.
9. Shiny, dull, earthy, metallic, glassy, and waxy all describe this property of a mineral.
10. These two properties of a mineral must be tested to be ob-served. One uses a nail and another uses a special plate.

a – Luster
b – A test that shows a mineral’s true color
c – Solid
d – Hardness and Streak
e – It’s the mineral’s resistance to scratching
f – Your finger, fingernail, glass, Mohs scale
g – Color
h – Cleavage
i – Hardness

2.5. Mineral formation processes

To remove strain in the Earth's crust,
Where her firmament is worried
There is a magma chamber in it
In places, it is formed.
The fluidity of magma gives it
Opportunity for promotion
To the Earth's surface
So that there is an eruption
Frozen in the depths
(By no means their fault)
Magma gives birth to wonderous,
Intrusive massifs,
Which gases and heat
For us people, a great gift
Born, get stronger, and grow
Accumulations of various ores ...

Author unknown

As an introduction to this chapter, it is appropriate to recall the words of the great USSR scientist and academician Vladimir Ivanovich Vernadsky (1863–1945): "*A mineral should be studied at all stages of its existence, and not only when it acquires a stable structure, becomes a "stone". It is necessary to comprehend the role of the mineral in the general life of the Earth and its dependence on the external environment. The more accurate such knowledge, the easier it is to search for minerals, mineral deposits....* "

Minerals at various stages of their origin, formation, and transformation are in close association with each other. Here it is appropriate to introduce the concept of paragenesis. *Paragenesis* is co-occurrence of genetically related minerals.

> ***Information:*** *In 1798, the famous Russian mineralogist Vasily Mikhailovich Severgin (1765–1826) was the first to introduce the concept of "contiguity of minerals", or their co-occurence. The same scientist was also responsible for the introduction of the concept of "rock" as a natural aggregate of minerals of more or less constant composition. The term paragenesis in the name in which it was fixed and to this day was formulated later in 1849 by German mineralogist F.A. Breithaupt (1791–1873).*

Therefore, the natural association of minerals is called a *rock* and is an independent body in the Earth's crust. Rocks, unlike minerals, are most often heterogeneous, that is, they consist of several minerals. However, this ensemble of minerals, as already emphasized earlier, is not accidental, but corresponds to certain physicochemical conditions of their joint formation.

Minerals in nature are formed in various ways, and the processes of their formation (*genesis*), transformation, and destruction occur in accordance with the physicochemical conditions in the Earth's crust and on its surface. The *genesis of minerals* is determined by the geological processes that form the Earth's crust. Based on the energy source, the processes by which minerals and rocks form are divided into *endogenic* and *exogenic*.

Endogenic geologic processes include those occurring inside the Earth by the energy released during transformation of matter. Endogenic processes include the movement and redistribution of the substance that composes the Earth, and its transition from one state to another during magmatism, tectonic movements, and metamorphism. These processes are manifested as igneous intrusions into the Earth's crust, the formation of large fracture systems in the Earth's crust, enormous folded systems hundreds to thousands of kilometers long (e.g., the Alps, Caucasus, and the Himalayas), oscillatory movements of the Earth's crust, volcanic eruptions, and earthquakes [10].

Exogenic geologic processes include those that develop as a result of the interaction of rocks and minerals within and on Earth's crust with the atmosphere, hydrosphere, and biosphere. An important role in exogenic processes is played by the force of gravity, the electromagnetic field of the Earth, streams of solar energy and matter from space, the activity of organisms and humans, and technogenic human activity. Previously formed minerals undergo chemical, mechanical, biochemical, and anthropogenic processing, which leads to the formation of new minerals in accordance with the new physicochemical conditions.

Thus, endogenic processes determine the beginning of "life" of chemical elements and minerals in and on the Earth's crust, whereas their modification and destruction is determined by exogenic processes.

Magmatic process

Igneous rocks can be divided into two main groups: 1) *intrusive* rocks (from the Latin intrusio – intrusion, invasion), which crystallize at depth within the Earth, and 2) *extrusive* (from the Latin effusio – outpouring), which crystallize on Earth’s surface. Visually, these rocks differ in texture and structural features. Intrusive rocks are often well crystallized and coarse grained. Extrusive rocks, however, are finer grained and can be glassy since they do not have sufficient time to crystallize due to the sharp drop in temperature upon eruption onto the Earth's surface. Because of this, macroscopic study of minerals is largely restricted to intrusive igneous rocks, which are characterized by coarser grain sizes and structures than extrusive igneous rocks.

The variety of igneous rocks is the result of *magma differentiation*. Differentiation is a combination of various physicochemical phenomena that leads to the formation of minerals and residual silicate melt. It also includes *liquation,* which is the separation of a silicate melt into two immiscible liquids – a heavy liquid enriched in iron oxides and sulfides, and a lighter liquid enriched in volatiles and salts. When both melts are cooled, they result in rocks with different compositions. Some researchers refer to the term "liquation" as the compositional evolution of magma due to its interaction with fluids [11].

Fluids are primarily a supercritical hydrothermal phase composed of a mixture of various gases, mainly H_2O and CO_2 with admixtures of CO, N_2, H_2, CH_4, and other hydrocarbons. This phase is capable of transporting and depositing chemical elements, dissolving them into silicate melts, and increasing the rates of many geologic processes by several orders of magnitude.

Three primary mechanisms of fluid transport within the Earth have been studied, one of them being dissolution into silicate melts. Allocate free filtration of fluids through cracks, channels and pores in rocks and high-temperature dissolution followed by crystallization of minerals at the front of motion of fluid unsaturated with rock components.

1. *Transport by magmas* is the most efficient mechanism of fluid transport. It is determined by the duration of magmatic activity and fluid saturation of a magma. Solubility of fluids into melts reduces the density of the melts by tenths of a fraction, and their viscosity by orders of magnitude, facilitating their movement to the Earth's surface.
2. *Free filtration* of fluid through a rock is determined not only by the properties of the fluid, but also by the porosity of the rock, and temperature and pressure. A fluid with a low density and viscosity always tends towards a region of lower pressure. By interacting with a rock, a fluid facilitates

reactions between itself and the minerals making up the rock – this is called alteration or metasomatism. Typically, its components become part of the newly formed minerals, or the fluid itself is captured by the mineral during growth in the form of inclusions.

3. *Recrystallization.* With slow percolation of fluid through a rock, a fluid is able of dissolving minerals in a rock at the interaction front and precipitating the same minerals behind the front. In each local volume, the concentration gradient is so small that the fluid is able to become saturated in the components making up a rock and equilibrate with it. The energy of the fluid–rock system, including the energy at the surface of crystals, reaches a minimum at this point. As a result, recrystallization occurs, causing crystals to enlarge, the size of which can sometimes reach tens of centimeters. This is one way in which pegmatites can form [12].

This is only a short description of the influence that fluids can have on the composition of magmas. Accordingly, with regards to the Earth's mantle, one cannot imagine it as some kind of homogeneous substance. Its composition is likely as heterogeneous as the chemistry of the Earth's crust. The mantle likely contains zones with reduced fluids, as well as zones with more oxidizing fluids. Fluids significantly affect magmatic processes, determining the temperature of the onset of melting and crystallization, and the rate of chemical reactions. One of the processes with the participation of fluids can be the separation of an initially homogeneous melt into immiscible parts with sharp boundaries between the formed phases, which arises due to the unequal chemical affinity of volatile components to the main rock-forming elements. Because of this interaction of fluids with magma components, it is separated into immiscible parts with different chemical compositions, for example, basic and ultrabasic (in its most general form, this process can be represented as a process of separating water and oil from their mixture). Accordingly, rocks of different compositions will crystallize from the separated magmas.

Crystallization differentiation occurs due to the crystallization of minerals from magma and results in the redistribution of elements among the residual silicate melt and the newly formed crystals. Heavy iron–magnesium-bearing minerals, such as *olivine*, are usually the first minerals to crystallize. Because of their density, *olivine* crystals will sink through the melt from which they crystallized and accumulate at the base of a magma chamber. Such differentiation occurs when the viscosity of magma is not particularly high (e.g., an ultramafic–mafic magma).

However, not all minerals sink and accumulate in the lower parts of magma chambers; some can be suspended in a melt for extended periods and react with it. For example, if olivine remains in contact with silicate melt, it can react with it and be transformed to pyroxene. If the newly formed crystals are lighter than the melt from which they crystallized, they float up and accumulate in the upper parts of a magma chamber. Both scenarios lead to the redistribution of elements between minerals and magma.

> ***Information:*** *The order of crystallization of the main rock-forming minerals from magmas was established by the American petrographer Norman Levi Bowen (1887–1956). He identified two reaction series.*

Bowen's reaction series (Fig. 28) illustrates the order of mineral crystallization from magma. Two reaction series exist – the discontinuous series describes the crystallization of mafic minerals and the continuous series describes the change in plagioclase composition from Ca-rich to Na-rich. In the discontinuous series, as the temperature of magma decreases, olivine will crystallize first. Upon further cooling, it reacts with the residual melt, resulting in the formation of pyroxene, which eventually reacts with the melt to form amphibole and then biotite minerals (Fig. 28). Plagioclase in the continuous series, however, crystallizes continuously, but changes composition as the temperature decreases and the composition of the residual melt evolves [11].

The most refractory minerals, which crystallize first, comprise a limited set of elements, mainly Si, Mg, and Fe. The minerals that crystallize at progressively lower temperatures have more diverse compositions, which include the elements Al, Ca, Na, K, and volatiles (e.g., OH and F).

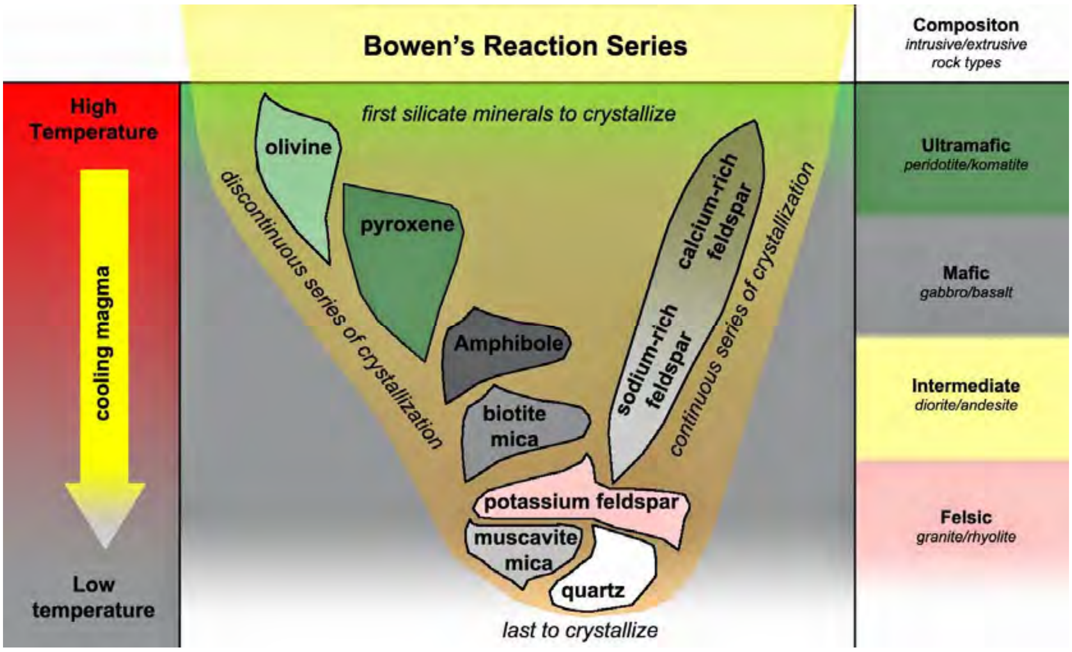


Fig. 28. Schematic diagram of Bowen's reaction series illustrating the sequence of crystallization of minerals from magma along with two reaction series

As is evident in Figure 28, as temperature decreases, the types of silicates that crystallize change: nesosilicates [SiO_4] → single-chain inosilicates [SiO_3] → double-chain inosilicates [Si_4O_{11}] → phyllosilicates [Si_4O_{10}]. Sodium-bearing minerals are represented by feldspars belonging to the subclass of framework silicates. Framework silicates comprise large cations of calcium, sodium, and/or potassium, which are much larger than the edges of SiO_4 tetrahedrons and push them apart, forming a three-dimensional framework. As one moves down through Bowen's reaction series, the degree of substitution of aluminum for silicon in the minerals increases – substitution of Si^{4+} by Al^{3+} does not occur in nesosilicates and is not significant in single-chain inosilicates; in double-chain inosilicates, however, Al^{3+} can replace up to one quarter of the Si^{4+}, and up to half of the Si^{4+} in inosilicates. The replacement of a tetravalent silicon ion with a trivalent aluminum ion leads to a charge imbalance. The negative charge acquired in this way is compensated by the addition of cations, such as K^+, Na^+, and Ca^{2+}. This, in part, explains why the later-formed minerals (i.e., micas and feldspars) comprise these minerals, while earlier-formed minerals do not. The majority of the Si contained in a magma is consumed by the crystallization of silicate minerals; excess Si at the final stages of crystallization forms quartz (SiO_2).

The Bowen's reaction series is a generalized model of the formation of minerals that compose igneous rocks. In nature, however, there are rocks that comprise 90 % or more of olivine or Ca-plagioclases + pyroxenes or Na-plagioclases + hornblende + biotite. Meaning, not all end products of magma crystallization will contain the lower members of the reaction series. This is due to several reasons, the meain reason being the original composition of the magma.

Magmas form by partial melting of the upper mantle or by melting of the lithosphere as it is subducted into the mantle. The chemical compositions of the upper mantle and lithosphere are different, and so magmas that form by their melting will also be different. Magmas that arise due to the melting of the mantle are enriched in FeO, MgO, and CaO. Therefore, depending on their composition, such magmas are called ultrabasic (ultramafic) and basic (mafic), and crystallize to ultrabasic and basic igneous rocks, respectively. Magmas that form by the melting of the Earth's crust, which is depleted in FeO, MgO, and CaO, but enriched in silica, are called acidic (felsic); these magmas crystallize to acidic rocks. Thus, the following families of primary magmas are distinguished based on their percentage of silica (SiO_2): ultrabasic (ultramafic) (<45 % SiO_2), basic (mafic) (45–52.5 % SiO_2), medium (intermediate) (52.5–65 % SiO_2), and acidic (felsic) (> 65 % SiO_2). As is evident, the crystallization of magma is accompanied by the accumulation of silica, alkalis, and water in the residual melt [11].

Despite the existence of only four families of primary magmas, the rocks formed from them are very diverse. This is because variations in igneous rocks do not only result from differentiation processes, but also *assimilation processes*. *Assimilation* is the entrapment and remelting of rocks into which magmas intrude, leading to a change in their composition. Particularly strong compositional changes are observed at the contact between the magma and the surrounding rock, where *assimilation* processes are most intense. *Contamination* is another term often used to describe assimilation.

> ***Information:*** *The term "contamination" was originally introduced in 1923 by the English scientist G. Read, who described it as the process of polluting magma by mixing into it sedimentary and metamorphic rocks. Contamination is most evident when magma interacts with rocks of a contrasting composition (for example, when granite magma comes into contact with limestones or ultrabasic rocks). Contamination can occur at different depths in the Earth's crust.*

In contrast to assimilation, relics of foreign material are preserved in magma. Sometimes, the boundaries of inclusion are also preserved, making it possible to describe their primary form.

The mineralogical composition of igneous rocks is very diverse. The most common minerals are feldspars, quartz, amphiboles, pyroxenes, and to a lesser extent olivine, nepheline, magnetite, apatite, and other minerals. Through a study of more than 700 samples of igneous rocks, it was found that these minerals occur in the following approximate percentages: feldspars – 60 %, amphiboles, and pyroxenes – 17 %, quartz – 12 %, other silicates – 6 %, mica – 4 %, other minerals – 1 %.

Pegmatite process

Pegmatite formation is associated with alkali-enriched and volatile-rich magmas. They are often very coarse-grained bodies, similar in composition to the magmatic intrusions with which they are spatially associated, and other types. They are typically characterized by an abundance of rare metals and rare earth minerals.

The close spatial relationship of pegmatites with intrusive rocks is indicative of their genetic link. The distance of pegmatites from the parent intrusions, in general, does not exceed two kilometers. Most pegmatites are associated with felsic intrusions (granite pegmatites); alkaline pegmatites and gabbroic pegmatites occur to a lesser extent. The composition of a pegmatite reflects the composition of the parent intrusion, representing a residual melt rich in volatile components, such as fluorine, chlorine, and boron. This residual melt, due to pressure differences, is squeezed upwards into overlying rock and fills voids in them. Granite pegmatites are composed of large crystals of quartz, feldspar, and mica. Where quartz and feldspar jointly crystallize, graphic granite forms. A more detailed description of the process of simultaneous crystallization of quartz and feldspar is described in the chapter "*Crystal shapes and growth*". The temperature range over which pegmatites form, according to A.E. Fersman, is 700–350°. As a result of the interaction of the residual pegmatite melt with the host rocks.

Several types of granite pegmatites occur, which form at different depths and temperatures: 1) *ceramic* (consisting mainly of microcline and quartz), 2) *mica-bearing* (muscovite), 3) *rare metal* (containing high concentrations of lithium, beryllium, cesium, niobium, and tantalum), 4) *crystal-bearing* (topaz, beryl, rock crystal) (Table 2).

Table 2

Mineral assemblages of granite pegmatites

Types	*Rock-forming minerals*	*Accessory minerals*
Ceramic and mica-bearing	microcline, acidic plagioclase, quartz, muscovite, biotite	aluminum garnets (almandine-spessartine), beryl, zircon, apatite
Rare metal	lamellar albite (clevelandite), spodumene, microcline (sometimes amazonite), lepidolite	muscovite, polychrome tourmaline, beryl
Crystal-bearing	rock crystal, quartz	muscovite, biotite, smoky quartz, morion, albite, beryl
«Hybrid line»	Feldspars, biotite	hornblende, beryl (emerald), talc, phlogopite, actinolite, chlorite fluorite, muscovite

Contact metasomatic process

The phenomena of contact metasomatism are most clearly manifested during the intrusion of granite bodies into strata of carbonate rocks. As a result of this interaction, a complex of new minerals is formed, characteristic exclusively for the contact zone of these rocks. A prerequisite for the formation of skarns is liquid and gaseous solutions, which cause metasomatic alteration (input and removal of matter).

Skarns are metasomatic rocks composed of calcareous-ferruginous and magnesian silicates, formed as a result of the reaction interaction of carbonate and aluminosilicate rocks with the participation of postmagmatic solutions.

> ***Information**: The term metasomatism was first introduced in 1828 by the German mineralogist and geologist Karl Friedrich Naumann (1797–1873) as a type of pseudomorphism (replacement of one mineral with another while maintaining the shape of the first).*

Metasomatism (μετα – after, after; soma – body), i.e. literally "over the body" or pseudomorphic alteration. During metasomatism, the rock remains solid and does not change its original volume. The method of movement of matter during metasomatism is different: *diffusion (transfer is carried out in aqueous solutions)* and infiltration (*filtration and percolation through rocks*).

There are *magnesian skarns*, developed on dolomites and *calcareous skarns* developed on limestones. Their mineral associations are different (Table 3).

Table 3

Mineral assemblages of skarns

Types	*Rock-forming minerals*	*Accessory minerals*
Calcareous	calcite, calcium garnets (andradite-grossular), diopside-hedenbergite, epidote	magnetite, tremolite, molybdenite, cobaltite, fluorite, galena, sphalerite, pyrite, chalcopyrite, gold, plagioclase
Magnesian	diopside, forsterite, phlogopite, calcite, dolomite, magnesite	spinel, magnetite, sphene, actinolite, plagioclase, apatite

In addition to *contact* metasomatism, an example of which is skarns, there are several more types of metasomatism: *autometasomatism*, *peri-vein*, *regional*.

Autometasomatism manifests itself in the upper parts of igneous bodies. An example is the *albitization* of granite massifs. The *vein metasomatism* forms symmetrical metasomatic zoning on each side of the vein, along which the solutions are filtered. *Regional* metasomatism is characterized by the scale of the process, covering vast areas under different geological settings. The manifestation of such metasomatism is often associated with the intrusion of large magmatic intrusions, and its nature is alkaline.

Hydrothermal process

The cycle of endogenous processes of mineral formation completes the hydrothermal process. *Hydrothermal fluids* are hot aqueous solutions that are separated from magmas and are formed as a result of the liquefaction of gases. Hydrothermal solutions carry out a number of metal compounds from the magma chamber. In addition, fluids can borrow various substances from the side rocks along which they move. Since hydrothermal fluids move along the path of least resistance, that is, along cracks, contact zones, tectonic faults, the shape of their crystallization products is predominantly veined.

The main vein mineral is quartz. Hydrothermal deposits are divided by temperature regime into high-temperature (450…300 °C), medium-temperature (300…200 °C) and low-temperature (below 200 °C). Most non-ferrous ores (Cu, Pb, Zn) and rare metals, gold are of hydrothermal genesis.

The most favorable conditions for the manifestation of hydrothermal processes are at shallow and medium depths (up to 3…5 km from the surface). The main body of hydrothermal formations, similarly to pegmatites, is associated with felsic rock intrusions. The area of circulation of the solution, starting almost from the upper parts of the magma chambers, sometimes reaches the earth surface. The formation of hydrothermal solutions seems to continue for a very long time – during the entire life of the magma chamber.

Hydrothermal deposits are one of the main sources of rare (W, Mo, Sn, Bi, Sb, Hg), nonferrous (Cu, Pb, Zn), noble (Au, Ag), and radioactive (U, Ra, Th) metals (Table 4).

Table 4

Mineral assemblages of hydrothermal deposits

Types of hydrothermal veins	*Gangue minerals*	*Opaque minerals*
High temperature	quartz, beryl, topaz, fluorite	wolframite, arsenopyrite, pyrite, molybdenite, pyrrhotite
Medium temperature	quartz, siderite, barite, fluorite, fine-flaked muscovite (sericite)	gold, pyrite, chalcopyrite, galena, sphalerite
Low temperature	calcite, quartz, barite, chalcedony, fluorite	cinnabar, antimonite, realgar, orpiment

Exogenic processes

Among the exogenic processes of mineral formation occurring on the earth surface or on the surface of the Earth, the main ones are *weathering, sedimentary* and *biogenic* processes.

Weathering (hypergenesis) is the sum of the processes of mechanogenic destruction and chemical decomposition of rocks and minerals under the influence of factors and environmental conditions. During the *physical processes of weathering*, rocks turn into fragments of various sizes, new minerals are not formed. However, during these processes, there is a concentration and accumulation of *placers of gold, diamond, zircon, tungsten minerals, garnets, magnetite*, that is, minerals that are most resistant to destruction processes and have an increased specific gravity.

Chemical weathering leads to the decomposition of minerals and rocks under the influence of carbon dioxide, water, oxygen, humic acid. During chemical weathering, the following reactions can occur: hydration, oxidation, hydrolysis, dissolution, carbonatization, reduction.

Hydration is expressed in the formation of new minerals due to the adsorption of water molecules. For example, the transition of anhydrite to gypsum under the influence of groundwater.

Oxidation, as a rule, leads to the transformation of acidic compounds into oxide ones. For example, the transition of *magnetite to hematite* with the formation of pseudomorphism (martite).

Hydrolysis causes decomposition of the substance under the influence of hydrolytic dissociation of water, accompanied by the formation of new minerals in place of the original ones. For example, hydrolysis of *feldspars* to form *kaolinite*.

In areas with an arid climate, precipitation of various salts occurs with the formation of deposits of *gypsum* and *rock salt*. These chemical processes cause the formation of other deposits, sometimes on a grandiose scale: iron ore, manganese, phosphorite, uranium.

Biogenic processes play an important role in the exogenous formation of minerals.

When organic matter decomposes directly in the bodies of plants and animals, minerals are formed, which are part of cell secretions, skeleton, shells, shells, etc. This is how *calcite*, *opal* and other minerals can be formed. The second group of biogenic minerals arises outside the bodies of organisms from the products of their vital activity.

Sedimentation is widely manifested in rivers, lakes, seas, oceans and consists in the accumulation of material from detrital rocks. Sediments can have a different character of deposition: mechanical (sedimentation of particles), due to the processes of coagulation of colloidal solutions, due to crystallization from saturated true solutions, with the participation of biota, including various bacteria. There are *mechanical, colloidal, chemical* and *biochemical* sediments.

Diagenesis manifests itself immediately after the deposition of sediments in the form of their transformation: dehydration of hydroxides, crystallization of colloidal sediments, replacement of organic residues with carbonates. Then there is further silicification and the formation of sedimentary rocks.

Metamorphic process

Minerals formed in the process of endogenous and exogenous mineral formation processes can undergo further significant changes if they fall into the region of high temperatures and pressures. The main factors of metamorphism are temperature and pressure. Metamorphic processes are expressed mainly in dehydration and recrystallization of rocks. There are two types of metamorphism: *regional* and *contact*.

Regional metamorphism occurs at great depths and covers huge areas. The upper limit of metamorphism is the temperature at which melting does not occur yet, that is, 800…850 °C at significant depths and 1000…1100 °C closer to the surface. The pressure can reach several tens of thousands of atmospheres. Particularly important is the role of unilateral lateral pressure – stress. It causes the appearance of the characteristic schistosity (banding) of many metamorphic formations.

The process of regional metamorphism can be divided into stages corresponding to certain paragenetic associations of minerals that are stable within certain ranges of temperatures and pressures. Such steps are called facies of regional metamorphism. The metamorphic facies corresponds to a group of rocks whose mineral parageneses reflect similar P-T metamorphic conditions (Table 5).

The mineral composition of metamorphic rocks is diverse but depends primarily on the composition of the original rocks. They can be composed of a few minerals (quartzite, marble) or a few complex silicates. The main rock-forming minerals are quartz, feldspars, micas, pyroxenes, and amphiboles.

Table 5

Mineral assemblages of facies of regional metamorphism

Metamorphic facies	*Typical minerals*
Facies of green schists	chlorite, actinolite, quartz, albite, muscovite, sericite, calcite, tremolite, talc, serpentine, magnetite, hematite
Epidote-amphibolite	hornblende, epidote, biotite, muscovite, quartz, acidic plagioclase, garnet, magnetite
Amphibolitic	hornblende, medium plagioclase, disthene, magnetite, biotite, quartz
Granulite	rhombic and monoclinic pyroxenes (diopside, hypersthene), garnet (almandine), basic plagioclases, orthoclase, quartz, forsterite

If in the early magmatic period all chemical elements (both petrogenic and metallogenic) were more or less uniformly distributed in the total mass, then during the period of differentiation and crystallization of magma, especially in deep conditions, we already have a different picture. Metallogenic elements (Pt, Cu, Fe, Au, Ag, Zn, Pb, Bi and another picture) show a pronounced tendency towards concentration and, with the participation of volatile components of magma, to spatial separation from petrogenic elements with the formation of ore deposits (magmatic, contact-metasomatic, hydrothermal). Petrogenic elements, on the contrary, during the formation of igneous rocks remain in a state of more or less uniform distribution, only slightly enriched during the process of magma differentiation. Only elements with small and very large sizes of ionic radius (in comparison with ordinary petrogenic elements) are able to accumulate in significant quantities in pegmatite formations [13].

In exogenous processes, the opposite phenomena are observed. These processes, due to the energy of the sun in a highly oxidizing environment, have a negative effect on everything that was created during endogenous processes of mineral formation, and in the final stage lead to the formation of huge strata of sedimentary rocks. On the other hand, petrogenic elements (Na, K, Mg, Ca, Al, as well as C, Cl, B, S, P, etc.), with exogenous ones, there is a noticeably pronounced tendency to accumulation with the formation of many non-metallic minerals (limestone, gypsum, salt-bearing lakes, bauxite, phosphorite, coal, oil, etc.).

During the processes of regional metamorphism, in essence, no significant concentrations of chemical elements occur. There is only the transformation of mineral products arising from endogenous processes [13].

In general, each mineral is a monument to the physical and chemical process that took place on Earth, often at a time distant from us. Knowledge of the genesis of minerals, their stability in certain physicochemical conditions helps to predict the deposits of the most valuable minerals.

Exercise 12. ***Describe the following statements:***

1. Describe the endogenic processes of mineral formation.
2. Describe the exogenic processes of mineral formation.
3. List magmatic process and its mineral associations.
4. List pegmatite process and its mineral associations.
5. List metamorphic process and its mineral associations.

Exercise 13. ***Choose and explain why true or false the following statements:***

1. Endogenic geologic processes include those occurring outside the Earth by the energy released during transformation of matter.

2. Exogenic geologic processes include those that develop as a result of the interaction of rocks and magma on Earth's crust.

3. Igneous rocks can be divided into three main groups.

4. Heavy iron–magnesium-bearing minerals, such as feldspar, are usually the first minerals to crystallize.

5. The most refractory minerals, which crystallize first, comprise a limited set of elements, mainly Al, Ca, Na, K.

6. The distance of pegmatites from the parent intrusions, in general, exceed from two for five kilometers.
7. The main vein mineral is olivine.
8. Pegmatite deposits are one of the main sources of rare (W, Mo, Sn, Bi, Sb, Hg), nonferrous (Cu, Pb, Zn), noble (Au, Ag), and radioactive (U, Ra, Th) metals.
9. Weathering (hypergenesis) is the sum of the processes of mechanogenic destruction and chemical decomposition of rocks and minerals under the influence of factors and environmental conditions.
10. The process of regional metamorphism can be divided into stages corresponding to certain paragenetic associations of minerals that are stable within certain ranges of temperatures and pressures.

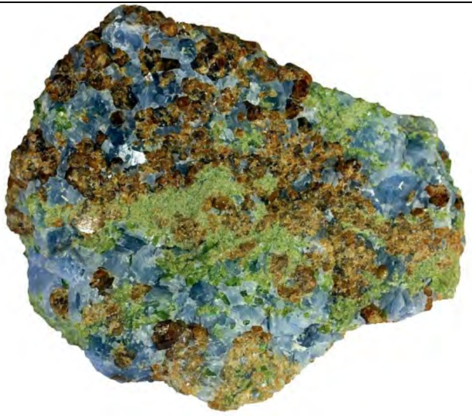
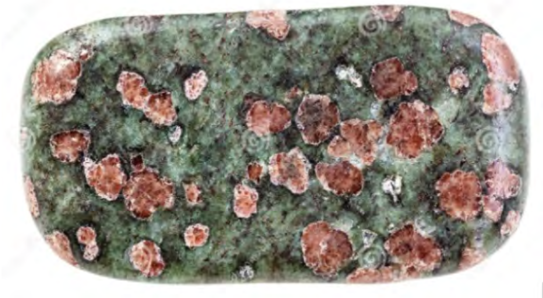
Exercise 14. ***Choose and underline the correct answer.***

1. The variety of igneous rocks is the result of **hydrolysis/magma differentiation**.
2. Fluids are primarily a supercritical hydrothermal phase composed of a mixture of various gases, mainly **H_2/H_2O** and **CO_2/NH_4**.
3. Plagioclase in the continuous series crystallizes continuously, but changes composition as the temperature **increases/decreases** and the composition of the residual melt evolves.
4. **Skarns/Greisens** are metasomatic rocks composed of calcareous-ferruginous and magnesian silicates.
5. During chemical weathering, the following reactions can occur: **hydration/assimilation**, **oxidation/liquation**, **hydrolysis/ crystallization differentiation**.

Exercise 15. ***Match the genesis in column "A" with characteristic minerals in column "B"***

"A"	**"B"**
Scarn	**A.** Mica
Pegmatite	**B.** Disthene
Placer	**C.** Zircon
Metamorphic	**D.** Epidote

Exercise 16. ***Name the rock by the picture and define its genesis.***

1		4	
2		5	
3		6	

2.6. Practical recommendations for the diagnosis of minerals

For the correct definition of minerals, it is necessary to adhere to the *principle of exclusion*; you should not immediately name the mineral by the "eye". Initially, based on external signs, it is necessary to distinguish a group of minerals with similar properties (color, luster, aggregates, etc.). Then you should check the main physical properties of the mineral under study: hardness, streak, cleavage et al. In addition, special attention should be paid to the paragenesis (joint finding) of minerals. Ultimately, one mineral should remain from a group with similar properties by the method of elimination.

