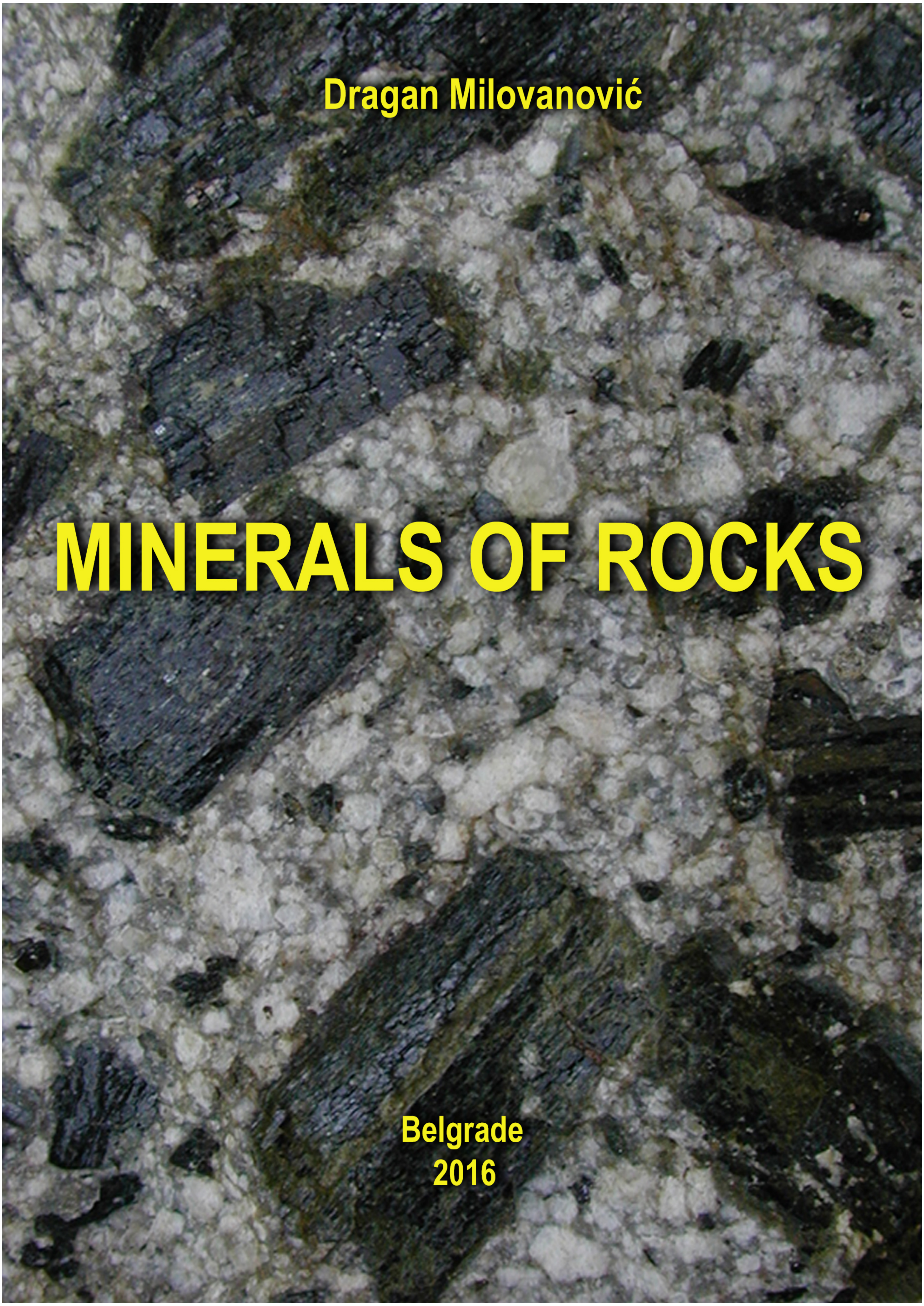

Dragan Milovanović

MINERALS OF ROCKS

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CONTENTS

Introduction

We live in technically oriented time with computers, internet and mobile phones all around us which leads to the fact that we have less and less time. Any information whether from science, technology, medicine, sport, politics, life etc. could be easily assessed at any time and at any place on the planet Earth. The same is with geology: volcanic eruptions, new minerals, ore exploitation, stock prices, etc. In spite of a numerous data concerning minerals, petrology, and geology is "disseminated" all over internet, the written word still have the key role in the education of youth. This was the reason for writing this publication, **Minerals of rocks**. It briefly presents and describes minerals, which take part in rock-forming processes, along with their physical and chemical properties, genesis and the most common associations.

Photos included, are made by authors themselves or were "borrowed" from available websites. All of it was modified using graphic software and adjusted to the text to illustrate things better.

Publication is meant for students of geology and mining, students of archeology, biology, geography, civil-engineering, architecture, ecology, etc. It will be of great value for studying minerals and rocks either when they take part in different geological, physico-chemical, biological and ecological processes, or when they are used for building, producing, living, for shelter and protection of mankind`s diverse items since the very first days of their existence.

Publication requires at least a basic knowledge of mineralogy, as a number of data, such as symmetry of crystals, structural and optical properties and systematic of minerals, are shortly-given. Otherwise, this publication would be incomprehensible.

A significant positive impact on the content, volume and a way of presentation had the questions and discussions of students during lectures and exercises from mineralogical, petrological and geological subjects along with directions that arose either during student`s seminar, final, and diploma works or master and doctor thesis. Neither less important were official and unendorsed discussions with our colleagues and scientists of other branches.

No similar publication appeared or has been published prior to this. The author hope that it will be helpful for students, explorers, for adornments of minerals, rocks, geology and other earth sciences, i.e. for all whose study, exploration, job, and inspiration encompasses even a bit of rock-forming minerals.

My deepest appreciation and thanks to Vidojko Jović, Ljiljana Karanović, Nebojša Vasić, Rade Jelenković and Nataša Gerzina whose valuable advice and help contributed to the quality and accuracy of this publication.

Author

1. MINERALS

There are more than 4000 different naturally occurring minerals, and new ones are constantly being discovered. Minerals may be elemental: native gold, sulphur, native copper, diamond, graphite, etc. More common are compounds of two or more elements: quartz is silica-dioxide, SiO_2 (fig. 1), orthoclase is potassium aluminosilicate, $KAlSi_3O_8$, and calcite is calcium-carbonate, $CaCO_3$. Water and oil are not minerals, but the ice is.

Minerals are natural substances of distinct chemical composition, structure and physical properties and were formed throughout geological processes within the crust and upper mantle of the Earth.

Minerals, which are formed out of our planet, i.e. in meteorites (fig. 1), are also classified as the "minerals of the Earth".

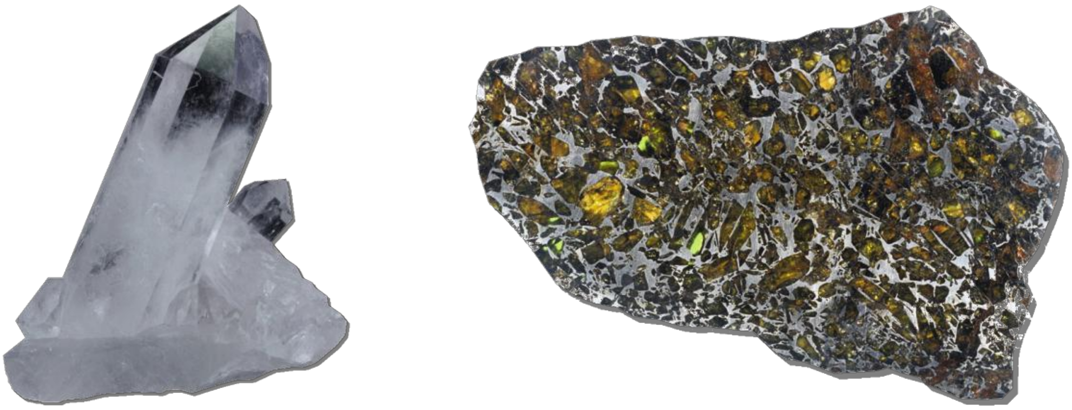

Fig. 1. Quartz is the one of the most frequent mineral in rocks (left). Although a yellow olivine, in meteorite (right), „arrived" from asteroid belt, it belongs to"Earth`s" minerals.

Man-made minerals of similar or quite identical properties with natural ones are synthetic or artificial minerals (fig. 2).

Fig. 2. Ruby, seen here is made by men and is synthetic mineral.

In spite of minerals in **ore deposits**, both metallic (galena and zinc, copper, gold) and non-metallic (magnesite, talc, asbestos and barite), which are not rock-forming minerals, some of them will be described in the following pages in order to explain their origin and their relationships with minerals that take part in rock forming processes.

Minerals were named after their composition, distinctive properties, or in the honor of scientist who discovered them, as well as to assign the localities of their notable occurrences.

Minerals that build rocks are petrogenic or rock forming minerals

According to the importance and role in rock formation, minerals are separated on:

- **Main** or **chief minerals**, which determine the rock type. For example, alkali feldspar and quartz in granite; basic plagioclase in gabbro; calcite in limestone and hornblende in amphibolite. Main minerals are commonly the most abundant minerals in rocks, too (fig. 3);
- **Accessory minerals,** such as magnetite, zircon, sphene, apatite, chromite, do not have the influence on rock determination. They occur in tiny grains up to few millimeters in size and in 1 to 5 % vol. abundances.

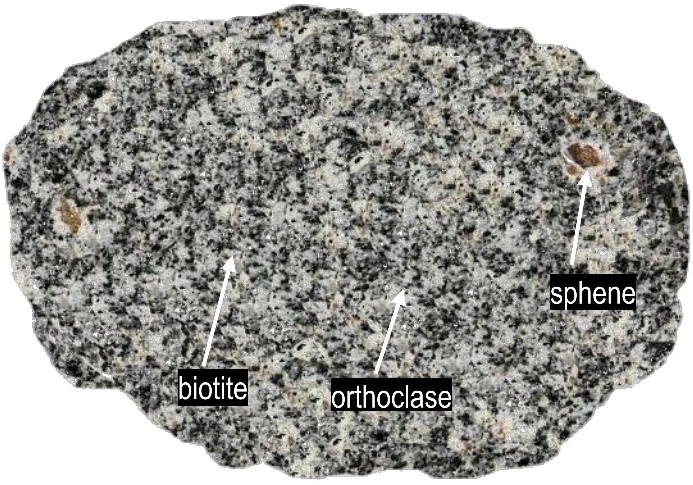

Fig. 3. Biotite (black) and orthoclase (white) are the main minerals in granite, whereas the sphene (yellow) is the accessory one.

According to their origin a rock-making minerals may be **primary and secondary**.

- **Primary minerals** are formed during the formation of the rock itself: crystallization of magma led to development of igneous minerals (fig. 4); deposition produces sedimentary minerals and metamorphic processes create metamorphic minerals.

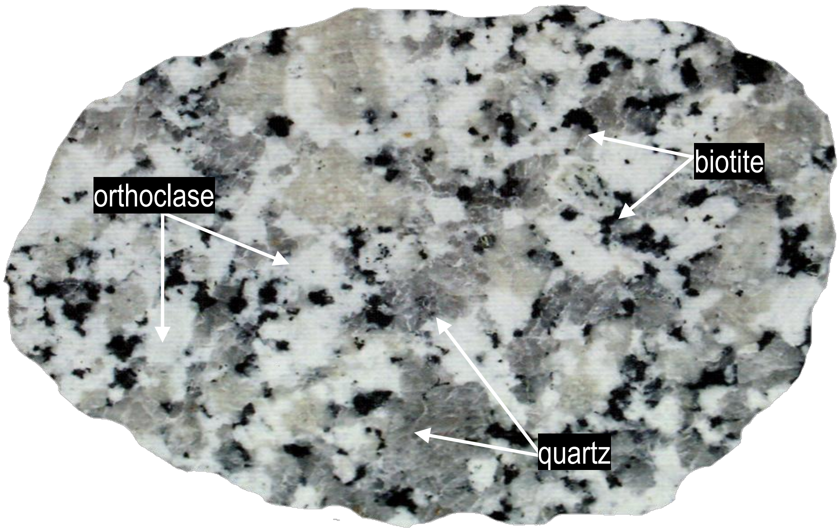

Fig. 4. Orthoclase (white), biotite (black) and quartz (grey) are the primary igneous minerals in granite.

- **Secondary minerals are** formed by weathering of already existing primary minerals under the influence of atmospheric agents, hydrothermal solutions, oxidation and reduction processes. The type and character of such processes are determined by the type of new-formed secondary minerals governed by physical-chemical properties of weathering agents, particularly of water, oxygen, temperature and pressure.

Majority of igneous minerals, which crystallized on high temperatures, are less resistant and easily transform into secondary minerals in respect to last crystallized. Alteration product of olivine as a result of water addition is serpentine; pyroxene (aluminum lacking) inverts into amphibole (actinolite, tremolite), while hornblende turns into epidote and chlorite. Biotite is commonly replaced with chlorite, dusty magnetite and iron hydroxide that distribute along the cleavage planes (fig. 5).

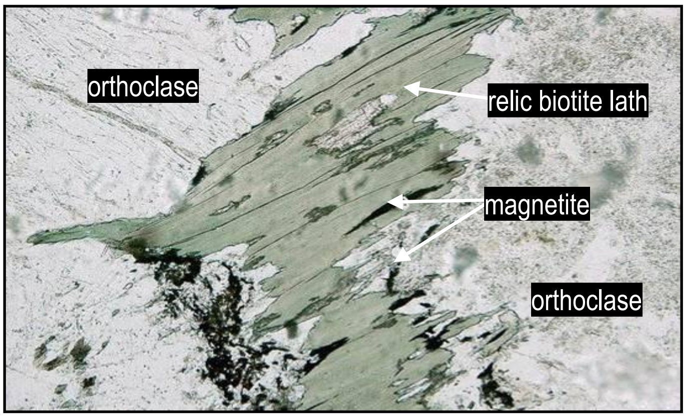

Fig. 5. Chlorite (green) is a secondary mineral derives during the decomposition of biotite when relic forms (laths) of it are left behind. Microphotograph, PPL[1], magnification 100×.*

Feldspars, subjected to the influence of hydrothermal fluids or hot water transform into sericite or kaolinite. Zoisite and prehnite may form as secondary minerals on the account of basic plagioclase, while limonite and iron oxides (magnetite and hematite) derive from iron rich minerals, such as olivine, pyroxene, hornblende, biotite, etc., in oxidizing conditions. The minerals mentioned above will be described in detail in the following text.

Some natural minerals are resistant to physical-chemical changes and require a pretty long time of exposure to atmospheric agents (presumably water), oxygen and hydrothermal solutions before being replaced by secondary minerals, which will be stable in new conditions. Such minerals are quartz, garnets, muscovite, etc.

Rocks composed of primary minerals that were partly transformed into secondary, commonly display lighter colors. Kaolinite and sericite bring light, whitish color to the rock; chlorite and epidote give green color to the rock, while the presence of limonite gives rock yellow and red color.

Majority of rock forming minerals do not have constant chemical composition. They often form a complex solid-solution series (isomorphism) or contain another elements or compounds as impurities. A number of main minerals in igneous, sedimentary and metamorphic rocks is a relatively small, approximately one hundred. Their chemical and physical properties will be presented in the following text along with conditions of their formation and their most common association in rocks.

All photos of crystals and rock samples are given in their natural size. Most of the microphotographs were performed in polarized microscope under crossed or parallel nicols with included magnification.

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*[1] PPL- plane-polarized light or parallel nicols; XPL-crossed nicols. These abbrevations are valid for the text at all.

2. OUTWARD APPEARANCE OF MINERALS IN ROCKS

Minerals come in a great variety of forms - from regularly-shaped bodies, **individual crystals** and **twins** to **crystalline** and **cryptocrystalline aggregates**, i.e. clusters.

2.1. CRYSTALS

Crystals are highly ordered mineral forms. They occur in regular, polyhedron forms: hexahedron, octahedron, rhombohedra, etc. Crystals are having formed under suitable conditions: chemistry of melt or solution, slow crystallization and enough space.

Due to their beauty, color, habit and brightness, crystals have significant role in mankind, particularly for ladies and jewelry making (the ring with sapphire seen on right). It should be emphasized that the most wonderful and the most precious crystals that have been discovered ever display violent, even bloody history.

Crystals have regular habit. Each of them consists of mutually separated atoms, ions or molecules that are regularly distributed forming a crystal lattice, which may be divided up to elementary cell that still retains the main structural properties.

Crystals range in size from thousandth part of millimeter to few tens of meters.

Synchronous growth of few crystals at same substrate, either of same or of different mineral species during crystallization of magma, sedimentary or metamorphic processes led to creation of **crystal druses** (fig. 6).

Fig. 6. Tourmaline crystal (left) and druzy amethyst (right).

Crystals have symmetrically distributed boundary elements: crystal **faces, edges and corners** (fig. 7) that determine polyhedral forms:

Faces are smooth surfaces which bound a crystal. Faces might be various in shapes: triangular, square, rectangle, rhombohedral.

Edges are bounded linear elements formed by intersection of two faces. Depending on the position the edges might be sharp or dull.

Corners are spotted bounded elements in crystal shared at least between three edges, i.e. three faces. According to a number of shared edges the corners may be intersection of three, four, six and eight edges.

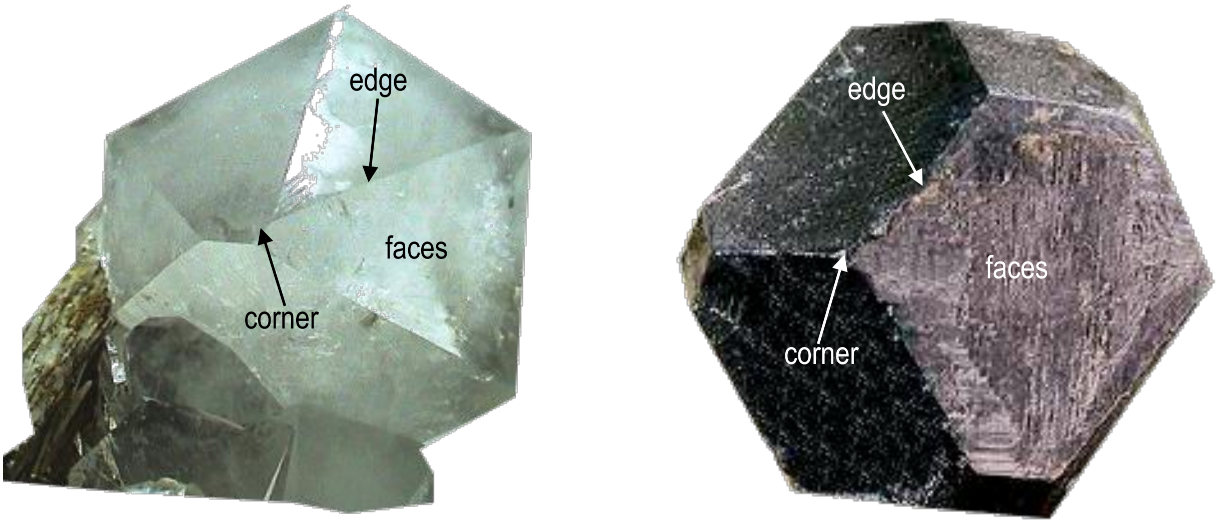


Fig. 7. Boundary elements in crystals of quartz (left), and of perovskite (right).

Crystals occur in simple forms if are limited with only one face, whereas various faces led to development of complex forms. The example of simple form is a cube or hexahedron, while any combination of cube and octahedron leads to more complex forms.

2.1.1. CRYSTAL SYMMETRY

Regular crystals display symmetry, which is defined by following elements: mirror planes, rotation axes and a center of symmetry.

Mirror plane shares a crystal on two equal halves, which act as an image and its reflection in a mirror. A number of mirror planes in crystals are different.

Axes of symmetry in crystal is an axis around whom crystal could be rotated for a certain angle and brought in a same position. Degree of symmetry means whether the repetition of same pattern occurs by rotation for every 180° (2-fold or binary symmetry), for 120° (3-fold symmetry), for 90° (4-fold symmetry), and for 60° (6-fold symmetry axes).

Center of symmetry is imagine point in an crystal around which bounded crystal elements are arranged in a way that each pair of identical faces, edges and corners are set on straight lines that transit across it.