The determination of the physical properties of minerals is carried out as follows:

1. Hardness is determined using the Mohs scale, represented by 6 standards, starting with calcite and ending with quartz. Determine whether a mineral is soft or hard using glass (5). It is necessary to carry out with an effort on the glass the protruding part of the diagnosed mineral, while if a scratch remains on the glass, then the hardness of the mineral is higher than 5, if there are no traces on the glass, therefore, the hardness of the mineral being determined is less than 5. To clarify the hardness of the mineral under study, use the available standards on the same principle.
2. Density or specific gravity can be easily diagnosed by the feeling of heaviness in the hand by approximate weighing.
3. Cleavage is determined visually or with a magnifying glass by the nature of the correct, clear, repeating planes on the surface of minerals, not to be confused with the edges of 1ё.
4. It is necessary to pay attention to the appearance of crystals and the morphology of aggregates, keeping in mind that minerals crystallizing in a cubic system most often form isometric (close to spherical) shapes; crystals of the middle category – elongated and prismatic, the lowest category – flattened.

Templet of a written account of mineral

The mineral is ___________ (color).

Crystal habit is ___________ (prismatic (призматический); columnar (столбчатый); tabular (таблитчатый); equnt (stout) (изометричный), cubic (кубический); bladed (уплощенный); platy (пластинчатый); stubby (короткостолбчатый), blocky (блочный).

Crystal structure is (cubic, tetragonal, rhombic, hexagonal, monoclinic, triclinic, trigonal).

Morphology of aggregates is __________ grainy/granular/discrete (зернистые); compact/solid/massive/continuous (сплошные); lamellar/laminal/fissil/foliated (листоватые); botryoidal/globular(натечные); scaly (чешуйчатые); dendritic/arborescent (древовидные, дендриты); rosette (роза); radiating (радиально-лучистые).

Cleavage in one or more direction (yes or now), (eminent/perfect/medium/imperfect/most imperfect cleavage (cohesion) – весьма совершенная, совершенная, средняя, весьма несовершенная спайность.

Hardness is_______

Specific gravity is about _________(light/medium/heavy, weighty – легкие (< 3 g/cm^3), средние (3…5 g/cm^3), тяжелые (> 5g/cm^3).

Fracture or **parting** is____conchoidal/splintery/flat/uneven (irregular)/hackly (скорлуповатый (раковистый)/расщепленный/плоский, неровный, зазубренный излом).

Streak is _________

Luster is _________ metallic (металлический); submetallic (полуметаллический); adamantine (алмазный); glassy (vitreous) (стеклянный); resinous (смолистый, смоляной); waxy (Greasy) (восковый, жирный); pearly (перламутровый); dull (earthy) (матовый, землистый).

Diagnostic (unique) properties are_________

Paragenesis (coexisting) with ________

Genesis/origin is (magmatic, metamorphic, hydrothermal, sedimentary, metasomatic).

2.7. Classification of minerals

The modern mineralogical classification is based on the chemical composition of minerals and a structural feature. It was found that minerals with the same anions (negatively charged particles) or anionic groups (radicals) exhibit similar properties. Moreover, the genesis of minerals with radical groups of the same type is also of the same type in many cases. The role of various minerals in the composition of the earth's crust is not the same. The most common minerals, which include the most common chemical elements – oxygen, silicon and aluminum. Therefore, the weight content of oxygen-containing minerals in the earth's crust reaches 98 %, of which about 75 % are silicates and aluminosilicates.

Minerals are usually grouped into *classes*, which in turn are divided into *subclasses* according to structural and chemical characteristics, then the subclasses are subdivided into *families* and *groups*, which are divided into series and, finally, mineral species, which are directly studied in this mineralogy course.

The mineral species combines a set of natural chemical compounds with a specific, uniform crystal structure and atomic composition, varying within certain boundaries due to the isomorphic substitution of the main elements by their crystal-chemical analogs.

Mineral species, in a sense, is a figurative concept that reflects the product of the integration of data on the chemical composition of real *mineral individuals* with the same constitution. *Mineral* individuals are natural solid homogeneous mineral bodies physically limited in space from other bodies by grain interfaces or face planes. *Mineral individuals* are single crystals, individual grains, spherules, being constituent parts of *mineral aggregates*. *Mineral individuals* compose mineral associations.

Within the limits of one *mineral species*, several varieties can be distinguished according to chemical, morphological, structural characteristics. To date, about 5000 minerals have been recognized as independent mineral species. New minerals are added to this list as they are discovered, and long-known ones are excluded, but discredited as the methods of mineralogical research have improved. This methodological guide uses the following classification:

Type I. Native elements
Type II. Sulfides and their analogs
Type III. Halide compounds
Type IV. Oxides and hydroxides
Class 1. Oxides
Class 2. Hydroxides
Type V. Oxygen salts
Class 1. Sulfates
Class 2. Tungstates
Class 3. Phosphates
Class 4. Carbonates
Class 5. Silicates

2.7.1. Type I. Native elements

Native elements consist of more or less stable individual individual chemical elements with stable electron shells. Compounds of this kind are not common, there are a little more than 40 of them. The percentage by weight of native elements from the weight of the Earth's crust is 0.1 %. However, in recent years, with the advent of new accurate methods for diagnosing a substance, the finding of native metals in various rocks is being established more and more often. The form of native elements occurring is varied. These can be whiskers, dendritic, lamellar, idiomorphic, etc. Native elements are divided into two groups: *native metals* and *native non-metals*. Native metals include *gold, silver, copper*. To native non-metals: *graphite, diamond, sulfur*. Native metals are characterized by a metallic type of bond, which causes opacity, strong metallic luster, good thermal and electrical conductivity.

Gold, silver and *copper* differ in color. *Gold* is bright yellow, poisonous yellow, *silver* – steel gray, pewter white, *copper* – red. From the reference shade of native metals, their own color names appeared – golden yellow, silver white, copper red. From the reference shade of native metals, their own color names appeared – golden yellow, silver white, copper red. For native metals, despite the fact that they all crystallize in a cubic system, formations in the form of dendrites, plates, scales, leaves, and irregular shapes are very common. Endogenous ore *gold* is most often found in the form of small phenocrysts, layers, and flakes in a quartz mass. Visible *gold* indicates industrial concentrations of the metal in the rock. Visually, gold can be confused with pyrite ("*fool's gold*"), however, it is important to remember the difference in hardness, the color of the trait (in native metals, the color of the trait is identical with the color of the mineral itself), the dimension of the precipitates. Silver is often oxidized and covered with black silver sulfides, it is not common and is absent from the educational collection.

It can be viewed in the TPU Mineralogical Museum or in electronic sources. *Native copper* can also oxidize, becoming covered with a black pating, but this coating can easily be mechanically removed with the help of a biscuit or glass at hand, which allows you to see the true color of the mineral (copper red). *Copper* can form solid masses, and then its specific gravity (8.5 g/cm^3) can be felt by weighing in the hand. This mineral is often associated with similar copper-containing minerals: *chalcocite, cuprite, malachite, azurite,* etc. This fact is explained by the genesis of these minerals in the zone of oxidation or secondary sulfide concentration of copper. *Nicolite* is sometimes mistakenly called *copper* because of its light copper-red color and high specific gravity, but the streak of the nickel is black, which is difficult to confuse with the red streak of *copper*.

Native non-metals are characterized by a covalent bond. The degree of covalence increases from sulfur to diamond. Sulfur has an isle structure, graphite – layered, diamond – coordination. *Native sulfur* is easily diagnosed by its light yellow color, softness (hardness 1.5–2), fragility, light yellow streak, the smell of matches, flammability. By color, sulfur can be confused with a similar yellow *orpiment*, however, the latter is brighter, has a very perfect cleavage a successful minerals surviving prismatic flattened crystals, in contrast to crystals close to isometric *sulfur*. *Graphite*, having a layered structure, has low hardness, stains hands, greasy to the touch, gray-black in color with a similar color of the streak. Graphite is characterized by solid masses, which perfectly reflect its low specific gravity. It differs from *molybdenite* by the preservation of the gray-black color of the line when it is rubbed on paper.

Descriptive mineralogy

NATIVE METALS

Mineral name	**Copper**
Chemical composition (alloys are indicated in brackets)	**Cu** (Fe,Ag,Au)
Syngony	Isometric
Crystal Form	Skeletal crystals rarely form
Aggregate morphology	lamellar dendrites, solid plates
Color	Copper-red. Tarnishes to black or green in air
Streak	Copper-red, pink, metallic-lustrous
Luster	Metallic
Cleavage	Imperfect, none observed
Hardness	2.5–3, very malleable
Specific gravity (g/cm^3)	8.5–8.9
Diagn. signs	Maleable, hackly fracture, copper-red metallic-lustrous streak, low hardness, high density, often tarnished
Associate minerals	Cuprite, malachite, azurite, calcite, chalcocite
Genesis	Oxidation zones of copper deposits, hydrothermal deposits
Application	Electrical and mechanical engineering, as a ligature additive in jewelry production

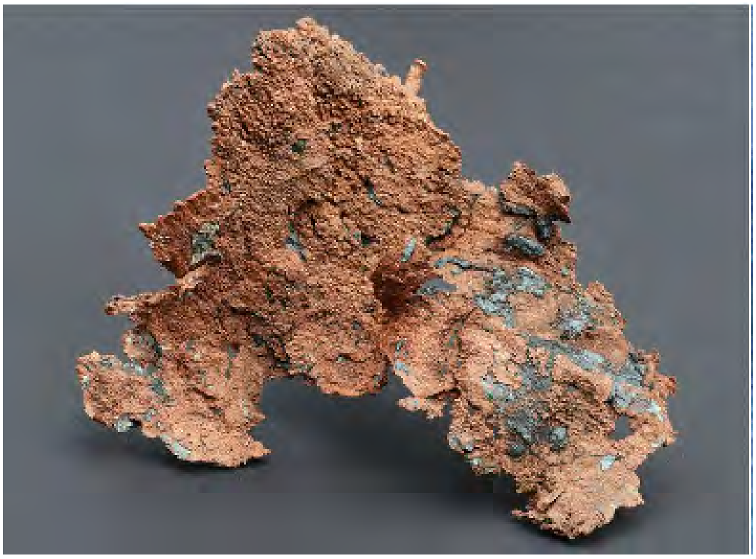


Fig. 29. Native copper dendrites with tarnished areas (Girilambone Copper Mine, Girilambone, Canbelego Co., New South Wales, Australia)

NATIVE METALS

Mineral name	**Silver**
Chemical composition (alloys are indicated in brackets)	**Ag** (Cu,Au,Sb)
Syngony	Isometric
Crystal Form	Crystals are rare
Aggregate morphology	Found in the form of "knitted" feathery dendrites. Mossy, hairy and wiry forms are characteristic. Observed as irregular grains, nuggets
Color	Silver-white, tarnishes dark gray to black
Streak	Silver-white, metallic-lustrous
Luster	Metallic
Cleavage	Imperfect, none observed
Hardness	2.5, very malleable
Specific gravity (g/cm^3)	10.1–11.1
Diagn. signs	low hardness, silvery color, tarnishes dark gray to black
Associate minerals	Silver sulfides and arsenides
Genesis	Zones of oxidation of deposits of sulfur and arsenic-antimony ores
Application	Electrical engineering, electronics, as coatings, jewelry, catalyst in oxidation reactions

Fig. 30. Matted-fibrous crystals of native silver (Měděnec, Chomutov District, Ústí nad Labem Region, Czech Republic)

NATIVE METALS

Mineral name	**Gold**
Chemical composition (alloys are indicated in brackets)	**Au** (Cu,Ag,Pd,Sb)
Syngony	Isometric
Crystal Form	Crystals are rare, mainly in the form of octahedra, less often rhombododecaers, and occasionally in the form of hexahedra
Aggregate morphology	In the form of irregular grains included in quartz or ore mass, dendritic twins, flattened grains and scales (gold dust)
Color	Rich and golden yellow
Streak	Golden yellow, shining yellow
Luster	Metallic, none observed
Cleavage	Imperfect
Hardness	2.5–3, it has malleability and ductility
Specific gravity (g/cm^3)	15.6–19.3
Diagn. signs	Pyrite, chalcopyrite
Associate minerals	Quartz, sulfides (pyrite, arsenopyrite, chalcopyrite, galena, sphalerite), limonite
Genesis	Hydrothermal deposits genetically associated with intrusive felsic igneous rocks; zones of oxidation of sulfide deposits
Application	Strategic and monetary metal, electronics, jewelry, luxury goods, physical and chemical devices, dentistry

Fig. 31. Dentritic crystals of gold (Hope's Nose, Torquay, Torbay, Devon, England, UK)

NATIVE NON-METALS

Mineral name	**Graphite**
Chemical composition	**C**
Syngony	Hexagonal
Crystal Form	Correctly formed crystals are rare, they look like hexagonal plates or tablets (Fig. 32)
Aggregate morphology	Graphite usually occurs in flakes
Color	Iron black to steel-grey
Streak	Gray-black, shiny
Luster	Sub-metallic, in the cryptocrystalline aggregates – greasy
Cleavage	Perfect on {0001}
Hardness	1, flexible in thin leaves. Greasy to the touch, stains on a paper and fingers
Specific gravity (g/cm^3)	2
Diagn. signs	Draws on paper, when rubbed, retains a gray-black color, unlike molybdenite, which turns green, micaceous fracture
Associate minerals	Often monomineral, sometimes with quartz (Fig. 32), with calcite
Genesis	Metamorphic, and magmatic. Formed in recovery processes at high temperatures
Application	Manufacture of graphite crucibles, foundry, manufacture of pencils, electrodes, paint industry

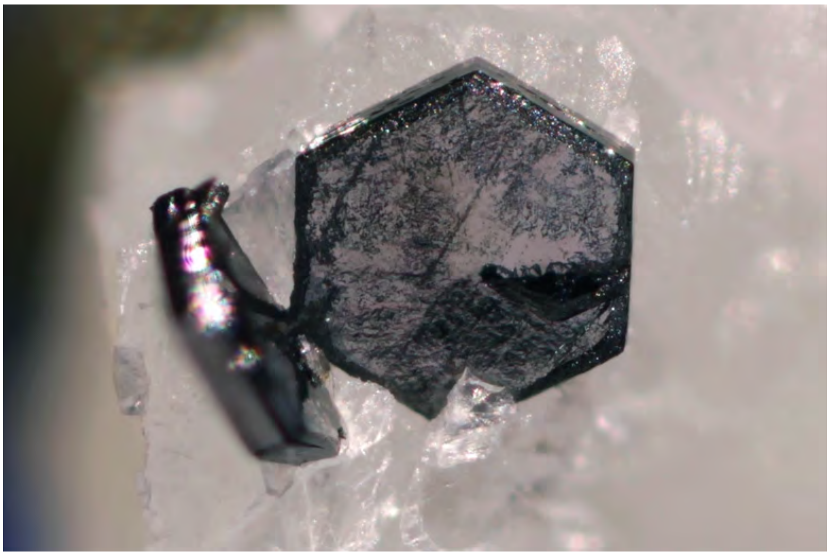


Fig. 32. Hexagonal crystals of graphite in quartz (Crestmore, Riverside Co., California, USA)

NATIVE NON-METALS

Mineral name	**Diamond**
Chemical composition	**C**
Varieties	*Board (in Rus.)* – irregularly shaped intergrowths and spherical radiant aggregates; *carbonado* – fine-grained, porous aggregates colored with amorphous graphite and foreign impurities in a brownish-black color
Syngony	Isometric
Crystal Form	Octahedral, rhombododecahedron, cubic (rare) and their combination
Aggregate morphology	Phenocrysts
Color	Colorless, light blue, blue, yellow, pink, cognac-brown, lilac (very rare)
Streak	–
Luster	Adamantine
Cleavage	Perfect on {111}
Hardness	10
Specific gravity (g/cm^3)	3.5
Diagn. signs	High hardness, luminescent in UV
Associate minerals	Olivine, chromite, pyrope, serpentine
Genesis	Ultrabasic igneous rocks of high alkalinity (kimberlites, lamproites, peridotites)
Application	Machinery, jewelry and abrasive industry

Fig. 33. Diamond crystal (Jwaneng Mine, Kanye, Ngwaketse North District, Southern District, Botswana)

NATIVE NON-METALS

Mineral name	**Sulphur**
Chemical composition (common impurites are indicated in brackets)	**S** (clay or organic matter, Se,Te)
Syngony	Rhombic, monoclinic
Crystal Form	Truncated bipyramidal, pyramidal
Aggregate morphology	Blocky dipyramidal ones most common, also tabular and sphenoidal; also found as powdery coatings, massive material, and in reniform and stalactic forms
Color	Yellow, sulphur-yellow, brownish or greenish yellow, orange, white, honey yellow, brown, black (from carbon impurities)
Streak	Pale yellow
Luster	Adamantine, resinous and greasy
Cleavage	Imperfect
Hardness	1–2, fragile
Specific gravity (g/cm^3)	2
Diagn. signs	Similar to orpiment, burns, smells
Associate minerals	Calcite, gypsum
Genesis	Volcanic sublimates and exhalation, oxidation zones (during pyrite decomposition), during decomposition of gypsum-bearing sedimentary strata, sedimentary (biochemical), origin is associated with the vital activity of anaerobic bacteria that process sulfates
Application	Sulfuric acid production, agriculture, industry, production of matches, fireworks, paints

Fig. 34. Idiomorphic crystals of native sulfur (yellow) (Cianciana sulphur mines, Cianciana, Agrigento Province, Sicily, Italy)

2.7.2. Type II. Sulfides and their analogues

Sulfides are compounds of *sulfur* with *metals* and are salts of hydrogen sulfide acid H_2S. The most common sulfides of chalcophilic elements, due to which most of them have a high specific gravity, but at the same time low and medium hardness. Electronic bonds between chemical elements included in the crystal lattices of sulfides are of ionic or mixed types, which determines the sharp difference in their optical properties. Many sulfides have a wide anisotropy of physical properties, including hardness. In the total mass of the Earth's crust, sulphides account for 0.15 %, while the number of mineral species is more than 200. Sulphides are formed mainly by hydrothermal means, as well as during exogenous processes in a reducing environment. Sulfides of magmatic origin are rare and their nature is sometimes questionable. Sulfides are ores of important metals: cobalt, nickel, copper, mercury, zinc, lead, antimony, iron. Arsenides, which are similar in properties, can also be referred to as sulfide analogs.

Among sulfides and their analogues, the course of the work program includes three groups of minerals: "*glances*", "*pyrites*" and "*blendes*".

The "*glances*" group includes sulfides with a lead-gray color and a dark gray line, metallic luster and low hardness (<3).

The group of "*pyrites*" should include sulfides and their analogs, which have a metallic luster, relatively high hardness (> 4), and a dark-colored line. Separated by *yellow*, *red* and *white* pyrites.

The group of "*blendes*" unites sulfides with various bright colors and features, adamantine and hardness ranging from 1.5–4.

Despite a number of common features within each group, various signs can be distinguished.

The group of "*glances*" should include four sulfides: *galena*, *antimonite*, *molybdenite* and *chalcocite*. In order to learn to distinguish between them, you need to know a number of characteristic features for each mineral.

Firstly, it is the different appearance of the crystals. *Galena* is characterized by an isometric crystal habit (Fig. 35), while antimonite is characterized by an elongated (elongated) appearance (Fig. 36), the shape of molybdenite crystals is flattened (rosette) (Fig. 37), or it forms films and smears, chalcocite is more often all forms solid masses. Cleavage is most clearly manifested in galena (perfect cube), which is reflected in a stepped fracture and the appearance of a characteristic "parquet" (Fig. 41).

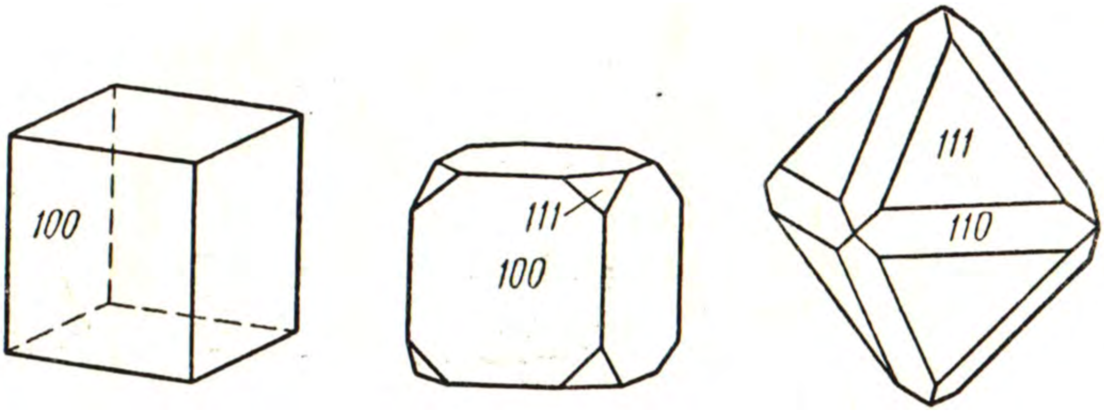


Fig. 35. Isometric shape of galena crystals

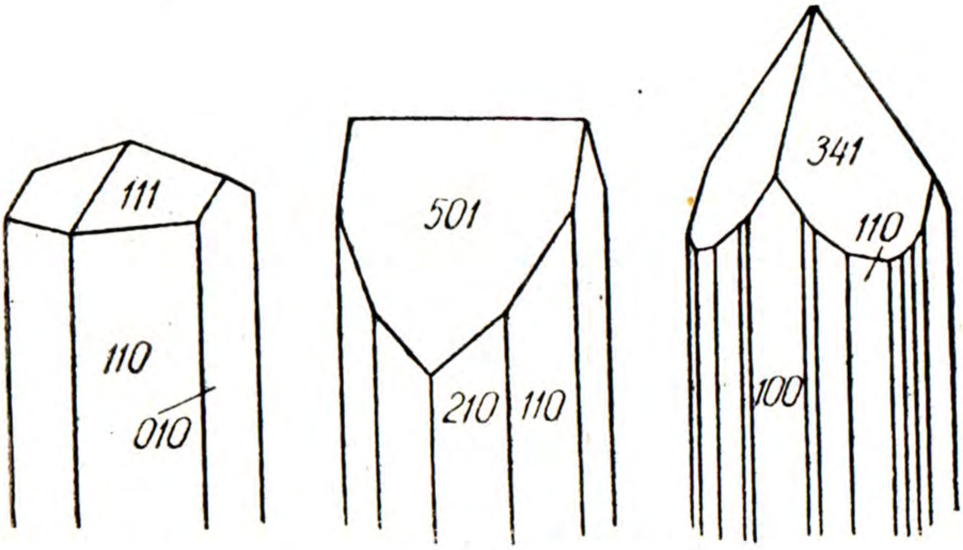


Fig. 36. Elongated (prismatic shape) crystals of antimonite

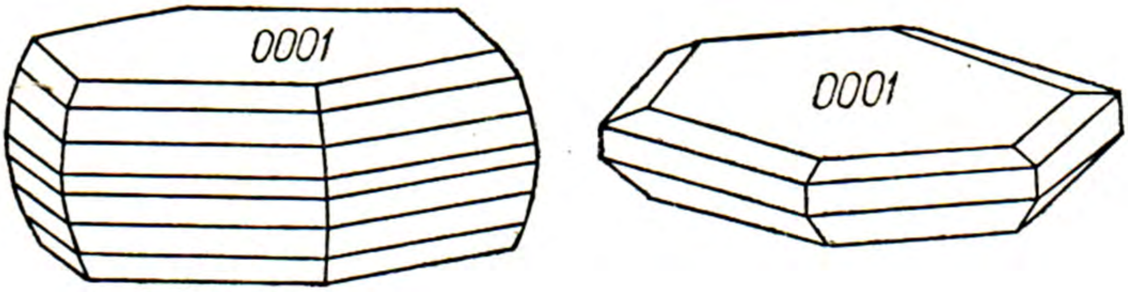


Fig. 37. Flattened form of molybdenite crystals

Secondly, their paragenesis plays an important role in the diagnosis of minerals. *Galena* is formed by the medium-temperature hydrothermal pathway and is most often associated with *sphalerite, pyrite, arsenopyrite*, and other minerals in this temperature range.

Antimonite is a typically low-temperature hydrothermal mineral; therefore, such minerals as *cinnabar, fluorite, calcite* and others are its companions.

Molybdenite, on the other hand, is a high-temperature hydrothermal mineral; therefore, potassium feldspar, quartz, chalcopyrite, or minerals of skarn genesis are often associated with it. This mineral from the entire group of «glances» is the softest (hardness 1), which is reflected in the fact that it is greasy to the touch, stains hands, when rubbed on paper it acquires a greenish tint, in contrast to graphite (hardness 1), which is rubbing on paper retains the gray color.

Chalcocite has a specific paragenesis with copper-bearing minerals such as *bornite, malachite, native copper* and others.

Thirdly, the color of the minerals of the "glances" group, although it is considered to be gray, all of them have their own shades. Antimonite and galena are the closest in color to each other, their color can be conventionally called lead-gray. However, *antimonite* sometimes has a bluish tint, which is not characteristic of galena. *Molybdenite* has a slightly bluish tint, while *chalcocite* is often oxidized with a black coating, acquiring a darker shade to black. Only by removing the oxidation film from its surface can you see the mineral's own gray color. Fourthly, a significant difference between sulfides of the "glances" group is the excellent specific gravity of each of them. The most weighty is *galena*, the density of which is 7.5 g/cm^3, in contrast to antimonite 4.6 g/cm^3. It is quite problematic to check the specific gravity of *molybdenite* by weighing in the hand, given the fact that it forms smears and leather coats and does not completely compose samples. *Chalcocite* is also difficult to determine by specific gravity, for a similar reason and frequent association with other copper-bearing minerals.

A more detailed description of each of the sulfides of this group is given in the summary table of minerals.

The «*pyrites*» group is divided into *yellow, white* and *red* by color.

Three minerals belong to yellow "*pyrites*": *pyrite*, *chalcopyrite* and *pyrrhotite*.

The color of *pyrite* is straw yellow, *chalcopyrite* is brass yellow and *pyrrhotite* is bronze yellow or creamy yellow.

Of the presented triad of minerals, only pyrite (6.5) has a hardness higher than 5, which allows it, in contrast to chalcopyrite and pyrrhotite, to leave a scratch on the glass. The streak of yellow "pyrites" is also different. The streak of *chalcopyrite* is characterized by a greenish tint, while in pyrite and pyrrhotite it is grayish-black. *Pyrrhotite* is magnetic.

The crystal shape of *yellow* "*pyrites*" is also different. The main thing at this point is not even the difference in the shape of the crystals, but their frequency of occurrence. *Pyrite*, possessing a high degree of idiomorphism (the ability to form well-faceted crystals), very often forms crystals of a cubic habit (Fig. 38). *Chalcopyrite* and *pyrrhotite*, on the other hand, have a low degree of idiomorphism; therefore, these minerals practically do not form crystals. It is very rare to see well-formed *chalcopyrite* or *pyrrhotite* crystals with perfect facets. *Pyrrhotite* and *chalcopyrite* are mainly found in the form of solid masses.

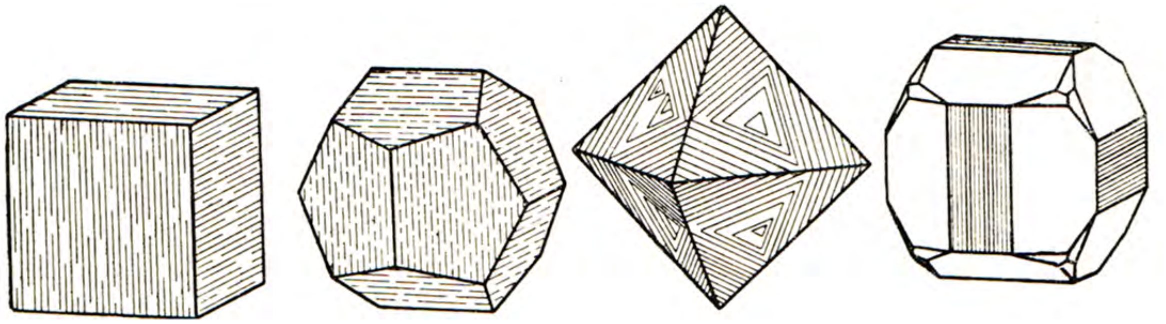


Fig. 38. Form of pyrite crystals

Three minerals should be referred to the group of *white* "*pyrites*": *arsenopyrite*, *cobaltite* and *smaltite*.

Arsenopyrite is characterized by a steel gray color, *smaltite* – tin white, *cobaltite* – steel gray with a pink tint. The different crystal shape dictated by the crystal system contributes to the correct diagnosis of white firestones. *Arsenopyrite*, crystallizing in monoclinic system, forms prismatic, elongated crystals with characteristic vertical shading (Fig. 39), in contrast to cubic *smaltite* and *cobaltite*.

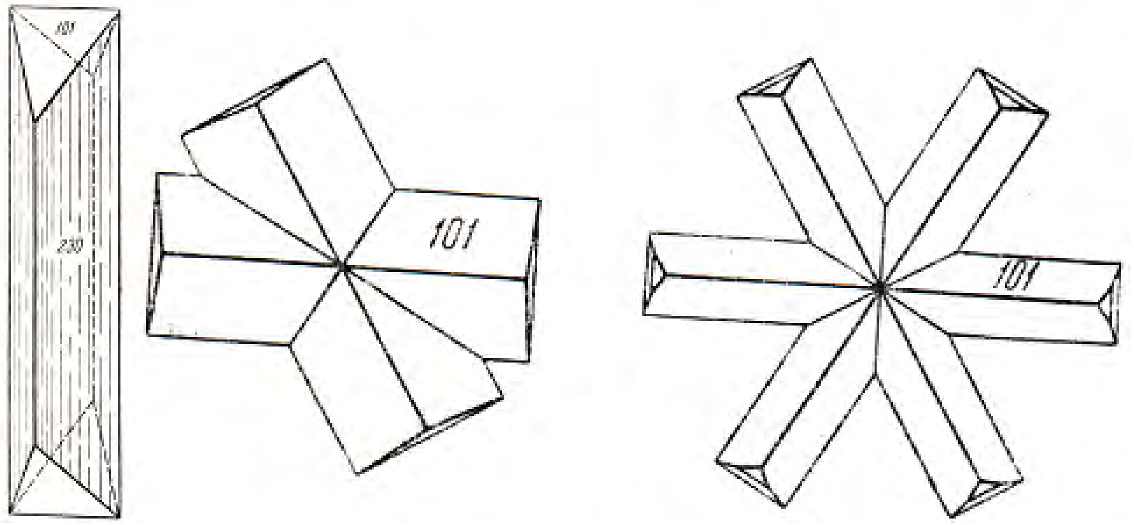


Fig. 39. Elongated prismatic crystals of arsenopyrite, twins and trillings of intergrowth

At the same time, and between the latter, you can find differences in the predominant forms of crystals. *Cobaltite*, as a rule, forms small crystals of a hexahedral appearance, while in *smaltite* the predominant forms are octahedrons, which manifests itself in the form of frequent triangular faces with a characteristic intersecting hatching at an angle of 60°. *Arsenopyrite* is characterized by intergrowth twins (Fig. 39).

Paragenesis in white pyrites is very individual. *Arsenopyrite* is the most abundant (high and medium temperature) and is found in association with *pyrite, sphalerite, galena,* and other sulfides, while smalt, which is more refined and rare, prefers to be found together with *nickeline. Cobaltite* can be monomineral and occur with *pyrrhotite, molybdenite,* and other minerals of high-temperature hydrothermal and skarn genesis.

The group of "white pyrites", in contrast to the minerals of the "glances" group similar in gray in color, are characterized by a higher hardness (above 5). "White pyrites" do not stain your hands, are not greasy to the touch, and are not scratched by glass.

The group of red firestones should include two minerals: *nickeline* and *bornite. Nickeline,* as noted earlier, is often associated with *smaltite,* which can be explained by the closeness and chemical relationship of the main ore components Ni and Co of these minerals. With its light copper-red color and metallic luster, *nickeline* resembles *native copper*, but differs from it in the dark, non-shiny color of the line.

Bornite is easily diagnosed by its ink tarnishing and joint paragenesis with copper-containing minerals, most often with oxidized *chalcocite*.

SULFIDES AND THEIR ANALOGUES

"Glances" Group

Mineral name	**Chalcocite** (copper glance**)**
Chemical composition (common impurity is indicated in brackets)	**Cu_2S** (Ag)
Syngony	Rhombic, monoclinic, hexagonal
Crystal Form	Crystals are rare, often found in tables and short prisms
Aggregate morphology	Continuous fine-grained masses, phenocrysts, pseudomorphs
Color	Lead gray
Streak	Dark gray
Luster	Metallic, sub-metallic
Cleavage	Imperfect
Hardness	2–2.5
Specific gravity (g/cm^3)	5.5–5.8
Diagn. signs	Resembles other «glances», from which it differs in its characteristic paragenesis with copper minerals, often tarnishes to black
Associate minerals	Native copper, bornite, cuprite, malachite, azurite, calcite
Genesis	Hydrothermal, exogenous (zone of secondary sulfide concentration of copper ores)
Application	Copper ore

Fig. 40. Chalcocite (earthy gray) (Mammoth Mine, Mount Gordon, Gunpowder District, City of Mount Isa, Queensland, Australia)

SULFIDES AND THEIR ANALOGUES

"Glances" Group

Mineral name	**Galena** (lead glance)
Chemical composition (impurity is indicated in brackets)	**PbS** (Ag)
Syngony	Isometric
Crystal Form	Cubes, octahedrons, less often their combinations
Aggregate morphology	Druses of crystals, granular aggregates
Color	Lead gray
Streak	Dark gray
Luster	Metallic, sub-metallic, dull
Cleavage	Perfect on {100}
Hardness	2.5–3
Specific gravity (g/cm^3)	7.5
Diagn. signs	Resembles antimonite, molybdenite, from which it differs in stepwise fracture, cube cleavage, high specific gravity, paragenesis
Associate minerals	Sphalerite, pyrite, chalcopyrite, calcite, fluorite
Genesis	Hydrothermal medium-temperature lead-zinc deposits
Application	Lead ore, silver is extracted along the way

Fig. 41. Cubic crystals of galena with a characteristic cleavage at an angle of 90° (Sweetwater Mine, Ellington, Reynolds County, Missouri, USA)

SULFIDES AND THEIR ANALOGUES

"Glances" Group

Mineral name	**Stibnite** (antimony glance)
Chemical composition (common impurities are indicated in brackets)	**Sb_2S_3** (As,Bi,Ag)
Syngony	Rhombic
Crystal Form	Long prismatic, columnar, needle-like
Aggregate morphology	Druse, radial-radiant, prismatic-granular aggregates
Color	Lead gray with bluish tarnishing
Streak	Dark gray
Luster	Metallic
Cleavage	Perfect on {010}
Hardness	2–2.5
Specific gravity (g/cm^3)	4.6
Diagn. signs	Resembles galena, from which it differs in an elongated crystal shape and a lower specific gravity
Associate minerals	Valentinite, servantite (oxidation zone); cinnabar, calcite, fluorite (hydrothermal)
Genesis	Hydrothermal low-temperature deposits
Application	Antimony ore

Fig. 42. Elongated prismatic crystals of stibnite (Kremnica (Kremnitz) Au-Ag deposit, Kremnica, Žiar nad Hronom District, Banská Bystrica Region, Slovakia)

SULFIDES AND THEIR ANALOGUES

"Glances" Group

Mineral name	**Molybdenite (**molybdenum glance)
Chemical composition (impurity is indicated in brackets)	**MoS_2** (Re)
Syngony	Hexagonal
Crystal Form	Lamellar, flaky
Aggregate morphology	Scaly, rosette
Color	Lead gray, bluish gray
Streak	Dark gray, bluish gray
Luster	Metallic
Cleavage	Perfect on {0001}
Hardness	1
Specific gravity (g/cm^3)	5
Diagn. signs	Resembles graphite, in contrast to which it does not form monomineral accumulations, but occurs in the form of rosette phenocrysts and thin flakes. Greasy in touch; when rubbed on paper, the line takes on a greenish tint
Associate minerals	Quartz, feldspar, chalcopyrite
Genesis	Hydrothermal high-temperature deposits
Application	Molybdenum ore, rhenium is simultaneously extracted

Fig. 43. Rosette crystals of molybdenite with quartz (Crown Point Mine, Railroad Creek Mining District, Chelan Co., Washington, USA)

SULFIDES AND THEIR ANALOGUES

"Yellow pyrites" Group

Mineral name	**Pyrite** (iron pyrite)
Chemical composition (common impurities are indicated in brackets)	**FeS_2** (Co, Cu, Au)
Syngony	Isometric
Crystal Form	Often occurs as well-formed cube and pentagondodecahedron crystals
Aggregate morphology	Phenocrysts of crystals and rounded grains, as well as solid masses and nodules
Color	Straw yellow
Streak	Dark gray to brownish black
Luster	Metallic
Cleavage	Imperfect
Hardness	6–6.5
Specific gravity (g/cm^3)	5
Diagn. signs	Resembles gold, chalcopyrite, pyrrhotite, marcasite, from which it differs in hardness and appearance of crystals
Associate minerals	Diverse
Genesis	Magmatic, hydrothermal, contact-metasomatic, sedimentary
Application	Sulfuric acid production

Fig. 44. Pyrite dodecahedron, also known as "pyritohedron" (Elba, Italy)

SULFIDES AND THEIR ANALOGUES

"Yellow pyrites" Group

Mineral name	**Pyrrhotite** (magnetic pyrite)
Chemical composition (impurity is indicated in brackets)	**$Fe_{1-x}S$** (Ni)
Syngony	Hexagonal, monoclinic
Crystal Form	Crystals are rare
Aggregate morphology	Solid masses, phenocrysts of irregularly shaped grains
Color	Bronze yellow, cream
Streak	Grayish black, brownish black
Luster	Metallic
Cleavage	Imperfect
Hardness	4
Specific gravity (g/cm^3)	4.6
Diagn. signs	Weakly magnetic properties
Associate minerals	Chalcopyrite, pentlandite (magmatic genesis). Sphalerite, galena, pyrite, arsenopyrite (hydrothermal, contact-metasomatic)
Genesis	Magmatic, hydrothermal, contact-metasomatic, less often sedimentary
Application	Ferrous sulfate production

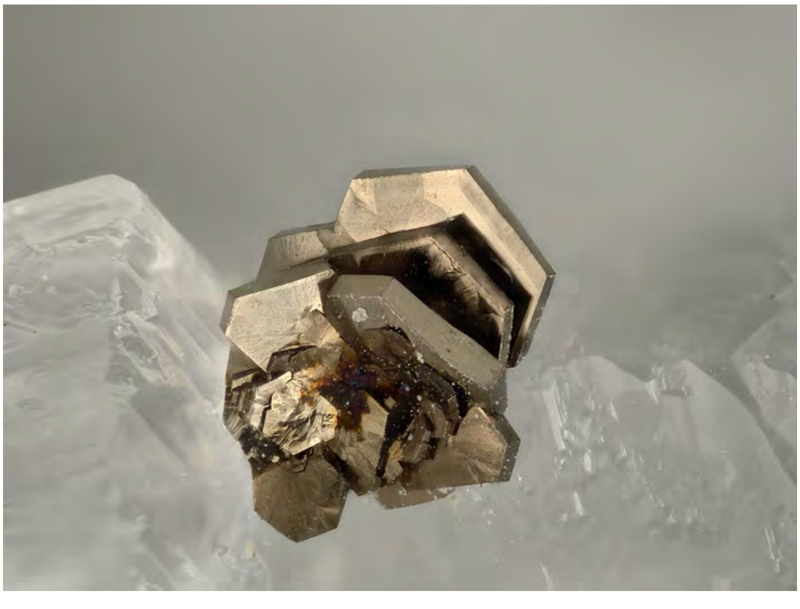


Fig. 45. Intergrowths of hexagonal crystals of Pyrrhotite (Rhomberg quarry, Unterklien, Hohenems, Dornbirn District, Vorarlberg, Austria)

SULFIDES AND THEIR ANALOGUES

"Yellow pyrites" Group

Mineral name	**Chalcopyrite** (copper pyrite)
Chemical composition (impurity is indicated in brackets)	**$CuFeS_2$** (Ni)
Syngony	Tetragonal
Crystal Form	Crystals are rare (Fig. 46), tetrahedral
Aggregate morphology	Solid masses, phenocrysts of irregularly shaped grains
Color	Brass yellow, often with iridescent tarnishing
Streak	Greenish black
Luster	Metallic
Cleavage	Imperfect
Hardness	4
Specific gravity (g/cm^3)	4.1–4.3
Diagn. signs	Brass yellow with a greenish tint, variegated tarnishing
Associate minerals	Pyrrhotite, pentlandite (magmatic genesis). Sphalerite, galena, pyrite, arsenopyrite, pyrrhotite, chalcocite (hydrothermal, contact-metasomatic)
Genesis	Magmatic, hydrothermal, contact-metasomatic, sedimentary
Application	Copper ore

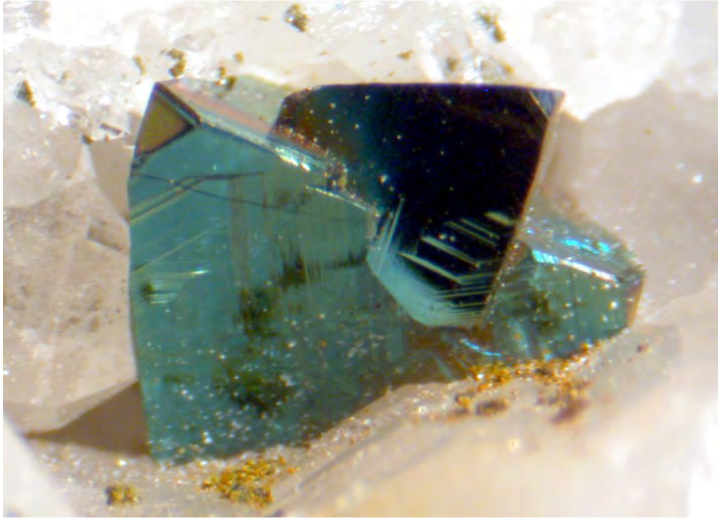


Fig. 46. Intergrowths of Chalcopyrite crystals (Wheal Basset, Basset Mines, Carnkie, Carn Brea, Cornwall, England, UK)

SULFIDES AND THEIR ANALOGUES

"White pyrites" Group

Mineral name	**Arsenopyrite** (arsenic pyrite)
Chemical composition (impurities are indicated in brackets)	**FeAsS** (Co,Ni)
Syngony	Monoclinic
Crystal Form	Crystals of a well-defined prismatic appearance from short-columnar to columnar and acicular. Rough longitudinal shading of the edges is characteristic
Aggregate morphology	In solid masses forms granular and columnar aggregates
Color	Steel gray
Streak	Grayish black, sometimes with a brown tint
Luster	Metallic, Sub-Metallic
Cleavage	Imperfect on {001}
Hardness	5.5, fragile
Specific gravity (g/cm^3)	5.9–6.2
Diagn. signs	Resembles cobaltite, smalt from which differs in steel gray color and elongated crystals
Associate minerals	Pyrite, sphalerite, galena, chalcopyrite, gold
Genesis	Hydrothermal
Application	Arsenic ore

Fig. 47. Trillings of prismatic crystals of arsenopyrite (Clara Mine, Oberwolfach, Wolfach, Ortenaukreis, Freiburg Region, Baden-Württemberg, Germany)

SULFIDES AND THEIR ANALOGUES

"White pyrites" Group

Mineral name	**Cobaltite** (white cobalt)
Chemical composition (impurities are indicated in brackets)	**CoAsS** (Fe,Ni)
Syngony	Isometric
Crystal Form	Cubic, octahedral, pentagondodecahedral
Aggregate morphology	In continuous masses forms granular aggregates, and also occurs in the form of phenocrysts of individual crystals
Color	Pewter white or yellowish white with pink tarnishing
Streak	Grayish black
Luster	Metallic
Cleavage	Perfect on {001}
Hardness	5.0–6, fragile
Specific gravity (g/cm^3)	6.4–6.8
Diagn. signs	Resembles arsenopyrite and smaltite, from which it differs in pink tarnishing and a cubic shape of crystals, differs from pyrite in a whiter shade
Associate minerals	Molybdenite, pyrrhotite, chalcopyrite
Genesis	Hydrothermal, skarn, in the oxidation zone is replaced by pink erythrin
Application	Cobalt ore

Fig. 48. Cubic crystal of cobaltite with pink tarnish (Håkansboda, Lindesberg, Örebro County, Sweden)

SULFIDES AND THEIR ANALOGUES

"White pyrites" Group

Mineral name	**Smaltite** (gray cobalt)
Chemical composition (impurities are indicated in brackets)	**$CoAs_{2–3}$** (Fe,Ni)
Syngony	Isometric
Crystal Form	Cubes, octahedra and their combinations
Aggregate morphology	Occurs in continuous masses, as well as phenocrysts of individual triangular crystals
Color	Tin-white to silver-gray, gray (tarnished)
Streak	Grayish black
Luster	Metallic
Cleavage	Distinct on {001}{111}
Hardness	5.5–6, fragile
Specific gravity (g/cm^3)	6.5
Diagn. signs	
Associate minerals	Nickeline
Genesis	Hydrothermal
Application	Cobalt ore

Fig. 49. Smaltite crystals (Schneeberg, Erzgebirgskreis, Saxony, Germany)

The "*blendes*" group, unlike other sulfides, is characterized by very specific features: adamantine luster, colors, and a low specific gravity (with the exception of cinnabar). This group includes: *sphalerite, realgar, orpiment, cinnabar.*

Sphalerite (zinc blende) is the most difficult to diagnose and should be given special attention. This mineral can have a different color range from colorless, slightly yellow (low-iron variety) – *cleiophane*, to dark-colored, brown – *marmatite*. In this case, the color of the sphalerite feature will also vary in proportion to the iron content in the mineral from light to dark brown. When rubbed, sphalerite reacts with hydrochloric acid (5 % HCl) to release hydrogen sulfide. Most often, *galena* closely associates with *sphalerite*. Zinc blende, crystallizing in a cubic system, forms crystals of a tetrahedral appearance, or solid masses. By its color palette and adamantine luster, sphalerite can be easily confused with wolframite, which, unlike the former, has flattened, elongated crystals (monoclinic crystal system), a higher specific gravity (7.5), a characteristic paragenesis with "rusty" quartz and does not react with 5 % HCl.

Realgar has a bright orange color and a similar streak color, which distinguishes it from *cinnabar*, whose trait color is red. Realgar has perfect cleavage, as does the orpiment, with which it is often associated in low temperature hydrothermal associations. Realgar, like all minerals of the "blende" group, is characterized by adamantine luster. It is fragile, due to the weak Van der Waals force of the chemical bond of electrically neutral parts in the structure (like native sulfur), and often forms loose, free-flowing masses.

Auripigment is easily recognized by its bright yellow color, adamantine luster, perfect cleavage, which distinguishes it from native sulfur, which does not have cleavage.

Orpiment has the most significant specific gravity (8.5) of all the minerals of the "blende" group. If the *cinnabar* forms solid masses, its high specific gravity is well felt by weighing the mineral in the hand. If the cinnabar forms crystals, then adamantine luster is observed on their faces, sometimes to a metallic one. Twins of germination are characteristic of *cinnabar* (Fig. 55).

SULFIDES AND THEIR ANALOGUES

"Red pyrites" group

Mineral name	**Nickeline** (arsenical nickel)
Chemical composition	**NiAs**
Syngony	Hexagonal
Crystal Form	Crystals are rare
Aggregate morphology	Solid masses, sometimes in the form of reniform, dendritic and other forms
Color	Pale copper-red
Streak	Brownish black
Luster	Metallic, matt on an oxidized surface
Cleavage	Imperfect
Hardness	5
Specific gravity (g/cm^3)	7.5
Diagn. signs	Resembles native copper, from which it differs in higher hardness and dark-colored streak. In the oxidation zone, it is replaced by green annabergite
Associate minerals	Smaltite
Genesis	Hydrothermal
Application	Nickel ore

Fig. 50. Solid masses of nickeline
(Schneeberg, Erzgebirgskreis, Saxony, Germany)

SULFIDES AND THEIR ANALOGUES

"Red pyrites" Group

Mineral name	**Bornite** (purple copper ore)
Chemical composition	**Cu_5FeS_4**
Syngony	Isometric
Crystal Form	Crystals are rare. Typically found as massive metallic masses
Aggregate morphology	Forms solid masses, phenocrysts of grains
Color	Copper-red to pinchbeck-brown, quickly tarnishing to an iridescent purplish surface
Streak	Grayish black
Luster	Metallic to semi-metallic
Cleavage	Imperfect
Hardness	3–3.5
Specific gravity (g/cm^3)	4.9–5.3
Diagn. signs	Resembles native copper and nickeline, from which it is distinguished by the presence of a bright blue tarnish
Associate minerals	Chalcocite, covellite (sulf. enrichment zone) chalcopyrite (hydrothermal)
Genesis	Hydrothermal, exogenous (in zones of secondary sulfide concentration)
Application	Copper ore

Fig. 51. Crystals of bornite with an iridescent purplish surface (Dzhezkazgan mining district, Karaganda Region, Kazakhstan)

SULFIDES AND THEIR ANALOGUES

"Blendes" Group

Mineral name	**Sphalerite** (zinc blende)
Chemical composition (impurities are indicated in brackets)	**ZnS** (Fe,Cd, In,Ga)
Varieties	*Marmatite – ferruginous dark-colored sphalerite* *Cleiophane – low-iron light-colored sphalerite*
Syngony	Isometric
Crystal Form	Cube, tetrahedron, rhombododecahedron
Aggregate morphology	Druses, granular
Color	Brown, light yellow, green, red
Streak	Light to dark brown
Luster	Adamantine
Cleavage	Imperfect on {110}
Hardness	4
Specific gravity (g/cm^3)	4.08–4.1
Diagn. signs	Resembles wolframite, from which it differs in isometric crystals and a lower specific gravity. Decomposes in 5 % HCl producing hydrogen sulfide (H_2S)
Associate minerals	Galena, pyrite, arsenopyrite, chalcopyrite
Genesis	Hydrothermal medium-temperature Pb-Zn deposits
Application	Ore for Zn (Cd, In, Ga)

Fig. 52. Tetrahedral shape of sphalerite crystals
(Dalnegorsk, Dalnegorsk Urban District, Primorsky Krai, Russia)

SULFIDES AND THEIR ANALOGUES

"Blendes" Group

Mineral name	**Realgar** (arsenic red)
Chemical composition	**As_4S_4**
Syngony	Monoclinic
Crystal Form	Prismatic with fine vertical shading (Fig. 53)
Aggregate morphology	Solid granular masses, crusts, loose aggregates
Color	Orange-red
Streak	Orange-yellow, orange-red
Luster	Adamantine, greasy
Cleavage	Good on {010}
Hardness	1.5–2
Specific gravity (g/cm^3)	3.5
Diagn. signs	Resembles cinnabar, from which it differs in an orange-red line
Associate minerals	Orpiment
Genesis	Hydrothermal low-temperature deposits
Application	Arsenic raw materials

Fig. 53. Prismatic form of realgar crystals
(Lengenbach Quarry, Fäld, Binn, Goms, Valais, Switzerland)

SULFIDES AND THEIR ANALOGUES

"Blendes" Group

Mineral name	**Orpiment**
Chemical composition	**As_2S_3**
Syngony	Monoclinic
Crystal Form	Prismatic
Aggregate morphology	Commonly in foliated columnar or fibrous aggregates; may be reniform or botryoidal; also granular or powdery; rarely as prismatic crystals
Color	Lemon yellow, sometimes with a brownish tinge
Streak	Lemon yellow
Luster	From adamantine to semi-metallic
Cleavage	Perfect on {010}
Hardness	1.5–2
Specific gravity (g/cm^3)	3.5
Diagn. signs	Resembles sulfur, from which it differs in the appearance of crystals, lack of smell, paragenesis
Associate minerals	Realgar
Genesis	Hydrothermal low-temperature deposits
Application	Arsenic raw materials

Fig. 54. Prismatic form of orpiment crystals (Quiruvilca Mine, Quiruvilca District, Santiago de Chuco Province, La Libertad, Peru)

SULFIDES AND THEIR ANALOGUES

"Blendes" Group

Mineral name	**Cinnabar**
Chemical composition	**HgS**
Syngony	Trigonal
Crystal Form	Thick-tabular, rhombohedral
Aggregate morphology	Grainy solid masses, phenocrysts of irregular shape, powdery smears and deposits
Color	Red, sometimes with lead tarnishing
Streak	Red
Luster	From adamantine to strong semi-metallic, metallic
Cleavage	Perfect on{1010}
Hardness	2.0–2.5
Specific gravity (g/cm^3)	8.5
Diagn. signs	Resembles realgar, from which it differs in red color
Associate minerals	Chalcedony, calcite, antimonite, fluorite, barite
Genesis	Hydrothermal low-temperature deposits
Application	Mercury ore

Fig. 55. Cinnabar crystals with association of calcite (Tongren Mine, Bijiang District, Tongren, Guizhou, China)

2.7.3. Type III. Halogen compounds

Halogen compounds form a group of minerals that contain volatile components or halogens (Cl, F), which have a negative oxidation state. We should be acquainted with fluorides (*fluorite*) and chlorides (*halite*). From a chemical point of view, these are salts of hydrofluoric (HF – hydrogen fluoride) and hydrochloric (HCl – hydrogen chloride) acids. These are compounds with an ionic type of chemical bond, crystallizing in a isometric system.

The studied halides are characterized by a hardness below 5, transparency, glass luster, low specific gravity and light color; if the minerals acquire a colored color, then it, as a rule, has an allochromatic character.

Fluorite is included in the Mohs scale, corresponding to a hardness of 4, therefore, when diagnosing it, it is easy to use a comparative analysis with a reference fluorite from a training Mohs scale. Crystallizing in a isometric system, *fluorite* has perfect octahedral cleavage; this property manifests itself in the presence of gouges at an angle of 60°, which are very characteristic of this mineral. The color of *fluorite* is often irregular and varies from purple, pink to green.

Color zoning is often observed. The color of fluorite is associated with hole centers or structural defects. Sometimes *fluorite*, due to its greenish-blue color and similar optical properties, is confused with *apatite*, however, it should be remembered that *apatite* has no cleavage, one unit harder than fluorite and is characterized by elongated crystals.

Halite (rock salt) is easily diagnosed by a number of signs: transparent, light-colored (usually white), light, soft (1.5–2), salty in taste, dissolves in water; due to which it has flowing forms in the samples under study. Possessing a perfect cube cleavage, one can see a stepped fracture in the mineral and gouges at an angle of 90°. Unlike similar soft and transparent *gypsum*, it has a different crystal shape and a different cleavage pattern, unlike calcite, it does not react with 5 % HCl.

HALOGEN COMPOUDS

Mineral name	**Fluorite (**fluorspar)
Chemical composition (common impurites are indicated in brackets)	**CaF_2 (U,Ce,La…)**
Syngony	Isometric
Crystal Form	cube, octahedra and their combinations
Aggregate morphology	Granular, druze, phenocrysts, earthy masses
Color	Varied from colorless to purple, green, yellow
Streak	White
Luster	Vitreous, dull
Cleavage	Perfect on {111}
Hardness	4.0, fragile
Specific gravity (g/cm^3)	3.2
Diagn. signs	Characteristic gouges at an angle of 60°, due to perfect cleavage along the octahedron
Associate minerals	Quartz, antimonite, cinnabar, galena, barite (hydrothermal), beryl, tourmaline, wolframite (metasomatic altered zones)
Genesis	Hydrothermal veins, pegmatite, cavities in sedimentary rocks
Application	Metallurgy (hydrofluoric acid), optics

Fig. 56. Octahedral and isometric habit of fluorite crystals (Rogerley Mine, Rogerley Quarry, Stanhope, County Durham, England, UK)

HALOGEN COMPOUDS

Mineral name	**Halite** (rock salt**)**
Chemical composition	**NaCl**
Syngony	Isometric
Crystal Form	Cube, octahedra and their combinations
Aggregate morphology	Loose, dense crystalline-granular, druses, crystals
Color	Colourless, purple or blue white, gray, yellow, red, brown
Streak	White
Luster	Vitreous
Cleavage	Perfect on {100},{001}
Hardness	2.5, fragile
Specific gravity (g/cm^3)	2.1–2.2
Diagn. signs	Soft, light, salty taste, soluble in water
Associate minerals	Sylvite, carnallite
Genesis	Sedimentary
Application	Food industry

Fig. 57. Cubic crystals of halite (Wieliczka Mine, Wieliczka County, Lesser Poland Voivodeship, Poland)

2.7.4. Type IV. Oxides and hydroxides

Oxides (oxides) are compounds of elements with oxygen. They are a common class of minerals (about 350 mineral types). The types of chemical bonds in oxides are different, which determines their wide differences in physical properties. The most common oxides in the earth's crust are Si (12.6 %), Fe (3.9 %), Al, Ti, Mn, Cr. The most common among them are *quartz*, *hematite* and *magnetite* (Fe oxides), *pyroluzite*, etc. The crystal lattices of oxides are simple (a variety of structures with ionic or strongly polar covalent bonds).

They are represented by hard, dense, refractory well-crystallized minerals (accessory in igneous rocks) resistant to weathering. Most of the oxides are concentrated in the upper parts of the earth's crust: at the border with the atmosphere, which contains free oxygen. The depth of penetration of free oxygen into the earth's crust is controlled by the level of groundwater. Compounds Mg, Al, Si are colorless or have an allochromatic color. Fe, Mn, Cr compounds are intensely dark colored. Black colors are especially common. Minerals are often dark-colored with dark-colored features. Many minerals are opaque or translucent in thin chips, showing brown or red hues. The luster of the oxides is usually semimetallic. Oxides are usually divided into *simple* and *complex*. Simple oxides are composed of one chemical element and oxygen. Complex oxides are composed of several chemical elements combined with oxygen. Simple oxides include *cuprite, corundum, hematite, pyrolutite, rutile, quartz*. Complex oxides include *magnetite, chromospinelide*.

Cuprite (copper oxide) is brick red if it forms earthy masses and is darker to black in crystals, but the color of the streak remains invariably brick-red, which in some cases leads to the fact that it can be confused with *hematite*, which has a similar cherry red line. However, the characteristic paragenesis of cuprite with copper-bearing minerals makes it impossible to misdiagnose. *Native copper, chalcocite, malachite*, etc. are associated with *cuprite*.

Corundum is the hardest of the entire class of oxides presented. This feature makes it possible to almost accurately distinguish it from all other minerals. The streak that it leaves on the glass resembles a rough fosse, and not a slight scratch, characteristic, for example, of the same *quartz*. The color of the mineral is varied, but mainly in the university collections, it is a classic gray-blue. A barrel-shaped bulk habit, sometimes flattened, is typical for corundum in crystals. *Corundum* can also form solid masses. The fine crystalline variety of this mineral is called *abrasive*.

In the educational collections of the department, there is a cherry-brown *emery*, which should also be diagnosed mainly by its high hardness. *Corundum* is found in paragenesis with *feldspars* and *micas*, but not with *quartz*.

Hematite (bloodstone) has a plurality of aggregate morphology varieties. *Hematite* has a semi-metallic high *luster* and is dark to black in color. Often forms lamellar and flattened crystals. It is characterized by a cherry-red streak color, medium hardness (5.5) and density (5.0), lack of magnetic properties and cleavage.

It is appropriate here to talk about the frequent pseudomorphs of the replacement of *hematite* with *magnetite* and vice versa. As I hope, the reader will remember from the chapter on the morphology of aggregates that pseudomorphosis is the formation of one mineral in another, while maintaining the shape of the first. It is necessary to distinguish between *martite* – a pseudomorphism of *magnetite* over *hematite*, and *muschketowite* – a pseudomorphism of *hematite* over *magnetite*. What are their main differences? In the form of crystals, of course. Preservation of the shape of the crystals of the initial mineral, by which the subsequent mineral is formed, is the most important part of the key to the success of the correct diagnosis of these seemingly difficult pseudomorphs. That is, if the shape of the crystals is lamellar, characteristic of trigonal *hematite*, but there is a dark-colored streak and magnetic properties, then we are dealing with *muschketowite*, with octahedral crystals or solid masses with cherry-colored sreaks, these is *muschketowite*.

Thus, due to *magnetite*, both *martite* and *muschketowite* will have magnetic properties, in contrast to *hematite*. At the same time, a distinctive feature of *muschketowite* is characteristic lamellar crystals of hematite, while for *martite*, on the contrary, either solid masses or crystals of octahedral habit characteristic of *magnetite* are widespread.

Pyroluzite (manganese oxide) is blue-black with a greasy, sooty black streak. Unlike *magnetite* and the named pseudomorphs, this mineral does not possess magnetic properties; when interacting with 5 % HCl, it releases the smell of Cl. *Pyroluzite* crystallizes in the tetragonal system, and it is often possible to observe elongated acicular crystals of this mineral with a magnifying glass or even macroscopically. Forming sooty, earthy masses, its hardness can decrease to 2.0, in which case it stains hands, similar to graphite.

Rutile is characterized by a high degree of idiomorphism, which, I hope, immediately leads the reader to the idea that this mineral should occur in the form of well-formed crystals or their intergrowths, and this is indeed the case. *Rutile* has a varied color, but mainly in the academic collection of the department, these are brown-black crystals with a strong adamantine to semi-metallic luster, forming twin intergrowths. Despite the fact that the mineral is dark-colored, the color of the rutile streak is pale yellow, or orange-yellow. The hardness of the mineral is high; it leaves a good scratch on the glass. Often paragenesis with limonitized quartz and mica (muscovite).

G.G. Lemmlein, a brilliant researcher and connoisseur who devoted much effort to the study of quartz, called it an "elegant" mineral, apparently paying tribute not only to its appearance, but also to an amazing combination of properties. In most cases, quartz is a transparent mineral, diagnosed by its high reference hardness (7), lack of cleavage, concave fracture, relatively low specific gravity, glass luster. If this unique mineral forms crystals, then it is easy to recognize by their elongated habit and combinations of trigonal system.

Sometimes horizontal hatching is noted on the edges. As the most abundant mineral, silicon oxide comes in a variety of forms and manifestations. In our course, we will touch upon only some modifications of silicon oxide: 1) crystalline (trigonal ↓ t); 2) cryptocrystalline silicon oxide (*chalcedony*); 3) amorphous silicon oxide (*opal*); 4) siliceous rock (*jasper*).

Within crystalline quartz, there are a large number of color varieties: 1) amethyst – purple quartz; 2) citrine – yellow quartz; 3) rauchtopaz – smoky (gray) quartz; 4) morion – black quartz; 5) rock crystal –transparent quartz. There are no less varieties *in the chalcedony family*: 1) agates – banded varieties; moss agates – chalcedony interspersed with tree-like manganese minerals, usually psilomelan; 2) onyx – agates with alternating parallel or concentric-zonal stripes of different colors; 3) chrysoprase – a greenish-blue variety of chalcedony; 4) carnelian, sardonyx – orange variety. *Opals* can also be presented in noble varieties – opals with a bright optical effect of "opalescence" and not noble – matte, reminiscent of plastic. *Jasper* are the most diverse in color and in mineral composition, siliceous aggregates (rocks). By color, it is rather difficult to distinguish them due to the variegation and polygamy of color. If you attempt to understand all this quartz variety, then crystalline quartz is easily determined by the already listed characteristics, the name of the variety by color is already a secondary task. *Chalcedony,* in contrast to *opal,* has a higher hardness and density; it differs from crystalline *quartz* in the morphology of aggregates and in the absence of regular idiomorphic faces.