Crystals display various degree of symmetry depending on number of symmetry elements that determine one of 32 classes or groups of symmetry. Crystal forms within a same class have the same symmetry, same crystallographic elements and same or similar fabric.

Symmetry classes are grouped into seven crystal systems.

- **Tesseral system** (isometric or cubic) is of the highest category. Crystallographic axes are of equal length and perpendicular (emphasized by red lines on the figures for each system). Main forms are cube, hexahedron and tetrahexahedron. Garnets, halite, galena and pyrite crystallize in this system (fig. 8);

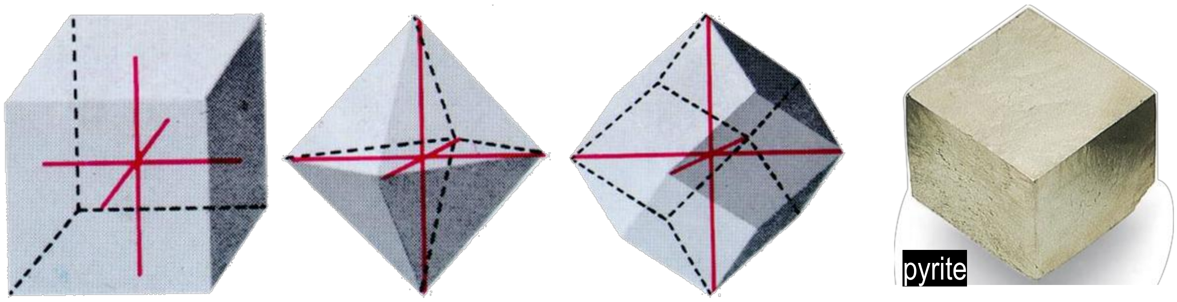


Fig. 8. Common crystal forms in tesseral system with the position of symmetry axes (red lines).

- **Tetragonal system** is of lower symmetry than the tesseral one. Between the three mutually perpendicular axes two are horizontal and of equal length, while the third one, vertical is either shorter or longer. Characteristic crystal forms are tetragonal prism and tetragonal bipyramid. Rutile, zeolite and idocrase (vesuvianite) crystallizes in this system (fig. 9);

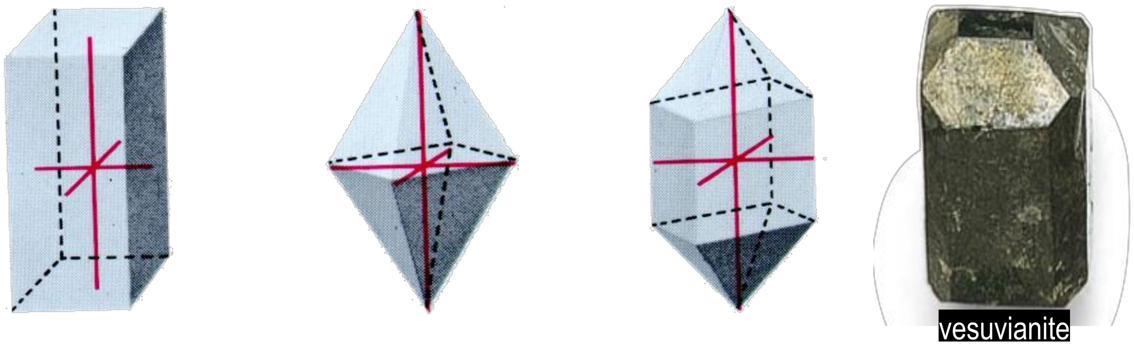


Fig. 9. Main crystal forms in tetragonal system with the position of symmetry axes.

➢ **Hexagonal system** has four crystallographic axes: three are of equal length and are intersecting at 120° angle, whereas the fourth axis, either shorter or longer is perpendicular. Common crystal forms are hexagonal prism and hexagonal pyramid (fig. 10). In this system crystallizes nepheline and beryl;

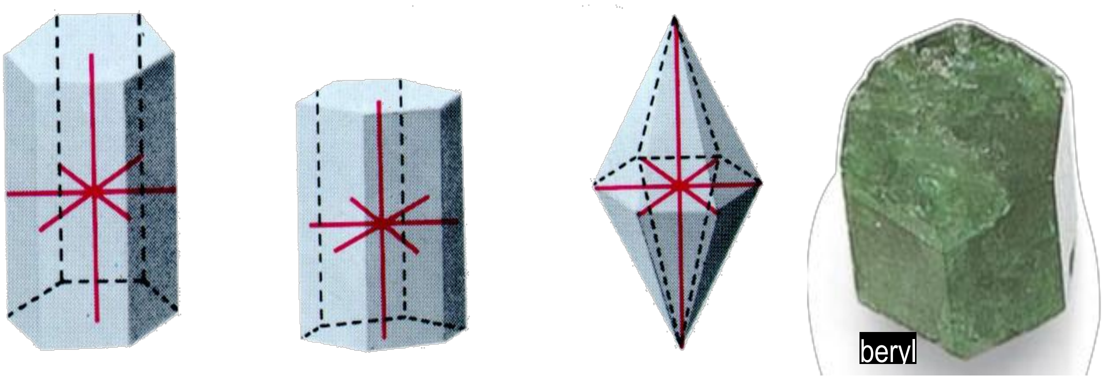


Fig. 10. Main crystal forms in hexagonal system with the position of symmetry axes.

➢ **Trigonal system** may have the same cross-section and the axes arrangement as the hexagonal system, but displays the lower category of symmetry. Unit cell in a form of rhombohedra with all three axes of equal length but under angles different from 90° is characteristic for trigonal system. The most important crystal form is the rhombohedra. In this system crystallizes hematite, corundum, calcite (fig. 11);

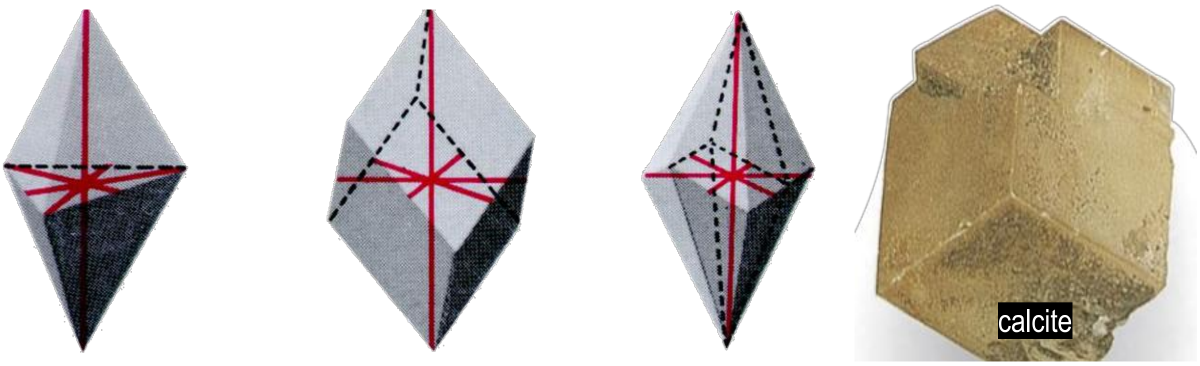


Fig. 11. Main crystal forms in trigonal system with the position of symmetry axes.

➢ **Orthorhombic system** (Rhombohedral) is concerning symmetry elements assigned to the lower category. It has three mutually perpendicular crystallographic axes of different lengths. Characteristic crystal forms are orthorhombic prism and orthorhombic bipyramids (fig. 12). In this system crystallizes orthorhombic pyroxene, amphibole and topaz;

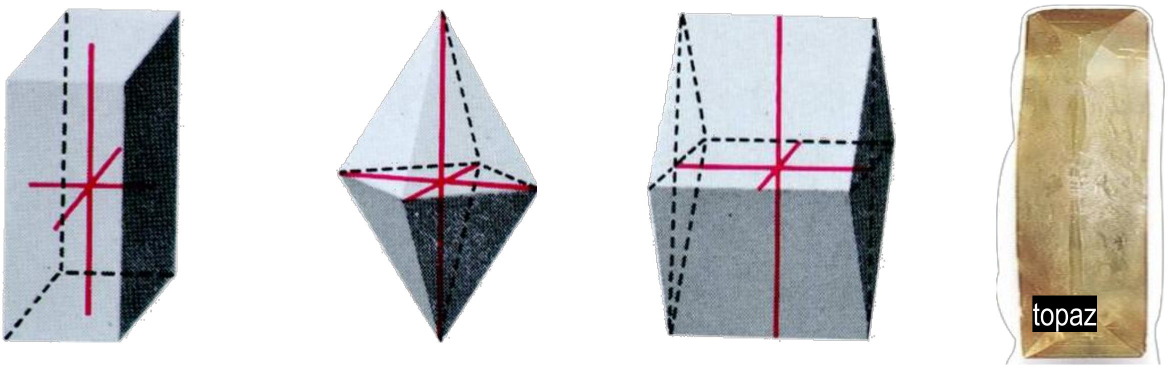


Fig. 12. Main crystal forms in orthorhombic system with the position of symmetry axes.

- **Monoclinic system** has lower symmetry than the trigonal system because it has three unequal axes, two are perpendicular and the third is inclined to them. Monoclinic system has only one mirror plane. Characteristic forms are monoclinic prism and monoclinic bipyramids (fig. 13). In this system crystallize feldspars, micas and gypsum.

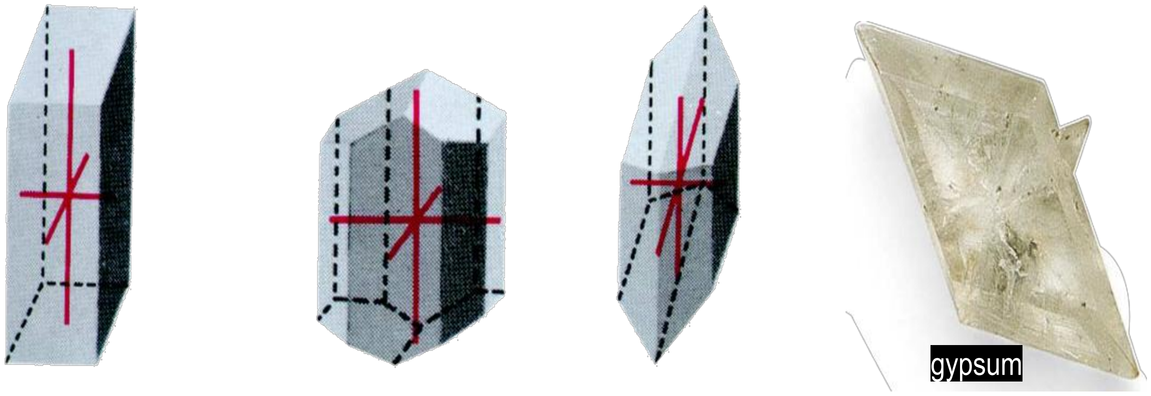


Fig. 13. Main crystal forms in monoclinic system with the position of symmetry axes.

- **Triclinic system** also has three unequal oblique axes. Degree of symmetry is the lowest and included crystal forms may have only the center of symmetry (fig. 14). Common triclinic rock-forming minerals are albite, microcline, and axinite.

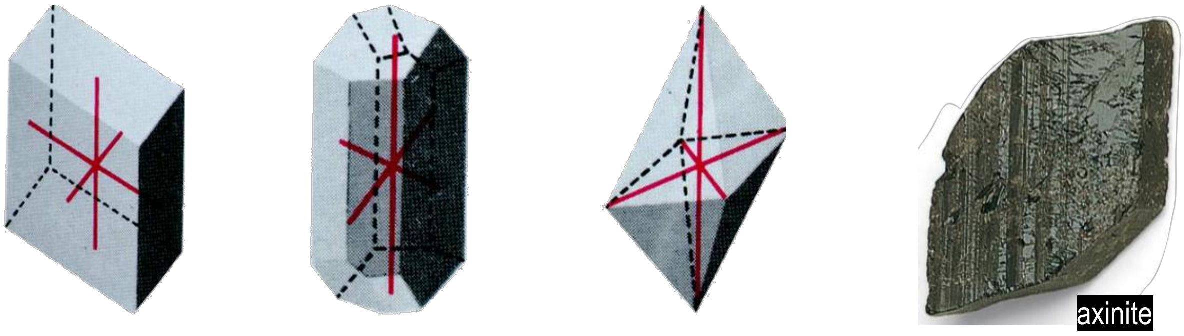


Fig. 14. Main crystal forms in triclinic system with the position of symmetry axes.

Crystals are rarely found in nature in simple geometric forms. Few forms commonly mutually combine and produce crystals with several forms of the same system (fig. 15).

Fig. 15. Magnetite appears in simple (left), and quartz in complex geometric forms (right).

2.1.2. TWINS

Twinning is a characteristic property of some minerals. Twins represent symmetrically intergrowth crystals of the same mineral species according to a certain crystallographic law. The twinning may be: **contact** (fig. 16), when the twin plane is equal to composition plane; **penetration**, when two crystals are in interpenetration at ¼, ½ or completely, and **polysynthetic,** which forms by multiple intergrowth or penetration that leads to a great many forms (fig. 17).

Fig. 16. Contact twinned gypsum crystals (left), penetration twinned staurolite (middle) and orthoclase (right).

Fig. 17. Polysynthetic twins of albite.

2.2. CRYSTALLINE AGGREGATES

Crystalline aggregates or crystal clusters are groups of well-developed crystals. Their development requires the quite same conditions as the generation of individual crystal does. Crystalline aggregates include crystal groups and crystal druses.

Number of crystals in a crystal group depends on number of already formed crystal nucleuses. According to the outlined geometry crystals may be arranged **spherical** or as **crystal druses,** if are irregularly spatially distributed (fig. 18 and fig. 19). Druses may consist of one mineral – monomineral, or of several different minerals-polymineral.

Fig. 18. Spherical, fan-shaped clusters of gedrite (left), and natrolite (right).

Fig. 19. Polymineral crystal druses bearing quartz, calcite and lead-zinc sulphides.

2.3. CRYPTOCRYSTALLINE AGGREGATES

The lack of time and space causes some „accelerated” crystallization of minerals in rocks, and they will appear as cryptocrystalline aggregates or clusters in spite their regular crystal habit. Cryptocrystalline aggregates come in a great variety of habits: columnar, prismatic, elongate, and needlelike (acicular), lathlike, massive, platy, fibrous, oolitic, kidney-shaped etc. The structure of mineral is very important in genesis of crystalline aggregates.

Granular aggregates or granular clusters are related to minerals, which appear as roughly isometric grains either angular or partly to completely rounded. We call them **macro granular** aggregates if grains exceed 0.1 mm (visible by naked eye), or **micro granular** aggregates if their recognition is possible only under the microscope (fig. 20). In granular aggregates occur minerals, such as olivine, garnet, feldspar, feldspathoid, quartz, carbonates.

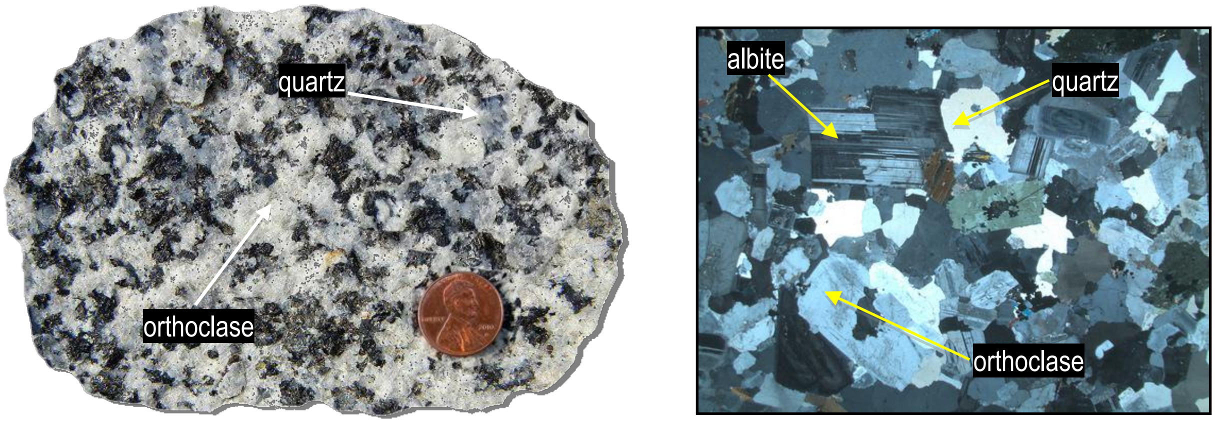


Fig. 20. Granular aggregates (clusters) of orthoclase and quartz in granite (left), and the microphotograph of fine-grained cluster of albite, alkali feldspar and quartz in granite (right). XPL, magnification 100 ×.

Columnar aggregates or clusters consist of minerals that occur in stubby prisms, commonly in size from few millimeters to a few centimeters (fig. 21). Such appearance is characteristic for minerals which crystallize in the monoclinic and orthorhombic systems, on occasion tetragonal, trigonal and hexagonal.

Prismatic aggregates comprise elongated minerals similar to previous but thinner (fig. 21).

Acicular aggregates are characteristic for minerals, which appear in needlelike fibers similar to prismatic but additionally thinner (fig. 21). Commonly appear as radiating or tightly interlocked grains.

Pyroxenes and amphiboles occur in the above mentioned aggregates. Prismatic grains thinner than 0.01 m determine **fibrous aggregate** (asbestos) (fig. 21).

Fig. 21. Columnar (upper left), prismatic (upper right), acicular aggregates of amphibole (lower left) and of fibrous asbestos (lower right).

Lathlike (micaeous) aggregates appear in thin flat sheets like pages of book. Such aggregates are characteristic for sheet silicates (phyllosilicate): muscovite, biotite, chlorite (fig. 22).

Fig. 22. Lathlike aggregates of muscovite in micaschist.

Massive (compact) aggregates are dense, compact masses without macroscopically recognizable grain boundaries. Plenty of minerals occur in such aggregates: calcite in metamorphic rock – marble; quartz in quartzite as well as olivine in dunite (fig. 23).

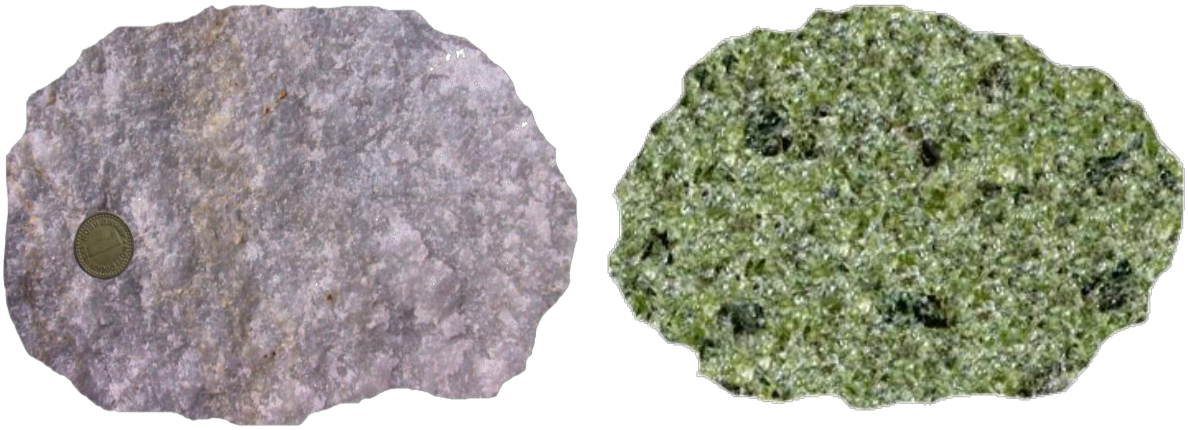


Fig. 23. Massive aggregates of calcite in marble (left), and olivine in dunite (right).

Kidney-shaped (botryoidal) aggregates morphologically resembles kidney, thus the name (fig. 24). Radiating acicular or spherulitic aggregates are usually apparent on its break. Iron and manganese hydroxides generally develop in such forms.

Fig. 24. Kidney-shaped (botryoidal) limonite.

Oolites are rounded aggregates up to 2 mm in diameter. Their concentric or radiating fabric is apparent on their breaks (fig. 25). Oolites are typical forms for sedimentary derived minerals in shallow and wave-influenced water environments. Grains exceeding 2 mm in diameter are called pisolites.