Based on the chemical composition of *opal*, it is obvious that the water in its composition distorts the crystal lattice of the mineral and, as a result, reduces its strength characteristics. *Opal* is easily recognizable by its porcelain-like fracture and low specific gravity.

The main difference between *simple* oxides and *complex* ones is that the latter consist of two simple ones. These include *magnetite* and *chromite*.

Magnetite (magnetic iron ore) has magnetic properties, black in color and similar color to the features. Crystallizing in the isometric system, the most frequent form of manifestation is the octahedron.

Chromite has increased hardness (6.5–7.5), greenish-brown features, rounded grains ("nodulars"). This refractory mineral is formed exclusively by magmatic means and is often found in paragenesis with greenish *serpentine*, which, as a rule, completely replaced early *olivine*.

OXIDES

Mineral name	**Cuprite** (red copper ore)
Chemical composition	$\mathbf{Cu_2O}$
Varieties	*Brick copper ore – earthy aggregates of cuprite with admixture of limonite*
Syngony	Isometric
Crystal Form	Octahedra and rhombododecahedra or combinations thereof
Aggregate morphology	Druse, parallel-fibrous, loose, earthy, dense
Color	Dark brown, brownish red
Streak	Brownish red (brick red), when rubbing biscuits turns yellow
Luster	Adamantine, sub-metallic, earthy
Cleavage	imperfect
Hardness	3.5–4
Specific gravity (g/cm^3)	6.0
Diagn. signs	Resembles cinnabar, realgar, goethite, hematite from which it differs by paragenesis
Associate minerals	Native copper, tenorite, malachite, azurite
Genesis	Exogenous
Application	Ore for copper

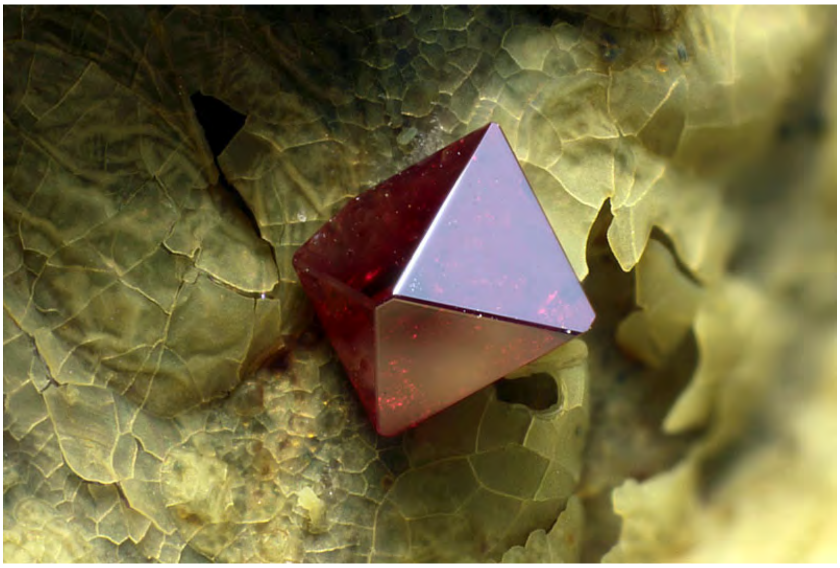


Fig. 58. Brick-red cuprite with a rim of malachite (Madonna di Fucinaia (Madonna della Fucinaia) slag heaps, Campiglia Marittima, Livorno Province, Tuscany, Italy)

OXIDES
(Hematite Group)

Mineral name	**Corundum**
Chemical composition (common impurities are indicated in brackets)	**Al_2O_3** (Fe,Ti,Cr)
Varieties	*Emery* – fine-grained corundum aggregate, *sapphire (Fe- and Ti-bearing)* – blue transparent corundum, *ruby (Cr-bearing)* – carmine red transparent corundum
Syngony	Trigonal
Crystal Form	Barrel-shaped, tabular, prismatic, columnar
Aggregate morphology	crystal phenocrysts, granular masses
Color	Bluish, pinkish, yellowish gray
Streak	White
Luster	Adamantine, Vitreous, Pearly
Cleavage	Imperfect, None Observed; Rhombohedral and basal parting {0001}
Hardness	9
Specific gravity (g/cm^3)	4.0
Diagn. signs	Similar to quartz (excellent in color, crystal shape), disthene (excellent in hardness), beryl (excellent in hardness, cross-sectional shape), hatching on the faces intersecting at an angle of 60°
Associate minerals	Feldspars (pegmatites) almandine, hornblende, biotite, chlorites (metam.)
Genesis	Pegmatite (desilicated quartz-free pegmatites), regional-metamorphic
Application	Abrasive material, precision physical instruments, jewelry

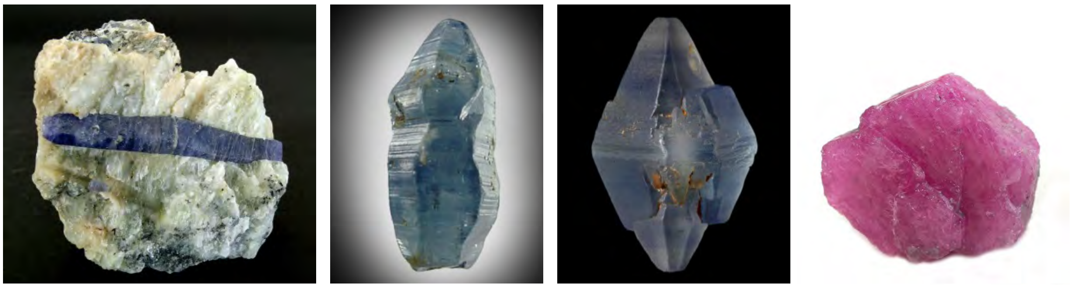


Fig. 59. Barrel-shaped and tabular form of corundum crystals (Mogok Township, Pyin-Oo-Lwin District, Mandalay Region, Myanmar)

OXIDES
(Hematite Group)

Mineral name	**Hematite** (iron glance)
Chemical composition	**Fe_2O_3**
Syngony	Trigonal
Crystal Form	Lamellar, tabular
Aggregate morphology	Scaly, earthy
Color	Steel gray, iron black, reddish brown
Streak	Reddish brown ("rust-red")
Luster	Metallic, Sub-Metallic, Dull, Earthy
Cleavage	None Observed
Hardness	5.5–6
Specific gravity (g/cm^3)	5.0
Diagn. signs	Similar to cuprite (excellent crystal shape and paragenesis), wolframite (excellent hardness, crystal shape, streak), goethite (excellent streak)
Associate minerals	Different
Genesis	Diverse
Application	Iron ore

Fig. 60. Iron rose (Saint-Christophe-en-Oisans, Grenoble, Isère, Auvergne-Rhône-Alpes, France)

OXIDES

Mineral name	**Pyrolusite**
Chemical composition	**MnO_2**
Syngony	Tetragonal
Crystal Form	Prismatic, needle-like
Aggregate morphology	Granular, cryptocrystalline, radial-radiant, nodules, sooty, earthy
Color	Black, very dark grey, sometimes with a bluish tinge
Streak	Black to bluish-black
Luster	Metallic, Dull, Earthy
Cleavage	Perfect on {110}
Hardness	5.0–6.0 (in earthy aggregates decreases to 1)
Specific gravity (g/cm^3)	5.0
Diagn. signs	Similar to magnetite (excl. lack of magnetic properties), psilomelan (excl. thicker streak), manganite (excl. streak color)
Associate minerals	Manganese and iron hydroxides
Genesis	Exogenous (sedimentary, as well as during the oxidation of other manganese minerals)
Application	Manganese ore, in electrical engineering

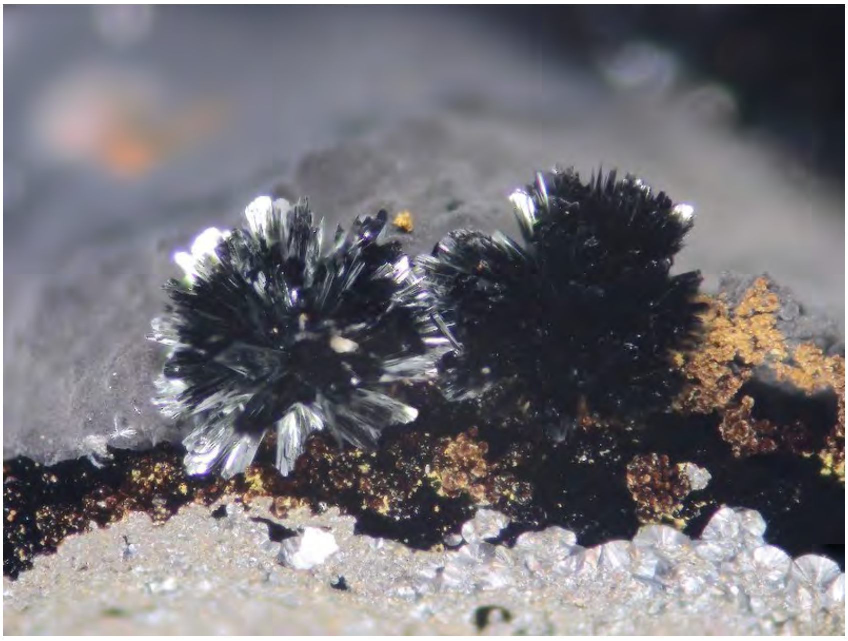


Fig. 61. The shape of crystals and aggregates of pyrolusite (Clara Mine, Oberwolfach, Wolfach, Ortenaukreis, Freiburg Region, Baden-Württemberg, Germany)

OXIDES

Mineral name	**Rutile**
Chemical composition (impurity elements are indicated in brackets)	**TiO_2** (Fe,Nb,Ta)
Varieties	*Sagenite* is a fine-fibred variety of rutile bickering at an angle of 60°
Syngony	Tetragonal
Crystal Form	Prismatic, often cranked twins, hatching along the elongation on the edges of the prism
Aggregate morphology	Acicular, radial-radiant, prismatic
Color	Blood red, brownish yellow, brown-red, yellow, greyish-black, black, brown, bluish or violet
Streak	Pale yellow, light brownish yellow
Luster	Adamantine, Metallic
Cleavage	Good on {110}
Hardness	6.0
Specific gravity (g/cm^3)	4.0
Diagn. signs	Similar to zircon (excellent crystal shape, paragenesis, line), tourmaline (excellent cross-sectional shape)
Associate minerals	Quartz, mica
Genesis	Endogenous varied
Application	Ore for titanium

Fig. 62. Prismatic form of rutile crystals and cranked twins (Diamantina, Minas Gerais, Brazil)

OXIDES

Mineral name	**Quartz**
Chemical composition	**SiO_2**
Varieties	*Chalcedony* is a cryptocrystalline variety of quartz, *opal* is an amorphous variety of silicon oxide, *jasper* is a siliceous rock
Syngony	Trigonal, hexagonal
Crystal Form	Prismatic, columnar, horizontal shading on the prism faces
Aggregate morphology	Druse, granular masses, grain phenocrysts, dense cryptocrystalline
Color	Milky, smoky, reddish brown, orange, black
Streak	–
Luster	Vitreous, in a fracture – conchoidal, dull in chalcedony
Cleavage	Imperfect
Hardness	7.0
Specific gravity (g/cm^3)	2.65
Associate minerals	Various
Genesis	Various
Application	Glass industry, optics, construction, jewelry

Fig. 63. Druzes of amethyst crystals
(Las Vigas de Ramírez Municipality, Veracruz, Mexico)

OXIDES

Mineral name	**Magnetite**
Chemical composition (impurities are indicated in brackets)	**$FeFe_2O_4$** (Ti,Mg,Cr,V)
Syngony	Isometric
Crystal Form	Octahedral
Aggregate morphology	Phenocrysts of crystals, grains, druze, continuous granular masses
Color	Greyish black or iron black
Streak	Black
Luster	Sub-metalllic
Cleavage	Imperfect
Hardness	5–6
Specific gravity (g/cm^3)	5.0
Diagn. signs	Similar to martite (excellent crystal shape and streak color), chromian spinel (hardness, streak color)
Associate minerals	Various
Genesis	Endogenous (magmatic, pegmatite, hydrothermal, contact-metasomatic, regional-metamorphic)
Application	Iron ore

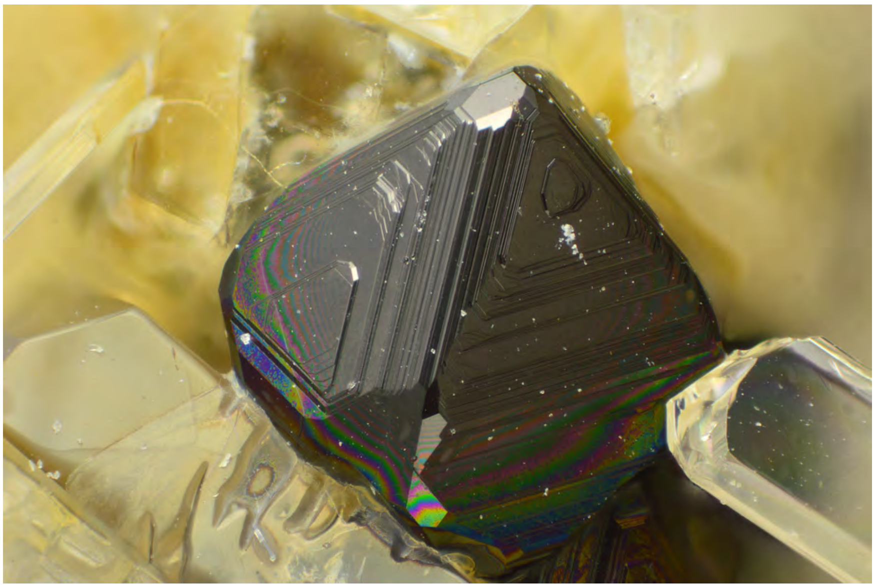


Fig. 64. Octahedral crystal habit of magnetite crystal (Ischia di Castro, Viterbo Province, Lazio, Italy)

OXIDES
(complex oxides)

Mineral name	**Chromite**
Chemical composition (impurities are indicated in brackets)	**$FeCr_2O_4$** (Ti,Mg,Al,V)
Syngony	Cubic/Isometric
Crystal Form	Octahedral
Aggregate morphology	Rounded grains (nodules), solid granular masses
Color	Black, brownish black
Streak	Brown
Luster	Resinous, Greasy, Metallic, Sub-Metallic, Dull
Cleavage	Imperfect, none observed
Hardness	5.5–7.5
Specific gravity (g/cm^3)	4.0–4.8
Associate minerals	Serpentine, magnetite, olivine, pyroxenes
Genesis	Ultrabasic igneous rocks
Application	Chrome ore

Fig. 65. Octahedral form of chromite crystals (Pic du Champ-de-Bataille, Mont Dore, Southern Province, New Caledonia, France)

Hydroxides differ from oxides in that they contain water, either constitutional in the form of a hydroxyl group OH^{-}, or molecular in the form of H_2O molecules. As you know, when water enters the composition of a mineral, its strength characteristics decrease. So, hydroxides, in contrast to oxides, are characterized by low hardness from 1…5 (depending on the form of precipitates). The origin of hydroxides is in most cases exogenous; they are often the products of oxidation of various previously formed minerals in the oxidation zone. The morphology of the aggregates of these minerals is diverse, but in most cases, they are loose, fine-grained, xenomorphic masses, sometimes dendrites (psilomelan) and radial-radiant aggregates (goethite). In this class, you will need to study the following minerals: *goethite, hydrogoethite (limonite), manganite, psilomelan.*

Goethite (ferrous hydroxide), sometimes occurs in the form of a variety characterized by a flat, shiny, smooth surface with a radial-radiant internal structure – "brown glass head". The mineral has a dark brown color and a rusty-brown color of features, does not possess magnetic properties, and is often found in paragenesis with *hydrogoethite*. The latter, as an amorphous substance, is characterized by a lower hardness, free-flowing aggregates and an ocher-yellow color of the line. It is not characterized by a radial-radiant structure and generally any crystals.

Manganese hydroxides include *manganite* and *psilomelan*, they are often associated together; this pair is also often accompanied by *pyrolusite*. In contrast to iron hydroxides, manganese minerals are characterized by a darker color and feature color. As I hope, the reader will remember, *pyrolusite* has a sooty-black color of features, *psilomelane*, in turn, is gray-black, and manganite is dark brown. The mineral association of manganese minerals is usually represented by continuous soot-black loose masses that stain hands, but, in contrast to graphite, have a higher specific gravity.

HYDROXIDES

Mineral name	**Goethite**
Chemical composition	**$FeO(OH)$**
Varieties	*Acicular iron ore*
Syngony	Rhombic
Crystal Form	Tabular, needle-like, columnar
Aggregate morphology	Massive, reniform, botryoidal, stalactitic. Bladed or columnar. Compact or fibrous concretionary nodules. Oolitic
Color	Brownish black, yellow-brown, reddish brown
Streak	Ocher-yellow
Luster	Adamantine, Silky, Metallic, Dull
Cleavage	Perfect on {010}
Hardness	4.5–5.5
Specific gravity (g/cm^3)	4–4.5
Diagn. signs	Similar to hydrogoethite (ex. hardness, aggregates), hematite (ex. feature color), cuprite (ex. feature color, paragenesis)
Associate minerals	limonite
Genesis	Zone of oxidation of sulfide deposits (iron hats), sedimentary, hydrothermal (rarely).
Application	Raw materials for smelting iron, steel, important ore for iron

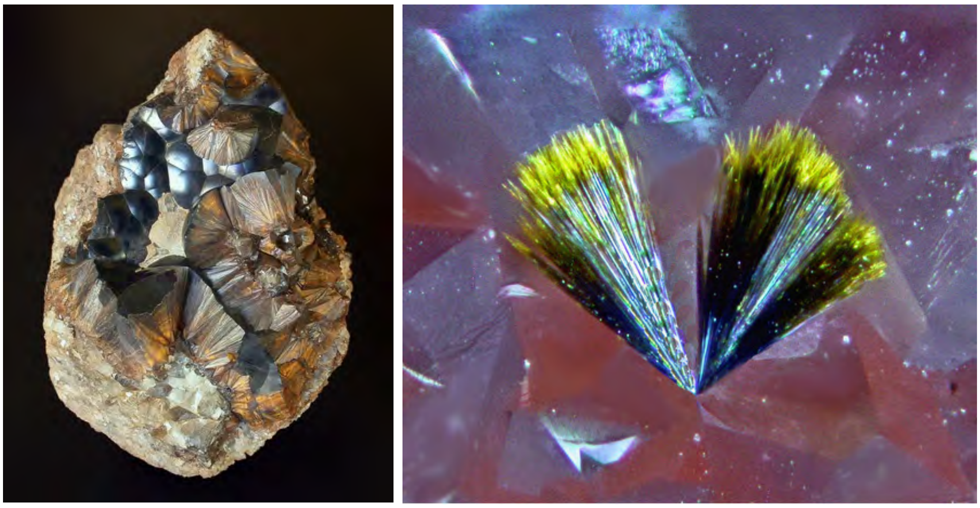


Fig. 66. Botryoidal goethite with well-developed concentric-radiating structure and goethite crystals on quartz (Wheal Drea, Botallack, St Just, Cornwall, England, UK)

HYDROXIDES

Mineral name	**Hydrogoethite**
Chemical composition	**$FeO(OH)*nH_2O$**
Syngony	Amorphous
Crystal Form	–
Aggregate morphology	Earthy, powdery, porous, slag-like, pyrite pseudomorphs
Color	Yellow-brown
Streak	Ocher-yellow
Luster	Dull
Cleavage	–
Hardness	1–5
Specific gravity (g/cm^3)	3–4
Diagn. signs	Similar to goethite (excellent in hardness, aggregates, lack of radial structure)
Associate minerals	Goethite
Genesis	Zone of oxidation of sulfide deposits (iron hats), sedimentary, pyrite pseudomorphs
Application	Iron ore

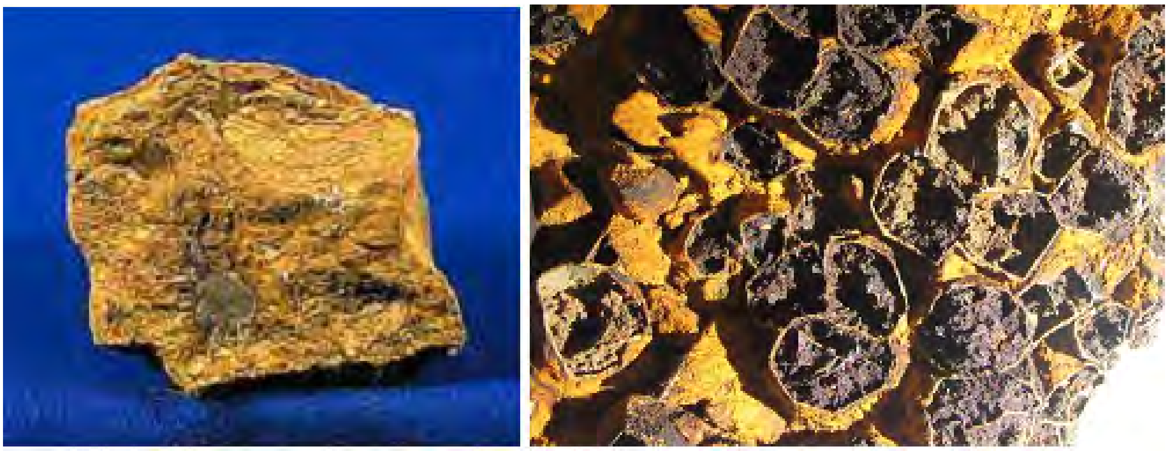


Fig. 67. Amorphous structure of hydrogoethite

HYDROXIDES

Mineral name	**Manganite**
Chemical composition	**MnO_2*$Mn(OH)_2$**
Syngony	Monoclinic
Crystal Form	Prismatic
Aggregate morphology	Crystals often grouped or markedly composite subparallel {001} (Fig. 68). Stalactitic; granular (rare)
Color	Dark brown, grey-black, black
Streak	Brown
Luster	Resinous, Sub-Metallic, Dull
Cleavage	Perfect on {010}
Hardness	3–4
Specific gravity (g/cm^3)	4.0
Diagn. signs	Similar to goethite (excellent in structure), pyrolusite, psilomelan (excellent in color of the streak).
Associate minerals	Pyrolusite, psilomelan
Genesis	Exogenous, sedimentary
Application	Manganese ore

Fig. 68. Form of aggregates of manganite (Manganese deposit, Ilfeld, Harztor, Nordhausen District, Thuringia, Germany)

HYDROXIDES

Mineral name	**Psilomelane**
Chemical composition	**$mMnO*MnO_2*nH_2O$**
Syngony	–
Crystal Form	Crystals form extremely rarely
Aggregate morphology	Continious masses, oolites
Color	Black
Streak	Black, sometimes with a grayish tinge
Luster	Sub-Metallic, Dull
Cleavage	–
Hardness	5–6
Specific gravity (g/cm^3)	4.8
Diagn. signs	Similar to pyrolusite (excl. less bold line of gray-black color)
Associate minerals	Pyrolusite, manganite
Genesis	Exogenous, sedimentary
Application	Manganese ore

Fig. 69. Psilomelan skeletal crystal shape
(Restormel Royal Iron Mine, Lostwithiel, Cornwall, England, UK)

2.7.5. Type IV. Salts of oxoacids

2.7.5.1. Class 1. Sulphates

Sulfates are a class of minerals that combine sulfuric acid salts. Sparingly soluble sulfates of strong bivalent bases Ba^{2+}, Sr^{2+}, Ca^{2+} etc. are more widespread. Sulfates can be concentrated in the hypergenesis zone, hydrothermal deposits (*baryte*), and as products of the fumarolic activity of volcanoes.

Sulfates in this condensed mineralogy course are represented by the two most common minerals: *baryte* and *gypsum*.

Baryte (heavy spar) in Greek. "baros" means *heaviness*, got its name from the specific gravity (4.5). When weighed in hand, samples with barite have a noticeable density, unlike other light-colored minerals with a hardness below 5, for example, carbonates. In addition, unlike carbonates, barite does not react with 5 % HCl. It is characterized by lamellar crystals, perfect cleavage, light color. Paragenesis with *baryte* may contain *hematite*, due to the mechanical impurity of which it turns pink, *chalcocite*, *malachite*, etc.

Gypsum corresponds to the second position in the Mohs hardness scale, is easily scratched with a fingernail and is diagnosed by a perfect cleavage, due to which a mother-of-pearl tint is noted on the crystal planes. Often *gypsum* forms dovetail twins (Fig. 70). If gypsum forms fine-grained free-flowing masses, cleavage is weak. Gypsum is a light, soft, light-colored mineral. Unlike *halite*, it does not have a salty taste and cube cleavage, it has a flattened crystal shape. Unlike «Iceland spar» (a transparent type of calcite) does not react with 5 % HCl, has a lower hardness.

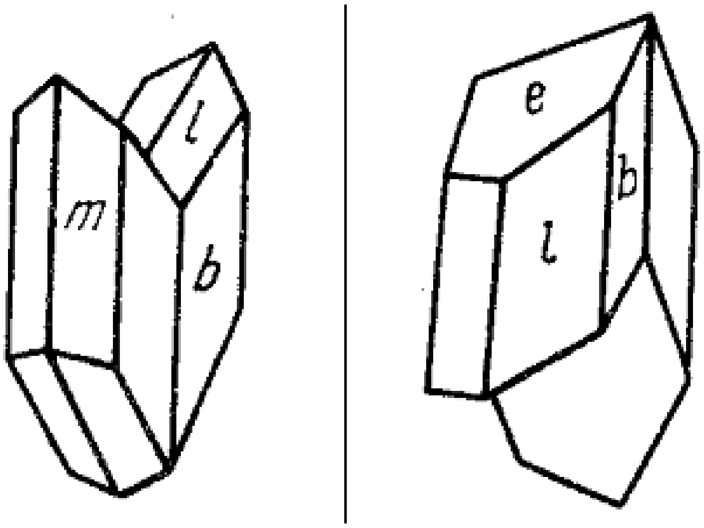


Fig. 70. Twins of gypsum accretion

2.7.5.2. Class 2. Tungstates

Tungstates (salts of tungstic acids) are represented by one representative of the class – *wolframite*. Due to tungsten, *wolframite* has a high specific gravity (7.5), and due to the inclusion of elements-chromophores of iron and manganese in its composition, it is a dark-colored mineral. At the same time, two of its color varieties are distinguished, related to the end members of an infinite series: *hubnerite* (light-colored Mn-variety), *ferberite* (dark-colored Fe-variety).

Along with the change in color saturation from light brown to dark brown, the color of the mineral's features also changes from light yellow to brown. *Wolframite* has a strong diamond luster and perfect cleavage along the second pinacoid – along the crystal elongation. Visually it resembles *sphalerite*, from which it differs in a flattened elongated crystal shape, increased specific gravity, lack of reaction with 5 % HCl, paragenesis with "rusty quartz".

2.7.5.3. Class 3. Phosphates

In *phosphates* (salts of phosphoric acid), similar to tungstates, consider one representative of the class – apatite. A.G. Werner called this mineral a "deceiver" ("apatao" in the translation from the Greek "I deceive"). *Apatite* corresponds to a hardness of 5 on the Mohs scale, is characterized by the absence of cleavage, average specific gravity, bluish-green color, transparency. Sometimes, by color, students tend to diagnose apatite as *fluorite*. In this case, it is worth paying special attention to the presence or absence of cleavage pits, which are absent in *apatite*, and are observed everywhere in *fluorite* at an angle of 60° (perfect cleavage along the octahedron).

Fluorite can always be viewed on the hardness training scale using comparative analysis. *Apatite* can be represented by two morphological varieties: *crystalline* and *sugar-like (fine-grained) apatite*. Crystallizing in the hexagonal system, crystalline apatite has prismatic elongated bluish crystals, often found in association with *calcite*. Sometimes crystalline *apatite* in its crystal appearance, hexagonal cross-section and color range can be confused with beryl, from which it can be easily distinguished by its lower hardness. Fine-grained sugary apatite, as a rule, is associated with alkaline magmatic minerals: *aegirine*, *nepheline*, *sphene*, *albite*.

SULPHATES
(*Baryte Group*)

Mineral name	**Baryte (*heavy spar*)**
Chemical composition	**$Ba[SO_4]$**
Syngony	Ortorhombic
Crystal Form	Tabular, split, less often prismatic, columnar
Aggregate morphology	Granular, solid, cryptocrystalline, earthy
Color	White, gray with various shades (due to mechanical impurities of other minerals)
Streak	White
Luster	Vitreous, Pearly
Cleavage	Perfect on {001} and inperfect on {210}
Hardness	3.0–3.5
Specific gravity (g/cm^3)	4.3–4.5
Diagn. signs	High specific gravity, thin tabular crystals
Associate minerals	Hematite, sphalerite, pyrite, chalcopyrite, siderite, chalcocite
Genesis	Hydrothermal, sedimentary, weathering zone
Application	Chemical, rubber, paper, paint and varnish industry, production of photographic paper, glass melting, weighting agent for clay solutions

Fig. 71. Tabular crystals of barite (Clara Mine, Oberwolfach, Wolfach, Ortenaukreis, Freiburg Region, Baden-Württemberg, Germany)

SULPHATES
(Gypsum Supergroup)

Mineral name	**Gypsum**
Chemical composition	**$Ca[SO_4]*2H_2O$**
Varieties	*Satin spar gypsum – fine-fiber crystals of gypsum with a silky sheen*
Syngony	Monoclinic
Crystal Form	Tabular, columnar, prismatic
Aggregate morphology	Rosette-like clusters of lenticular crystals are common. Also found as granular masses, massive beds, and fibrous masses ("satin spar")
Color	White, colorless, water-transparent, gray, with blue, grayish, reddish, black tint
Streak	White
Luster	Vitreous, Sub-Vitreous, Silky, Pearly, Dull
Cleavage	Perfect on {010}
Hardness	2.0
Specific gravity (g/cm^3)	2.8–3.0
Diagn. signs	Differs from carbonates by the absence of reaction with 5 % HCl, differs from baryte by a lower specific gravity
Associate minerals	Anhydrite, pyrite, chalcopyrite
Genesis	Hydrothermal, sedimentary
Application	Production of paints, enamels, glazes

Fig. 72. Intergrowths of gypsum crystals (Boldut Mine, Cavnic, Maramureș, Romania)

TUNGSTATES
(Wolframite Group)

Mineral name	**Wolframite**
Chemical composition	**$(Fe,Mn)[WO_4]$**
Varieties	*Ferberite – $Fe[WO_4]$ dark colored wolframite; Hubnerite – $Mn [WO_4]$ light colored wolframite*
Syngony	Monoclinic
Crystal Form	Prismatic, thick-plate, flattened
Aggregate morphology	Grains, solid masses
Color	From light brown, orange to dark brown, black
Streak	Light yellow to dark brown
Luster	Sub-metallic
Cleavage	Perfect on {010}
Hardness	4.5–5.5
Specific gravity (g/cm^3)	6.7–7.5
Diagn. signs	Brownish-black color, high specific gravity, perfect cleavage in one direction, differs from sphalerite in elongated crystal shape, lack of reaction with 5 % HCl
Associate minerals	Limonitized quartz, scheelite
Genesis	High-temperature hydrothermal veins, in greisen, granitic pegmatites; in alluvial and eluvial deposits
Application	Ferrous metallurgy, in ceramics for the manufacture of glass and porcelain, tungsten is used for the manufacture of filaments for electric bulbs, anti-cathode in X-ray tubes


Imaged by Heritage Auctions, HA.com

Fig. 73. Prismatic crystals of wolframite with quartz (Yaogangxian Mine, Yaogangxian W-Sn ore field, Yizhang Co., Chenzhou, Hunan, China)

PHOSPHATES

Mineral name	**Apatite**
Chemical composition	**$Ca_5[PO_4]_3$ (F, OH, Cl)**
Varieties	*Phosphorites – are exogenous rocks of concretional forms of apatite accumulation, containing numerous inclusions of sand grains of foreign minerals (quartz, calcite)*
Syngony	Hexagonal
Crystal Form	Well-formed crystals in the form of hexagonal prisms (Fig. 74), sometimes in the form of short-columnar or tabular crystals
Aggregate morphology	Granular, dense, fine crystalline
Color	Colorless, slightly green, bluish green, blue
Streak	White
Luster	Vitreous, Dull
Cleavage	Imperfect
Hardness	5.0
Specific gravity (g/cm^3)	3.2
Diagn. signs	Recognizable by its bluish-green color, hexagonal prismatic appearance, differs from beryl in lower hardness
Associate minerals	Calcite; nepheline, aegirine, titanite (magmatic)
Genesis	Contact-metasomatic, magmatic, hydrothermal, pegmatite, sedimentary
Application	A source of fertilizers, phosphoric acid, phosphorus

Fig. 74. Prismatic crystals of apatite (Cerro de Mercado Mine, Victoria de Durango, Durango Municipality, Durango, Mexico)

2.7.5.4. Class 4. Carbonates

Carbonates are a group of naturally occurring minerals that are salts of carbonic acid H_2CO_3. The basis of the structure of carbonates is a flat triangle $[CO_3]^{2-}$, in which carbon is in triple coordination with respect to oxygen atoms. The $[CO_3]^{2-}$ groups are isolated and are connected through cations or additional anions $(OH)^-$, F^-, Cl^-. In other words, carbonates are represented by compounds of carbonic acid with lithophilic (Na, Ca, Mg, Sr, Ba, TR), as well as with chalcophilic (Zn, Cu, Pb, Bi) elements. Carbonates contain one or two main cations with or without added anions. Flat groups $[CO_3]^{2-}$ are located either in the form of mutually parallel layers and chains, or in another symmetric order.