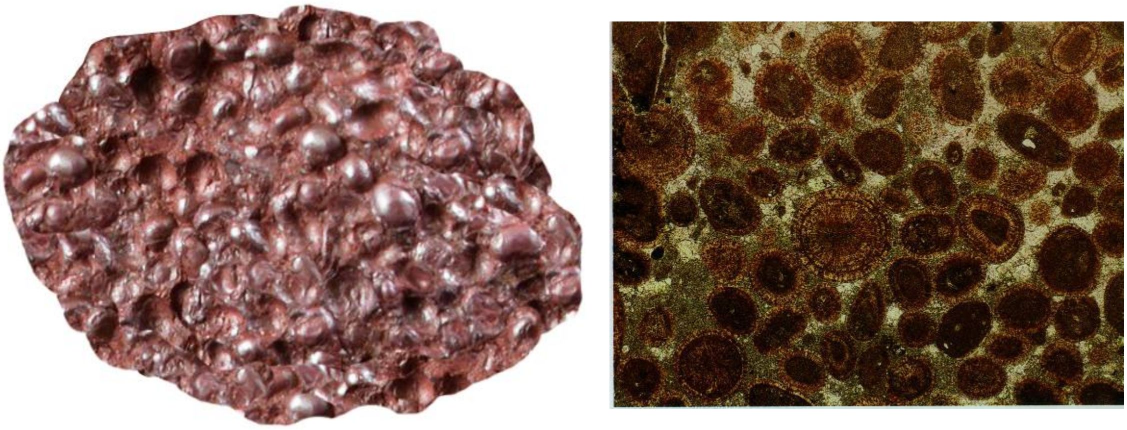


Fig. 25. Oolites in a bauxite sample (left), and in limestone (right). Microphotograph of oolites, magnification 20×, XPL.

Minerals may beside the mentioned mode of appearance occur in rocks as a platy aggregates of various thickness (gypsum, barite), as banded accumulations or as dendrites (fig. 26).

Fig. 26. Dendritic pyrolusite (manganese oxide) pattern on the surface of Struganik limestone.

3. PHYSICAL PROPERTIES OF MINERALS

Macroscopic determination of minerals (identification by naked eye or under loupe for magnifying specimens up to 10 x) is based on their **physical properties** that depend on structure and composition of minerals. Such properties are color, streak, lustre, cleavage, fracture, opacity, hardness and specific gravity. Minerals display optical, elastic, thermal, radioactive, electrical and magnetic properties, and a certain minerals exhibit specific physiological properties: taste, odor and touch.

3.1. COLOR OF MINERALS

Color is important physical property of minerals and is revealed by the first glance. Minerals occur in color of a wavelength of a part of spectrum which is not absorbed. Some minerals transmit a light; other reflects it, and a certain minerals absorb the light. The former considers to transparent minerals, whereas those reflecting light are opaque. Color is a fairly constant and durable feature.

Small number of minerals displays its own, permanent **idiochromatic color** (fig. 27). Such color is influenced by chemical composition and elements called chromophores, which occupy the different sites in mineral structure: Fe^{2+}, Fe^{3+}, Cr^{3+}, Ni^{2+}, Mn^{2+}, Co^{2+} revealing a certain colors.

*Fig. 27. Fe^{2+} and Fe^{3+} reveal **idiochromatic** brownish to black color to biotite (left) and deep red to garnet (right).*

Iron gives either brownish or brownish-green and black color to biotite. The same element causes red color in garnet. Cr^{3+} colors ruby red, whereas Mn^{2+} and Mn^{3+} provide pinkish color of spodumene (fig. 28).

*Fig. 28. Cr^{3+} gives to corundum (ruby) **idiochromatic** red color (left), and Mn^{2+} and Mn^{3+} pinkish to spodumene (right.)*

Pure quartz is white to transparent mineral. Trace amounts of Fe^{3+} in quartz colored it violet (amethyst), while the presence of Al_2O_3 reveals brownish to black color to smoky quartz (fig. 29).

Fig. 29. Varieties of quartz: rock crystal (left), amethyst (middle) and smoky quartz (right), have ***idiochromatic*** *colors.*

Minerals are colored **allochromatic** when owe their color to impurities, i.e. to tiny, fine-dispersed micaceous or granular inclusions (foreign impurities). Aventurine, a variety of orthoclase, owes its allochromatic red color to fine-dispersed hematite, while a hydrothermal calcite is colored green by chalchantite (copper sulphate), chlorite and some other minerals (fig. 30).

Fig. 30. Aventurine, a variety of orthoclase (left), and green calcite (right) displays allochromatic colors.

Pseudochromatic color of minerals derives throughout impregnation, i.e. “coating” with thin layer of another mineral over a crystal or aggregate (fig. 31). Tints of different colors form at the surface of a primary mineral during these processes. Mineral, which is responsible for pseudochromatic color is commonly of secondary origin.

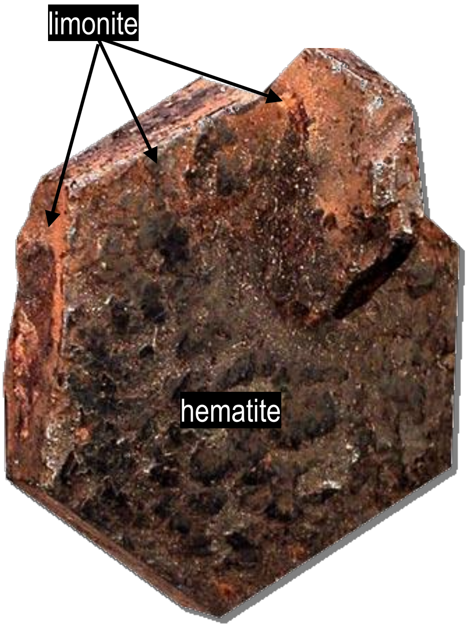


Fig. 31. Hematite occurs in brownish or black color. Partial oxidation led o formation of limonite and resembles red or yellowish-red color, which is recognized as ***pseudochromatic****.*

3.2. STREAK OF MINERALS

Colored streak or coloration of powder depends of the color of mineral. The determination of streak requires rubbing the mineral on a rough, unglazed porcelain plate (fig. 32) or crushing and powdering of it.

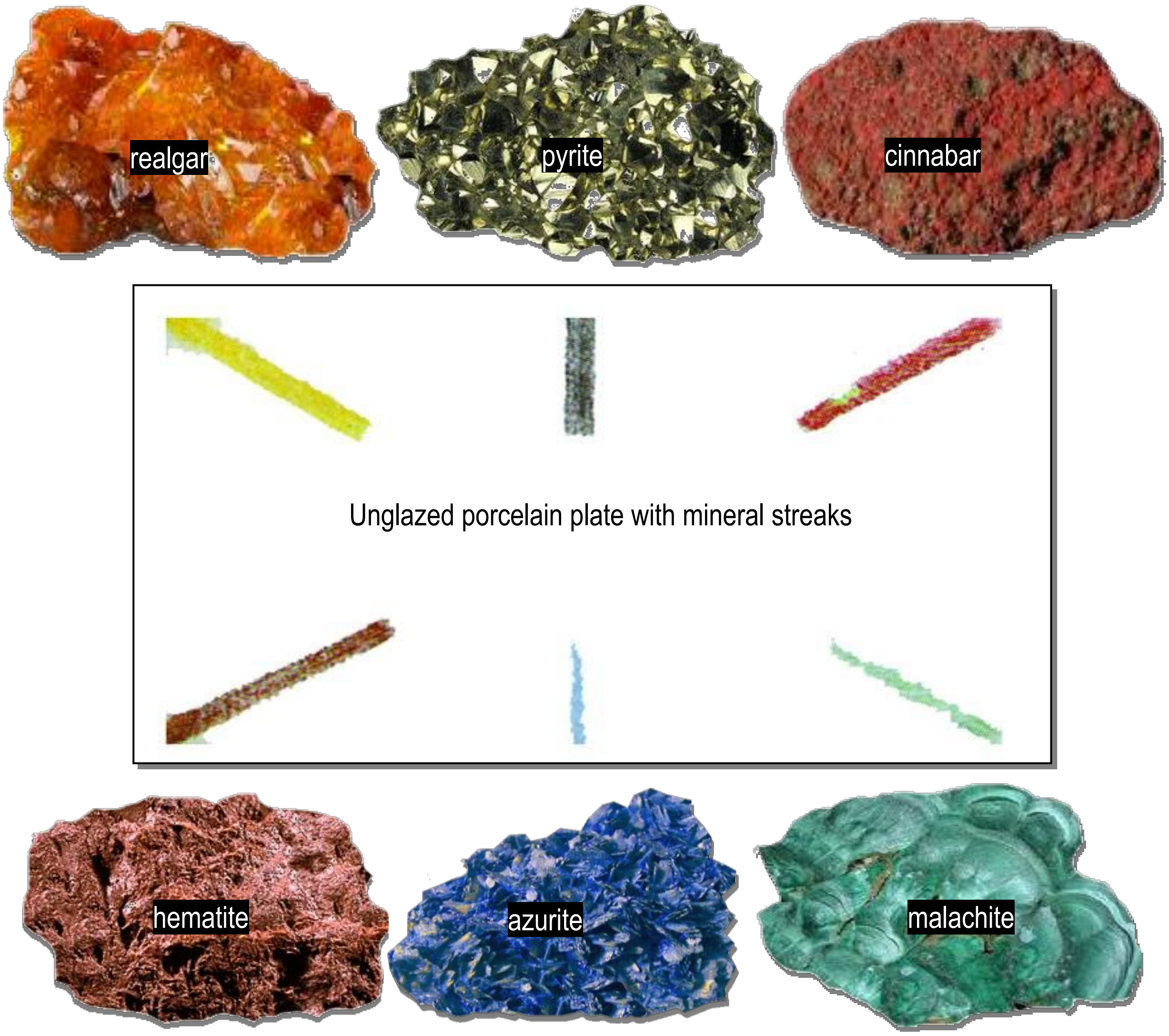


Fig. 32. Some examples of the streak color.

The streak is important physical property and a very convenient in identification of same-colored minerals due to their different streak color. Hematite, iron oxide is commonly grayish black to black in color, but displays a red streak always (its idiochromatic color). Pyrite is yellow, but its streak is black. Colorless minerals are characterized by white streak (powder), whereas the majority sulphide minerals have black streak. Streak of minerals with notable hardness, above 7 at the Mohs scale, could not be determined by rubbing on a porcelain plate as the plate is of lower hardness. In such cases, minerals should be powdered. Similar situation is with brittle minerals.

3.3. LUSTRE OF MINERALS

Lustre is the ability of mineral to reflect a light. This property relies on refractive indices and amount of reflected light. Lustre is not dependant on the color of mineral. This is very distinctive property since a certain minerals reveal lustre even when their grains, for example micas, are of very small dimensions, beneath 1 mm. Lustre depends directly on the type of surface that reflects the light. Reflection is greater from the faces of crystal and cleavage planes, then from uneven surfaces or fine-grained kidney-shaped accumulations.

Common types of lustre are:

- **Metallic lustre** has minerals that reflect light strongly (high refractive indices). This lustre is characteristic for opaque metalliferous minerals, hence the name. Such minerals are magnetite, pyrite, galena, etc. (fig. 33);
- **Adamantine luster** is characteristic for minerals with moderate refractive indices. It should be compared qualitatively with the lustre of crystal glass that contains lead oxide. It is typical for very few minerals: diamond, hence the name, zircon, sphalerite (fig. 33);

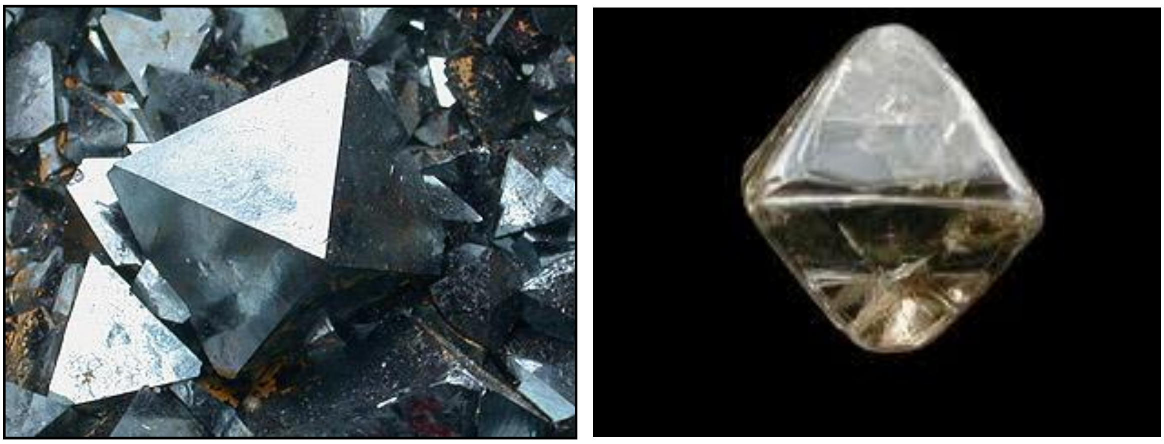


Fig. 33. Metallic lustre of magnetite (left) and adamantine of diamond (right).

- **Vitreous** lustre has minerals with moderate refractive indices. Such kind of lustre displays glass, hence the name. It is important property of the most widespread minerals: silicates, carbonates, sulphates, etc. (fig. 34);
- **Resinous** lustre has minerals whose cleavage is not observable at all or minerals with uneven or conchoidal fracture. It is commonly observable on broken crystals of light-colored minerals, quartz for example (fig. 34), or on dark-colored minerals, when is called greasy;
- **Silky** lustre has micaceous minerals, such as muscovite, biotite and chlorite (fig. 35);
- **Pearly** lustre is characteristic for fibrous minerals, such as asbestos (fig. 35).

Very fine-grained minerals (clays, limonite, and bauxite) are lacking of lustre. Such minerals are often assigned to have earthy or dull lustre.

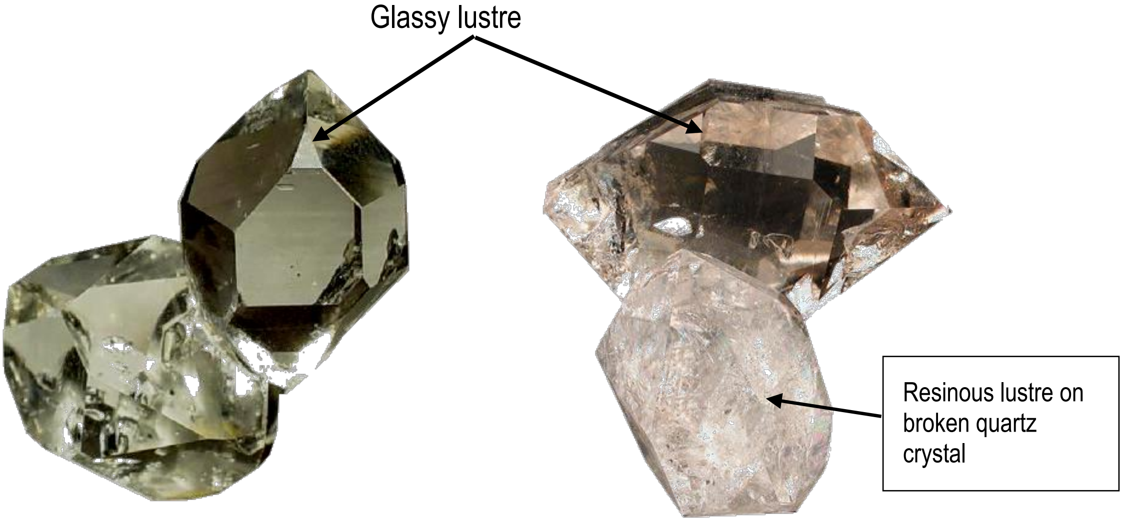


Fig. 34. Glassy lustre in quartz (left) and resinous on broken, twinned quartz crystal (right).

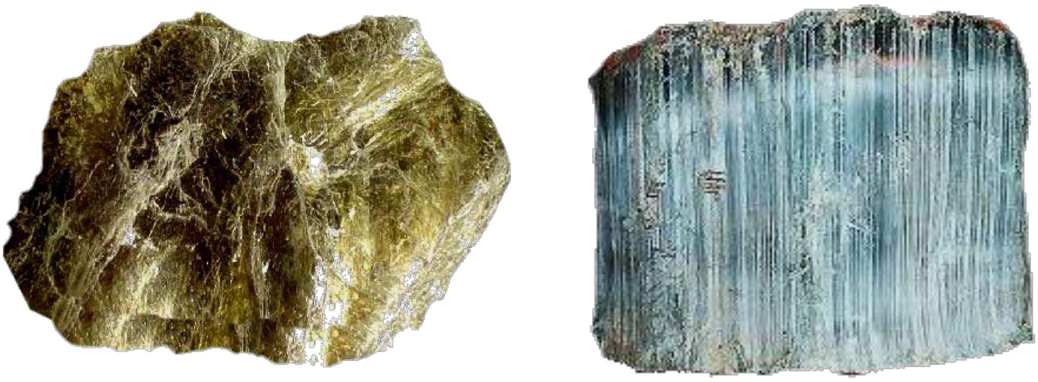


Fig. 35. Silky lustre in muscovite (left) and pearly lustre in asbestos (right).

3.4. CLEAVAGE

Cleavage is the property of mineral to split or separate along smooth surfaces under mechanical force, hit or pressure (fig. 36).

Fig. 36. Cleavage of minerals.

Cleavage planes are generally parallel to crystallographic indices, i.e. to crystal faces, depending on the strength of bonding within the crystal. Bonds in minerals with layered structures (micas) are weaker between layers in respect to bonds within layers themselves. Cleavage is the property of mineral whether it appears in crystal form, or in granular, platy and micaceous forms. Cleavage planes are distinct, constant surfaces for each mineral. Cleavage is designated by certain or possible crystal faces, parallel to it: **octahedral cleavage, prismatic cleavage**, etc.

Minerals may split along several directions, when they show two or more directions of cleavage. Calcite is the mineral with two directions of cleavage, and muscovite is with one (fig. 37). Distinct cleavage along few directions has feldspars, too (fig. 38)

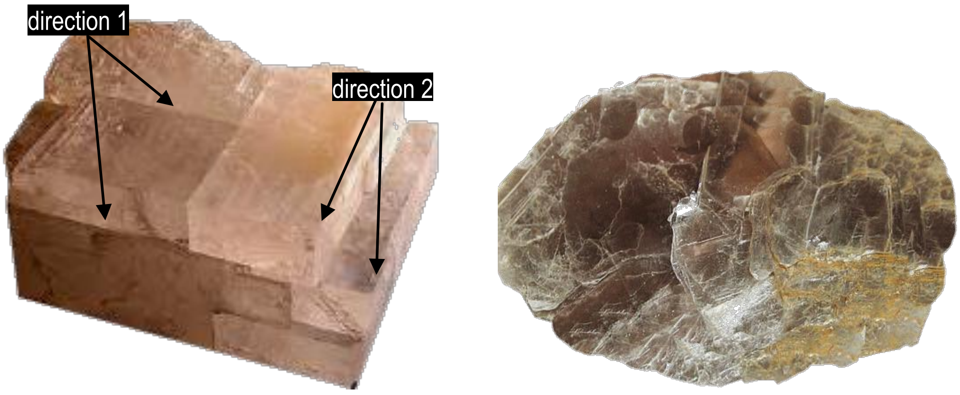


Fig. 37. Two directions of cleavage in calcite (left) and thin flakes of muscovite (right) with one cleavage plane.

Fig. 38. Crystal of orthoclase splits along the cleavage plane.

Significant property of minerals is the intensity of cleavage, which may very within a single crystal. There is the scale for the intensity of cleavage which range from **eminent, perfect, discrete,** and **imperfect** to **poor**. In coarser crystal or grain, exceeding a few centimeters, the cleavage is macroscopically evident (obvious by naked eye).

Cleavage is significant criterion for identification of minerals under the polarizing microscope.

Amphiboles have two perfect cleavages that intersect at about 124° (fig. 39), while pyroxene, also having two perfect cleavages intersecting at 87 to 90° (fig. 40).