Most carbonates crystallize in trigonal, orthorhombic, less often monoclinic systems. Carbonates are characterized by a hardness of 3 to 5 on the Mohs scale and a slight solubility in hydrochloric acid. Most of the carbonates are colorless or lightly colored. The color of brightly colored carbonate minerals depends on the presence of chromophore ions. So, for example, copper carbonates are green and blue, iron carbonates – brown, manganese carbonates – pink.

The conditions for the formation of carbonates are diverse: in sedimentary-marine sediments, calcium carbonates form huge strata of limestones and dolomites (mainly of biogenic origin); in hydrothermal ore deposits, calcite, siderite, and ankerite are found; in the weathering crust – magnesite, in metasomatic formations – magnesite, siderite; in the oxidation zone of polymetallic deposits – malachite, azurite, smithsonite, cerussite. Carbonatites arise by magmatogenic way, with which deposits of apatite and rare earths are associated. Many carbonates (for example, malachite, siderite, smithsonite, cerussite, etc.) are used as ore for Cu, Zn, Pb, Bi, Ba, Sr, Fe, Mn, rare earths and other metals, as raw materials for the cement and chemical industries (dolomite, magnesite) and as a building material (limestone, marble).

The *calcite group* includes common minerals: *calcite, siderite, magnesite, dolomite, and smithsonite.*

All minerals of the calcite group crystallize in the ditrigonal-scalenohedral form of trigonal symmetry.

1. Among the minerals of the calcite group, the ability to form isomorphic mixtures is very common. This is especially true for Mg, Zn and Fe^{2+}, which often substitute for each other. A continuous series of isomorphic mixtures is also formed by the carbonates Fe^{2+} and Mn^{2+}.
2. All minerals of the calcite series are colorless or grayish and only occasionally are colored in various light shades, mainly due to impurities. They have a white or colorless line, glassy sometimes pearlescent luster.

3. These minerals are characterized by perfect cleavage along the rhombohedron, low hardness (from 3 to 5), fragility and relatively low density (from 2.6 to 3.9).

4. Most of these minerals are formed mainly under exogenous conditions (in water reservoirs and the weathering crust), much less often they occur as hydrothermal formations in sulfide veins.

The *aragonite group* includes *aragonite* and *cerussite*.

The *malachite group* includes *malachite* and *azurite*.

The trigonal carbonate group (calcite group) includes the following minerals: *calcite, siderite, magnesite, dolomite, smithsonite*.

Calcite has a varied color palette, but in most cases it is light-colored. Often the bright color of *calcite* is caused by mechanical admixture of other colored minerals and is not its own color. The appearance of calcite crystals is the most diverse (it has an exceptional variety of forms of separation that has no equal in the mineral kingdom) more than 500 combinations of simple forms. The most common crystals are scalenohedral, less often tabular, lamellar columnar, prismatic, and rhombohedral. Asbestos-like calcite (*satin spar*), veined with a silky sheen, is rarely observed, the fibers of which are located perpendicular to the walls of cracks in the rocks. *Stalactites* and *stalagmites* are widely known for dripstone formations of *calcite*. Granular and continuous aggregates in large dense masses are called *marbles*. Dense cryptocrystalline varieties of calcite rocks, often layered and rich in fauna, are called *limestones*. Loose limestones containing the smallest phenocrysts of foraminifera are known as *chalk*. There are also oolitic limestones – *caviar stones*. *Lime tuff* or *travertine* is called spongy formations of calcium carbonate, which occurs at the exit point of both cold and hot mineral springs saturated with lime. *Calcite* has perfect rhombohedral cleavage and corresponds to 3 on the Mohs scale of hardness, it can always be viewed by comparative analysis. *Calcite* reacts violently in cold weather with 5 % HCl, releasing carbon dioxide. *Aragonite* has a similar reaction with 5 % HCl, being a polymorphic modification of *calcite*. However, when crystallizing in the rhombic system, *aragonite* is characterized by elongated prismatic crystals and twins. Pseudo-hexagonal trillings (Fig. 75), fourling and complex polysynthetic twins are also widespread. In this case, recessed corners in the form of grooves are usually formed between the faces of the prisms (Fig. 75). Non-twinned crystals are rare. There is no cleavage along the rhombohedron.

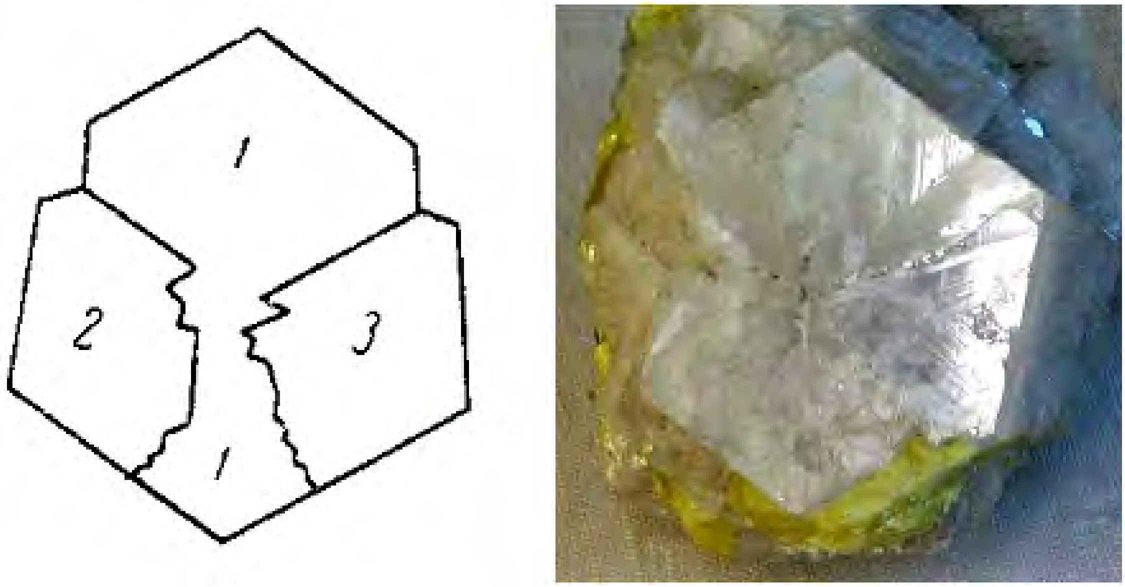


Fig. 75. Borders of intergrowths of aragonite individuals in a cross section

Siderite (iron spar) shows all the signs of calcite group carbonates. The main distinguishing feature of *siderite* is its brown-yellow color due to the inclusion in the composition of the iron mineral and a slightly higher specific gravity (3.9). Another name for siderite is associated with this fact – pea stone. The reaction in the cold with 5 % HCl does not go, the mineral reacts only with hot 5 % HCl, a weak reaction occurs in the powder, after exposure to 5 % HCl, an insignificant greenish speck remains.

Magnesite is presented in two varieties, visually significantly different from each other: *crystalline* and *amorphous*. Crystalline magnesite has a variegated, gray-white, like "hazel grouse" color. Amorphous magnesite, as a rule, is formed in the weathering crust of magnesian minerals and is represented by colomorphic loose chalk-like white aggregates. The reaction with 5 % HCl is the same as for siderite, very weak in powder.

Dolomite, unlike calcite, does not react violently with 5 % HCl in the cold; the reaction proceeds only in powder. To carry out a correct diagnosis, you must first drop 5 % HCl onto the sample, and then convert it into powder, while observing the appearance of the reaction. Due to the simultaneous incorporation of Ca and Mg into the mineral, a slight deformation of the crystal lattice of the mineral occurs, which is expressed in the appearance of saddle-bent crystals and distorted forms (Fig. 76).

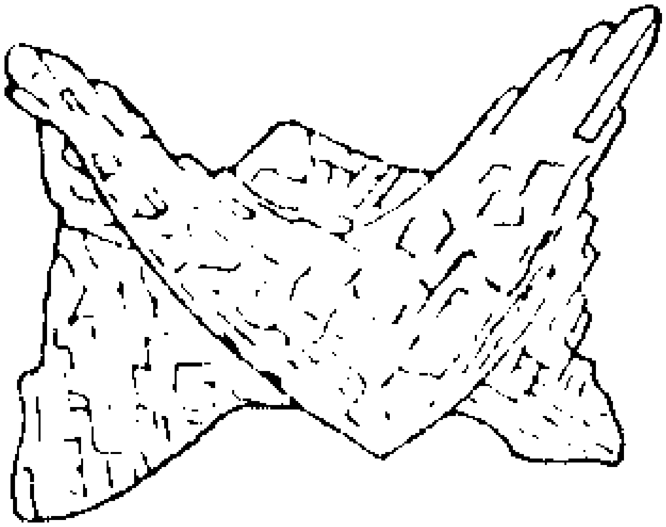


Fig. 76. The shape of dolomite crystals with saddle-bent faces

Smithsonite (zinc spar) has the highest hardness (5) and specific gravity (4.1–4.2) of the entire group of trigonal carbonates, very specific crusty, dense cryptocrystalline aggregates and a greenish-blue color. The *aragonite group*, in addition to the aragonite itself, includes one more mineral, *cerussite* (squeaky ore). *Cerussite* has increased fragility and, when crushed, emits a characteristic creak, for which it received its second name – «creak». It forms small transparent needle-like, elongated crystals, which are in paragenesis with dissolved galena and *anglesite* ($PbSO_4$) in the oxidation zone of lead-zinc deposits. Sometimes in the literature you can find another name for this mineral – white lead ore. *The malachite group* combines two monoclinic carbonates: *malachite* and *azurite*. Due to the bright chromophore element (Cu), this group is characterized by bright colors. *Azurite*, when included in its composition of three copper molecules, has a more saturated indigo blue color, malachite less saturated – grassy green. Both carbonates react with 5 % HCl. Often they associate together in the oxidation zone of copper deposits, forming tarnish, powdering, and coating.

CARBONATES
(Calcite Group)

Mineral name	**Calcite**
Chemical composition (common impurities are indicated in brackets)	**Ca[CO_3]** **(Mn,Fe,Zn,Co,Ba,Sr,Pb,Mg,Cu,Al,Ni,V,Cr,Mo)**
Varieties	*Icelandic spar – transparent crystals of calcite*
Syngony	Trigonal
Crystal Form	Rhombohedral, scalenohedral, tabular, lamellar, columnar.
Aggregate morphology	Coarse-grained, drip, loose, spongy, stalactites, stalagmites
Color	Colorless, white, gray, yellowish, reddish, brown, black
Streak	White
Luster	Vitreous
Cleavage	Perfect on {1011}
Hardness	3.0, fragile
Specific gravity (g/cm^3)	2.7
Diagn. signs	Low hardness, perfect rhombohedral cleavage, violent reaction with 5 % HCl
Associate minerals	various
Genesis	Contact-metasomatic, hydrothermal, carbonatites, sedimentary
Application	Icelandic spar – used for the manufacture of various optical devices; chemical and construction industry, ornamental stone

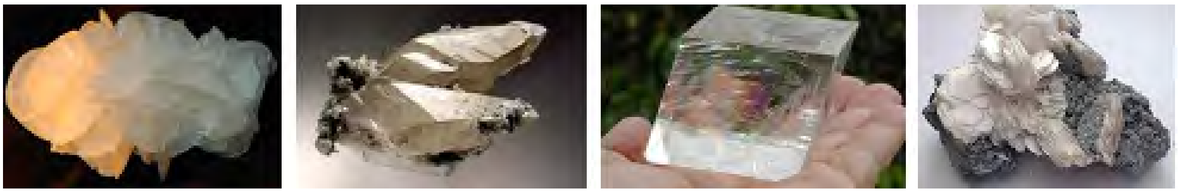


Fig. 77. Morphological crystal habit of calcite crystals

CARBONATES
(Calcite Group)

Mineral name	**Siderite** *(Iron spar)*
Chemical composition (common impurities are indicated in brackets)	**$Fe[CO_3]$** **(Mn,Mg,Ca,Zn,Co)**
Varieties	*Spherosiderite – globular nodules with cryptocrystalline or radial-radial structure*
Syngony	Trigonal
Crystal Form	Rhombohedral
Aggregate morphology	crystalline-granular, spherical, earthy, oolitic
Color	Yellowish-brown to greyish-brown, pale yellow to tannish, grey, brown, green, red, black. When weathered, it turns brown intensely, covered with limonite
Streak	White
Luster	Vitreous
Cleavage	Perfect on {1011}
Hardness	3.5–4.5, fragile
Specific gravity (g/cm^3)	3.9
Diagn. signs	Reacts very slowly with 5 % HCl in the cold
Associate minerals	Magnetite, hematite and other iron sulfides (pyrrhotite, chalcopyrite), pennine
Genesis	Hydrothermal
Application	Source of iron ores

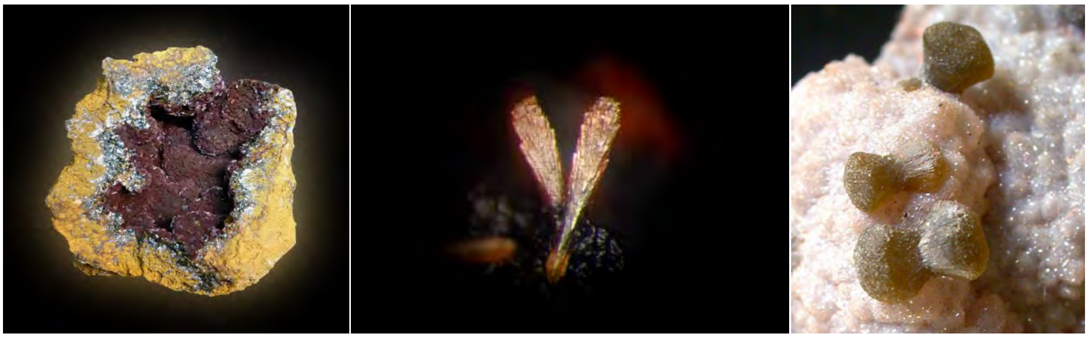


Fig. 78. Rhombohedral crystals of siderite and spherosiderite (Wheal Drea, Botallack, St Just, Cornwall, England, UK)

CARBONATES
(Calcite Group)

Mineral name	**Magnesite** (magnesium carbonate)
Chemical composition	**$Mg[CO_3]$**
Varieties	*Crystalline – granular aggregates of magnesite "hazel grouse" or "chipmunk" color; Amorphous_– white, porcelainous, cryptocrystalline masses, often resembling cauliflower in shape*
Syngony	Trigonal
Crystal Form	Rhombohedral
Aggregate morphology	Massive, coarse- to fine-granular, very compact and porcelainous; earthy to rather chalky; lamellar; coarsely fibrous
Color	Colourless, white, greyish-white, yellowish, brown, faintly pink
Streak	White
Luster	Vitreous, Silky, Pearly
Cleavage	Perfect on {1011}
Hardness	4.0–4.5, fragile
Specific gravity (g/cm^3)	2.9–3.1
Diagn. signs	Decomposes in 5 % HCl only when heated
Associate minerals	Often monomineral, dolomite, etc.
Genesis	Weathering of ultrabasic rocks, hydrothermal
Application	Manufacture of refractory bricks, cement, electrical insulators

Fig. 79. Crystalline varietiy of magnesite (Clara Mine, Oberwolfach, Wolfach, Ortenaukreis, Freiburg Region, Baden-Württemberg, Germany)

CARBONATES
(Dolomite Group)

Mineral name	**Dolomite**
Chemical composition	**$CaMg[CO_3]_2$**
Syngony	Trigonal
Crystal Form	Rhombohedral with saddle curved faces
Aggregate morphology	Massive, coarse to fine granular, fibrous or pisolitic.
Color	Grayish-white, sometimes with a yellowish, brownish, greenish tint
Streak	White
Luster	Vitreous, Sub-Vitreous, Resinous, Waxy, Pearly
Cleavage	rhombohedral perfect
Hardness	3.5–4.0, fragile
Specific gravity (g/cm^3)	1.8–2.9
Diagn. signs	In 5 % HCl decomposes in powder, very slowly in the cold
Associate minerals	Magnesite, calcite, sulfides, quartz and other minerals
Genesis	Weathering of ultrabasic rocks, hydrothermal
Application	As a building stone, for the manufacture of binders, thermal insulation material mixed with asbestos, as a refractory material and a flux in metallurgy, in the chemical and a number of other industries

Fig. 80. Dolomite aggregates (Nikolaevskiy Mine, Dalnegorsk, Dalnegorsk Urban District, Primorsky Krai, Russia)

CARBONATES
(Calcite Group)

Mineral name	**Smithsonite** *(zinc spar)*
Chemical composition	**Zn[CO$_3$]**
Syngony	Trigonal
Crystal Form	Rhombohedral
Aggregate morphology	Are usually observed in earthy or dense cryptocrystalline aggregates, often in spherulite forms in the form of crusts, as well as shelly cellular and porous masses
Color	White, white with greenish, grey, yellow, green to apple-green (Fig. 81), blue, pink, purple, bluish grey, and brown
Streak	White
Luster	Vitreous, Pearly
Cleavage	Perfect on {1011}, visible only in explicit crystalline aggregates
Hardness	5.0, fragile
Specific gravity (g/cm^3)	4.1–4.2
Diagn. signs	Dissolves slowly in 5 % HCl in the cold
Associate minerals	Opal, galena, sphalerite, calcite, dolomite
Genesis	Oxidation zone of lead-zinc deposits
Application	Zinc source

Fig. 81. The drip form of smithsonite crystals (San Antonio Mine, East Camp, Santa Eulalia Mining District, Aquiles Serdán Municipality, Chihuahua, Mexico)

CARBONATES
(Aragonite Group)

Mineral name	**Aragonite**
Chemical composition (common impurities are indicated in brackets)	**$Ca[CO_3]$ (Sr,Pb,Zn)**
Syngony	Orthorhombic
Crystal Form	Prismatic, pseudohexagonal, acicular
Aggregate morphology	Columnar, radial-radial, stellate accretions of individuals, sinter
Color	White, yellowish white, light green, colorless
Streak	White
Luster	Vitreous
Hardness	3.5–4.0, fragile
Specific gravity (g/cm^3)	2.9–3.0
Diagn. signs	With 5 % HCl reacts violently in cold, but differs from calcite in the absence of cleavage along the rhombohedron and the appearance of crystals with grooves on the faces of prisms
Associate minerals	Sulfur, gypsum, goethite, limonite
Genesis	Low temperature hydrothermal, exogenous
Application	

Fig. 82. Aragonite stalagmites (Holzappel Mine, Holzappel, Diez, Rhein-Lahn District, Rhineland-Palatinate, Germany)

CARBONATES
(Aragonite Group)

Mineral name	**Cerrusite**
Chemical composition	**Pb [CO_3]**
Syngony	Orthorhombic
Crystal Form	Prismatic, pseudohexagonal, acicular
Aggregate morphology	Columnar, radial-radial, stellate accretions of individuals, sinter, twins and tees are very frequent
Color	White, with a grayish, yellowish or brownish tinge
Streak	White
Luster	Adamantine, Vitreous, Resinous, Pearly, Dull, Earthy
Cleavage	Good on {110} and {021}
Hardness	3.0–3.5, very fragile
Specific gravity (g/cm^3)	6.5
Diagn. signs	High specific gravity, adamantine luster, increased fragility, paragenesis with galena, anglesite and limonite, emits a creak when destroyed
Associate minerals	Galena, anglesite, limonite
Genesis	Oxidation zones of lead-zinc sulphide deposits
Application	Important lead ore

Fig. 83. Prismatic intergrowths of cerussite crystals (Tsumeb Mine, Tsumeb, Oshikoto Region, Namibia)

CARBONATES
(Malachite Group)

Mineral name	**Malachite** *(green copper ore)*
Chemical composition	**$Cu_2\ [CO]_3[OH]_2$**
Syngony	Monoclinic
Crystal Form	Prismatic, pseudohexagonal, acicular
Aggregate morphology	Reniform masses with radial-radiant fibrous, concentric-zonal structure, earthy masses
Color	Bright green, with crystals deeper shades of green, even very dark to nearly black
Streak	Pale green
Luster	Silky, Earthy
Cleavage	Perfect on {201}
Hardness	3.5–4.0, fragile
Specific gravity (g/cm^3)	3.9–4.0
Diagn. signs	Recognizable by its characteristic green color, collomorphic forms and radial-radiant structure, interaction with 5 % HCl
Associate minerals	Calcite, chalcopyrite, chalcocite, cuprite, native copper
Genesis	Oxidation zones of copper sulphide deposits
Application	Ornamental stone, copper ore, paint making

Fig. 84. Radial-radiant structure of malachite aggregates (Mashamba West Mine, Sicomines copper-cobalt project, Kolwezi mining district, Lualaba, DR Congo)

CARBONATES
(Malachite Group)

Mineral name	**Azurite** *(azure copper ore)*
Chemical composition	**$Cu_3 [CO_3]_2 [OH]_2$**
Syngony	Monoclinic
Crystal Form	Columnar, prismatic, thick-tabular, needle-like
Aggregate morphology	Solid granular masses, sometimes radial-radiant aggregates and in an earthy state
Color	Azure blue, blue, light blue, or dark blue
Streak	Blue
Luster	Vitreous
Cleavage	Perfect on {011}; imperfect on {100}
Hardness	3.5–4.0, fragile
Specific gravity (g/cm^3)	3.8
Diagn. signs	Recognizable by its characteristic blue color, paragenesis with malachite, reaction with 5 % HCl
Associate minerals	Malachite, calcite, chalcopyrite, chalcocite, cuprite, native copper
Genesis	Oxidation zones of copper sulphide deposits
Application	Copper ore, making blue paint

Fig. 85. Crystals of azurite (Santa Lucía Mine, Rambla Seca, La Peza, Granada, Andalusia, Spain)

2.7.5.5. Class 5. Silicates

Silicates are among the most common class of minerals. In terms of chemical composition, they are salts of various silicic acids (H_4SiO_4, $H_4Si_2O_6$ …). Silicates account for 1/3 of all known minerals, taking into account the fact that the earth's crust at a depth of 16 km is 85 % silicates (according to V.I. Vernadsky). The following chemical elements take part as cations in the composition of silicates: K, Na, Ca, Mg, Ti, Al, Mn, Fe, Li, Zr, TR, Li, Be (2nd and 3rd periods of the periodic table). Silicates are distinguished by their complexity and variability of the chemical composition, which determines the increased ability to form isomorphic mixtures. The bonds of silicon with oxygen are mixed ionic-covalent, with different degrees of ionicity in minerals of different structures and with different cations. The structure of silicates is based on the silicon-oxygen tetrahedron (SOT) $[SiO_4]^{4-}$. Silicon-oxygen tetrahedra can be single, connecting in the general structure of the mineral through a cation, they can also polymerize, forming various anionic groups. The nature of complex anionic radicals determines the whole variety of mineral compounds of silicates and aluminosilicates. The systematics of silicates is based on structure. The class of silicates is divided into subclasses, taking into account the degree of polymerization of silicon-oxygen tetrahedra (SOT) (Fig. 86).

Thus, the following subclasses are distinguished:

1. *Silicates with isolated tetrahedra with isolated groups of tetrahedra (nesosilicates)* $[SiO_4]^{4-}$, (*sorosilicates*) $[Si_2O_7]^{6-}$. Necosilicates are formed even under constrained growth conditions in the form of good crystals. This is due to their high crystallization power, which is due to the relative compactness and simplicity of the structures of these silicates, the multiply charged anionic complexes and the significant strength of the bonds of the cations that make up their composition. However, at the same time, due to the island structure, silicates with isolated tetrahedra have increased brittleness (olivine), but high hardness and average specific gravity. The shape of the minerals is close to isometric. As a rule, the minerals of this group are colorless or weakly colored, intense coloration is observed in varieties containing chromophore elements (Fe, Mn, Ti, Cr). The *nesosilicates* to be studied in this course are: *olivine, zircon, topaz, disthene, staurolite, titanite, and garnet group* and the *sorosilicate* is *epidote.*

2. *Silicates with flat tetrahedral rings (cyclosilicates).* The crystal lattices contain silicon-oxygen tetrahedrons linked into rings. Minerals of this subclass are characterized by complex anions $[Si_6O_{18}]^{12-}$ and $[Si_3O_9]^{6-}$. This subclass includes, among others, minerals of the *beryl* and *tourmaline* groups $[Si_6O_{18}]^{12-}$.

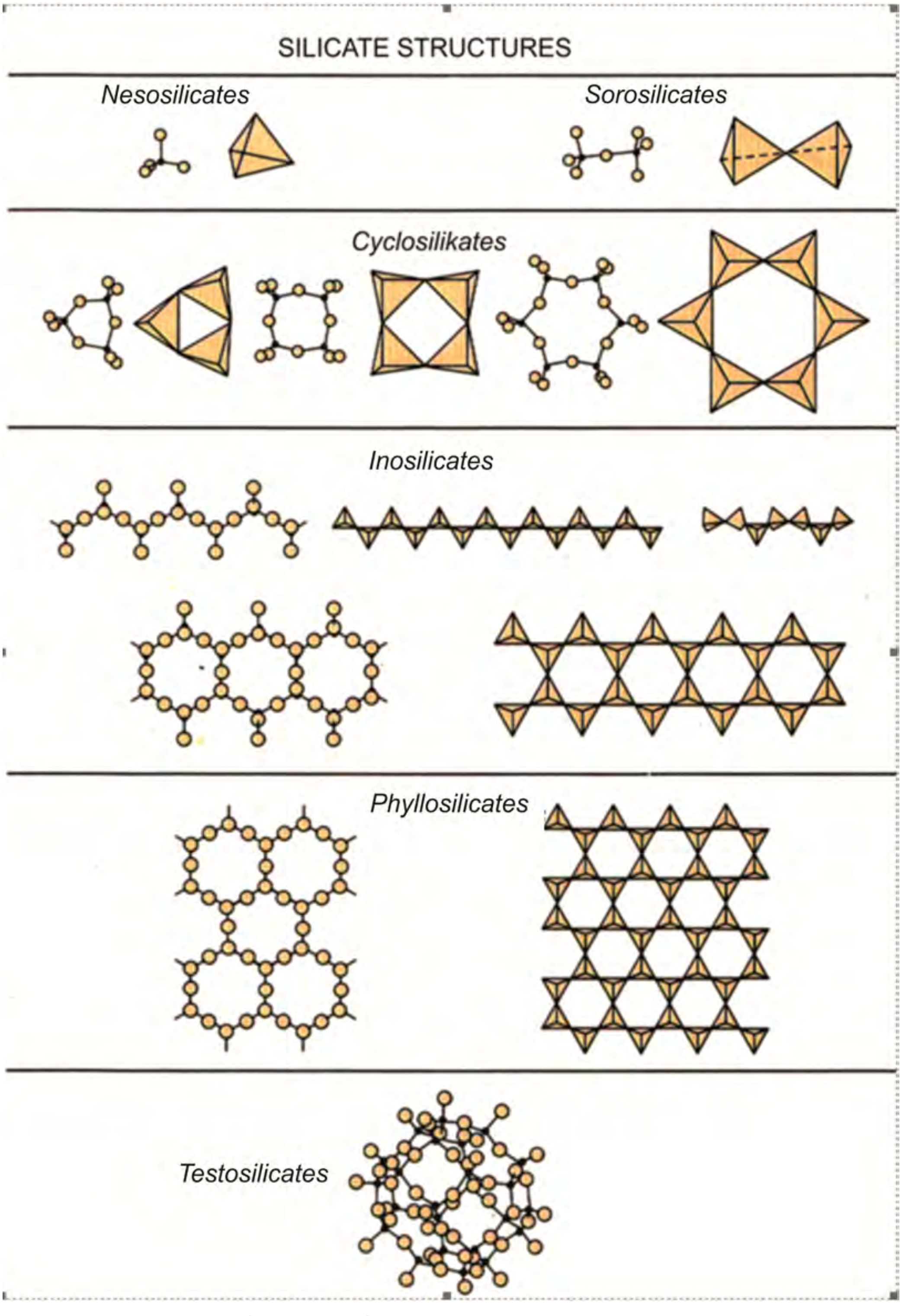


Fig. 86. Classification of silicates by structural characteristics

3. *Silicates with chains of silicon-oxygen tetrahedra (inosilicates)* $[Si_2O_6]^{4-}$ *(pyroxene supergroup).* This subclass includes *orthopyroxene group*: *enstatite, bronzite, hypersthene* and *clinopyroxene group*: *diopside, hedenbergite, aegirine, and spodumene, and wollastonite, rhodonite* $[Si_3O_9]^{6-}$.

Silicates with ribbons of silicon-oxygen tetrahedra inosilicates $[Si_4O_{11}]^{6-}$ *(amphibole supergroup).* Other minerals in this subclass include *tremolite, actinolite, hornblende, arfvedsonite, glaucophane.*

- Pyroxenes and amphiboles have a number of *common features*:
  - a similar appearance of crystals (elongated in one direction);
  - perfect cleavage in elongation (prism);
  - close specific gravity;
  - the same hardness;
  - the same main cations Mg^{2+}, Fe^{2+}, (Mn), Ca^{2+}, Na^{1+}, (K), Li^{1+}, Al^{3+}, (Cr), Ti^{4+}.

Differences:

- In crystal structures, pyroxene radicals are represented by single chains, amphibole radicals – double. This property is reflected in the appearance of crystals of two compared groups: the predominance of short-prismatic tabular crystals in pyroxenes and strongly elongated to fibrous in amphiboles.
- Difference in the angles of prismatic cleavage (87° in pyroxenes and 124° in amphiboles), cleavage in amphiboles is clearer. Cross sections: square (for pyroxenes) and rhombus (for amphiboles), respectively.
- The presence of separateness in pyroxenes and silky tint in amphiboles.
- Mandatory presence of constitutional water in amphiboles in the form of a hydroxyl group $(OH)^-$.

4. *Silicates with layers (sheets) of silicon-oxygen tetrahedrons (phyllosilicates).*

The type of crystal structure of layered silicates can be geometrically deduced from the structure of amphiboles, just as the structure of tremolite is easily deduced from the structure of diopside by transformation of chains $[Si_2O_6]$ in ribbons $[Si_4O_{11}]$. If the transformation (condensation) process is continued, two-dimensional $[Si_4O_{10}]^{4-}$ layers will appear. This subclass includes minerals with a layered structure: *muscovite, biotite, phlogopite, lepidolite (mica group), pennine (chlorite group), talc, serpentine, kaolinite*. The skeleton of the structure of layered silicates is the network of silicon-oxygen tetrahedra. They are located parallel to each other and alternate with flat meshes of a different composition, forming packets of layers. All layered silicates and aluminosilicates have their own structural varieties due to different displacement (shift) and reversal of the packages relative to each other, which is easily carried out in nature due to the small forces of bonds between the packages.