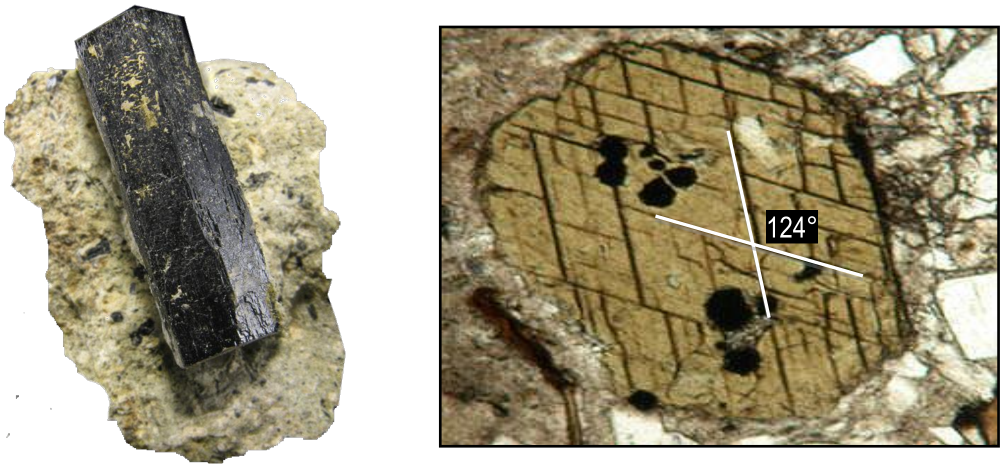


Fig. 39. Crystal of hornblende (left) and hornblende in polarizing microscope with two apparent cleavages at about 124° (right). XPL, magnification 100 x.

In some minerals is the cleavage absent: quartz, garnets, tourmaline, olivine etc. (fig. 41). These minerals generally have uneven fracture and are resistant to physical and chemical weathering thus occur commonly as clasts, i.e. fragments in sedimentary rocks, particularly in sand and sandstone.

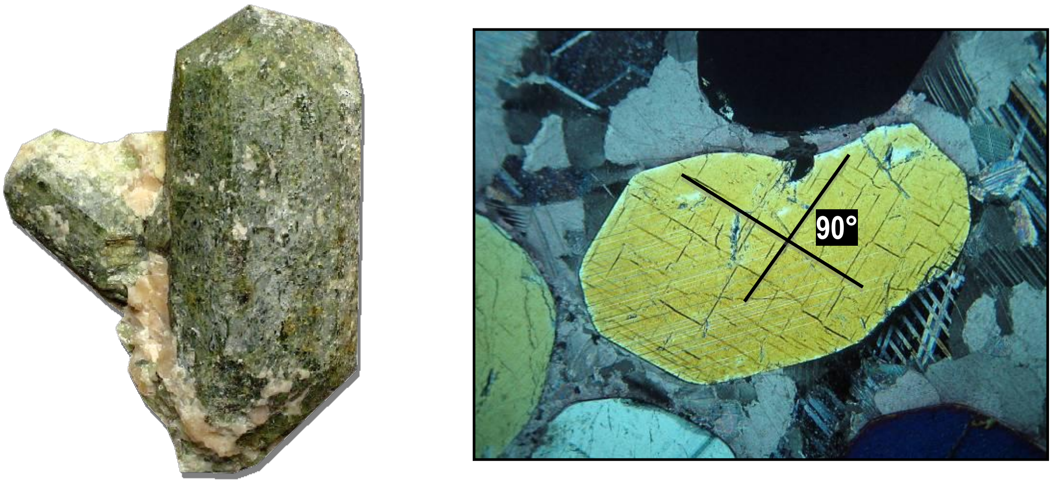


Fig. 40. Crystal of pyroxene, diopside (left) and in polarizing microscope (right) with two cleavages intersecting at 90°. XPL, magnification 80 x.

Fig. 41. Minerals lack of cleavage: quartz (left), garnet (middle) and tourmaline (right).

3.5. FRACTURE OF MINERALS

Minerals exposed to mechanical force, when hammered, split along surfaces other than those of cleavage. These surfaces refer to as the **fracture** of **minerals**. This property is characteristic for minerals with poor or absent cleavage. There are several types of fracture: **even, uneven, conchoidal, splintery, earthy** etc**.** (fig. 42). They are characteristic for certain minerals and may be used for their identification.

Conchoidal fracture is observed in very fine-grained microcrystalline to cryptocrystalline minerals, most frequently carbonates (magnesite).

Amorphous minerals do not have cleavage and usually display conchoidal or uneven fracture.

Fig. 42. Even fracture in fluorite (left), uneven in beryl (middle) and conchoidal in magnesite (right).

3.6. TRANSPARENCY OF MINERALS

Transparency or translucency is the property of minerals to let the light pass through. The majority of minerals are opaque, but semi-transparent to transparent (rarely) minerals also can be found (fig. 43). Such property has quartz (rock crystal), gypsum and occasionally calcite, etc.

Fig. 43. Semi-transparent crystal of quartz (left) and opaque crystal of microcline (right).

Optical, microscopic determination of minerals under polarized light is performed on thin, transparent sections of minerals approximately 0.02 mm thick, when the most of minerals are semi-transparent to transparent. Optical properties of minerals enable their identification along with the time and conditions during their genesis (fig. 44).

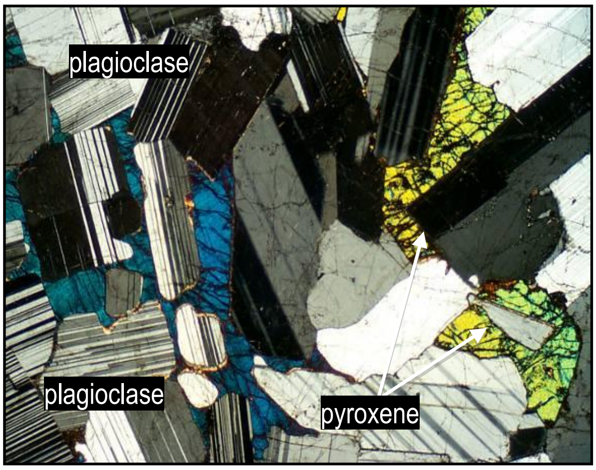


Fig. 44. Minerals in polarizing microscope, XPL, magnification 50 x.

3.7. HARDNESS OF MINERALS

Hardness of a mineral is its resistance to scratching. It depends on the structure of a mineral and strength of bonds between elements. Some minerals may be scratched by a finger nail, while another could not be scratched even with a knife. Due to the anisotropy of crystals, hardness in some minerals varies with crystallographic directions. On the contrary, in isotropic and amorphous minerals the hardness is equal in all directions.

Hardness has a significant influence on the stability of minerals, i.e. on their resistance to physical and chemical weathering. Minerals, having a higher hardness are more stable and commonly present in sedimentary rocks, like clasts in sand. The most frequent minerals are quartz and garnets. Minerals with low hardness and a perfect cleavage also exist in nature and are stable under the influence of atmospheric agents (muscovite).

Hardness of a mineral is precisely measured by sclerometer, but in exploration is commonly used a scale of relative hardness, which rates hardness from 1 to 10. It has been developed in 1822 by an Austrian mineralogist, Friedrich Mohs (fig. 45) and named the Mohs scale of hardness (fig. 46).

Fig. 45. F. Mohs (1773–1839).

Hardness of an unknown mineral can be determined by comparing it to the reference minerals from the *Mohs scale*. In the field, the explorer has to do without reference minerals; therefore the hardness of a mineral should be determined:

- Minerals of hardness 1 and 2 scratch by finger nail;
- Minerals of hardness 3, 4 and 5 scratch by knife;
- Minerals of hardness 6 and 7 scratch glass;
- Minerals of hardness 8, 9 and 10 cut glass.

It should be emphasized that minerals of the same hardness do not scratch mutually and that the soft mineral leaves a streak on the mineral of greater hardness.

Fig. 46. The Mohs hardness scale.

3.8. OPTICAL PROPERTIES OF MINERALS

Visible part of spectrum of the light is between wavelengths of 400-780 nanometers (10^{-9} m) and frequencies from $4x10^{14}$ Hz to $7.9x10^{14}$ Hz. Non-polarized light is characterized by diffraction, interference and polarization. The last one is of particular importance in optical mineralogy.

Oscillations of electrical field in polarized light are within the one single plane, perpendicular to direction of wave propagation. Polarized light is produced by polarizators.

In polarizing microscope (it uses polarized light in respect to another types of microscope) the magnification up to 1200 x could be attained. Rock-forming minerals are investigated by observation of thin-section, a glass plate of 48x28 mm in size. Using a special technique a thin rock or mineral chip, from 0.02 to 0.05 mm (being transparent) is glued with canada balsam or another glue with known refractive index (fig. 47).

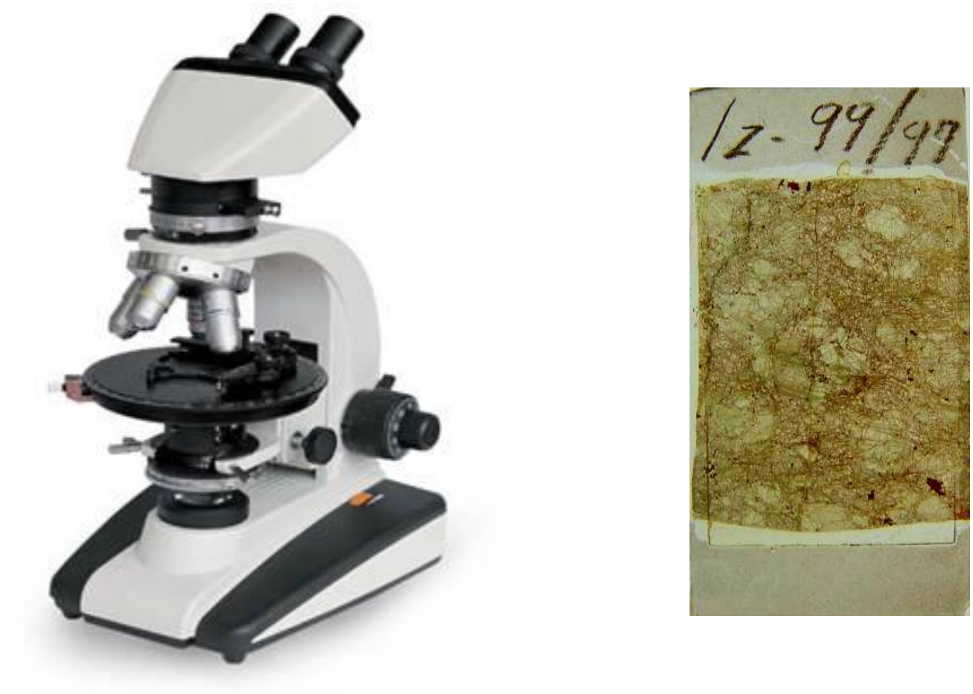


Fig. 47. Polarizing microscope approximately 40 cm height (left) and the petrographic thin-section (right).

Optical properties, which are specific for each mineral species, are significant data for identification of minerals, their chemistry, mutual relationships and the alteration type and degree.

Minerals are classified, due to their behavior in polarized light into optical isotropic and anisotropic.

OPTICALLY ISOTROPIC minerals are those crystallizing in isometric system or amorphous. Under cross nicols in polarizing microscope such minerals are black in color. Refractive indices of isotropic minerals are equal in all directions as these minerals do not have double refraction. Such characteristics display garnets, leucite etc. (fig. 48).

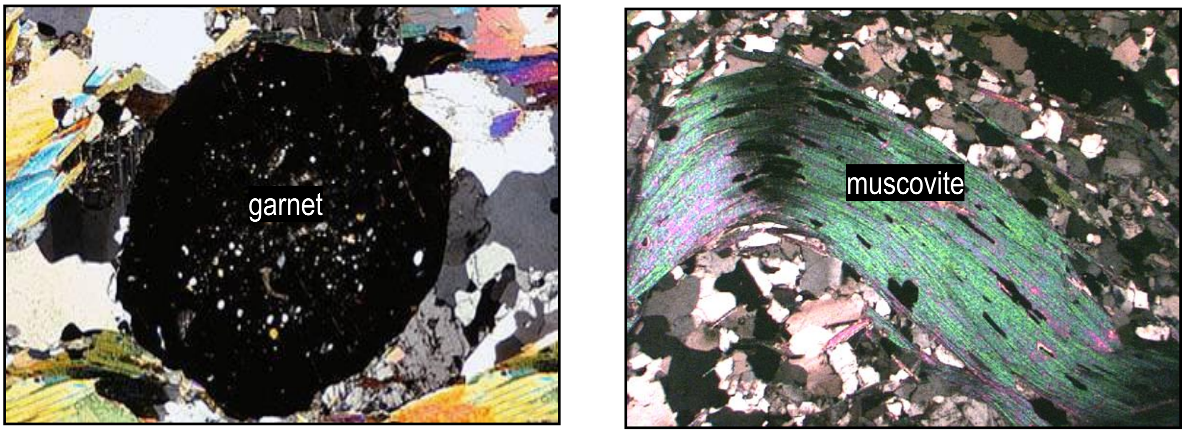


Fig. 48. Optically isotropic mineral, garnet (left) and flakes of anisotropic muscovite (right). XPL, magnification 60x

OPTICALLY ANISOTOPIC minerals are those crystallizing from tetragonal to triclinic system. Such minerals display high interference colors in polarizing microscope due to different refractive indices and double refraction. Such properties are typical for quartz, feldspars, olivine, pyroxene, amphibole, micas (fig. 48).

Optical investigations also include metal bearing, commonly ore minerals besides the rock-forming minerals. Thin-section represents a smooth cut and polished sample of one or several minerals. Determination and analysis of minerals also requires polarized, but reflected light as metal bearing minerals are opaque. Silicate minerals, including carbonates, sulphates etc. generally display in thin-sections grey color, whereas metal bearing minerals are of high interference colors (fig. 49).

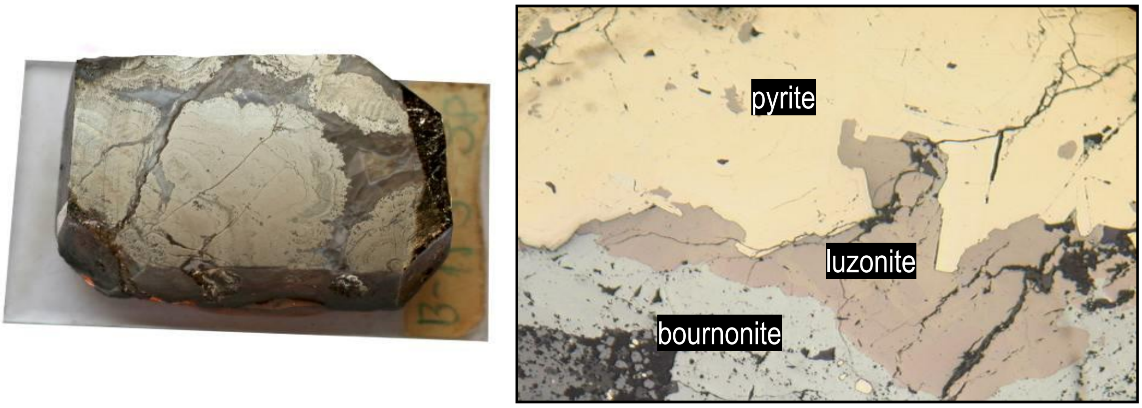


Fig. 49. Sample of metal-bearing, opaque mineral prepared for optical studies (left) and microphotograph of the same sample (right). XPL, magnified 100x.

3.9. SPECIFIC GRAVITY OF MINERALS

The specific gravity of minerals, or density, just like the density of substances, is shown as its **mass per unit volume** and is frequently expressed in grams per cubic centimeter (gr/cm^3).

The density of minerals depends on the chemical composition and the internal structure of mineral. Average density of rock-forming minerals varies between 2.5 and 3.5 (fig. 50).

Fig. 50. Specific gravity of pyroxene, augite (left) is 3.2-3.5 and 2.56 of orthoclase (right).

A natural mineral may have different density due to changes in chemical composition, crystal structure or presence of the impurities and enclaves. For example, the iron-rich pyroxene and amphibole are of higher density than the same mineral species with less iron and more calcium and magnesium.

For instance, graphite and diamond are of same composition, but their different structure causes their different specific gravity.

Several techniques are available for determination of the density: pycnometer, aerometer, hydrostatic balance, torsion balance or liquid of known density. Sinking of mineral in liquid of given density implies on its higher density, when neither rises nor sinks its density is the same or nearly the same as that of the liquid. Finally, when it floats its density is lower than that of the liquid.

3.10. ELASTIC PROPERTIES OF MINERALS

Elasticity is the property of a mineral to experience plastic deformation and return to the original shape when the force is removed. It could be determined as the change in shape until the point at which elastic deformation gives way to crushing.

Some natural minerals are very elastic, another sustains only partial elastic deformation and finally the third group includes inelastic, brittle minerals. Elasticity depends, like cleavage, on the structure of mineral. Minerals occurring in crystal forms exhibit different elasticity along different directions and the same values within the same crystallographic orders. Amorphous minerals display equal elasticity in all directions.

Micas, muscovite and biotite exhibit notable elasticity. Apart of it, some minerals with very low elasticity refer to inelastic or brittle minerals. The latter group includes quartz (fig. 51).

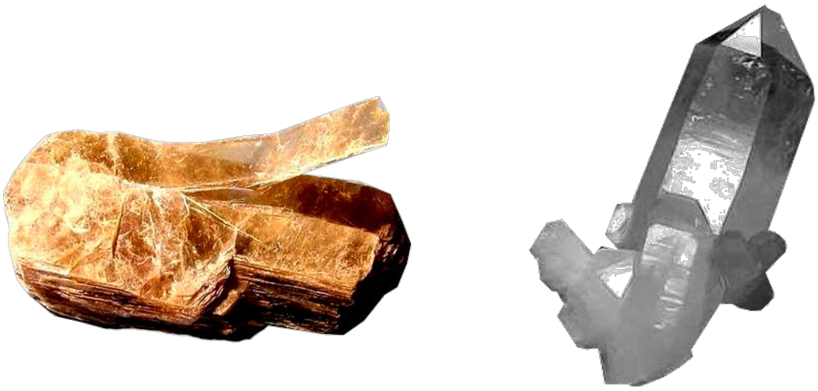


Fig. 51. Muscovite (left) is elastic, and quartz (right) is brittle mineral.

Minerals, which preserve their bent form after the force is removed and remain permanently deformed, are **plastic minerals**. Such minerals are clay minerals, which could be shaped in the presence of water (fig. 52). Clay minerals are the source for ceramic that is used for production of pottery plates, in electro industry, for sanitary items etc.

Fig. 52. Clay mineral, kaolinite, becomes plastic in the presence of water.

3.11. THERMAL PROPERTIES OF MINERALS

Minerals behave different when heated. Some minerals absorb certain amount of heat (endothermic processes) and broaden, leading to change of their crystal structure. Typical endothermic processes are the loss of water (dehydration) and polymorphic transitions. Other minerals, however, release heat during warming (exothermic processes or reactions). This is particularly common during crystallization, i.e. formation of new phases.

Heat transfer is governed by the internal fabric of mineral. Heat conductivity (transfer of heat in a given direction) has influence on minerals causing them to compress or to expand. Minerals of isometric system and amorphous transfer heat equally in all directions though change the volume homogenously. However, minerals of other crystal systems exhibit variable heat conductivity and their volume undergo variable changes (fig. 53). Heat transfer, and extension or contraction of minerals is important property of minerals that determines their behavior during physical weathering.

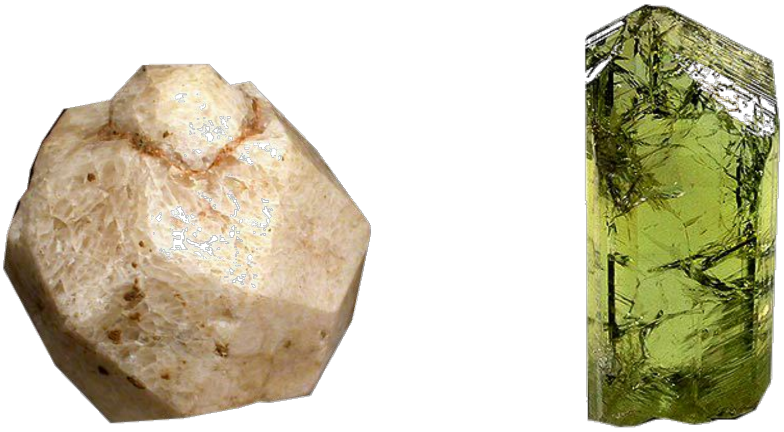


Fig. 53. Leucite (left) crystallizes isometric and has the equal heat conductivity in all directions. Zoisite (right) crystallizes in monoclinic system and has different heat conductivity in different directions.

The amount of heat energy required to rise a temperature of one mol of a mineral for one Celsius degree is named the heat capacity of mineral. Heating the mineral to a point of its transition into liquid state is **the melting point of mineral**. During the melting process, minerals will absorb heat energy until the last crystal turns into the liquid state. The required heat energy is called **latent heat of fusion**. Melt will continue to warm up just after solid state (crystals) disappeared at all. The inverse process, melt cooling, takes place after a certain amount of heat, known as the **latent heat of crystallization**, is released. The early first crystals will evolve afterwards.

Amorphous mineral does not have the determined melting point. It depends on the chemical composition and minerals most frequently gradually transit into liquid state.

3.12. MAGNETIC PROPERTIES OF MINERALS

Magnetic properties of minerals are primarily dependant on electron configuration of atoms and behavior of free electrons, which generate a magnet field. Magnetization of minerals is related to the presence of permanent, magnetic domains, oriented in its structure. Different minerals differently experience magnetic field. The majority of minerals are poorly magnetic. Only a few minerals are attracted to an electromagnet and deserve the name - magnetic minerals. The most magnetic mineral is magnetite, iron oxide (fig. 54).

Magnetic properties of minerals have a high potential for several application: in electromagnetic separation of sand, in flotation processes and for crushed concentrate.

Geological discipline, Geophysics, uses magnetic properties of minerals as the diagnostic in prospection of new ore bodies.

Sl. 54. Magnetite with „adhered” iron sticks.

Some minerals are magnetic only in strong magnetic field. Such minerals are referred to as paramagnetic minerals.

Paramagnetic silicate minerals are pyroxene, amphibole and biotite. Paleomagnetic properties of minerals are very useful in research focused on the evolution of the planet Earth enabling the spatial and temporal reconstruction since the early first days of its existence.

3.13. ELECTRICAL PROPERTIES OF MINERALS

Electrical properties of minerals rely on the type of chemical bonds. Metal bonds with free electrons enable electrical properties of a mineral. In the nature occur some minerals that are good conductors: elemental gold, silver, cooper, graphite, a few metal sulfides and iron oxides.

Minerals with dominantly ionic and covalent bonds are bad conductors or do not conduct electricity at all. This group includes the majority of rock-forming minerals: clay minerals, feldspars, carbonates, sulphates (fig. 55). This property is important for application of mentioned minerals as insulator.

Electrical properties find its application in separation, the division of useful from gangue minerals.

Fig. 55. Graphite (left) is a good conductor and a calcite (right) is not.

Some minerals obtain electricity from crystal surfaces when a mechanical stress is applied (piezoelectricity). This phenomenon is characteristic for quartz and has been discovered in 1880. It is used in electronic (fig. 56), electrometry, in instruments for precise measuring, etc.

Fig. 56. Quartz watches.

Concerning behavior of the above mentioned physical properties, the minerals of rocks may be isotropic and anisotropic:

- **Isotropic** minerals have the **same physical properties in all directions** (fig. 57). This property is characteristic for minerals of isometric system and for amorphous minerals. In garnets and in limonite the light passes in all directions with the save velocity. These minerals have one refractive index, and one heat or electricity transfer coefficient;

Fig. 57. Garnets, dark-colored crystals (left) and amorphous, kidney-shaped (botryoidal) aggregate of limonite (right) are of isotropic physical properties.

- **Anisotropic** minerals display **different physical properties in different directions** (fig. 58). Tetragonal, hexagonal and trigonal minerals have two refractive indices, two heat transfer coefficients; in rhombohedral, monoclinic and triclinic minerals, three directions of distribution of physical properties exist. Most of the minerals of rocks are anisotropic.

Fig. 58. Microcline exhibits anisotropic physical properties.

3.14. RADIOACTIVE PROPERTIES OF MINERALS

Radioactivity of minerals arises in the presence of isotopes, i.e. radioactive elements that decay.

The amount of products of their decay temporally increases. Knowing the time, velocity and the rate of decay of radioactive elements as well as their residual, the age of a given mineral and a host rock may be precisely measured. This method involves the **geochronology,** the dating geological discipline.

The most frequently used minerals for dating are biotite, hornblende, zircon (fig. 59), apatite, garnets. The presence of radioactive elements potassium, argon, rubidium etc. in biotite and hornblende, which are the main minerals in certain igneous and metamorphic rocks, enable determination of the time of their crystallization, i.e. development. Application of this method is limited due to "reset" isotopic values under repeated heating of mineral at temperatures exceeding 500 °C when a mineral is being “born” again.

Determination of the presence of uranium, lead and thorium isotopes in zircon and apatite, which occur as accessory constituents in igneous, metamorphic and sedimentary rocks, points the time of their origin, actually the age of rock whose constituents they are. Repeated heating of rocks to a high temperature does not impact the accuracy of obtained results.

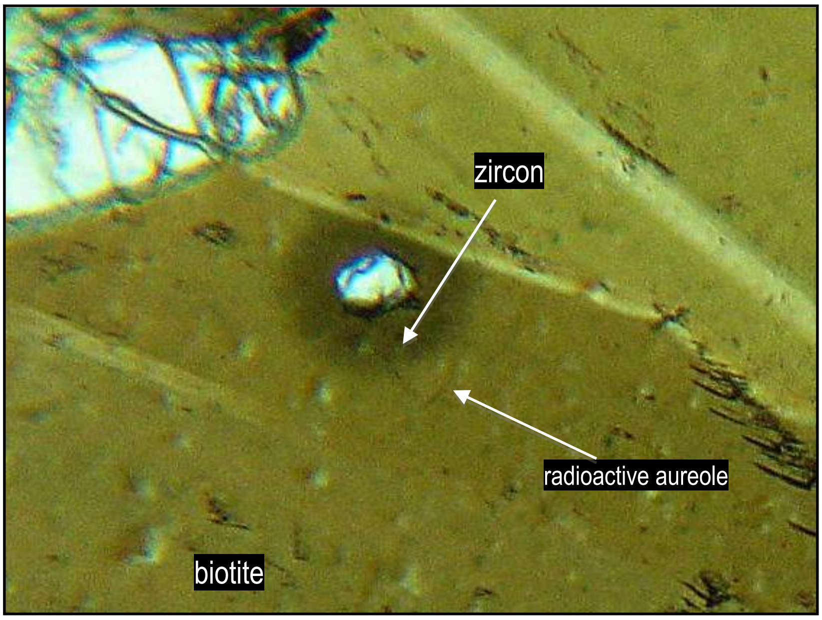


Fig. 59. Inclusion of zircon in biotite with pleochroic halos from radioactive decay. Microphotograph, XPL, magnification 100 x.

3.15. PHYSIOLOGICAL PROPERTIES OF MINERALS

Physiological properties of minerals are those we recognized by senses. These involve taste, odor and touch. These properties are very characteristic for certain minerals.

Taste have soluble minerals, such as halite, NaCl (fig. 60); sylvite testes more bitter then halite, whereas the most bitter mineral epsomite is often called "epsom salt";

Odor has minerals that contain organic matter (carbonates with bitumen), sulphur, and some sulphides particularly when hammered or crushed. Specific ammoniac odor gives off some clay minerals, and garlic odor give off arsenic minerals while pyrite resembles rotten-egg if struck.

Touch is characteristic property of a mineral and could help in identifying it: talc (fig. 60) and asbestos are greasy. Good conductors are cool (metallic minerals, galena, sphalerite, chalcopyrite), wet clay sticks for fingers.

Fig. 60. Halite(left) tastes salty, sulphur (middle) has characteristic odor, and talc (right) is greasy on touch.

4. CHEMICAL COMPOSITION OF MINERALS

Rock-forming minerals are built of numerous elements. Their content varies and depends on the way of their origin including physical-chemical conditions during it.

Major elements determine mineral species and as a rule, are the most abundant. Their content ranges from a few percents to few tens percents. Orthoclase is potassium aluminum silicate mineral ($KAl_3Si_3O_8$) and consists of 16.9% K_2O, 18.4% Al_2O_3 and 64.7% SiO_2.

Although microelements, commonly present in minerals, do not have influence on determination of mineral species they provide minerals with characteristic properties, which reflect on conditions during their formation: composition and origin of melt (magma), sedimentary or metamorphic processes, and the role of assimilation or alteration. Microelements are commonly present in small concentrations and expressed in ppm, parts per million (milligram versus kilogram) or in ppb (parts per billion, which is one thousandth of one ppm).

Results of performed chemical analyses, either by classical chemical methods or using modern equipments, such as microprobe, are given in weight per cents of elements or oxides. Calculation of empiric and crystallochemical formulas relies on these data.

Chemical formula of minerals commonly gives cations as the first, then anions and anion groups. Cations of the same coordination are presenting together in parenthesis, and separated by commas. Anions are presenting successive towards those of lower coordination number, whereas anion groups are given in angular bracket. The majority of empiric formulas that represent the chemical composition of minerals in this publication are taken from the book *An introduction of the rock forming minerals (Deer, Howie and Zussman, second edition, 1999)*.

There are minerals which represent isomorphic series of two minerals (end members) that substitute mutually in variable proportions and create mixed crystals. As an example, let's mention the olivine, or plagioclase.

Olivine is built of forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_2), which combine completely. The rule 50% should be applied to a minerals name, meaning that olivine with more than 50% forsterite considers to forsterite olivine, and those with less than 50% are fayalite olivine. Plagioclase also includes isomorphic series of albite ($NaAl_3SiO_8$) and anorthite ($CaAl_2Si_2O_8$).

According to abundances of albite and anorthite, the plagioclase crystal is named. Albite contains up to 10% anorthite, oligoclase has 10 to 30% anorthite, andesine from 30 to 50% anorthite, labradorite 50 to 70%, bytownite 70 do 90% anorthite and finally, anorthite from 90 to 100% anorthite, or up to 10% is albite.

4.1. WATER IN MINERALS

A large number of minerals include water, which is genetically different:

- **CONSTITUCIONAL WATER** enters the structure and is strongly bond in crystal lattice of a mineral as the hydroxyl group (OH) or H_3O^+. Such minerals are amphibole and micas (fig. 61), chlorite, epidote, etc. The removal of constitutional water leads to breaking of a crystal lattice. Once removed constitutional water could not enter again in the structure of mineral.

➢ **CRYSTALLINE WATER** is present in the form of H_2O molecules and its amount is strictly determined in the structure of a mineral. Water molecules have steady position in crystal lattice, but are weakly held. Some minerals may receive again the lost water.

Gypsum has two molecules of crystalline water and a chemical formula of $CaSO_4$ x $2H_2O$ (fig. 62). By heating, this water is lost leading to change in physical and chemical properties of gypsum, which turns into anhydrite, $CaSO_4$.

➢ **ZEOLITIC WATER** got its name from the mineral zeolite, which includes water in a form of molecules (fig. 63). This water is specifically held in a structure of zeolite. It may be removed by heating within a wide temperature range on the order 80-400 °C, and could be regained easily or replaced by gasses: ammonia and hydrocarbons without breaking apart the lattice;

Fig. 61. Tremolite (left) and muscovite (right) contains constitutional water as the OH group.

Fig. 62. Gypsum has two molecules of H_2O in a form of crystalline water.

Fig. 63. Zeolites contain water that may be removed and either received again or replaced with gasses in the structure.

➢ **COLLOIDAL OR ADSORPTION WATER** occurs in colloids, for example in iron and aluminum hydroxides (limonite, bauxite). It is loosely held on the surface of a mineral (fig. 64) and could be easily removed when drying. Its amount is not consistent in the structure of mineral, thus its chemical formula is written as n x H_2O;

Fig.64. Bauxite (left) and limonite (right) have colloidal water.

➢ **HYGROSCOPIC WATER** is actually the humidity or capillary moisture adsorbed by a mineral from the air. It disappears by heating to approximately 100 °C and is not related to the crystal lattice. The amount of hygroscopic water is varying in minerals, depending on their composition and their structure. Some minerals, such as halite and a few clay minerals, display remarkable affinity for water adsorption from the air (fig. 65).

Fig. 65. Halite (left) and clay minerals (right) adsorb water (humidity) from the air.

➢ **MECHANICALLY BLENDED WATER** is water embedded in mineral during its growth and does not represent its chemical constituent (fig. 66). It can be removed only by heating to pretty high temperatures. It should not be included in chemical formula of a mineral;

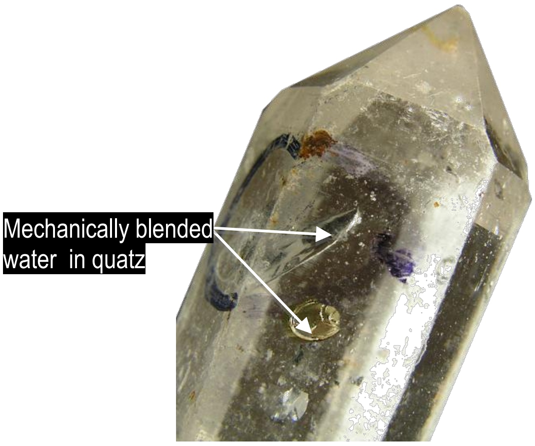


Fig. 66. Mechanically blended water (bubbles) in quartz.

5. POLYMORPHISM, ISOMORPHISM AND PSEUDOMORPHS

The distribution of atoms, ions and molecules in crystal lattice has significant influence on occurrence of polymorphism and isomorphism.

5.1. POLYMORPHISM

Polymorphism is the property of a chemically same mineral to occur in different morphologies. This property depends on the composition of melt or solution, along with the pressure-temperature conditions within the environment where the crystal growth. Minerals of the same chemistry, which crystallize in different crystal forms, refer to polymorphic modifications. Polymorphism has been discovered by German chemist and mineralogist Klaproth yet in 1798, much before the isomorphism has been noted (fig. 67). A famous scientist recognized that calcium carbonate crystallizes in trigonal (calcite) and orthorhombic symmetry (aragonite).

Fig. 67. M. Klaproth (1743-1817).

High temperatures and low pressures support the formation of minerals with lower density (loosely stacking), whereas at low to moderate temperatures and high pressures will form minerals of the same chemical composition, but denser due to different way of stacking of carbon atoms in the crystal lattice. Such are aluminum silicate minerals, andalusite, sillimanite and kyanite, very important minerals in metamorphic rocks. Andalusite develops at the lowest and kyanite at the highest pressures.

Silicon oxide (SiO_2) composes several minerals of specific morphological and physical properties, depending on the temperature of its growth. At the highest temperatures crystallizes cristobalite, at some lower tridymite, and at the lowest the β kvarc will form.

The most often referred example of polymorphism is elemental carbon (fig. 68) whose atoms may be „arranged” producing either six-sided prism or octahedron form of elementary cell. The former case corresponds to mineral graphite, and the latter to diamond.

Different crystal habit results in significant differences in physical properties and shapes between these two minerals. Graphite is one of the softest mineral in a nature, colored black, dusty and opaque. Diamond is translucent, colorless or exhibits a range of colors, high glossy shine and is among the hardest natural minerals.

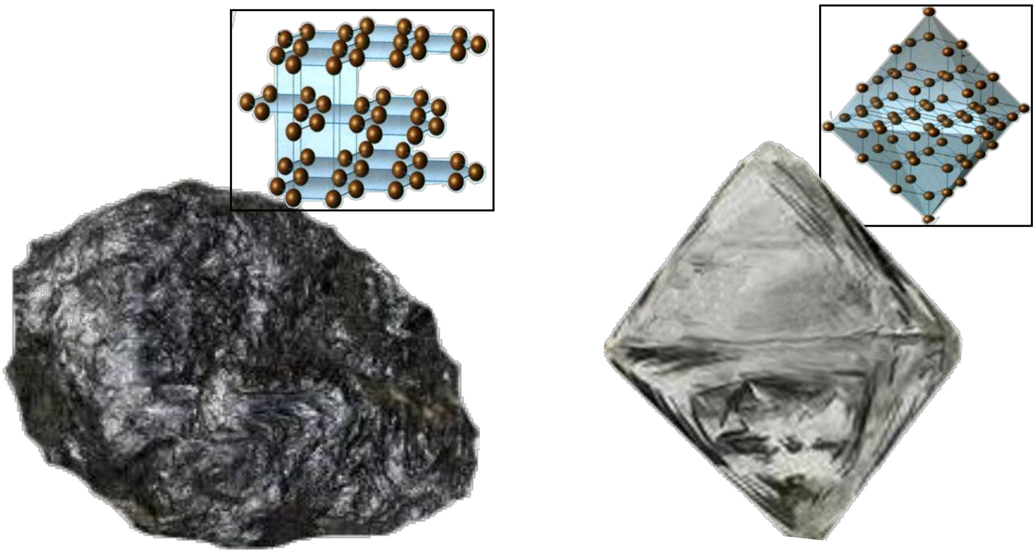


Fig. 68. Graphite (left) and diamond (right) are basically of the same chemical composition but of different structure.

5.2. ISOMORPHISM

Isomorphism is the property of chemically different minerals to occur in similar or equal crystal or crystalline shapes. This is the quite common phenomenon, particularly within the silicate minerals. Isomorphism was discovered by German scientist Mitscherlich in 1819 (fig. 69).

Fig. 69. E. Mitscherlich (1794–1863).

Microcline is alkali feldspar, potassium aluminum silicate in composition and crystallizes triclinic. Albite is acid plagioclase, sodium aluminum silicate in composition and crystallizes triclinic, also (both are presented within the feldspar group). Mentioned minerals occur in the same or in similar morphologies (fig. 70). Actinolite, tremolite and hornblende are minerals of the amphibole group. They are not chemically the same, but occur as prismatic to acicular aggregates, i.e. clusters. Similar situation is within minerals of the pyroxene group, olivine, and carbonates.

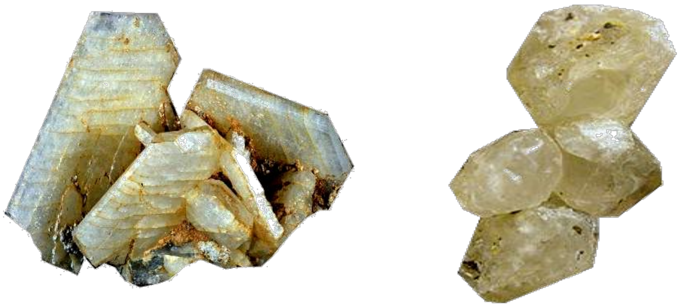


Fig. 70. Albite (left) and anorthite (right) occur in same or similar morphologies.

5.3. PSEUDOMORPHS

Pseudomorph minerals are those occurring in crystal form or crystalline aggregates after an earlier mineral. This could happen during deposition of a mineral over a previously formed (mechanical pseudomorphs) or throughout change of chemical composition of the already formed mineral with the new one (chemical pseudomorphs). For each given pseudomorphs is in use a term, which includes the names of the primary and the newly-formed minerals. For example: quartz pseudomorphs after epidote, chlorite after albite (fig. 71), and sericite after andalusite (fig. 72).

Fig. 71. Quartz pseudomorphs after epidote (left) and chlorite after albite (right).

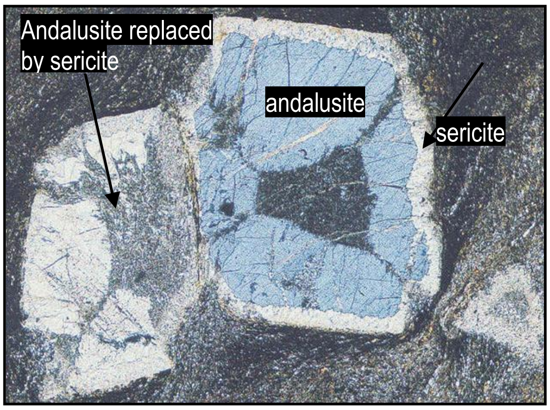


Fig. 72. Sericite pseudomorphs after andalusite: completely (left), and partly replaced crystal (right). Microphotograph, XPL, magnification 60x.

6. THE ORIGIN OF MINERALS

Minerals find their origin in the wide range of pressures and temperatures: crystallization from magma – **igneous**, superficial and chemical weathering of rocks – **sedimentary** and metamorphism of the existing rocks - **metamorphic**. There are minerals in the nature that can become in all of these three mentioned ways.

6.1. IGNEOUS MINERALS

IGNEOUS MINERALS form through crystallization from magma, which is created in different parts of the Earth (fig. 73).