5. Silicates with three-dimensional frameworks of tetrahedra (testosilicates). The structure is a three-dimensional framework, in the structure of which, along with a silicon-oxygen tetrahedron $[SiO_4]^{4-}$ alumo-oxygen tetrahedron takes part $[AlO_4]^{5-}$. Therefore, this subclass is usually called frame aluminosilicates. Anionic group $[(Si,Al)_nO_{2n}]$. Compounds of this subclass are widespread and important rock-forming minerals. Chemically, these are almost exclusively aluminosilicate (tetrahedrons AlO_4), in this case, the number of Si ions substituted by Al ions does not exceed half. Minerals of this subclass are combined into several groups: feldspars and feldsparids. Feldspars, in turn, are divided into plagioclase (*albite, labrador*) and K-feldspar (*orthoclase, microcline*); feldspatids are represented by *nepheline*.

Below we will consider silicates in detail separately.

1. Nesosilicates are represented by the following minerals*: olivine, zircon, titanite, disthene, topaz, staurolite, and garnet group.*

The features of the formation of nesosilicates are different.

The minerals of high T and P (igneous rocks) include: *olivine* as a rock-forming mineral (ultrabasic igneous rocks), *zircon, titanite*, some *garnets* as accessories (rare minerals composing up to 10 % of the total volume of rocks) (basic, medium and acid rocks), *topaz* (granite pegmatites). The minerals that are formed predominantly by the metamorphic way include: *aluminum garnets, staurolite, disthene*. By the contact-metasomatic way, calcium garnets (*grossular, andradite*) are formed; *topaz* (greisens).

Let us consider each mineral separately, highlighting their diagnostic features. Perhaps it is no coincidence that the study of necosilicates begins with *olivine*, the earliest magmatic mineral, which is the very first fractionated from magma. Hence follows a number of its distinctive and characteristic features of paragenesis. *Olivine* does not occur with *quartz* and other light-colored late minerals such as potassium *feldspars, micas*, and others. On the contrary, it is in association with dark-colored early igneous *Cr-spinels*, rhombic and monoclinic *pyroxenes*, and basic *plagioclases*. The color of *olivine* is bottle-green, it is transparent, there is no cleavage, it often resembles "broken glass" in appearance. The hardness of *olivine* is high (6.5–7.5), it differs from other green minerals (*diopside, epidote*) in a rounded short-prismatic shape of crystals, conchoidal fracture, transparency, lack of cleavage, and characteristic paragenesis. It differs from green garnets (*grossular, demantoid*) by the absence of zoning and shading characteristic of garnets, a specific early magmatic association.

Zircon, being an accessory mineral (composes up to 1 % of the volume of rocks), forms small idiomorphic crystals with regular outlines of a pyramidal habit (Fig. 87).

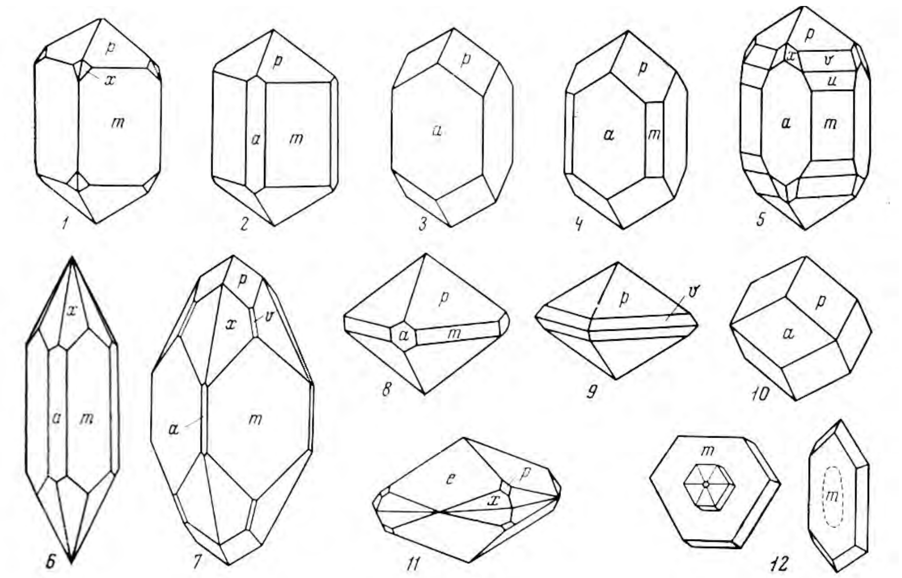


Fig. 87. Morphology of zircon crystals

The color of *zircon* is varied, but mainly in the samples provided by the department, it varies from honey-yellow to dark brown. The high hardness of this mineral (7.5) and the square section (tetragonal crystal system) make it possible to distinguish it from a similar honey-yellow sphene with a lower hardness (5.5) and a diamond-shaped section (monoclinic crystal system). It differs from brown *garnets* of the *andradite* series in the form of crystals, lack of zoning, lower dimensionality and a different paragenesis. *Zircon* is often associated with *albite*, *K-feldspar* (potassium feldspar), *lepidomelane* (mica with increased iron content), etc.

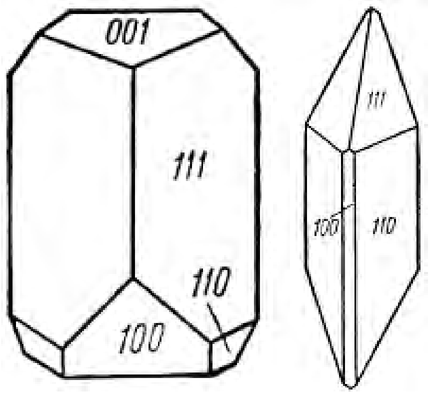


Fig. 88. "Envelope" shape of titanite crystals

Titanite is a typical accessory mineral in alkaline rocks. However, since the clarkes of the elements that make up *titanite* are higher than those of the same zircon, respectively, *titanite* is able to form larger crystals than *zircon*. *Titanite* has a strong diamond luster, honey-yellow color and characteristic envelope crystals (Fig. 88). If *titanite* acts as an accessory mineral of alkaline genesis, then its companions are such minerals as *nepheline, aegirine, apatite, albite, K-feldspar*. Occurring also in the skarn process, titanite readily associates with calcium garnets (*grossular-andradite*), *epidote*, *calcite*, *diopside,* etc.

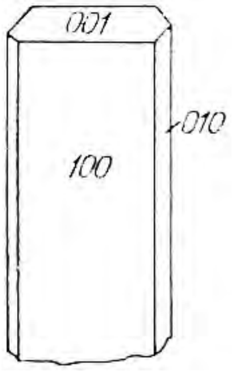


Fig. 89. Flattened (plank) form of disthene crystals

Disthen got its name not by chance, since it has several directions of hardness or resistance to external mechanical stress. Literally parsing the name of the mineral by letters, we get that "*di*" translated means two, "*sthen*" – resistance. That is, a mineral with double resistance. However, this interpretation of the mechanical properties of the mineral is not entirely correct, since disthene crystallizes in the triclinic system of the lowest category and has three different directions of hardness. The shape of *disthene* crystals is flattened, plank, which reflects a combination of several pinacoids (Fig. 89). For each pinacoid, *disthene* has different relative values of hardness for the first – 4.5, for the second 6.5, and for the third – 7.5.

Disthene color is bluish-gray, blue, heterogeneous: from deep intense blue to light. This mineral has a metamorphic origin, there is such a phenomenon that crystals are crumpled, deformed, bent. It sometimes resembles *corundum* in color, from which it fundamentally differs in hardness and in the shape of crystals.

Topaz is not often found in the university educational collection. However, in nature, it forms rather large crystals, which are used both in jewelry production and as collection raw materials. The color of *topaz* is varied from colorless to wine, tea, blue. The color of this mineral is allochromatic (associated with hole structural defects), which causes its instability. Of course, most of the *topaz* used for jewelry purposes is refined, which makes its color more deep and permanent.

Topaz, unlike *quartz* similar to it, has a number of differences: higher specific gravity and hardness, perfect cleavage, longitudinal rather than transverse (in quartz) shading.

The name of the mineral is *staurolite* due to its ability to form cruciform aggregates (germination twins). "Stavros" in Greek. means cross. The color of the mineral, due to the inclusion of iron impurities, is predominantly dark: from dark brown to black. There are several forms of manifestations of this mineral, often at first glance not similar to each other. In the samples of the TPU educational collection, staurolite is presented in the form of small black elongated crystals from 5…10 mm in length, and rather large well-formed brown intergrowths reaching 10 cm in length. In paragenesis, *staurolite* contains typically metamorphic minerals: *disthene, micas,* and *aluminum garnets* (more often almandine). The hardness of *staurolite* is high (7.5).

It should be distinguished from other minerals with similar hardness (garnets, for example) by the shape of the crystals.

2. *Sorocilicate* is represented by *epidote*.

Epidote is a very easily remembered mineral for a number of its characteristic features: pistachio-green color, prismatic crystal shape (Fig. 90), perfect cleavage in one direction along the second pinacoid, paragenesis with calcium minerals in the skarn process, and close association with quartz in hydrothermal process. It differs from diopside, slightly similar in color and prismatic habit, in greater hardness (6.5) and strong glassy luster. In addition, the color of *diopside* is dirty green, greenish gray, and the prisms are shorter-columnar, cleavage in diopside is less pronounced, but separation may be observed, which is not characteristic of *epidote*.

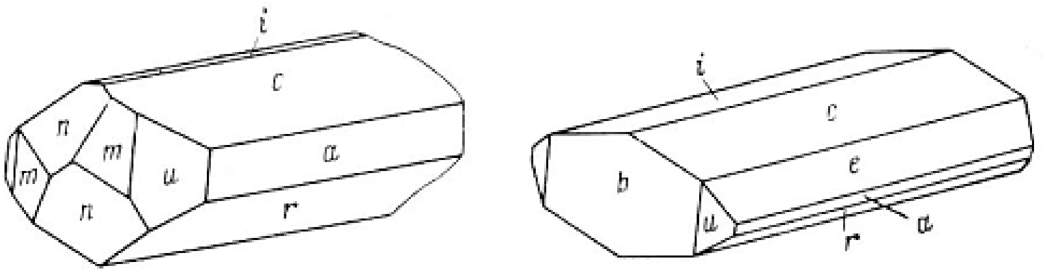


Fig. 90. Prismatic (elongated) shape of epidote crystals

In some cases, *epidote* can be confused with calcium garnets (*grossular, demantoid*) due to its green color, high hardness, and white streak. The tasks of diagnosing epidote are facilitated by finding at least one grain in the form of a well-formed prismatic crystal, in contrast to isometric garnets. However, what if the epidote composes granular masses? In this case, it is worth knowing well the diagnostic signs of not only *epidote*, but also *garnets*, which are characterized by specific growth zoning, shading, higher hardness (7.5) than *epidote*, and isometric crystal habit. *Garnets* are a broad group of minerals that share a number of common and distinct characteristics. Common features include the isometric appearance of crystals with a predominance of rhombododecahedron and tetragontrioctahedron forms (sometimes combinations thereof), hatching and growth zoning on the faces (Fig. 91), high hardness (6.5–7.5), lack of cleavage and streak.

The general formula for garnets should be written as $A^{2+}_{3}B^{3+}_{2}[SiO_4]^{4-}_{3}$. The composition of *aluminum garnets* can be expressed by one general formula $(Fe,Mn,Mg)_2Al_3[SiO_4]_3$, similar to calcium, the composition of which is correspons to $Ca_3(Al,Fe,Cr)_2[SiO_4]_3$. As the reader managed to notice, the named series correspond to an unchanged component in the formulas: *pyrope* (Mg), *almandine* (Fe), *spessartine* (Mn); to garnets of the calcium series: *uvarovite* (Cr), *grossular* (Al), *andradite* (Fe). One of the simplest distinguishing features of each individual mineral of the garnet group is its color, however, in order to establish the correct belonging to a particular mineral, you need to know the exact content of the components, which is not possible within our course. For this, special analyzes of the material composition are carried out, which is not included in the objectives of this practical course, therefore, we will give the name to these minerals by indirect signs (paragenetic association, aggregates, color). The general signs of garnets, with the help of which these minerals are diagnosed from others, were listed above, but how to distinguish them from each other?

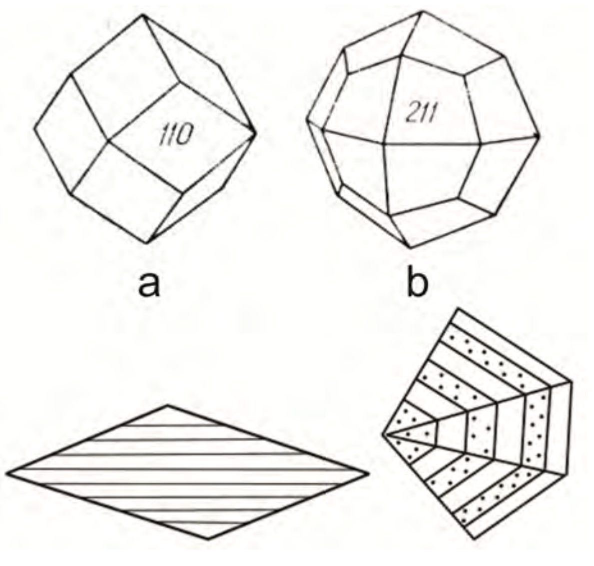


Fig. 91. The predominant forms of garnet crystals:
a) rhombododecahedron;
b) tetragontrioctahedron; shading and growth zones on crystal faces

There are a number of distinct features for each isomorphic series. For example, garnets of the *calcium series* can form both solid masses and individual phenocrysts, while garnets of the aluminum series tend to form exclusively individual phenocrysts. The colors of calcium garnets vary in warm greenish-brown tones to black (*schorlomite* is a black Ti-containing variety of andradite). The exception is *uvarovite*, which characterized by emerald green. At the same time, *uvarovite* also has a specific genesis, as well as small crystals in the form of "*brushes*". Genesis plays a very important role. As a rule, garnets of the aluminum series are characterized by cold red hues. Similar to *uvarovite*, *pyrope* breaks out of the general isomorphic series, being formed under conditions of a specific earlier magmatic genesis. In the academic collection of the department, the vast majority of calcium garnets are represented by *grossular* (green) and *andradite* (brown) or their mixed varieties, sometimes *shorlomite* (black). Calcium garnets are typical minerals of calcium skarns, respectively, they are in paragenesis with calcium silicates (diopside, sphene, hornblende, hedenbergite, wollastonite, etc.), calcite, sulfides. Most of the aluminum garnets are represented by almandine, which is predominantly distributed in metamorphic formations in paragenesis with *mica*, *disthene*, *staurolite*, *quartz*, etc. In rocks of metamorphic genesis, the main forming factor is pressure, as evidenced by their directional oriented structure, banding, often plastic deformation, and manifests itself as the curvature of the main pattern. *Spessartine* is characteristic of pegmatite veins, which is explained by the accumulation of Mn by the end of the magmatic process and its concentration in the residual pegmatite solution. In paragenesis with it are typical pegmatite minerals: *quartz*, *K-feldspar*, *mica*, *polychrome tourmaline*.

3. *Cyclosilicates* with radical $[Si_6O_{18}]^{12-}$ represented by *beryl* and *tourmaline*.

In cyclosilicates, silicon-oxygen tetrahedrons are arranged in a closed ring, at the vertices of which are Si atoms (Fig. 86). The crystal structure is reflected in the external habit of crystals, both beryl and tourmaline. In the cross section of beryl, there is a hexagon, for tourmaline, which crystallizes in the trigonal system, respectively, a ditrigon (spherical triangle). Tourmaline crystal heads are often well shaped and reflect combinations of simple forms of the trigonal system (Fig. 92). The hardness of *tourmaline* and *beryl* is high (7.5–8), the crystals are well-formed, volumetric, elongated along the single axis of a higher order. The color of *beryl* can be very diverse, however, in the collection samples of the department, greenish-yellow, bluish-green, light green predominates. The variety of deep green color (Cr^{3+}) is called emerald, the blue variety is aquamarine.

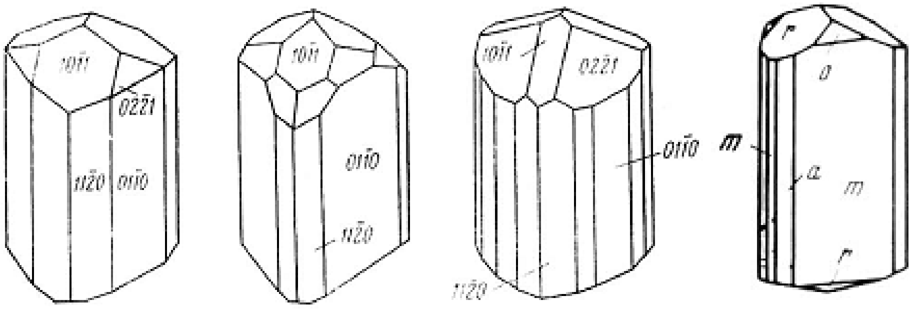


Fig. 92. Tourmaline crystal shape

Tourmaline is even more varied in color due to the complexity of its chemical composition. The type of black *tourmaline* is called *schorl. Schorl* can be distinguished from other black minerals by its volumetric cross-section in the form of a spherical triangle, coarse longitudinal shading, high hardness, lack of cleavage, absence of a feature (sometimes faint grayish-blue). *Hornblende*, similar in elongated crystal shape, has a lower hardness (5.5), a rhombus in cross-section, cleavage in several directions, and a silky tint. The inexperienced eye of a student can also hastily mistake elongated crystals of aegirine for tourmaline, however, a green line, a lower hardness (5.5), cleavage in several directions at an angle close to 90°, separation and alkaline genesis, make it possible, upon careful analysis, to distinguish these minerals apart.

NESOSILICATES

Mineral name	**Olivine**
Chemical composition	**$(Mg,Fe)_2[SiO_4]$** *Forsterite* **$(Mg)_2[SiO_4]$,** *Fayalite* **$(Fe)_2[SiO_4]$**
Varieties	*Chrysolite* – transparent olive yellow olivine variety
Syngony	Ortorhombic
Crystal Form	Crystals of isometric, prismatic, flattened appearance are rare
Aggregate morphology	Granular, phenocrysts of grains
Color	Bottle green
Streak	White
Luster	Vitreous
Cleavage	Imperfect, none observed
Hardness	6.5–7, fragile
Specific gravity (g/cm^3)	3.3
Diagn. signs	Rounded transparent green phenocrysts in dark-colored rocks (Fig. 93)
Associate minerals	Serpentine, pyroxenes, chromite
Genesis	Magmatic, carbonatites, contact-metasomatic (forsterite).
Application	Refractory raw materials, chrysolite in jewelry

Fig. 93. Prismatic form of olivine crystals (Sapat Gali, Naran, Kaghan Valley, Mansehra District, Khyber Pakhtunkhwa Province, Pakistan)

NESOSILICATES

Mineral name	**Zircon**
Chemical composition (common impurites are indicated in brackets)	**$Zr[SiO_4]$ (Hf,Th,U,REE)**
Syngony	Tetragonal
Crystal Form	Short-columnar, isometric, less often dipyramidal
Aggregate morphology	Phenocrysts
Color	Colourless, yellow, grey, reddish-brown, green, brown, black
Streak	White
Luster	Adamantine, Vitreous, Greasy
Cleavage	Indistinct on {110}{111}
Hardness	7.5–8
Specific gravity (g/cm^3)	4.7
Diagn. signs	Rutile (excellent crystal shape, hardness), titanite (excellent crystal shape, hardness, luster)
Associate minerals	Albite, K-feldspar, nepheline, apatite, black mica
Genesis	Alkaline and granite pegmatites, igneous rocks
Application	Refractory raw materials, extraction of zirconium, hafnium

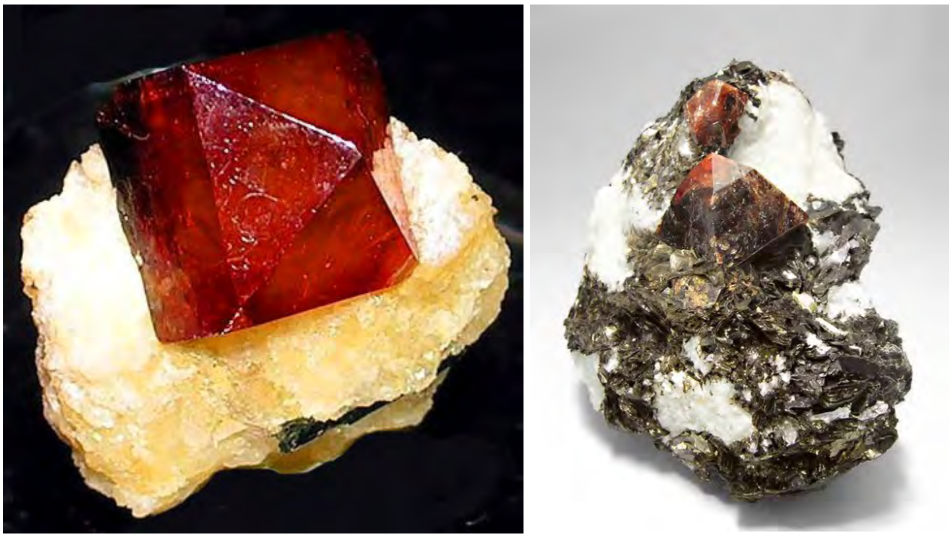


Fig. 94. Idiomorphic zircon crystals
(Astore Valley, Astore District, Gilgit-Baltistan, Pakistan)

NESOSILICATES

Mineral name	**Topaz**
Chemical composition	**$Al_2[SiO_4](F,OH)_2$**
Syngony	Orthorhombic
Crystal Form	Prismatic
Aggregate morphology	Phenocrysts
Color	Colorless, water-transparent, yellow, blue, pink
Streak	White
Luster	Vitreous
Cleavage	Perfect on {001}
Hardness	8
Specific gravity (g/cm^3)	3.5
Diagn. signs	Quartz (excellent crystal shape, cleavage, shading), beryl (excellent cross-section, cleavage)
Associate minerals	Quartz, tourmaline, fluorite, beryl, cassiterite, wolframite, sulfides
Genesis	Pegmatites, greisens, hydrothermal ↑ t
Application	Jewelery

Fig. 95. Short-columnar and prismatic transparent crystals of topaz (St Anns Mine, Mwami, Karoi District, Mashonaland West, Zimbabwe)

NESOSILICATES

Mineral name	**Titanite**
Chemical composition	**$CaTiO[SiO_4]$**
Syngony	Monoclinic
Crystal Form	Wedge-shaped envelope prisms
Aggregate morphology	Phenocrysts
Color	Brown, green, yellow, orange, rose-red, black, beige, grey, colourless, grey-blue, bluish
Streak	White
Luster	Adamantine, Resinous
Cleavage	Good on {110}
Hardness	5.5
Specific gravity (g/cm^3)	3.4
Diagn. signs	Envelope-shaped crystals, paragenesis with alkaline minerals
Associate minerals	Nepheline, aegirine, apatite, albite, feldspars (alkaline pegmatites); andradite, diopside (skarns)
Genesis	Alkaline pegmatites, metamorphic, contact-metasomatic
Application	Titanium oxide extraction

Fig. 96. Envelope-shaped crystals of titanite with adamatine luster (Caspar quarry, Ettringen, Vordereifel, Mayen-Koblenz District, Rhineland-Palatinate, Germany)

NESOSILICATES

Mineral name	**Disthen, Kyanite**
Chemical composition	**$Al_2O[SiO_4]$**
Syngony	Triclinic
Crystal Form	Crystals bladed or tabular
Aggregate morphology	Phenocrysts
Color	Blue, white, light gray, green, rarely yellow, orange, pink
Streak	Colorless
Luster	Vitreous, Sub-Vitreous, Greasy, Pearly
Cleavage	Perfect on {100}, good on {010}
Hardness	4.5 – in the first pinacoid, in other directions 6–7, fragile
Specific gravity (g/cm^3)	3.6
Diagn. signs	Genesis in mica shale, color dichroism and anisotropy of hardness, bluish-gray and blue coloration
Associate minerals	Mica, staurolite, tourmaline, almandine
Genesis	Metamorphic high-alumina rocks
Application	High-alumina raw materials, refractories, jewelry

Fig. 97. Table crystals of bluish-blue kyanite (Central St Gotthard Massif, Leventina, Ticino, Switzerland)

NESOSILICATES

Mineral name	**Staurolite**
Chemical composition	**$2Al_2O[SiO_4]*Fe(OH)_2$**
Syngony	Monoclinic
Crystal Form	Prismatic
Aggregate morphology	Crystal phenocrysts, cruciform aggregates
Color	Dark brown, brownish-black, red-brown
Streak	White to grayish
Luster	Sub-Vitreous, Resinous
Cleavage	Distinct on {010}
Hardness	7–7.5
Specific gravity (g/cm^3)	3.7
Diagn. signs	Cruciform twins
Associate minerals	Mica, disthen, tourmaline, almandine
Genesis	Metamorphic
Application	As a flux when smelting iron ores

Fig. 98. Cruciform intergrowths of staurolite crystals (Fânzeres, Gondomar, Porto, Portugal)

NESOSILICATES

Mineral name	**Garnet series (Al series; Ca series)**
Chemical composition	**Grossular – $Ca_3Al_2 [SiO_4]_3$, Andradite – $Ca_3Fe_2 [SiO_4]_3$, Uvarovite – $Ca_3Cr_2 [SiO_4]_3$, Almandine – $Fe_3Al_2[SiO_4]_3$, Spessartine – $Mn_3Al_2[SiO_4]_3$, Pyrope – $Mg_3Al_2[SiO_4]_3$**
Varieties	*Schorlomite* – Ti-containing variety of black andradite; *demantoid* – Cr-containing variety of andradite
Syngony	Cubic/Isometric
Crystal Form	Isometric, rhombic dodecahedral, shaded edges
Aggregate morphology	Phenocrysts (Al-row), continuous granular masses (Ca-row).
Color	*Grossular* – gooseberry yellow, green; *andradite*-brown; *uvarovite* – emerald green; *almandine* – manganese red, *spessartine* – orange red, *pyrope* – dark red, wine red
Streak	White
Luster	Vitreous, Greasy
Cleavage	None observed
Hardness	6.5–7.5
Specific gravity (g/cm^3)	3.5–4.2
Diagn. signs	Macroscopically recognizable by the characteristic isometric appearance of crystals, shading, high hardness and average specific gravity, differ from each other in aggregates and paragenesis
Associate minerals	*Grossular-andradite* with diopside, epidote, chlorites, magnetite; *almandine* with mica, chlorites, hornblende, albite; *spessartine* with quartz, albite, muscovite; *pyrope* with diamond, olivine
Genesis	Contact-metasomatic: grossular, andradite; metamorphic: almandine, spessartine; ultrabasic-magmatic: pyrope; granite pegmatites: almandine
Application	Jewelry, abrasive material

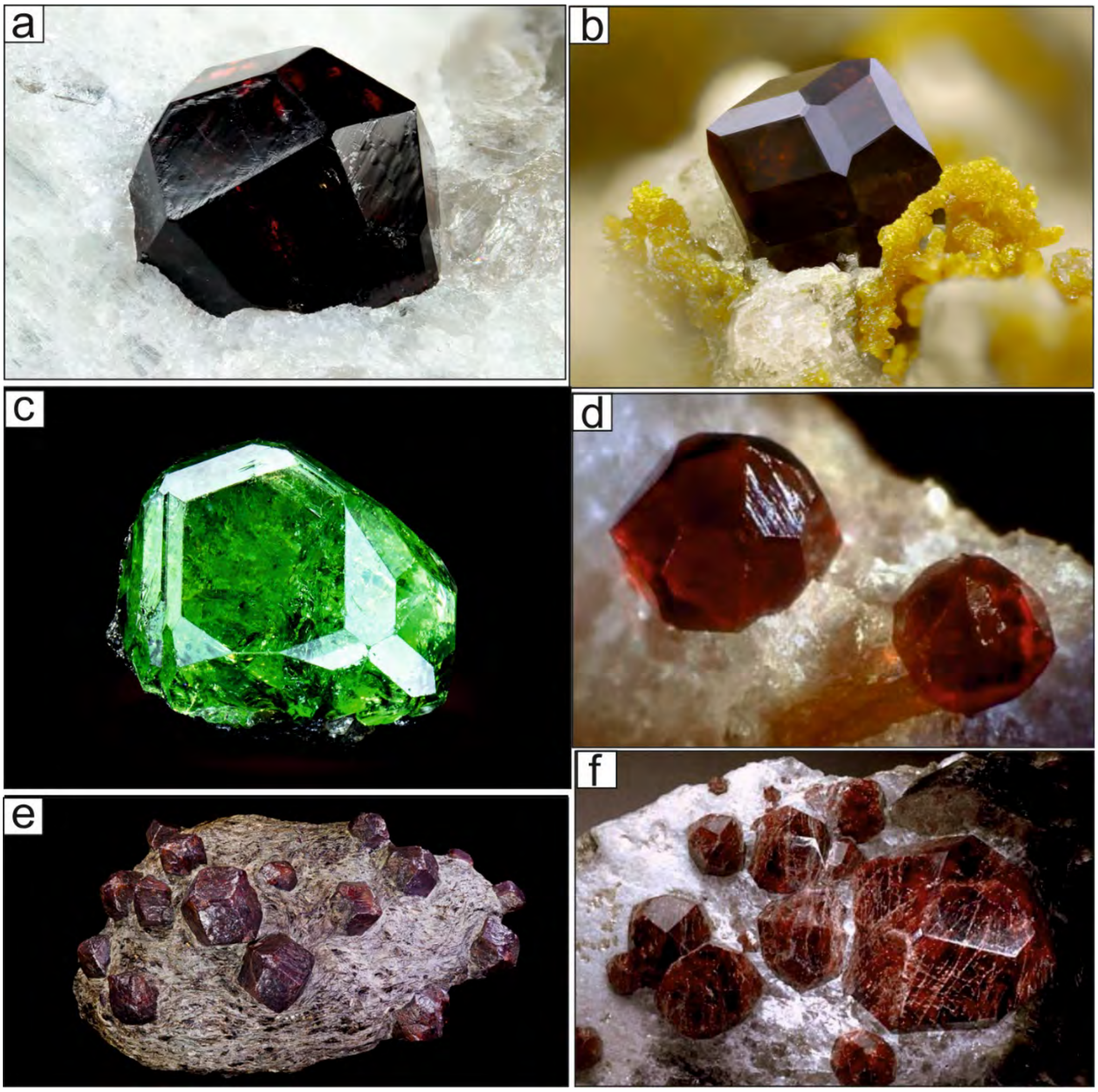


Fig. 99. a, b – Almandine; c – tsavorite; d – spessartite;
e, f – almandine phenocrysts in metamorphic schist

SOROSILICATES

Mineral name	**Epidote**
Chemical composition	**$Ca_2(Fe,Al)_3[SiO_4][Si_2O_7]O(OH)$**
Syngony	Monoclinic
Crystal Form	Prismatic, flattened, elongated, stubby, tabular
Aggregate morphology	Crystal phenocrysts, granular masses
Color	Yellowish-green, green, brownish-green, black
Streak	Colourless
Luster	Vitreous
Cleavage	Perfect on {001}, imperfect on {100}
Hardness	6–6.5
Specific gravity (g/cm^3)	3.4
Diagn. signs	Green color, prismatic crystals, high hardness. Diopside (excellent in hardness, color, character of cleavage) grossular (excellent in crystal appearance), tourmaline (excellent in cross-sectional shape)
Associate minerals	Calcite, diopside, hornblende, andradite (skarns), quartz (hydrothermal), hornblende (metamorphic)
Genesis	Skarns, hydrothermal, metamorphic

Fig. 100. Twinning of epidote crystals (Knappenwand, Knappenwand area, Neukirchen am Großvenediger, Zell am See District, Salzburg, Austria)