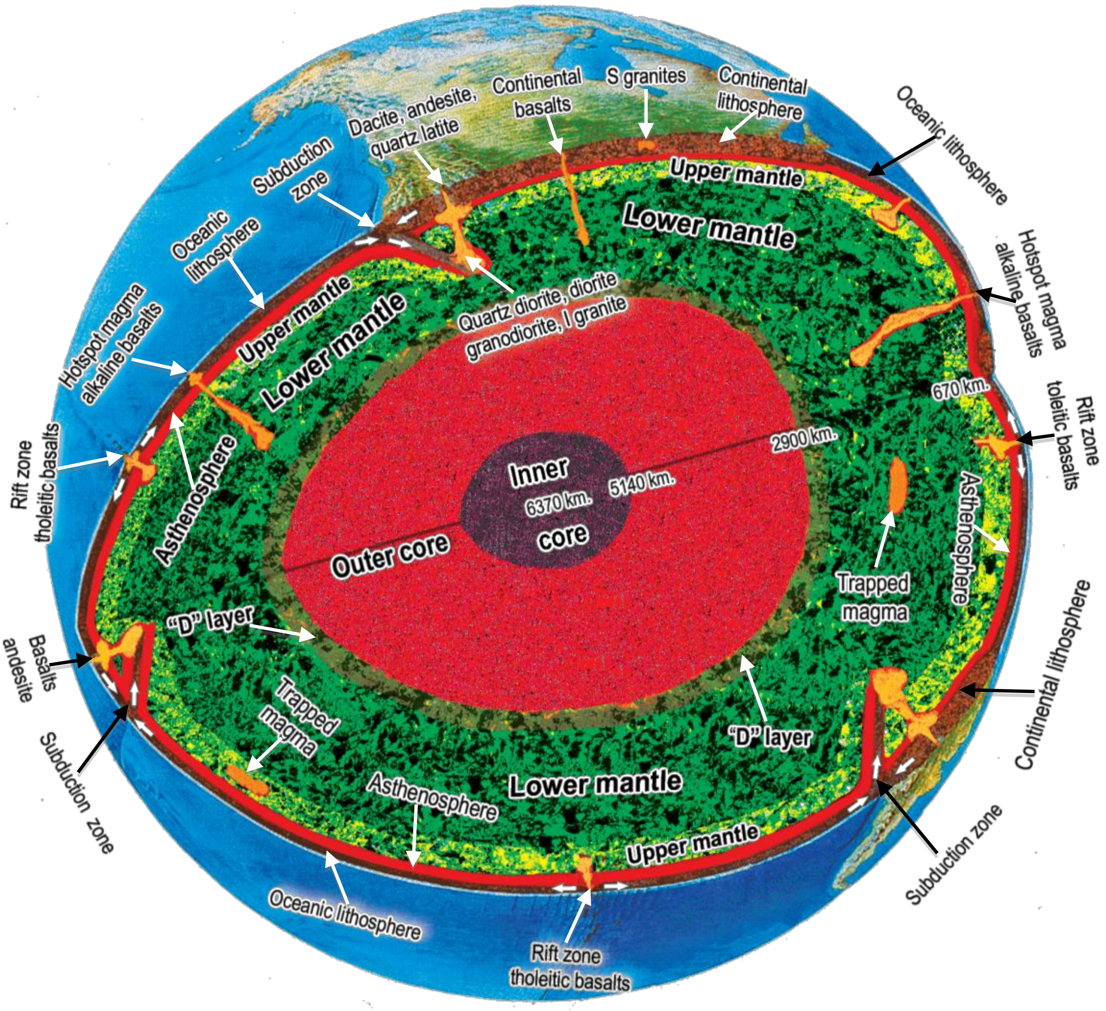


Fig. 73. Formation of the igneous minerals. The explanation is in the text.

The Earth is layered, made of inner and outer core, lower and upper mantle, lithosphere and crust.

The inner core is positioned in the middle part of the Earth, between 6370 and 5200 km below us. It is made of metals: Fe, Co and Ni and it make around 1.7% of the Earth's mass. Seismic waves run through it, thus we assume it is **solid**. In its middle part, the temperature is around 5000 °C and pressures around 360 GPa. The temperature in the outer layer is between

4000-5000 °C and pressures from 330 GPa. The density of the already mentioned metals in given conditions is about 12 g/cm^3. There is also a little bit of sulphur because of the strong affinity of this element towards iron. The composition of the iron meteorite approves this assumption because it consists of troilite (iron sulphide). But there are no silicates or oxides.

The outer core is above the inner core, at the depth between 2900 km and 5200 km and makes around 30.8% of the Earth's mass. It is also made of metals: Fe Co and Ni but seismic waves do not run through it, indicating that it is **liquid**. The temperature at the border between inner and outer core is 4000-5000 °C and at the border with lower mantle 3000-4000 °C. In the lower part of the outer core, the pressure is 330 GPa and at the border with lower mantle 100 GPa. The density of the metals in these conditions is from 9 to 12 g/cm^3.

The Earth's magnetic field is probably being made in the outer core due to high temperatures and convection currents, when the electrical power, that generates magnetic field, is being made. The outer core has about 8-15% less density than the inner one. That can be described with the presence of one or more elements with smaller atomic number, sulphur and/or oxygen.

Mantle makes around 67% of the Earth's mass and according to chemical, i.e. mineral composition, is divided on lower and upper mantle.

Lower mantle is a part of the Earth between 670 and 2900 km of depth and makes 49.2% of the Earth's mass. The pressure around 100 GPa and the temperature from 3000 to 4000 °C is considered in it's lower part, at the lower mantle-outer core border. In the upper part, at the border with upper mantle the temperature is from 1600 to 1800 °C, and pressure 23 GPa.

The border between the outer core and lower mantle is zone of around 200 km width and is called **"D" layer.** It is a mixture of molten metals from the outer core and densely packed minerals from the lower mantle. According to certain authors, „D“ layer is a very important source of hot spot magma (fig. 73) and magmatism inside the oceanic and continental lithosphere.

We haven't seen or touched the lower mantle so far. Of its composition, we have an indirect knowledge, thanks to experimental studies, the composition of meteorite and xenolith in basalt magma.

According to experimental studies of minerals and rocks, only associations with dominant perovskite structures: Mg-Fe-Ca perovskite, magnesiovustite, styshovite and poststyshovite phase have a certain density, around 5.5 g/cm^3. That density is necessary for the determined velocity of seismic waves running through the lower mantle. It is assumed that the further structural transformation of minerals that are the most densely packed isn't possible beneath 670 km. Therefore, the increase of depth leads only the rise of density of minerals, straight to the border with the outer core. It is not known whether this border matches with the change in the chemical structure or with the stable phases of minerals that occur in this region.

Geophysical data indicate that lower mantle is for about 5% denser than garnet lherzolite, which is found in lower parts of the upper mantle.

With low velocity of seismic waves, it is considered that magmatism exists in the lower mantle. Its partial melting creates mantle plume, with a few hundreds of kilometers in size. They are being created on the border of the outer, liquid core and lower mantle in „D“ layer, 2900 km below us. From this deep part of the Earth, mantle plume, which are warmer, more viscous and lighter than the nearby mantle “slip off” from time to time and like a diaper, driven by convection currents rise up, where can be „captured“ in the upper or lower mantle, lithosphere and crust, creating igneous chambers. Reactions, metasomatism, with the surrounding rocks are pretty often (fig. 73). When mantle plume pours out at the surface inside the oceanic lithosphere, which is often far away from the spreading zone, huge mass of basalt is being created. On that occasion, oceanic islands occur (Hawaii). Inside the continental lithosphere, out of these magmas, basalts are also effused creating plateaux a few kilometers thick. Mentioned volcanic basic rocks are made of basic plagioclase, olivine, and pyroxene. They have a specific content of incompatible elements and rare earth elements. The migration of mantle plume from „D“ layer to the surface is very long, when compared to a humans' lifetime. It can last from a few tens to a few hundreds of million years.

The upper mantle is a part of the Earth from the depth 670 km to the Moho discontinuity, which is only 20 to 60 km below us. It makes around 18% of the Earth's mass. Parts of the oceanic and continental lithosphere are also included in the upper mantle (fig. 74).

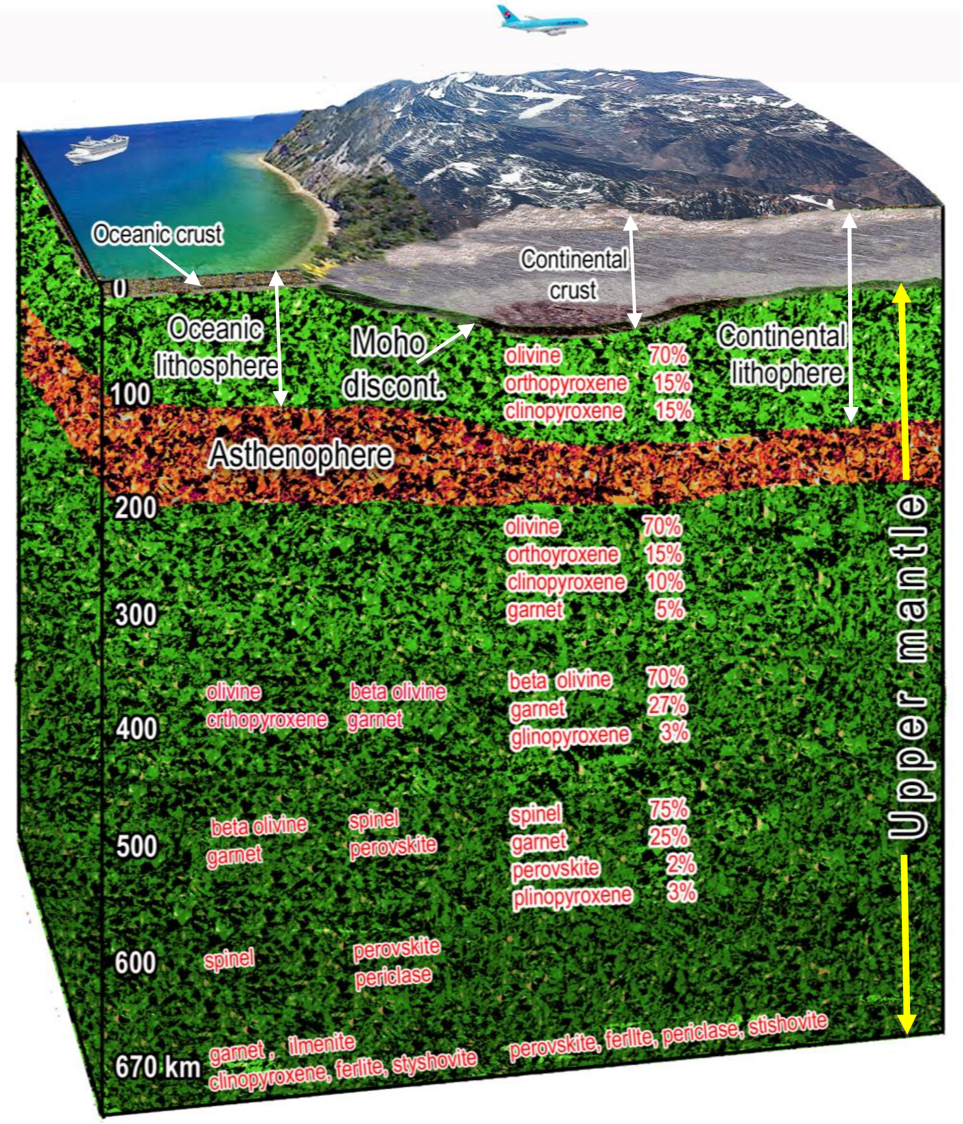


Fig. 74. Mineral composition of the upper mantle.

The samples of rocks from the upper mantle cannot be taken directly, but its composition can be discovered indirectly, as well as with the lower mantle. We use PT conditions, the stability of certain minerals, the composition of ophiolites, meteorite, xenolith, geophysical studies, etc.

According to experimental data, it is established that on high pressures and temperatures in the upper mantle, the elements have smaller radius and they are connected with stronger covalent bonds. That is why their content and mutual relationship changes inside the single mineral. Radius of elements determines the type of crystal structure. Taking into account the bonds between anions and cations, we can calculate the specific gravity/density of minerals and the conditions of their genesis in this part of our planet.

Studying ophiolites, we found peridotites as the dominant rocks in the upper part of the upper mantle. They are made of olivine, ortho and clinopyroxene, minerals that consist of aluminum: plagioclase, clinopyroxene, spinel, garnet, hornblende – appearing in small amounts, but very important in determination the conditions of their origin.

Peridotites, with basic plagioclase, **anorthite**, are stable up to 50 km depth, and they build lower parts of the oceanic crust. Peridotites with spinel appear at depths from 50 to 100 km, where **spinel** substituted plagioclase in reactions because of higher PT conditions in that part of the upper mantle: olivine + plagioclase = orthopyroxene + clinopyroxene + Mg, Ca **spinel**.

Peridotites with garnet (pyrope) appear at depths greater than 100km, where garnet substituted spinel in reactions: Mg, Fe, Ca spinel + orthopyroxene = olivine + **garnet**. These rocks build middle and lower parts of the upper mantle.

At greater depths, peridotites, i.e. garnet lherzolite transform into rocks built from minerals of high density, with perovskite or ilmenite structure. According to the velocity of seismic waves at depths greater than 350 km, it is very probable that more dense pack of pyroxene appears, where ¼ of silica atoms are in octahedron coordination leading to about 10% higher density. Moving down to the lower mantle, at the depths of 400 km, olivine transforms into beta modification with spinel structure, which is for about 8 % thicker than common olivine.

From 500 to 550 km below us, part of garnet transforms into perovskite, and beta modification of olivine transforms into gamma modification, which is for about 2% denser.

This reaction explains the seismic discontinuity at 670 km. According to experimental data, the area of transformation of garnet and spinel into perovskite is too wide for seismic discontinuity (around 30 km), which is only a few km wide at this depth. This border may be problematic for the change of chemical composition of minerals, as well. Certain authors claim that the mantle under the discontinuity is richer in iron.

At the border between lower and upper mantle, most of minerals have spinel structure. At greater depths, because of the high pressure and temperature, minerals transform into perovskite or ilmenite structure.

Most of petrologists and geochemists think that chemical and mineral composition of stony meteorite (fig. 75) is the same as the composition of the upper mantle. This group of meteorites is made of olivine, garnet, ortho and clinopyroxene and basic plagioclase, while accessory minerals are: ilmenite, magnetite and titanomagnetite.

Mineral composition of the upper mantle can also be determined according to the composition of xenolith and nodules, which represent "pieces" of the upper mantle affected by magmas during their motion and pouring out on the surface (fig. 76). According to the mineral composition, xenoliths are ultrabasic rocks, made of olivine, orthopyroxene, clinopyroxene, garnet, and spinel, which is in accordance with previously mentioned assumption.

Fig. 75. According to chemical and mineral composition, meteorites are the same as upper mantle.

The presence of minerals with water (phlogopite and amphibole) in some of xenolites of ultrabasic rocks suggests that there is water in the upper mantle. Olivines and pyroxenes sometimes have gas inclusions with water and CO_2.

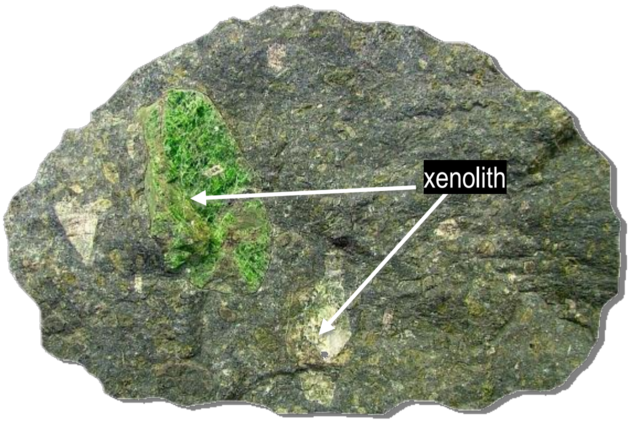


Fig. 76. Volcanic rock with xenoliths, 'brought' from the upper mantle.

The formation of magma in the upper mantle

Magmas generate in the upper mantle by its partial melting due to adiabatic decompression (decreasing of pressure without decreasing the temperature), or by contribution of volatile components in the system that lowers the temperature of crystallization of minerals, as well as due to geothermal gradient, which causes the decrease in pressure and temperature approaching the surface of the Earth.

There are still differences in opinions of: when, how and where are suitable conditions for partial melting and creating magmas in the upper mantle and when, where and how much magmas change their composition from the place of creation to intruding in the surrounding rocks or pouring out on the surface.

The content of volatile, water and gasses has great influence on the degree of partial melting and generation of magmas. The question is: has upper mantle been richer or poorer in water and gasses during the time? Or, has their content remained nearly the same, i.e. volatiles, released in volcanic eruptions were ‘compensated’ with subduction of rocks that contain water.

Convection currents (drift) in the lower and upper mantle are very important for understanding geological processes and the creation of magma. The movement caused by the difference in temperature is called the **convection currents** and it is connected to fluids. The main reason or cause of convective motions is the fact that the warmer water is lighter and colder is heavier. Convection drift in the lower and upper mantle is caused by the difference in temperature and density of the newly created magmas and surrounding rocks. It is acceptable for understanding the mechanism of their movement.

Convection drift is more intense if the temperature and density difference of magmas and rocks is greater. The border between lower and upper mantle at 670 km depth is determined according to the elevated density of minerals. Is that the barrier between convection drifts or does it coincide with the border of chemical changes? If the subducted part of lithosphere cannot go through thick rocks in the lower mantle, does it rise above? That is why certain authors think that there are convection drift zones in the mantle: one above and the other under the discontinuity at 670 km.

Within the upper mantle is **asthenosphere**, the zone of low velocity of seismic waves, due to the presence of igneous melt. It is made of partially melted ultrabasic rocks: the mixture of solid phase, olivine, garnet, and pyroxene crystals and up to 5% of the melt. Above the asthenosphere is oceanic and continental lithosphere.

Asthenosphere, being partially liquid, enables movements of the oceanic and continental lithosphere that ‘floats’ on it. It has different thickness. Under the continental lithosphere, asthenosphere creates the zone 30-50 km wide. It is thicker under the oceanic lithosphere, up to 100 km. In the zone of spreading oceanic lithosphere, rift zones, is asthenosphere positioned at significantly smaller depths. That is why it is considered a main source of basic magma that occurs in this region.

Lithosphere is a part of the Earth **above the asthenosphere until the surface**. It is made of a part of the upper mantle and the crust. Lithosphere can be seen as a mosaic, limited by spreading zones, oceanic rifts, subduction zones and transform faults. According to the mineral and chemical composition the oceanic and continental lithosphere are distinguished.

Oceanic lithosphere can be found under the oceanic realms where we can discover oceanic type of crust. It is mainly made of basic igneous rocks from the Mesozoic age. It is a part of the Earth above the asthenosphere, with parts of the upper mantle and oceanic crust, and with the Moho discontinuity in between. It is 100 km wide on the average. In the spreading, rift zone, however, is oceanic lithosphere around 50 km thick, where it is the weakest and the youngest. Away from the divergent zone, it becomes thicker, up to 100 km and older. In subduction zones oceanic lithosphere becomes ‘consumed’, but that ‘loss’ is being compensated by creating the new oceanic lithosphere in the zones of plate divergence (oceanic rifts). So, it is constantly being recycled this way.

Mohorovičić's discontinuity or, shorter **Moho** (got its name after famous Croatian scientist, A. Mohorovičić, fig. 77) is separating oceanic and continental crust from the upper mantle. It is determined by sudden increase of velocity of seismic P-waves, which is 7 km/sec in the oceanic crust, 6 km/sec in the continental crust, and around 8 km/sec in the upper mantle. It is considered that the increase of velocity of seismic waves with density is a consequence of higher density of the same minerals at higher pressure, or of different mineral composition of the rocks under, and rocks above the Moho discontinuity.

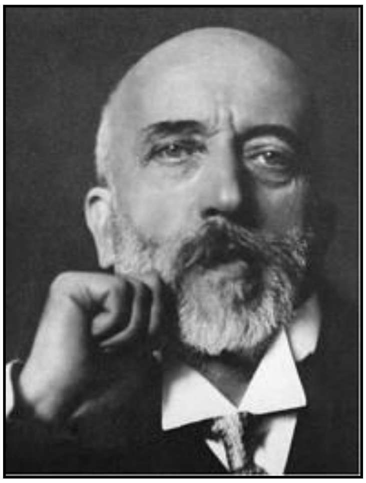


Fig. 77. A. Mohorovičić (1857–1936).

Upper part of the oceanic lithosphere, above the Moho discontinuity, is oceanic crust, 2-12 km thick.

Oceanic crust is made of cumulate peridotites and basic rocks, gabbro, diabase and basalts above. Upper, overlying parts of the oceanic crust are thin layers of sedimentary rocks, cherts, clays, which also could be absent (fig. 78).

Continental lithosphere is continental part of the Earth, above the asthenosphere. It is up to 200 km thick (fig. 79). It includes parts of the upper mantle, made of ultrabasic rocks and continental crust, with the Moho discontinuity between them.

Continental crust is made of peridotites, strongly metamorphosed underlying rocks, eclogite, granulite, with gneiss, and amphibolite above. Chlorite schists and phyllite take part all over the top. In the overlying part, we find limestone, sandstone, clays, etc. The thickness of the continental crust is up to 80 km. In the upper parts, where metamorphism is strong, rocks are being partially to completely melted, creating **S-**granites made of orthoclase, quartz and muscovite.

Magmas mostly become by partial melting in the lower and upper mantle, as we mentioned before. A part of them derive in asthenosphere and arise in the divergent zones (rifting) of oceanic and continental lithosphere. In their composition, magmas are basic, basalts made of olivine, basic plagioclase and pyroxene with specific content of incompatible elements and rare earth elements.

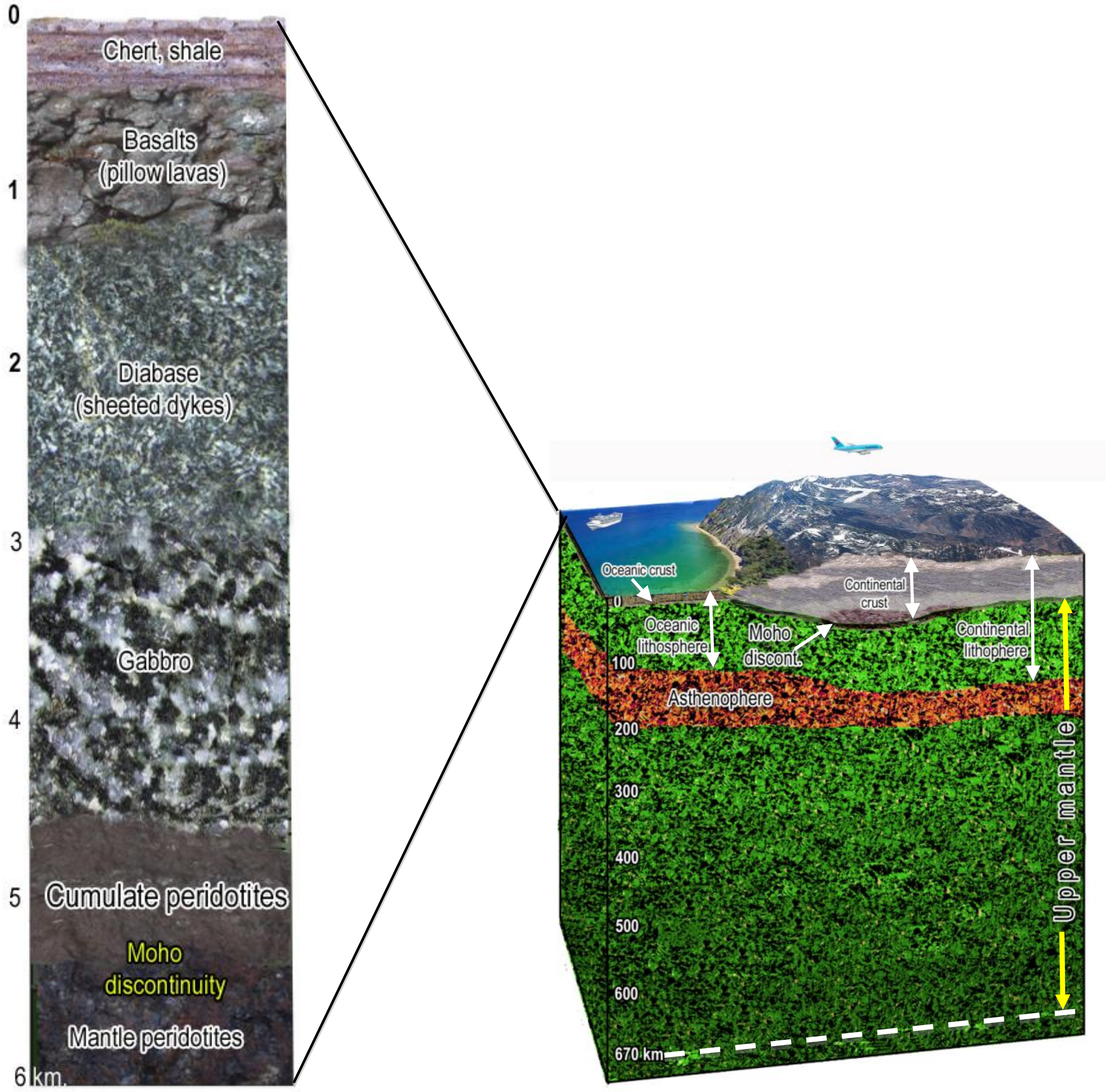


Fig. 78. Oceanic crust (left) lies above the upper mantle (right).

Magmas are also being created in the convergent zones (Fig.73), i.e. by subduction of the oceanic lithosphere under the oceanic lithosphere (oceanic arc) or oceanic under the continental lithosphere (volcanic arc). Intermediate to acid magmas are being created by partial melting and intensive contamination in volcanic arc. If they are being crystallized at depths, they make batholiths of quartz diorite, diorite, granodorite, quartz-monzonite or granite in composition. If these magmas reach the surface, followed by strong and explosive eruptions (due to the presence of water), they form: dacite, andesite, quartzlatite, etc. and they sometimes form huge mountain ranges (Andes).

The heat, accumulated in the inner and outer core, upper and lower mantle has the key role in geological processes in and on the planet Earth. Without sufficient heat, there wouldn’t be convection drifts, motions of lithosphere (plates), magmatism, volcanism, metamorphism or tectonics. Gravitational energy has an important role, and without it, motions would be chaotic.

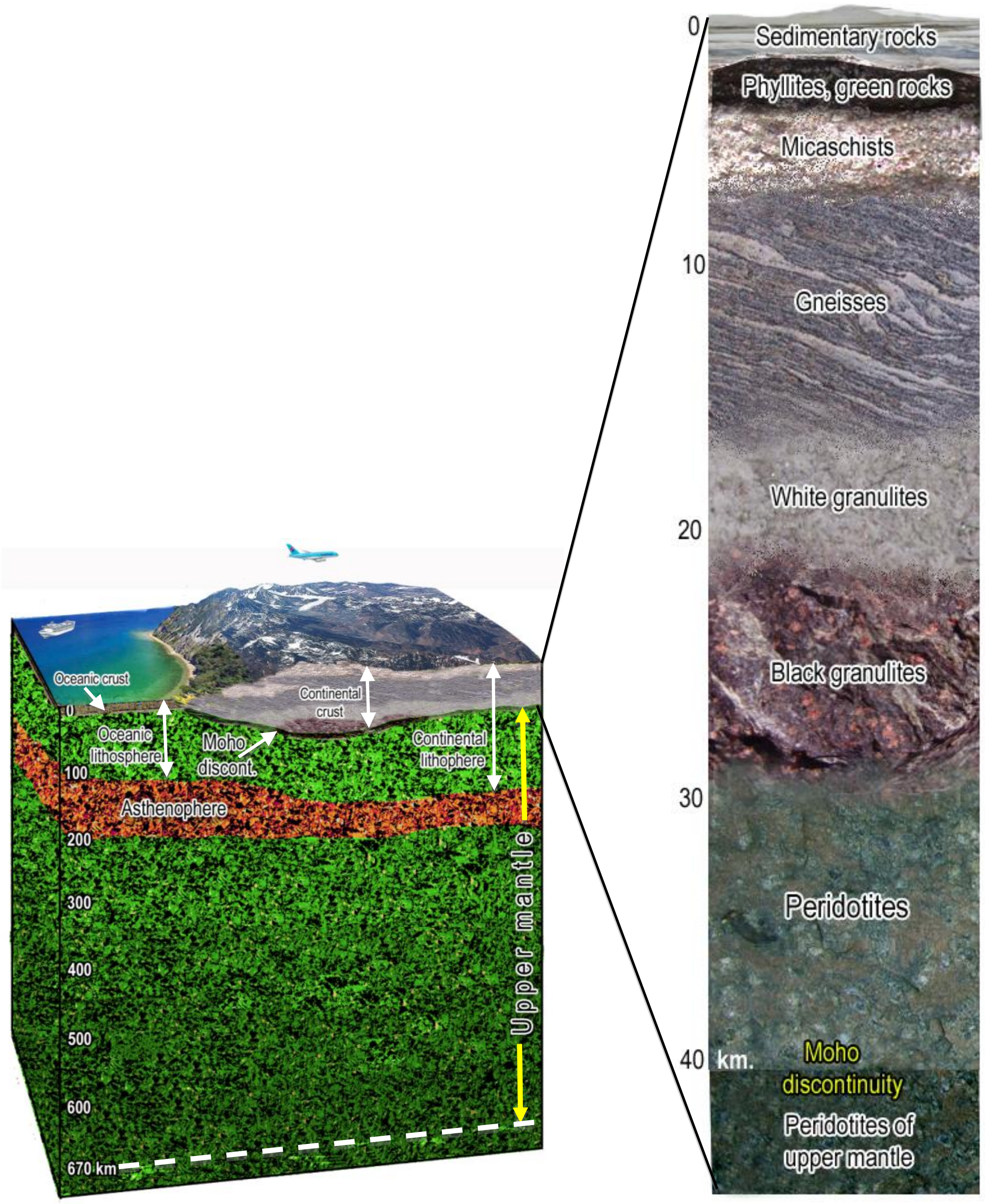


Fig. 79. Continental crust (right) lies above the upper mantle (left).

We have to mention the theory of plate tectonics that explains motions of oceanic and continental lithosphere (plates), their collision, moving apart or subduction and the creation of magmas of different composition. Geological processes are present at every part of our planet. They are steady and permanent, creating the conditions for the existence of the living creatures on Earth, including mankind.

6.1.1. MAGMA

Magmatic (igneous) minerals form by crystallization of magma, the melt consisting of silicate and alumosilicate groups like SiO_4^{4-}, $Si_2O_6^{4-}$, $AlSi_3O_8^{-}$, and cations Mg^{2+}, Fe^{2+}, Fe^{3} , Ca^{2+}, Na^{+}, K^{+}, etc. with volatile component (gas phase). In the latter dominates dissociated water and minor amounts of gases: CO_2, H_2S, HF, and HCl.

Magma with low content of volatile or lack of it considers to **dry magma.** Anhydrous minerals, olivine, pyroxene, feldspars etc. crystallize from it. Magma, containing volatile component, commonly from 2 to 10 % is **wet magma.** It enables crystallization of hydrous minerals, amphibole and mica.

Volatile component declines the temperature of crystallization along with the viscosity of magma.

Temperature of magma is considerably lower than the temperature of crystallization of any mineral included in it. The temperature of magma is a function of oxide and volatile component contents, as well as of place (depth) of consolidation and varies from 500 °C (carbonatites), to above 1000 °C (basic magma). Magma, which has reached the surface, is called lava.

Higher content of silica (SiO_2) and alkalis (Na_2O, K_2O) in melt produce dense, viscous and inert magma. Lower content of silica and alkalis cause magma to being more buoyant, crystallize at higher temperatures and commonly form at greater depths.

Crystallization of minerals from magma is a very complex process, influenced by temperature, pressure and composition of magma, which consists itself from numerous elements in a different ratio. This process is gradual and takes place following the order of crystallization minerals from the melt.

When the pressure and temperature decrease the minerals of the highest temperature of melting will begin to crystallize: zircon, sphene, apatite, oxides of Cr, Fe, Ti, Ni sulphides that commonly occur as accessory constituents. Their abundance in igneous rocks is very low, from 1 to maximally 5 % vol.

Further decrease in temperature of magma led to crystallization of essential (major) minerals in rocks. These minerals built anion groups of the highest energies, SiO_4, Si_2O_6, i.e. silicates of Mg, Fe, and Ca: olivine, pyroxene.

Feldspars will be produced from magma that contains Na, K, AlO_4 and AlO_6. Volatile component in magma led to crystallization of amphiboles and mica, which commonly associate with mentioned minerals.

Minerals have different role in igneous rocks and should be distinguished on:

- **Accessory or minor minerals,** which crystallize as the first and are not essential to defining the root name of the rock. They occur in small-sized grains, up to a few millimeters, and in low abundance from 1 to 5 % vol. The commonest accessories in igneous rocks are magnetite, spinel, chromite, zircon, sphene and apatite;
- **Major or essential minerals** whose presence affects the root name of the rock. For instance, olivine in peridotite, basic plagioclase in gabbros, alkali feldspar and quartz in granite. Generally, these minerals are the most abundant, too. Their transformation under the influence of hydrothermal solutions, oxidation or atmospheric agents led to formation of **secondary minerals**.

According to chemical com**position the minerals in igneous rocks may be sialic (light) and femic (colored or dark)** minerals (figs. 80 and 81).

Sialic minerals are silica and alumina-rich (their name is applied to chemical symbols for elements Si and Al) and light colored, white or gray minerals.

This group includes alkali feldspar, plagioclase, muscovite and quartz, which are main minerals in igneous rocks from granite to gabbro.

Femic minerals are rich in magnesium and iron (also named due to code for Fe and Mg). They are dark brownish or black, occasionally dark-green, but extremely rare are lighter in color. In this group match olivine, pyroxene, amphibole (hornblende) and biotite.

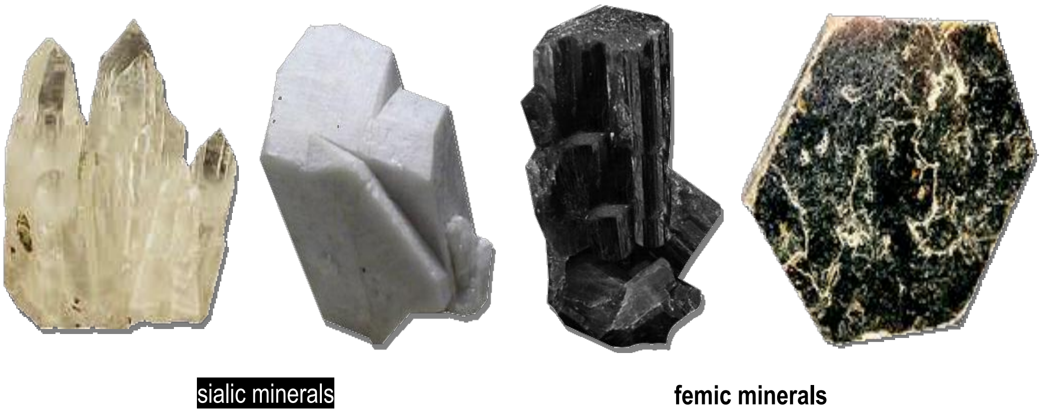


Fig. 80. Sialic (light) minerals, from left to right: quartz and orthoclase, and femic (dark) minerals, hornblende and biotite.

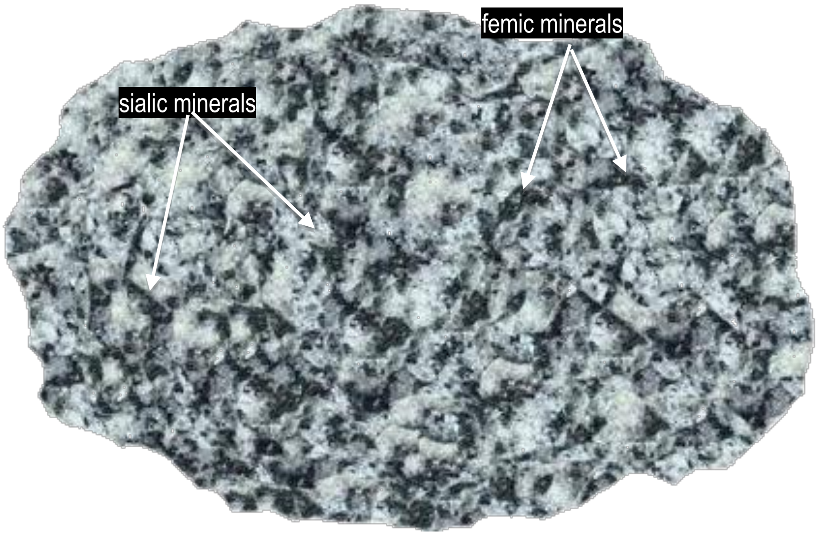


Fig. 81. Sialic (white), and femic (black) minerals in granodiorite.

Femic minerals are important constituents of ultrabasic and basic rocks (olivine, pyroxene) and intermediate rocks (pyroxene and amphibole). Presence of biotite, less frequent hornblende, is not uncommon in acid igneous rocks of granite group. Majority of femic minerals are susceptible and easily weathered, thus in rocks are commonly partly to completely replaced with secondary minerals. So, the olivine is in ultrabasic rocks as a rule transformed into serpentine, while pyroxene and amphibole in basic and intermediate rocks are chloritized or epidotized, whereas the biotite, femic mineral in acid rocks (granite) is often chloritized.

According to content of SiO_2 igneous rocks are divided on: **ultrabasic rocks** with up to 45 % SiO_2, **basic rocks** that contain 45-52 % SiO_2, **transitional** or **intermediate** with range of 52 to 66 % SiO_2 and **acid rocks**, if the amount of SiO_2 exceeds 66 %.

6.1.1.1. Ultrabasic magma

Cooling and crystallization of **ultrabasic magma** leads to formation of peridotite. High content of magnesium and iron (up to 50 % rock volume) and low content of silica (beneath 45 %) in the main, femic minerals, olivine, ortho and clinopyroxene reveals a dark-green to almost black color to these rocks.

When the temperature in ultrabasic magma starts to decrease, the **accessory constituents/ minerals,** with the highest temperature of crystallization (melting), start to crystallize: **nickel** and **cobalt sulphides** or Cr and Fe oxides, **chromite**, **magnetite**, as well as **spinel and platinum minerals**. Accessory minerals commonly segregate as a „liquid drops" of a few millimeters to a few centimeters in size (fig. 82). Sulphide and oxide minerals are only a few percents abundant in ultrabasic magma and thus are neither apparent nor recognizable except due to their metallic lustre or under polarizing microscope.

Already formed accessory minerals are of greater density than the melt is, and will sink and accumulate under gravitational force in downward parts of igneous mass. Their significant content, of oxides or sulphides, may produce ore deposits of nickel, iron, chromium and platinum. Depending on the aluminum content and conditions during crystallization, the garnet (pyrope), spinel, basic plagioclase (anorthite) may occur in peridotites as an accessory constituents, too.

Further fall of temperature, after segregation of sulphides or oxides, enables crystallization of silicate minerals, which are the main minerals in peridotites: **olivine** as the first, and then **orthopyroxene.** The **clinopyroxene** crystallizes as the last one and marks the end of crystallization of ultrabasic magma (fig. 82). The extremely rare presence of negligible water amounts in ultrabasic magma would allow hornblende to being formed, while the presence of alkalis enables the development of phlogopite.

Fig. 82. Segregated "drops" of chromite within the olivine mass (left),and peridotite built of olivine and pyroxene (right).

Some authors disagree with the existence of peridotite magma. Peridotites build the **upper mantle** and in present position have been placed tectonically either as cold, crystallized bodies or as „hot slabs" without significant thermal influence to adjacent rocks. Their contact is always tectonic (fig. 83).

Fig. 83. Peridotites nearby Kraljevo "arrived" from the upper mantle. Above left, the rock sample.

Ultrabasic rocks in lower parts of oceanic crust, cumulate peridotites, are exceptions. They formed by fractional and gravitational differentiation of gabbro magma (fig. 84).

Fig. 84. Peridotites of Deli Jovan are lower parts of the oceanic crust. Above right, the rock sample.