CYCLOSILICATES

Mineral name	**Beryl**
Chemical composition	$\mathbf{Be_3Al_2[Si_6O_{18}]}$
Varieties	*Emerald* – Cr-containing variety of grassy green color*; aquamarine – a blue variety*
Syngony	Hexagonal
Crystal Form	Columnar, prismatic, faces have vertical shading (Fig. 101)
Aggregate morphology	Crystal phenocrysts, rarely solid columnar masses
Color	Greenish yellow, light green
Streak	White
Luster	Vitreous, Sub-Vitreous, Waxy, Greasy
Cleavage	imperfect, irregular fracture
Hardness	7.5–8
Specific gravity (g/cm^3)	2.6–2.9
Diagn. signs	Cross-section in the form of a hexagon, high hardness, prismatic appearance of crystals, differs from apatite in hardness, differs from quartz in color and shape of crystals
Associate minerals	Feldspar, quartz, mica, topaz, tourmaline, fluorite, wolframite, sulfides
Genesis	Pegmatites, greisens
Application	Jewelry, beryllium ore

Fig. 101. Long-prismatic crystals of beryl
(Niyil-Bruk, Niyil, Braldu Valley, Shigar District, Gilgit-Baltistan, Pakistan)

CYCLOSILICATES

Mineral name	**Tourmaline**
Chemical composition (impurities are indicated in brackets)	**$(Na,Ca,K)_3$ $(Li,Mg,Mn,Fe,Al)_3$ $(Mg,Fe,Al)_6$ $[Si_6O_{18}](BO_3)_3(O,OH)$** – *complex aluminoborosilicate Na, Mg, Al, Fe*
Varieties	*Types: Dravite* – brown; *schorl* – black; *elbaite* – polychrome. Varieties of elbaite: *rubellite* – pink; *verdelite* – green; *indicolite* – blue
Syngony	Trigonal
Crystal Form	Columnar, prismatic, faces have vertical shading
Aggregate morphology	Crystal phenocrysts, radial and columnar masses, rarely solid masses
Color	Varied, often polychrome
Streak	–
Luster	Vitreous
Cleavage	Absent, sometimes weak
Hardness	7.5–8
Specific gravity (g/cm^3)	2.9–3.25
Diagn. signs	Cross-section in the form of a spherical triangle, high hardness, prismatic appearance of crystals, differs from hornblende and aegirine in hardness, feature color, paragenesis
Associate minerals	Quartz, feldspar, mica, topaz, beryl, fluorite, wolframite, sulfides
Genesis	Pegmatites, greisen
Application	Jewelry, radio engineering

Fig. 102. Tourmaline cystalls with vertical shading (Paprok, Kamdesh District, Nuristan, Afghanistan)

Often in the pegmatite association there is a multi-colored type of *tourmaline* (*elbaite*), a pink variety of elbaite is called *rubellite*, blue is *indigolite*, and green is *verdelite*. The pyroxens group combines minerals (*wollastonite* and *rhodonite*) with the abbreviated radical group $[Si_3O_9]^{6-}$. *Wollastonite* is characterized by a white color, elongated fibrous crystals, splinter fractures, and medium hardness (5). In contrast to the similar fibrous *tremolite* associated with *talc*, *wollastonite* is in paragenesis with *diopside, grossular-andradite, hedenbergite,* and *calcite* due to its contact-metasomatic nature. *Rhodonite* has a beautiful pink color due to the inclusion of a chromophore element (Mn) in its composition. The presence of manganese predetermines its close relationship with *psilomelane,* which often fills cracks and veins in *rhodonite,* giving a special landscape to this mineral. *Rhodonite* is formed by a metamorphic way and therefore its aggregates are represented by dense fine-grained masses with a banded, oriented structure. It is difficult to confuse *rhodonite* with other minerals because of its specific pale pink color, accentuated by the black veins of *psilomelan*. However, sometimes students confuse *rhodonite* with meat-red K feldspar, or with manganese carbonate (rhodochrosite), however, carbonates have a lower hardness, and K feldspar has cleavage in several directions and complex twins. *Inosilicates* are represented by rhombic and monoclinic pyroxenes. Rhombic pyroxenes, in turn, form an endless continuous series from *enstatite* $Mg_2[Si_2O_6]$ to *hypersthene* $Fe_2[Si_2O_6]$, the intermediate variety of which is bronzite $(Mg,Fe)_2[Si_2O_6]$. Rhombic pyroxenes form predominantly in basic and ultrabasic early igneous rocks. They are characterized by a tabular form of crystals, a noticeable nacreous tint on the edges, paragenesis with *talc*. *Enstatite* is a light-colored mineral, when it enters the composition of the iron mineral, the intermediate difference (*bronzite*) acquires a bronze (chocolate) hue, in the hypersthene there is even more iron, therefore it is a darker variety. *Enstatite*, along with magmatic formation, occurs in magnesian skarns. Here it can form large light gray crystals with a pearlescent sheen on the edges. *Talc* is ubiquitous in the form of enstatite substitution products.

INOSILICATES

Mineral name	**Wollastonite**
Chemical composition	**$Ca_3[Si_3O_9]$**
Syngony	Triclinic
Crystal Form	Tabular, elongated, board-shaped
Aggregate morphology	Leafy, radially-radiant, columnar, scaly, less often fibrous with a parallel and reticular arrangement of individual fibers
Color	White with a grayish tint
Streak	White
Luster	Vitreous, Pearly
Cleavage	Perfect on {001} Good on {001}
Hardness	4.5–5.0, splintered fracture
Specific gravity (g/cm^3)	2.78–2.91
Diagn. signs	Radial-columnar aggregates, paragenesis with other minerals of contact-metasomatic genesis (garnets, diopside)
Associate minerals	Andradite, grossular, diopside, hedenbergite, calcite
Genesis	Contact-metasomatic
Application	As a filler additive in plastics, non-ferrous metallurgy, paint and varnish industry

Fig. 103. Intergrowths of fibrous wollastonite crystals (Pargas, Southwest Finland, Finland)

INOSILICATES

Mineral name	**Rhodonite**
Chemical composition	$\mathbf{CaMn_4[Si_5O_{15}]}$
Syngony	Triclinic
Crystal Form	Crystals are rare
Aggregate morphology	Dense, grainy, monomineral accumulations
Color	Pink
Streak	White
Luster	Vitreous
Cleavage	Perfect on {110} and {110}
Hardness	5.5–6.5
Specific gravity (g/cm^3)	3.4–3.7
Diagn. signs	Pink color, cleavage character, black veins represented by psilomelan
Associate minerals	Psilomelan, rhodochrosite
Genesis	Contact-metasomatic, regional-metamorphic
Application	Ornamental stone

Fig. 104. Continuous masses of rhodonite with psilomelan veinlets

This substitution product is an important feature that can be used to distinguish enstatite from spodumene. If we pay attention to the spodumene formula $LiAl[Si_2O_6]$, then it becomes obvious that its formation conditions are clearly different from the genesis of *enstatite,* since Li is a rare metal accumulating in the residual solution enriched with rare and volatile components. Minerals companions of *spodumene* in rare-metal pegmatites of lithium specialization are: *lepidolite, quartz, clevelandite* (lamellar albite), *polychrome tourmaline, beryl, feldspar*. *Clinopyroxene gpoup* are represented by a broader group of minerals; our course includes diopside, hedenbergite, aegirine and spodumene.

In general, pyroxenes are characterized by a prismatic, elongated crystal shape; however, the nature of elongation and flattening is different for all. For *diopside,* short-columnar crystals are characteristic, *hedenbergite,* on the contrary, forms elongated and diverging ("clawed") crystals. *Aegirine* tends to form prismatic, predominantly elongated and radially-radiant crystals ("aegirine suns"). In most cases, *spodumene* has a flattened, "plank" shape. All pyroxenes are characterized by separation and cleavage at an angle of 87±3°.

Diopside is characterized by a dirty green or greenish-gray color, a prismatic, short-columnar form of crystals (Fig. 105), or solid granular masses. It is associated with *phlogopite (Mg-mica), calcite, calcium garnets, epidote, hornblende, actinolite, etc.*

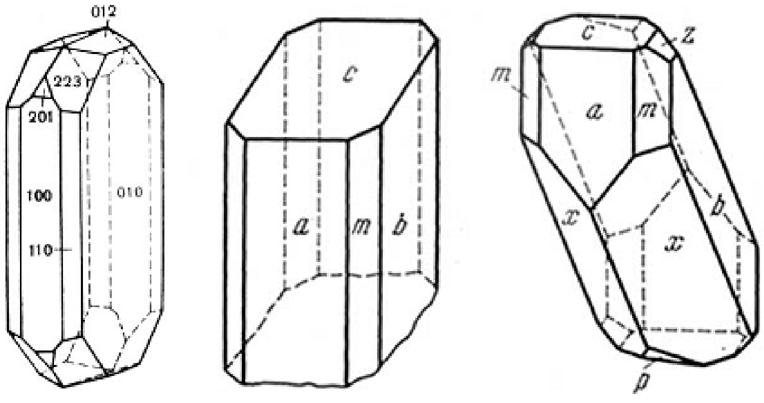


Fig. 105. The crystal habits of diopside crystals

Diopside, which is rich in chromium and has a bright green color, is called chrome diopside. The origin of this variety is associated with early igneous rocks, it is very rare. A light blue, fine-grained variety of *diopside* called *violan*. *Violan* is formed in skarn processes.

Aegirine is a typical femic (dark-colored) mineral of alkaline rocks, which causes its close association with such alkaline minerals as *nepheline, sphene, apatite, arfvedsonite,* etc. The color of the mineral is always black, the color of the line is green, separation and cleavage are observed. The shape of its crystals is shown in Fig. 106.

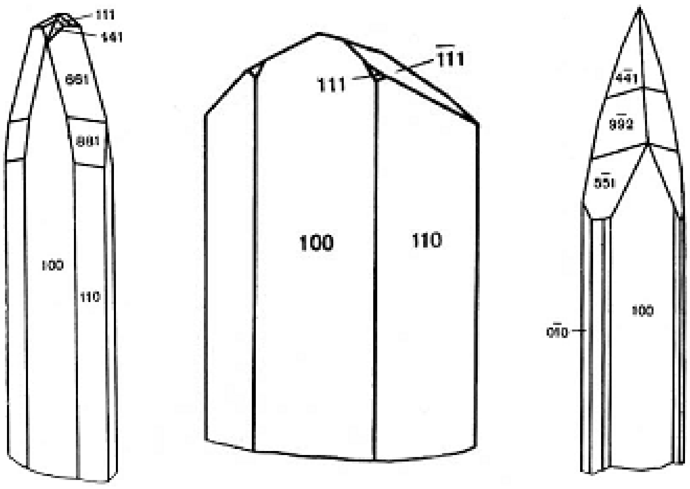


Fig. 106. Aegirine crystal shape

Hedenbergite, forming "paw-like" (fan-shaped, sheaf-like) crystals, as a rule, is colored from dark green to black, due to the inclusion in the composition of the iron mineral, has a light green feature, paragenesis with iron-containing sulfides (*pyrite*, *chalcopyrite*, *pyrrhotite*, *marmatite (ferruginous sphalerite)*, *galena*, etc.).

Spodumene has plank, flattened crystals of light gray (ash) color. It differs from albite by the absence of polysynthetic twins and optical effects, from orthoclase by its higher hardness, the presence of separation, is often unstable and is replaced by clay minerals.

4. *Inosilicates* or amphiboles are characterized by an elongated crystal habit, which is due to the internal features of the crystal structure of this subclass, where silicon-oxygen tetrahedra are arranged in the form of ribbons. Our program includes *tremolite, actinolite, hornblende, arfvedsonite, glaucophane*.

In general, amphiboles form a continuous endless isomorphic series, and under the predominance of certain conditions, a certain amphibole is stable. *Tremolite* is characterized by a light, white color; actinolite – dirty green; hornblende – dark green to black; arfvedsonite – black; glaucophan – bluish gray, blue. At the same time, the color of a feature of tremolite and actinolite is white, hornblende is from white to light green, arfvedsonite is bluish-gray, and glaucophane is blue. *Amphiboles* are diagnosed by elongated, fibrous crystals, their radial-radiant structure, splinter fracture, silky tint, medium hardness (5.5) and average specific gravity (3). Amphiboles are often formed by pyroxenes with similar chemistry, for example: *tremolite-actinolite*, formed by *diopside*, *arfvedsonite* by *aegirine*, etc.

Tremolite is often associated with *talc*, which helps distinguish it from other light colored fibrous minerals. *Actinolite* (radiant stone) is diagnosed by its characteristic dirty green color, similar to *diopside* (prismatic crystals) and *chlorite* (flaky crystals with a lower hardness (2.5)). *Hornblende* is very similar to *aegirine*, from which it differs in the shape of a cross-section in the form of a rhombus, while *aegirine* has a cross-section close to square. In transverse sections of *hornblende,* either acute or obtuse angles between the cleavage planes are visible. In transverse sections of *hornblende*, either acute or obtuse angles between the cleavage planes are visible. *Hornblende* is characterized by a strong silky tint. Paragenesis plays a key role in distinguishing *hornblende* from *aegirine*. *Hornblende* is formed in many intermediate and basic igneous and metamorphic rocks, skarns, while *aegirine* has a very specific alkaline genesis, associated with *arfvedsonite, nepheline, sphene, apatite*, etc. *Hornblende* is confused with *sherl,* from which it differs in a flattened crystal habit, a diamond-shaped cross-section, lower hardness, and a faint green line. *Hedenbergite* is distinguished from *hornblende* by the paragenesis with iron-bearing sulfides and the crested form of crystals.

Glaucophan often forms gray-blue or light blue monomineral fibrous masses.

5. The structure of *phyllosilicates* leaves an imprint on the mechanical properties of minerals of this subclass, significantly lowering their hardness (<3) due to the weak bond strength between layers – pseudohexagonal networks formed by silicon-oxygen tetrahedra. Layer silicates unite the mica group (*muscovite, biotite, phlogopite, lepidolite*), the chlorite group (*pennine*), *talc, serpentine, kaolinite.*

Micas are characterized by a very perfect cleavage, mother-of-pearl shimmer on its planes, despite their low hardness, they are characterized by elasticity (the ability to recover after external influence). Crystallizing in the monoclinic system, the crystal structure of micas predetermines their pseudohexagonal crystal appearance. All of them are characterized by approximately the same hardness of 2–2.5.

Micas have various colors: *muscovite* – light-colored, transparent white; *biotite* – black; *phlogopite* – dark-colored with a golden tint; *lepidolite* – lilac, violet. However, in addition to color, they should be distinguished from each other by paragenesis.

Muscovite and *biotite*, along with quartz and feldspar, are the main minerals of granites and their pegmatites. *Phlogopite* in magnesian skarns is associated with *diopside* and *calcite*. *Lepidolite* tends to pegmatites of rare metal Li-specialization.

Pennine is one of the representatives of *chlorites*, which, in turn, are divided into two rows: *magnesian* and *ferruginous*. However, it is not possible to macroscopically establish belonging to one or another series, therefore the student's task is to diagnose the mineral, like *chlorite* with the general name *pennine*. *Chlorite* has a dirty green color, which is similar to several other silicates: *diopside* and *actinolite*, but the low hardness (2.5), light green line and flaky, lamellar form of chlorite crystals help to distinguish it from the named minerals.

In addition to all other processes, *chlorite* is also formed by the metamorphic way (facies of chlorite shales), therefore, samples with it are often represented by banded oriented rocks, crumpled, deformed, and dense. *Chlorite* is often associated with *tourmaline* (schorl), *Al-series garnet* (almandine), *talc*, etc.

Talc or steatite, in most cases, is a light-colored mineral, occupies the first position in the Mohs scale, therefore it is easily scratched with a fingernail (2.5) and is greasy to the touch. Often forms dense solid masses, sometimes it can form transparent lamellar crystals of light green color – noble talc. It is in paragenesis with magnesian minerals: *enstatite, tremolite, serpentine, and chlorite. Serpentine* got its name from its variegated, green color, reminiscent of snake scales. Its greenish-yellow color and black phenocrysts, represented by *magnetite,* are easy to remember and diagnose. Due to *magnetite,* samples with serpentine can be magnetic. The close association with *magnetite* is explained by the fact that serpentine is formed hydrothermally along the early magnesian rocks due to the decomposition of *olivine*, which, in turn, contains Fe in addition to Mg. The latter is released in the form of an independent phase – *magnetite*. Early igneous rocks predominate in zones of increased tectonomagmatic activity, where, in turn, various types of movements of crustal blocks, faults, shears, thrusts, etc. occur. *Serpentine*, possessing dense soft aggregates, is a kind of "plasticine" or "oil", along which the movement of blocks of the earth's crust most easily occurs, which is reflected in the appearance on samples with serpentine of even shiny and smooth surfaces – "polish faults". Early igneous rocks prevail in zones of increased tectonomagmatic activity, where, in turn, various types of movements of crustal blocks, faults, reverse faults, shears, thrusts, etc. occur. *Serpentine* may be in paragenesis with *talc, enstatite* (light tabular crystals), *magnetite*. The color of the dash is white, which is a very common ornamental material. *Kaolinite* has a white color, low hardness (1.5–2) and, being a clay mineral, has the property of hygroscopicity (the ability to absorb water). Unlike *talc*, which is oily to the touch, *kaolinite*, on the other hand, gives a dry feeling when it comes into contact with the skin. Often formed due to the decomposition of aluminosilicate rocks. As independent monomineral samples, *kaolinite* is not often found in the collection of the department, however, in the form of a matte film, it can be observed on many aluminosilicate rock-forming minerals, for example, *feldspars*.

INOSILIKATES
(Pyroxene Supergroup)

Mineral name	**Enstatite**
Chemical composition	**$Mg_2[Si_2O_6]$**
Varieties	*Bronzite* (bronze-yellow variety), *Hypersthene* **$Fe_2[Si_2O_6]$** (dark colored mineral)
Syngony	Orthorombic
Crystal Form	Prismatic, tabular
Aggregate morphology	Lamellar-columnar
Color	Colorless, grayish white, ash gray
Streak	White
Luster	Vitreous
Cleavage	Good on {210}
Hardness	5.5
Specific gravity (g/cm^3)	3.1–3.3
Diagn. signs	Covered with talcum powder, pearlescent tint on cleavage planes
Associate minerals	Forsterite, phlogopite, talc (contact-metasomatic rocks); olivine, serpentine (ultrabasic igneous rocks)
Genesis	Magmatic, contact-metasomatic (magnesian skarns)
Application	Multifunctional dielectric

Fig. 107. Enstatite (Roc de Courlande, Chastreix, Issoire, Puy-de-Dôme, Auvergne-Rhône-Alpes, France)

INOSILIKATES
(Pyroxene Supergroup)

Mineral name	**Diopside**
Chemical composition	**$CaMg[Si_2O_6]$**
Varieties	*Violan* is a fine-grained blue variety*; Chromium-bearing diopside* – emerald green transparent variety
Syngony	Monoclinic
Crystal Form	Prismatic Prismatic crystals with square cross sections
Aggregate morphology	Granular, solid masses, sometimes columnar aggregates
Color	Dirty green pale and gray shades
Streak	White
Luster	Vitreous, Dull
Cleavage	Good on {110}
Hardness	5.5–6.0
Specific gravity (g/cm^3)	3.3
Diagn. signs	Dirty green, prismatic crystals
Associate minerals	Calcite, hornblende, andradite, epidote (skarns), quartz (hydrothermal), hornblende (metamorphic)
Genesis	Skarns, igneous (pyroxenites, peridotites, gabbro)
Application	Chromium-diopside in jewelry

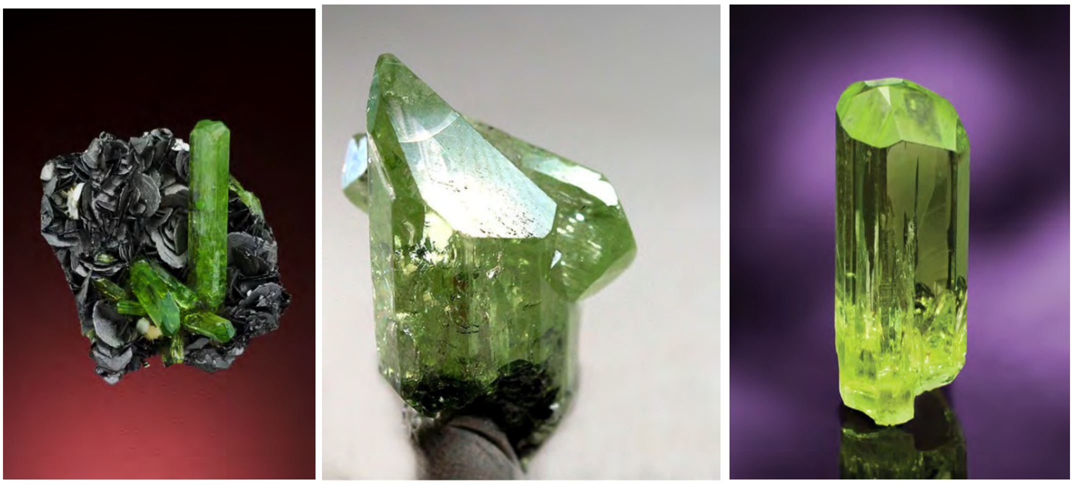


Fig. 108. Prismatic crystals of chromium-diopside (Merelani Hills, Lelatema Mountains, Simanjiro District, Manyara Region, Tanzania)

INOSILIKATES
(Pyroxene Supergroup)

Mineral name	**Hedenbergite**
Chemical composition	**$CaFe[Si_2O_6]$**
Syngony	Monoclinic
Crystal Form	Prismatic
Aggregate morphology	Radial and coarse aggregates
Color	Dark green to green-black
Streak	Light gray with a greenish tint
Luster	Vitreous
Cleavage	Good on {110}
Hardness	5.5–6.0
Specific gravity (g/cm^3)	3.5–3.6
Diagn. signs	Dark green to black, radial crystals
Associate minerals	Pyrrhotite, chalcopyrite, marmatite (ferrous type of sphalerite), calcite, epidote (skarns)
Genesis	Ferruginous skarns
Application	

Fig. 109. Radial-radiant crystals of hedenbergite (Iron Cap Mine, Landsman Camp, Aravaipa, Aravaipa Mining District, Graham County, Arizona, USA)

INOSILIKATES
(Pyroxene Supergroup)

Mineral name	**Aegirine**
Chemical composition	**$NaFe[Si_2O_6]$**
Syngony	Monoclinic
Crystal Form	Columnar, needle-like
Aggregate morphology	Radial-radiant, star-shaped aggregates
Color	Greenish black, dark green
Streak	Light green
Luster	Vitreous
Cleavage	Good on {110}
Hardness	5.5–6.0
Specific gravity (g/cm^3)	3.4–3.6
Diagn. signs	light green line, characteristic paragenesis
Associate minerals	Nepheline, tithanite, albite, K-feldspar, apatite, arfvedsonite, sodalite, cancrinite
Genesis	alkaline intrusive rocks
Application	

Fig. 110. Form of aegirine crystals
(Mount Malosa, Zomba, Southern Region, Malawi)

INOSILIKATES
(Pyroxene Supergroup)

Mineral name	**Spodumene**
Chemical composition	**$LiAl[Si_2O_6]$**
Variety	*Kunzite* – pink transparent variety
Syngony	Monoclinic
Crystal Form	Boardwalk, flattened, prismatic
Aggregate morphology	Lamellar-columnar
Color	Ash gray, pinkish white
Streak	White
Luster	Vitreous
Cleavage	Good on {110}
Hardness	6.5–7.0
Specific gravity (g/cm^3)	3.1–3.2
Diagn. signs	Characteristic paragenesis, flattened crystal shape
Associate minerals	Lepidolite, clevelandite (lamellar albite), polychrome tourmaline, K-feldspar, quartz
Genesis	Rare metal and granite pegmatites of lithium specialization
Application	A source for obtaining lithium preparations used in pyrotechnics, medicine, photography, radiography, etc., transparent varieties in jewelry

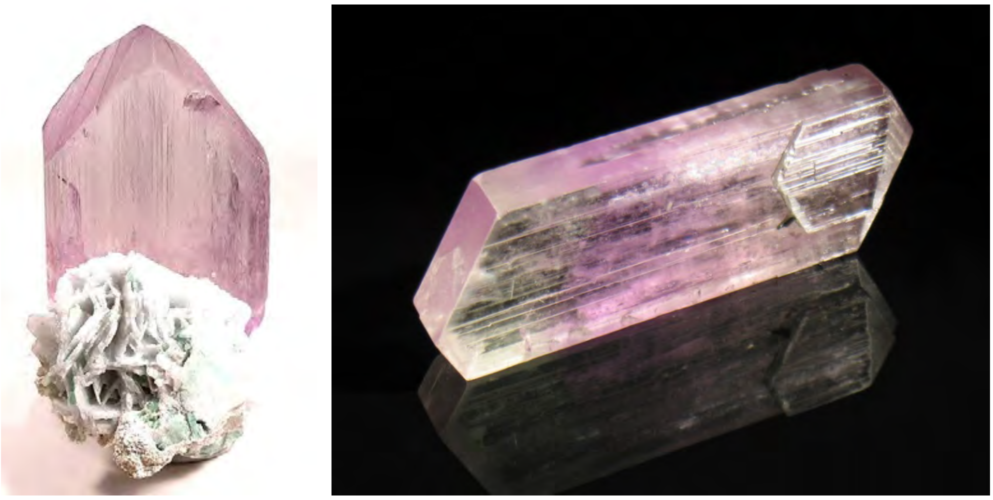


Fig. 111. Flattened spodumene crystals with longitudinal shading along elongation; kunzite (pink variety of spodumene)

INOSILIKATES
(Amphibole Supergroup)

Mineral name	**Tremolite**
Chemical composition	$\mathbf{Ca_2Mg_5[Si_4O_{11}]_2(OH)_2}$
Varieties	*White nephrite* – fibrous aggregate
Syngony	Monoclinic
Crystal Form	Long prismatic, needle
Aggregate morphology	Elongated, stout prismatic, bladed, fibrous, granular, finely fibrous, fibrous, columnar crystals
Color	Light-colored, white with a grayish tinge
Streak	White
Luster	Vitreous, Silky
Cleavage	Perfect on {110}
Hardness	5.5–6.0, fragile, splintered fracture
Specific gravity (g/cm^3)	2.9–3.0
Diagn. signs	Light color, needle-shaped crystals
Associate minerals	Diopside, talc
Genesis	Epimagmatic mineral of igneous rocks, formed after calcium-magnesian pyroxenes, metamorphic
Application	As heat-and sound-insulating materials

Fig. 112. Fibrous crystals of tremolite
(Prince's Soapstone Quarry, Lafayette, Philadelphia Co., Pennsylvania, USA)

INOSILIKATES
(Amphibole Supergroup)

Mineral name	**Actinolite**
Chemical composition	$\mathbf{Ca_2(Mg,Fe)_5[Si_4O_{11}]_2(OH)_2}$
Varieties	*Green nephrite – fibrous aggregate*
Syngony	Monoclinic
Crystal Form	Long prismatic, needle
Aggregate morphology	Elongated, stout prismatic, bladed, fibrous, Finely fibrous, fibrous, felt-like, columnar, radiant
Color	Bottle green, dirty green in various shades
Streak	White
Luster	Vitreous, on cleavage planes with a silky sheen
Cleavage	Perfect on {110}
Hardness	5.5–6.0, fragile, splintered fracture
Specific gravity (g/cm^3)	3.1–3.3
Diagn. signs	Dirty green color, needle-shaped crystals
Associate minerals	Diopside, talc, calcite, epidote
Genesis	Epimagmatic mineral of igneous rocks, formed after calcium-magnesian pyroxenes, metamorphic (crystalline schists)
Application	As heat-and sound-insulating materials, ornamental material

Fig. 113. Fibrous (Otjiwarongo, Otjozondjupa Region, Namibia) and elongated crystals of actinolite (Otjiwarongo, Otjozondjupa Region, Namibia)

INOSILIKATES
(Amphibole Supergroup)

Mineral name	**Hornblende**
Chemical composition (impurities are indicated in brackets)	**$Ca_2Na(Mg,Fe)_4(Al,Fe^{3+})[(AlSi)_4O_{11}]_2(OH)_2$**
Syngony	Monoclinic
Crystal Form	Long prismatic, columnar
Aggregate morphology	Crystal phenocrysts, granular masses, twins
Color	Dark green to black
Streak	Light green
Luster	Vitreous, Silky
Cleavage	Perfect on {110}
Hardness	5.5–6.0, fragile, splintered fracture
Specific gravity (g/cm^3)	3.1–3.3
Diagn. signs	Dirty green color, needle-shaped crystals
Associate minerals	Varied, replaced by chlorite, epidote, calcite
Genesis	Mineral of igneous intrusive basic rocks, metamorphic

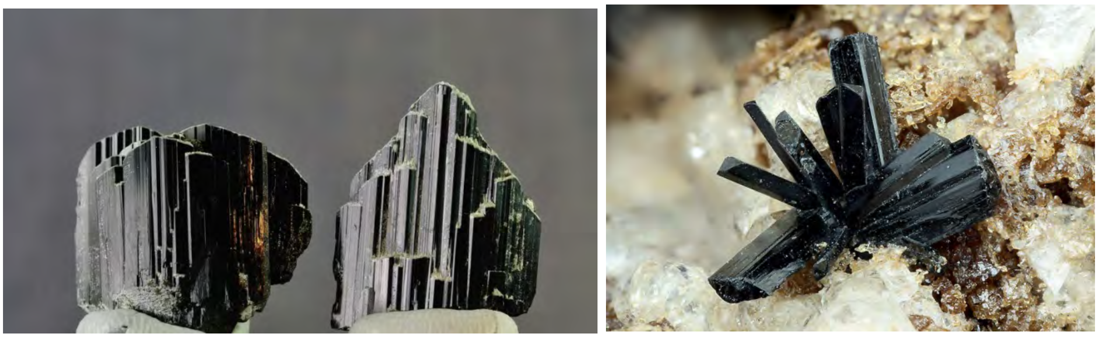


Fig. 114. Magnesio-hornblende (two individual dark-green crystals) (Traversella Mine, Traversella, Metropolitan City of Turin, Piedmont, Italy), and ferro-hornblende (dark-colored prismatic crystals) (Monte Somma, Somma-Vesuvius Complex, Naples, Campania, Italy)

INOSILIKATES
(Amphibole Supergroup)

Mineral name	**Arfvedsonite**
Chemical composition	**$Na_3 (Fe,Mg)_4(Fe,Al)[Si_4O_{11}]_2(OH,F)_2$**
Syngony	Monoclinic
Crystal Form	Long prismatic, columnar
Aggregate morphology	Solid, granular, radiant masses
Color	Bluish-black to black
Streak	Deep bluish gray, gray-green
Luster	Vitreous, Silky
Cleavage	Perfect on {110}
Hardness	5.5–6.0, splintered fracture
Specific gravity (g/cm^3)	3.44–3.46
Diagn. signs	Needle-shaped crystals, deep bluish-gray, gray-green streak
Associate minerals	Sodalite, nepheline, aegirine, sphene, apatite
Genesis	Mineral of alkaline igneous intrusive rocks, nepheline pegmatites

Fig. 115. Crystals of arfvedsonite in paragenesis with nepheline (Mount Malosa, Zomba, Southern Region, Malawi) and aggregates of arfvedsonite long prismatic crystal habit of crystals with silky luster (Poudrette quarry, Mont Saint-Hilaire, La Vallée-du-Richelieu RCM, Montérégie, Québec, Canada)

INOSILIKATES
(Amphibole Supergroup)

Mineral name	**Glaucophane**
Chemical composition	**$Na_2(Fe,Mg)_3Al_2[Si_4O_{11}]_2(OH,F)_2$**
Syngony	Monoclinic
Crystal Form	Long prismatic, columnar, elongated
Aggregate morphology	Solid, radiant, fibrous aggregates
Color	Blue, bluish-gray, bright blue
Streak	Bluish-gray, blue
Luster	Vitreous
Cleavage	Perfect on {110}
Hardness	6.0–6.5, splintered fracture
Specific gravity (g/cm^3)	3.1–3.2
Diagn. signs	Blue, bluish gray, needle-shaped crystals
Associate minerals	Monomineraline, albite, chlorite, epidote, quartz
Genesis	Crystalline schists (metamorphic)

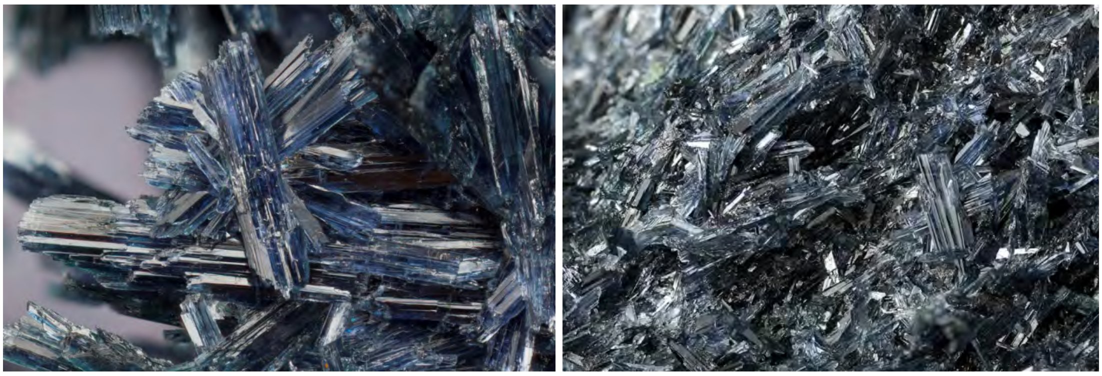


Fig. 116. Intergrowth of glaucophane crystals
(Rio Oremo, Chiavolino, Pollone, Biella Province, Piedmont, Italy)

PHYLLOSILICATES
(Mica Group)

Mineral name	**Muscovite**
Chemical composition	**$KAl_2[AlSi_3O_{10}](OH,F)_2$**
Syngony	Monoclinic
Crystal Form	Tabular, lamellar, pseudohexagonal
Aggregate morphology	Solid, scaly, leafy-granular masses
Color	Colorless in thin leaves, often with a yellowish-gray, greenish and reddish tint
Streak	White
Luster	Vitreous, silky, pearly
Cleavage	Perfect on {001}
Hardness	2.0–3.0, the plates are elastic
Specific gravity (g/cm^3)	2.7–3.1
Diagn. signs	Light color, pearlescent luster on cleavage planes, easy splitting into separate leaves, differs from phlogopite in paragenesis, from other micas in color
Associate minerals	Quartz, K-feldspar, albite, beryl (pegmatites), hornblende, disthene (regionally metamorphic)
Genesis	Magmatic, pegmatite, hydrothermal, regional metamorphic
Application	Ceramic, electrical, rubber industry

Fig. 117. Intergrowth of lamellar muscovite crystals from Linópolis, Divino das Laranjeiras, Minas Gerais, Brazil, and twince of pseudohexagonal muscovite crystals from Zé Pinto prospect, Aldeia, Conselheiro Pena, Minas Gerais, Brazil

PHYLLOSILICATES
(Mica Group)

Mineral name	**Biotite**
Chemical composition	**$K(Mg,Fe)_3[AlSi_3O_{10}](OH,F)_2$**
Syngony	Monoclinic
Crystal Form	Tabular, lamellar, pseudohexagonal
Aggregate morphology	Solid, scaly, leafy-granular masses
Color	Black, brown
Streak	White
Luster	Vitreous, silky, pearly
Cleavage	Perfect on {001}
Hardness	2.0–3.0, the plates are elastic
Specific gravity (g/cm^3)	3.0–3.1
Diagn. signs	Dark color, pearlescent luster on cleavage planes differs from phlogopite in paragenesis, from other micas in dark color
Associate minerals	Quartz, K-feldspar (pegmatites), hornblende, almandine (regional-metamorphic)
Genesis	Magmatic, pegmatite, regional-metamorphic
Application	Ceramic, electrical, rubber industry

Fig. 118. Pseudohexagonal crystals of biotite (Wannenköpfe Quarry, Ochtendung, Maifeld, Mayen-Koblenz District, Rhineland-Palatinate, Germany)

PHYLLOSILICATES
(Mica Group)

Mineral name	**Phlogopite**
Chemical composition	**$KMg_3[AlSi_3O_{10}](OH,F)_2$**
Syngony	Monoclinic
Crystal Form	Tabular, lamellar, pseudohexagonal
Aggregate morphology	Solid, scaly, leafy-granular masses
Color	Brown sometimes with an orange, golden tint
Streak	White
Luster	Vitreous, silky, pearly
Cleavage	Perfect on {001}
Hardness	2.0–3.0, the plates are elastic
Specific gravity (g/cm^3)	3.0–3.1
Diagn. signs	Brown color, pearlescent luster on cleavage planes differs from biotite in paragenesis, from other micas in golden hue
Associate minerals	Diopside, calcite (contact-metasomatic)
Genesis	Magmatic, contact-metasomatic
Application	Ceramic, electrical, rubber industry

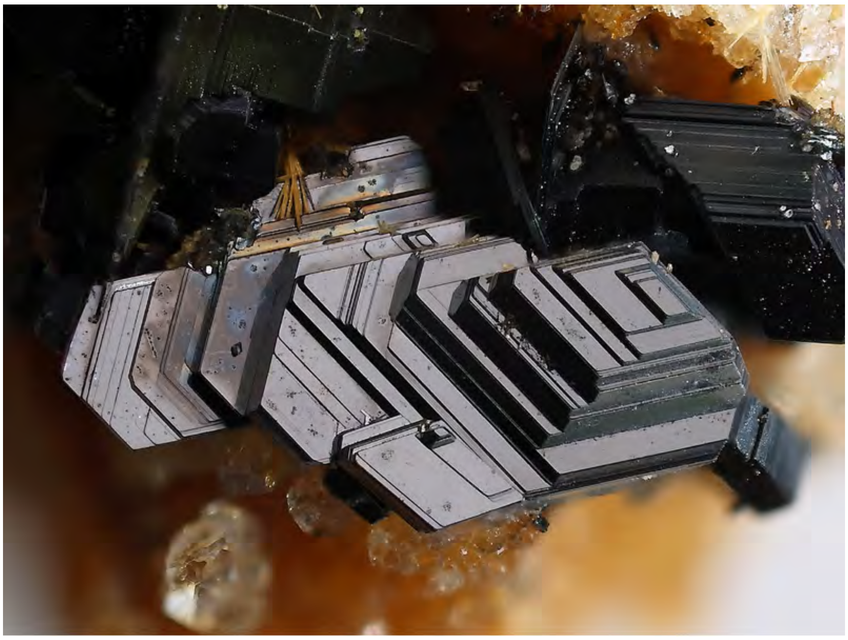


Fig. 119. Tabular crystal of phlogopite (In den Dellen quarries, Mendig, Mendig, Mayen-Koblenz District, Rhineland-Palatinate, Germany)

PHYLLOSILICATES
(Mica Group)

Mineral name	**Lepidolite**
Chemical composition	$\mathbf{KLi_{1,5}Al_{1,5}[AlSi_3O_{10}](OH,F)_2}$
Syngony	Monoclinic
Crystal Form	Tabular, lamellar, pseudohexagonal
Aggregate morphology	Solid, scaly, occasionally druses
Color	Lilac, urple
Streak	White
Luster	Vitreous, silky, pearly
Cleavage	Perfect on {001}
Hardness	2.0–3.0, the plates are elastic
Specific gravity (g/cm^3)	2.8–2.9
Diagn. signs	Purple color
Associate minerals	Clevelandite, quartz, spodumene, rubellite, fluorite
Genesis	Li-specialization pegmatites, greisens
Application	Lithium ore

Fig. 120. Lamellar and shelllike crystals of lepidolite

PHYLLOSILICATES

Mineral name	**Talc** (soap stone; steatite)
Chemical composition	**$Mg_3[Si_4O_{10}](OH)_2$**
Syngony	Monoclinic/Triclinic
Crystal Form	Crystals are rare
Aggregate morphology	Tabular, lamellar
Color	White with a yellowish, brownish, pale green tint
Streak	White
Luster	Sub-Vitreous, Resinous, Waxy, Greasy, Pearly
Cleavage	Perfect on {001}
Hardness	1.0
Specific gravity (g/cm^3)	2.7–2.8
Diagn. signs	Low hardness, greasy to the touch
Associate minerals	Tremolite, chlorite, magnetite, serpentine
Genesis	Hydrothermally altered magnesian rocks
Application	Paper, rubber, cosmetic, textile, electrical industry

Fig. 121. Transparent lamellar talc crystals from Trimouns Talc Mine, Luzenac, Foix, Ariège, Occitanie, France, and green talc continius masses from Green Mountain Mine, Day Book, Yancey Co., North Carolina, USA

PHYLLOSILICATES
(Serpentine Subgroup)

Mineral name	**Serpentine**
Chemical composition	**$Mg_6[Si_4O_{10}](OH)_8$**
Syngony	Monoclinic
Crystal Form	Crystals are rare
Aggregate morphology	Solid, dense, cryptocrystalline masses with sliding mirrors
Color	Dark green, bottle green, yellow green
Streak	White
Luster	Vitreous, greasy, wax
Cleavage	Perfect on {001}, macroscopically poorly manifested
Hardness	2.0–3.5
Specific gravity (g/cm^3)	2.5–2.7
Diagn. signs	Low hardness, green color, denser than chlorite
Associate minerals	Enstatite, magnetite, chrysotile asbestos, chrome spinel
Genesis	Hydrothermal alteration of ultramafic rocks
Application	Facing and heat-insulating material, ornamental stone

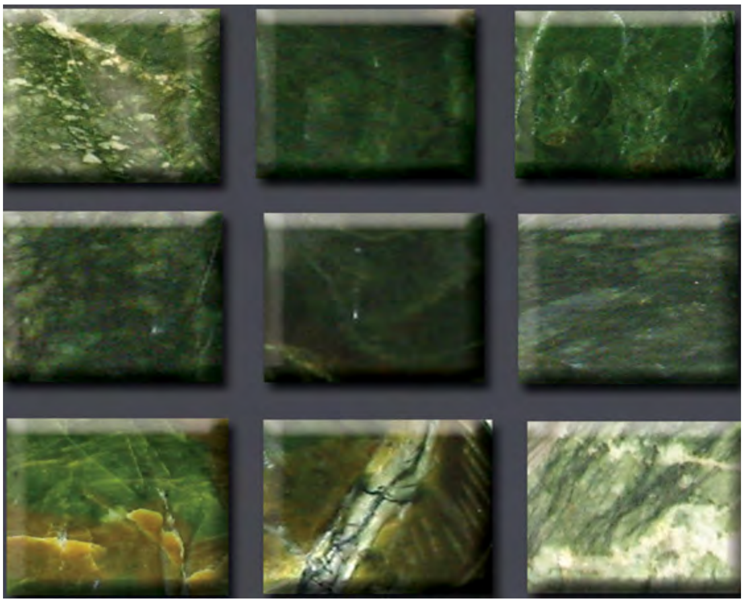


Fig. 122. Various polished cuts of serpentine

Mineral name	**Pennine**
Chemical composition	**$Mg_5Al[AlSi_3O_{10}](OH)_8$**
Syngony	Monoclinic
Crystal Form	Lamellar, scaly, pseudohexagonal, sometimes barrel-shaped
Aggregate morphology	Cryptocrystalline, scaly masses
Color	Green, yellowish green, olive green, blackish green, bluish green, white,
Streak	White, light green
Luster	Vitreous, dull
Cleavage	Perfect on {001}
Hardness	2.0–2.5
Specific gravity (g/cm^3)	2.5–2.7
Diagn. signs	Low hardness, flakes are not elastic, dirty green color
Associate minerals	Tremolite, magnetite, serpentine
Genesis	Metamorphic
Application	Papermaking (to make the paper shine)

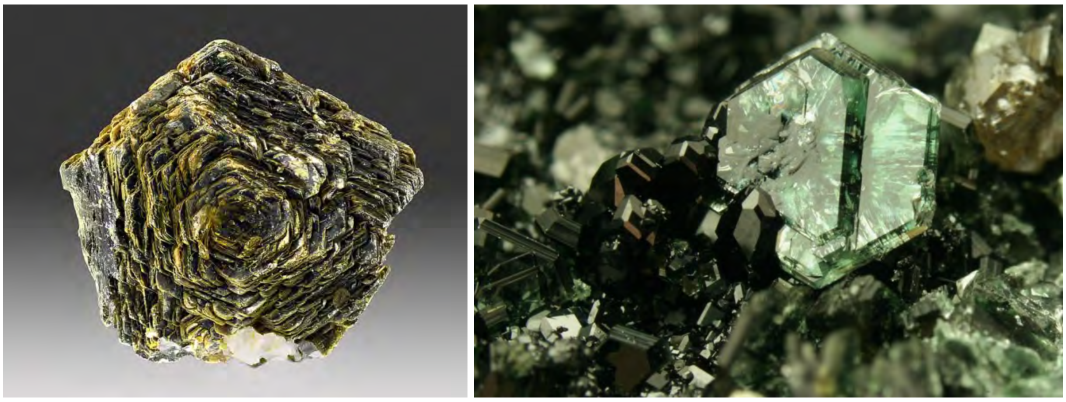


Fig. 123. Platy crystals of chlorite with yellowish green (Gneiss quarry, Ebersdorf, Klein-Pöchlarn, Melk District, Lower Austria, Austria) and green color (Zermatt – Saas Fee area, Valais, Switzerland)

PHYLLOSILICATES

Mineral name	**Kaolinite (clay mineral)**
Chemical composition	**$Al_4[Si_4O_{10}](OH)_8$**
Syngony	Triclinic
Crystal Form	Well-formed lamellar crystals are rare
Aggregate morphology	Loose, scaly, dense, fine-grained, sometimes in the form of drip forms
Color	White with a yellowish, grayish, greenish tint due to impurities
Streak	White
Luster	Dull
Cleavage	Perfect on {001}
Hardness	1.0, dry to touch
Specific gravity (g/cm^3)	2.5–2.6
Diagn. signs	Low hardness, dry to the touch, hygroscopic
Associate minerals	White mica, feldspars, topaz
Genesis	Weathering of aluminosilicate rocks, low-temperature hydrothermal processes
Application	Ceramic, porcelain, cosmetic, construction industry

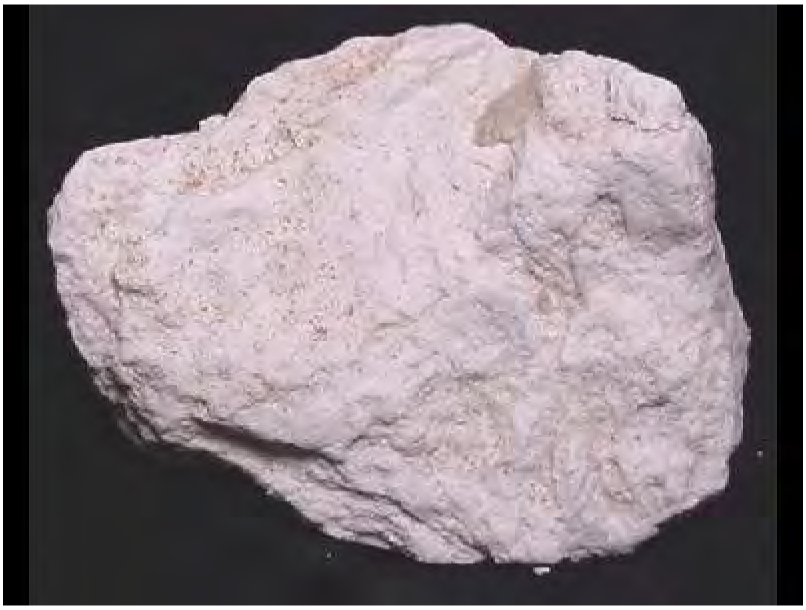


Fig. 124. Loose solid masses of kaolinite
(McMichael Mine, Andersonville, Macon Co., Georgia, USA)

6. *Silicates with three-dimensional frameworks of tetrahedra (testosilicates)* in the course of our program are represented by *feldspars.*

It is known that in aluminosilicates silicon can be replaced by aluminum by no more than 50 %. Al can act as a cation (*microcline*) and be a member of the anionic group.

Feldspars are the most common silicates in the Earth's crust. *Feldspars* form isomorphic mixtures (Fig. 125) and are divided into two groups: *plagioclases* and *potassium feldspars* (K-feldspars).

Major radical groups $[AlSi_3O_8]^-$ and $[Al_2Si_2O_8]^{2-}$. The main cations occupying vacancy in the frameworks: Na^+, Ca^{2+}, K^+ и Ba^{2+}. This subclass is characterized by the absence of chromophore ions: Fe, Mn. Specificity of physical properties: light color, low specific gravity (2.6–2.7), average hardness 5–6, average or perfect cleavage in several directions.

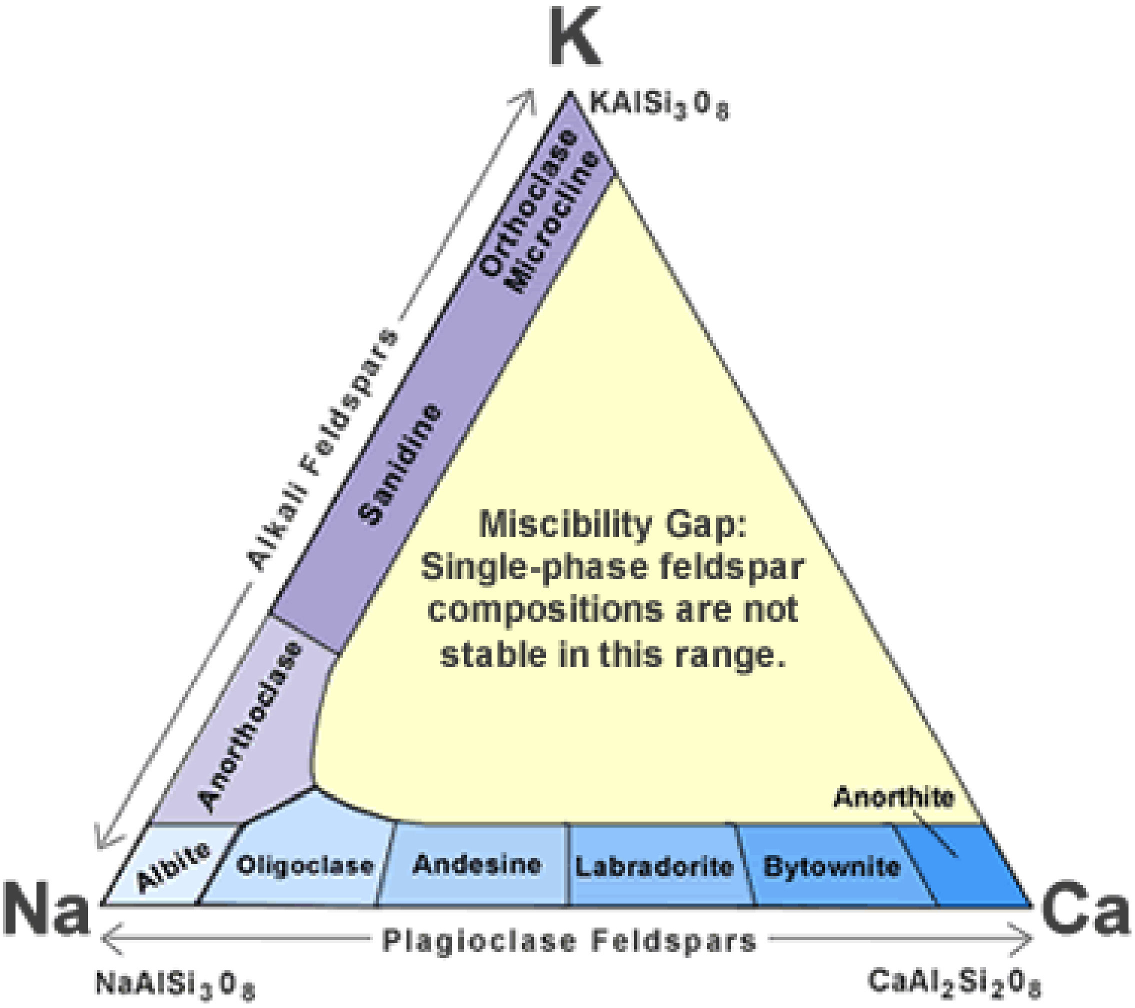


Fig. 125. Triangular diagram of the fields of compositions of feldspars

In Fig. 125, *plagioclases* form a continuous ismorphic series from *albite* to *anorthite* and, depending on the conditions and chemistry of the environment of formation, one or another plagioclase is stable. *Plagioclases* are a prime example of heterovalent isomorphism. The composition of plagioclase depends on the percentage of the anorthite molecule $Ca[Al_2Si_2O_8]$. Acid plagioclases include (*albite, oligoclase*), medium (*andesine*), basic (*labradorite, bitownite, anorthite*). This classification also determines the composition of which igneous rocks, the named plagioclases will be preferable. In the earliest basic igneous rocks, basic plagioclases predominate, in the middle ones, intermediate plagioclases, and in acidic ones, acidic plagioclases. Note that there is no common compositional field between anorthite and K-feldspar, which means that the conditions for the formation of K-feldspar and basic plagioclases are different. K-feldspar is more preferable to associate and form solid solutions of decomposition with *acidic plagioclases* (*albite-oligoclase*). Plagioclases crystallize in the triclinic system and have several cleavage directions. They are characterized by complex ones – polysynthetic twins, glass luster, due to cleavage and polysynthetic twinning, the luster is very bright. The exact composition of plagioclase is determined by studying their optical properties, or additional studies. The objectives of this course include the determination and diagnosis of minerals using available macroscopic studies, so the student will need to determine *albite* and *labradorite* from plagioclases.

Albite can have several morphological varieties: *clevelandite* (lamellar variety), sugar albite (fine-grained variety). The albite color is white; optical effects are often manifested in the form of overflows in bluish-gray tones (the effect of internal luminescence), which is associated with the crystalline structure and polysynthetic twinning of plagioclases. *Albite* with a bright optical effect of iridescence in blue colors is called *moonstone*. A similar phenomenon is observed in the Labrador, however, being a darker colored mineral, the labrador exhibits its glow in the form of rich blue bright overflows. This optical effect has its own name – *iridescence*. Rocks compose entirely by labradorite are called *labradorites*, they are an excellent facing material.

Potassium feldspars are represented by *sanidine*, *orthoclase*, *microcline*. Unlike plagioclases, they are most characterized by simple twins, cleavage also manifests itself in several directions and the angle between the cleavage planes is close to 90°. *Sanidine* is the highest-temperature K-feldspar feldspar; it often forms phenocrysts in effusive rocks. *Orthoclase* and *microcline* are represented on a larger scale in the samples of the department's collection. *Orthoclase*, as a rule, is light-colored, gray, and ashy, crystallizes in a monoclinic system, is earlier and higher-temperature than microcline. The *microcline* crystallizes in the triclinic system, is characterized by a meat-red color and corresponds to a hardness of 6 in the Mohs distribution scale. A rare variety of aqua-colored microcline is called *amazonite*.

Microcline forms decay perthites joint with albite. At high temperatures, mixed homogeneous feldspars can include K and Na in any ratio and their distribution in structural channels is unsystematic. At low temperatures, the difference in the sizes of these ions creates a large tension in the lattice and the crystals cease to be homogeneous, the process of decomposition of the «solid solution» occurs with the release of two phases enriched in either K or Na. As a result, intergrowth of these minerals is formed in the form of parallel plates, which are called perthites. Thus, regular ingrowths of albite in K-feldspar are called decay perthites, while the opposite picture (K-feldspar ingrowths in albite) are called antiperthites. The scales of their manifestation are very different: from visible plates to very thin lamellae.

Various minerals, the most common of which is nepheline, represent Feldspars. It is a mineral indicator of an alkaline process. The main rock-forming mineral of alkaline rocks. *Nepheline* has a hardness similar to feldspars (6), however, unlike them, it has no cleavage. The color palette of nepheline is varied from light gray, white, pink to green, however, one way or another, it belongs to salic (light-colored minerals). Nepheline tends to form regular hexagonal, square, rectangular phenocrysts, solid masses, rarely well-formed crystals. Its surface is often weathered, matte, and a greasy luster is observed in the fracture. The mineral does not occur with quartz, from which it differs in less hardness and paragenesis. *Aegirine, sphene, apatite, arfvedsonite, K-feldspar, albite* can be found in association with nepheline.

TESTOSILICATES
(Feldspars)

Mineral name	**Plagioclase**
Chemical composition	Albite ($Na[AlSi_3O_8]$ (Ab) – Anortite($Ca[Al_2Si_2O_8]$)(An) Oligiclase (10…30 % An), Andesine (30…50 % An), Labradorite (50…70 %An), Bitownite (70…90 %An)
Varieties	*Clevelandite* – bladed albite, *moonstone* – albite with an optical overflow effect in blue tones*; sugar albite* – fine-grained albite aggregate
Syngony	Triclinic
Crystal Form	well-formed crystals are found, their appearance is tabular and tabular-prismatic, polysynthetic twins are characteristic
Aggregate morphology	granular crystalline aggregates, drusen (clevelandite), sugar-like varieties
Color	white, grayish-white, sometimes with a greenish, bluish tint, labrador – dark gray with iridescent effect
Streak	White
Luster	Vitreous
Cleavage	Perfect on [001], good on [010], imperfect on {110}
Hardness	6.0
Specific gravity (g/cm^3)	2.6–2.7
Diagn. signs	Polysynthetic twins, oblique cleavage angle
Associate minerals	Various
Genesis	Magmatic, regional-metamorphic, pegmatite, etc.
Application	Orament material, glass production

Fig. 126. Varieties of plagioclases:
albite (Lohning quarry, Rauris, Zell am See District, Salzburg, Austria);
labradorite (Ampanihy, Atsimo-Andrefana, Madagascar)

TESTOSILICATES
(Feldspars)

Mineral name	**Potassic Feldspar**
Chemical composition	**($K[AlSi_3O_8]$) sanidine; orthoclase; microcline**
Varieties	*Amazonite* – a blue-green variety of microcline
Syngony	Monoclinic (sanidine, orthoclase), triclinic (microcline)
Crystal Form	Tabular or prismatic crystals, often twins
Aggregate morphology	Phenocrysts (sanidine), granular, dense masses (orthoclase, microcline)
Color	Light colored (sanidin) with cream, flesh (orthoclase), meat-red tint (microcline)
Streak	White
Luster	Vitreous
Cleavage	Perfect
Hardness	6.0
Specific gravity (g/cm^3)	2.6
Diagn. signs	The angle between the cleavage planes is close to right
Associate minerals	Various
Genesis	Pegmatite, felsic igneous rocks
Application	Ceramic industry, orament material

Fig. 127. Prismatic crystals of feldspar
(Konso, Southern Nations Nationalities and Peoples' Region, Ethiopia)

TESTOSILICATES

Mineral name	**Nepheline**
Chemical composition	**$Na[AlSiO_4]$**
Syngony	Hexagonal
Crystal Form	Prismatic, short-columnar, thick-tabular
Aggregate morphology	Crystalline phenocrysts of regular shape, solid, granular masses
Color	Varied from grayish white, brownish red to light green
Streak	White
Luster	Vitreous
Cleavage	–
Hardness	5.0–6.0
Specific gravity (g/cm^3)	2.6
Diagn. signs	Oily sheen, replaced by secondary decomposition products
Associate minerals	Aegirine, titanite, apatite, albite, K-feldspar
Genesis	Alkaline igneous rocks and their pegmatites
Application	Ceramics and glass industry, source of aluminum

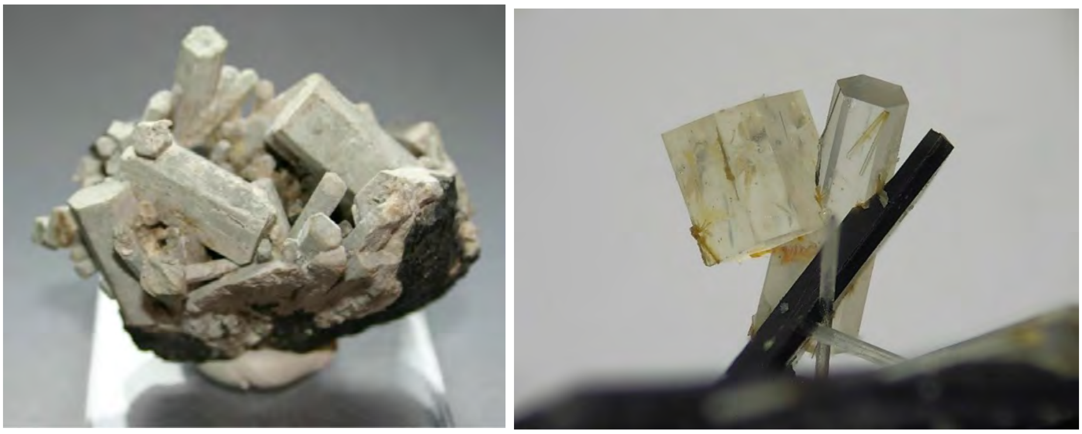


Fig. 128. Hexagonal-shaped crystalls of nepheline
(Jebel Bou-Agrao, Amersid, Aït Rhineland-Palatinate, Germany)

CONCLUSION

Acquaintance with the information contained in the textbook helps the student to form general ideas and concepts in the discipline "Fundamentals of crystallography and mineralogy" and assimilate the main issues raised within the course. Knowledge and understanding of the terms and concepts presented in this manual is sufficient to pass successfully the exam or credit in the subject. Diagnostic tables act as an auxiliary basic material that allows you to navigate quickly in the diagnosis of minerals. Systematic and gradual memorization and delivery of tabular data forms the accumulation of knowledge about minerals necessary for intuitive identification of samples. Constant work with the educational collection using the methodological manual contributes to the successful passing of the final test, or the exam on time, facilitating the student's independent work in acquiring the skills of visual diagnostics of minerals.

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Annex

Final Discipline Questions
"Fundamentals of crystallography and mineralogy"

1. Determination of the crystal. What is meant by symmetry, elements of crystal symmetry?
2. State of aggregation of minerals, what substances are called crystalline and amorphous?
3. Classification of crystals. List the syngony. Describe them.
4. What is called a simple form and a combination of simple forms.
5. Forms of real crystals. What are the deviations of the shapes of real crystals from ideal ones?
6. Describe the chemical composition of the minerals. Isomorphism
7. What types of water are possible in minerals?
8. Describe the optical properties of minerals.
9. What is called the hardness of a mineral. Name the Mohs scale
10. What mechanical properties of minerals do you know?
11. Name the aggregates of minerals.
12. Describe the endogenous processes of mineral formation.
13. Describe the exogenous processes of mineral formation.
14. Magmatic process and its mineral associations.
15. Pegmatite process and its mineral associations.
16. Metamorphic process and its mineral associations.
17. General characteristics of native elements.
18. General characteristics of sulfides and their analogs.
19. Name the minerals of the gloss group and their properties.
20. Name the yellow pyrites and their properties.
21. General characteristics of tungstates, sulfates, phosphates.
22. General characteristics of carbonates.
23. General characteristics and physical properties of halogens.
24. General characteristics and physical properties of oxides and hydroxides.
25. Features of chemistry and classification of silicates.
26. General characteristics of nesosilicates.
27. Name the minerals of the garnet group. How do they differ from each other?
28. Chemical composition and physical properties of pyroxenes.
29. Chemical composition and physical properties of amphiboles.
30. What are the distinctive features of pyroxenes and amphiboles?
31. General characteristics of inosilicates.
32. Chemical composition and physical properties of the phyllosilicates.
33. General characteristics of testosilicates.
34. Chemical composition and physical properties of the group of feldspars.
35. What is the classification of feldspars?

Educational Edition

Национальный исследовательский
Томский политехнический университет

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ОСНОВЫ
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