6.1.1.2. Basic magma

Cooling of **basic magma** with 45 - 52 % SiO_2 gives rise to gabbroic rocks. The **accessory minerals,** minerals of the highest temperature of crystallization have been formed as the first, too. Most of them are titanium minerals: **sphene**, **ilmenite**, **rutile**, and **titanomagnetite**, although apatite and zircon are not uncommon. Mentioned minerals are hardly visible in rocks macroscopically as are low abundant (make up to a few percents of the rock mass) and are colored black like pyroxene. Their size, up to a few millimeters, is additional disambiguating factor. Accessory minerals in gabbro are recognizable due to metallic lustre and crystal habit, commonly octahedrons, or under polarizing microscope due to their optical properties. Ilmenite and rutile may be locally abundant and of economic importance, producing titanium ore deposits.

Further temperature drop enable silicate minerals, which represent the essential minerals in basic rocks, to crystallize from basic magma. Depending on composition, **olivine** and **orthopyroxene,** the essential minerals in olivine gabbro and norite, are the earliest phases. Afterwards crystallize **basic plagioclase** (bytownite, anorthite) and **clinopyroxene** (augite, diallage), giving rise to „common gabbro”, olivine lack (fig. 85).

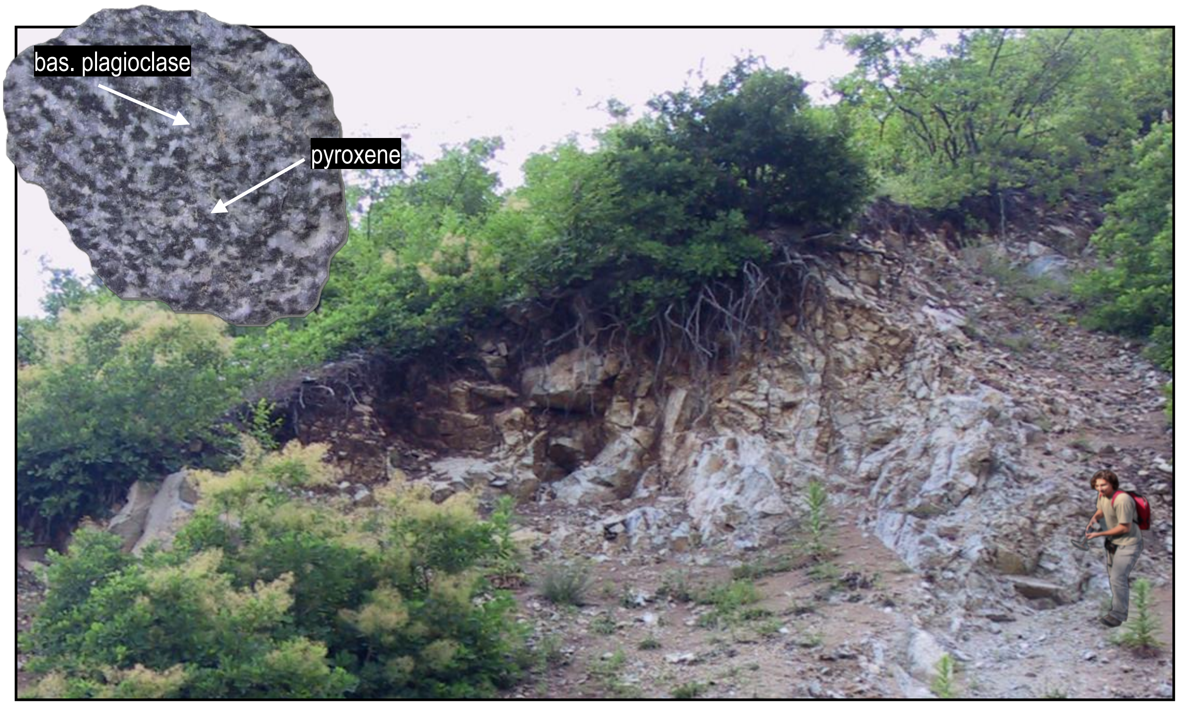


Fig. 85. Outcrop of gabbro near Priboj, and the sample of it, above left.

If there is some water in magma, the hornblende and/or biotite would appear, too. This is the final stage of crystallization of minerals from gabbro magma. Gabbros, as has been mentioned above, build lower layers of the oceanic crust.

When the gabbro magma, generated deep in the Earth`s interior, come to a surface, the basalt develops. Basalt has the same composition as the host rock gabbro, but displays porphyritic texture.

The vast basalt masses erupt in rift zones, the sites of oceanic lithosphere (oceanic plates) divergence where they cover ocean bottoms, sometimes a few thousandths square kilometers spatially. Basalt is composed of basic plagioclase (bytownite, anorthite) and pyroxene. Olivine occurs occasionally. Basalt flows commonly deserve shape of pillows, hence in the literature are named „pillow” lavas (fig. 86).

Fig. 86. „Pillow" lava of basalts at Bistrica (near Prijepolje) is submarine effusions.

Basalts are exposed in rift zones within the continental lithosphere (so called, continental plateau basalts). They have similar mineral composition as those mentioned before, but are enriched with a certain incompatible microelements and instead to occur as "pillow" lavas build vast shields. Basalts also derive in „hot spot" areas, pretty far from an active tectonic zone (rift, subduction zone etc.). Such generated basalts are alkali basalts and have been formed throughout low-degree partial melting of the mantle at great depths.

The low volatile content leads to „peaceful" eruptions, without explosion and emission of volcanic bombs and ash. They commonly occupy wide craters of "lava lakes". Because of the low viscosity they are buoyant and appear also as lava „flows". Such are the Hawaii basalts (fig. 87).

Fig. 87. Basalt lava flow on the island of Hawaii.

6.1.1.3. Transitional (intermediate) magma

Intermediate or transitional magmas have higher contents of SiO_2 (52 to 66 %) than the basic does, thus are lighter and less viscous. Under cooling, these magmas create diorite, quartzdiorite, granodiorite and quartzmonconite.

The first minerals that would crystallize from intermediate magma are **accessory minerals** that are chemically quite different from those in gabbro magma. The most frequent are **apatite** and **zircon**. These minerals make only a few percents of the rock volume and occur in crystals of a few millimeters in size, hence are not obvious except under the microscope.

Afterwards crystallize **the essential minerals**: **intermediate plagioclase** and **pyroxene**. Water is commonly present in this magma, and enables **hornblende** and **biotite** to be formed. The crystallization of mentioned minerals may left behind an "excess" of silica when the quartz will crystallize as the last one (fig. 88).

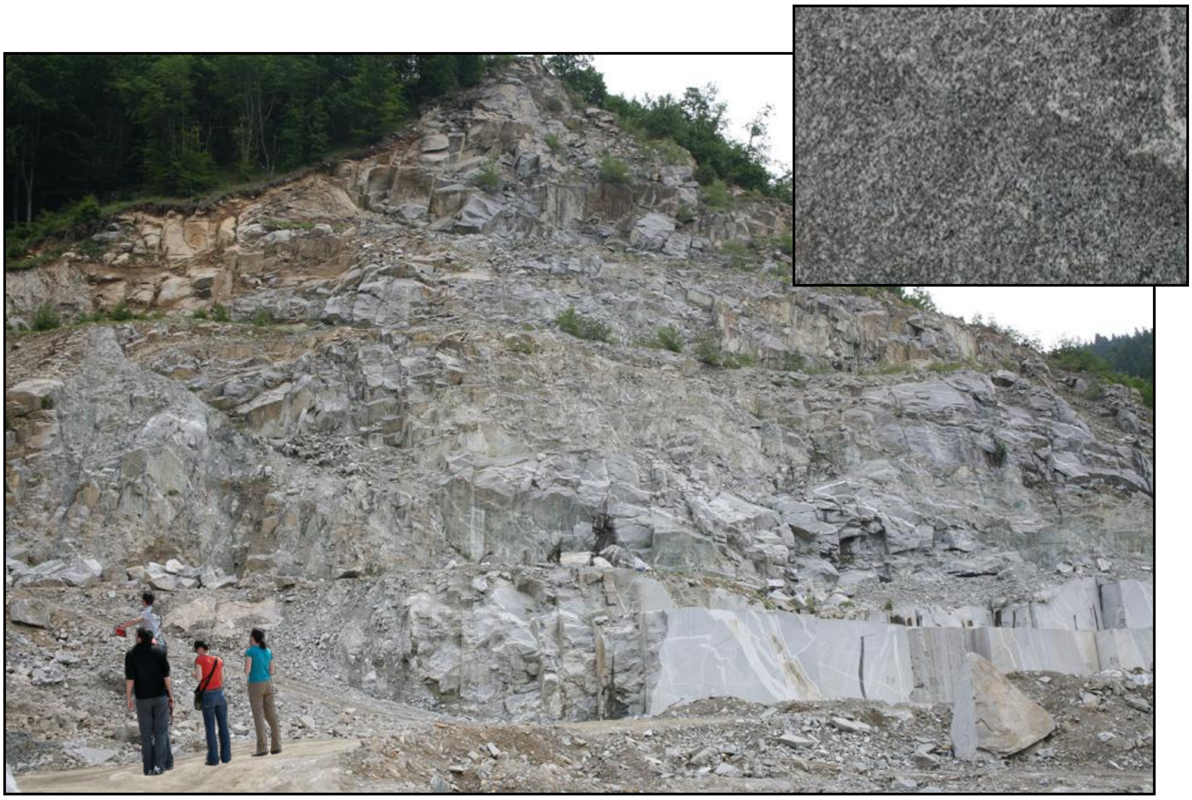


Fig. 88. Quartzdiorite of Cezlak (Slovenia), right above – the rock sample.

Intermediate (and acid) magmas generate in subduction zones where the oceanic lithosphere is underthrusting beneath continental lithosphere. Intensive tectonics and complex igneous processes in root zones of subduction regions generate magmas, which cools within the crust to form diorite, quartzdiorite and rocks with higher silica (SiO_2) and alkalis (K, Na): granodiorite, quartzmonzonite and granite with hornblende and biotite. If magma rises to the surface along tectonic faults or cracks (volcanic arc setting) it forms andesite (fig. 89), dacite and quartzlatite, which are significant carriers of metallic, copper, gold, led and zinc minerals.

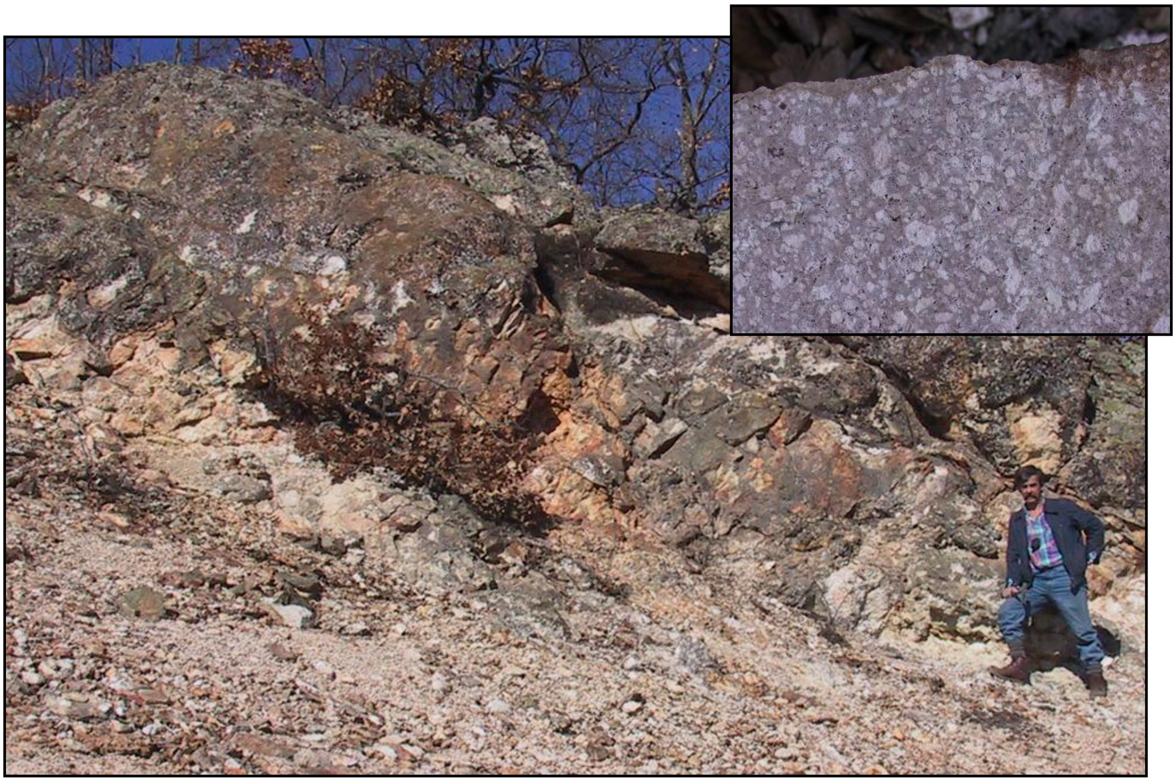


Fig. 89. Andesites of Lece bear mineralization of copper and gold. Right above - the rock sample.

6.1.1.4. Acid magma

Acid magma contains over 66 % SiO_2, and is rich in alkalis (K i Na), alumina (Al_2O_3) and silica (SiO_2), and depleted in Mg, Fe and Ca. Such magma gives rise to granite.

Crystallization of acid magma starts with **accessory minerals**, **apatite**, **zircon** and **sphene,** which similarly to previous mentioned are up to a few percents in abundance. These minerals occur in tiny crystals up to a couple millimeters and therefore are not apparent except under polarizing microscope.

The **earliest silicate** minerals, which are the essential minerals in granite, will crystallize subsequently. When **magma is anhydrous**, dry (rarely), the **pyroxene** would crystallize immediately. If there is some **water** (more often), the **hornblende** and/or **biotite** will form. Feldspars crystallize synchronously or immediately after those minerals: **acid plagioclase** (albite), than **orthoclase** and/or microcline. At last the **quartz** will crystallize (fig. 90).

The rock form through crystallization of **acid magma**, **granite,** always includes **quartz**.

As the consequence of high silica content and low Fe, Mg and Ca, granites are lighter in color than gabbros, diorites, quartzdiorites, granodiorites and quartzmonzonites.

Granites generate also in root parts of subduction zones where the oceanic lithosphere underthrusts continental lithosphere (so called I-granites). Only granites composed of muscovite, orthoclase and quartz, and lack of hornblende and biotite (so called, **S-**granites), generate by metamorphism, partial to complete melting of sedimentary rocks (sandstone). This process takes place at high pressures and temperatures within the continental lithosphere, which is much thicker than the oceanic lithosphere (fig. 91).

Fig. 90. I-granite of Straža nearby Ljubiš, right above-the rock detail.

Fig. 91. S–granite of Konjuša at the Cer Mt. Right above-the rock sample.

The given order of crystallization is valid for magmas of „general" composition, which cooled slowly and gradually and was not affected by significant tectonic movements.

The mentioned order of crystallization may be changed as a function of the depth of storage, content of volatile component, influence of tectonic forces, velocity of cooling, etc.

6.1.1.5. Pegmatite and aplite

Pegmatite derives in final stage of crystallization of magma, commonly granite in composition, which is volatile rich. The development of pegmatitic melt requires the closed system, which will prevent a migration of volatile component as well as a certain depth (over 10 km) where magma would be stored, cooled and crystallized.

The drop of temperature leads to crystallization of accessory constituents, than hornblende, biotite, alkali feldspar and quartz and generates granite, from wet granite magma with 5 to 10 % of volatile components. Only the minor amount of volatile component enters into amphibole and mica structure. This process of gradual cooling was continuous and all minerals were slowly and completely crystallized producing the rock with granular texture. In this process were „spent” more than 90 % of magma.

After granite has been formed, the rest of melt composed of „excess” of not yet crystallized orthoclase and quartz (which were the most abundant minerals in granitic magma) and volatiles that is mostly composed of water, dissociated on OH and H ions as supercritical fluid (temperature exceeding 374.5 °C), and less abundant HCl, HF, B, Cl, H_2S, etc. Content of volatile component is in the residual melt significantly higher than in the beginning, approaching to 20% of its mass.

In the rest of melt retain oxides of elements that, due to their geochemical properties and low abundance, did not form their own minerals during the main phase of crystallization. These elements are with small ion radius, such as: Li, Be, B or large ion incompatible elements like: Cs, Rb, Ba, rare earth elements, U, etc.

Further drop in temperature yields to crystallization of feldspars and quartz from the rest of granitic magma. These two minerals are still the most abundant and will left behind a „new” rest of melt, with more volatile component and enriched with incompatible elements. Such change in composition of the rest of melt is continual and dependable of the order of crystallization.

Melt with feldspar, quartz and volatile component over one third or occasionally a half of it, is **pegmatitic melt,** whose temperature is approximately 500 °C.

The interplay of the not yet crystallized orthoclase and quartz, incompatible elements: Li, Be, B, and rare earth elements etc. with the volatile component in such melt when cooled, leads to creation of numerous **pegmatitic minerals**: lithium pyroxene and mica, beryl, tourmaline, topaz, including biotite, garnet and epidote from iron-bearing systems (fig. 92).

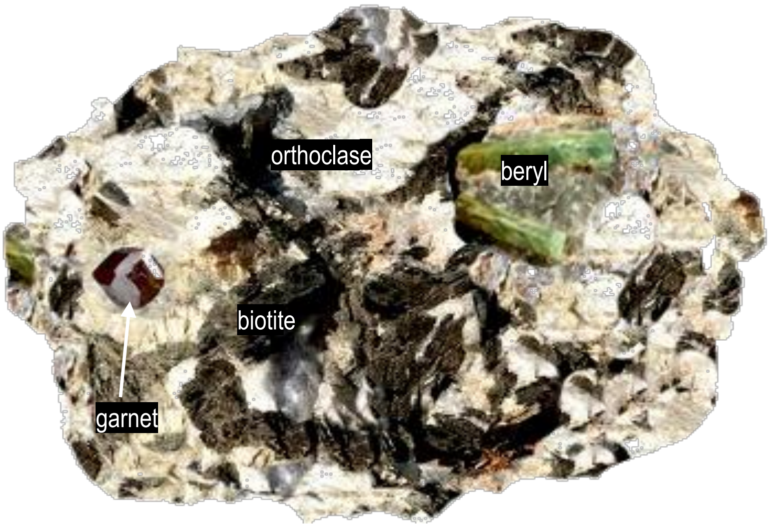


Fig. 92. The sample of pegmatite.

Orthoclase and quartz are the most abundant minerals in pegmatitic melt and should be only partially spent in building of mentioned minerals. Consequently, these two minerals occur in individual crystals that commonly build up to a half mass of pegmatite.

With further temperature decrease (at 400 °C) the „remaining" minerals with rare earth elements (orthite), uranium minerals, etc. crystallize.

Mineral composition of pegmatite is highly variable and depends on the amount and chemistry of volatile component, as well as on the amount and type of incompatible elements. Majority of pegmatites built orthoclase, quartz and muscovite, and biotite, garnet and tourmaline occasionally. Lithium micas and pyroxene, beryl and topaz are rare. It should be emphasized that the most amazing and far largest crystals of aquamarine (beryl variety) and topaz were found in pegmatites (fig. 93).

Fig. 93. Emerald crystal (left), and topaz (right), found in pegmatite.

A large amount of volatile component, which approach to almost 50 % of pegmatitic melt causes a high internal pressure and low viscosity leading to it's pronounce mobility and intrusive ability - incorporation into the host, just solidified rock, granite, quartzmonzonite or granodiorite. It is not unusual for pegmatitic melt to „walk off" the host rock and "inhabits" surrounding rocks along the already existing mechanical discontinuities, faults, fissures or schistosity planes.

When this melt intrudes into the host rock, or less frequently into the adjacent rocks, the internal pressure rapidly drops down forcing minerals to crystallize very fast as they are not able to remain in the melt any more. High mobility of ions and low viscosity of melt, due to high content of volatiles, supports the formation of large crystals in spite pretty fast crystallization. Consequently, the pegmatites are very coarse-grained igneous rocks and may bear crystals up to a few meters in length.

Pegmatites commonly form veins in the genetically related host rocks: granites, quartz-monzonites and granodiorites. Veins are from a few centimeters to one meter thick, rarely thicker (fig. 94).

Pegmatite is rare in gabbro or in quartzdiorite, as these rocks generate from magma which is poorer in volatile component and incompatible elements than granitic melt. Pegmatites related to gabbros consist of basic plagioclase and pyroxene (gabbro-pegmatite), whereas pegmatites related to quartzdiorite is built of intermediate plagioclase, amphibole, biotite and quartz.

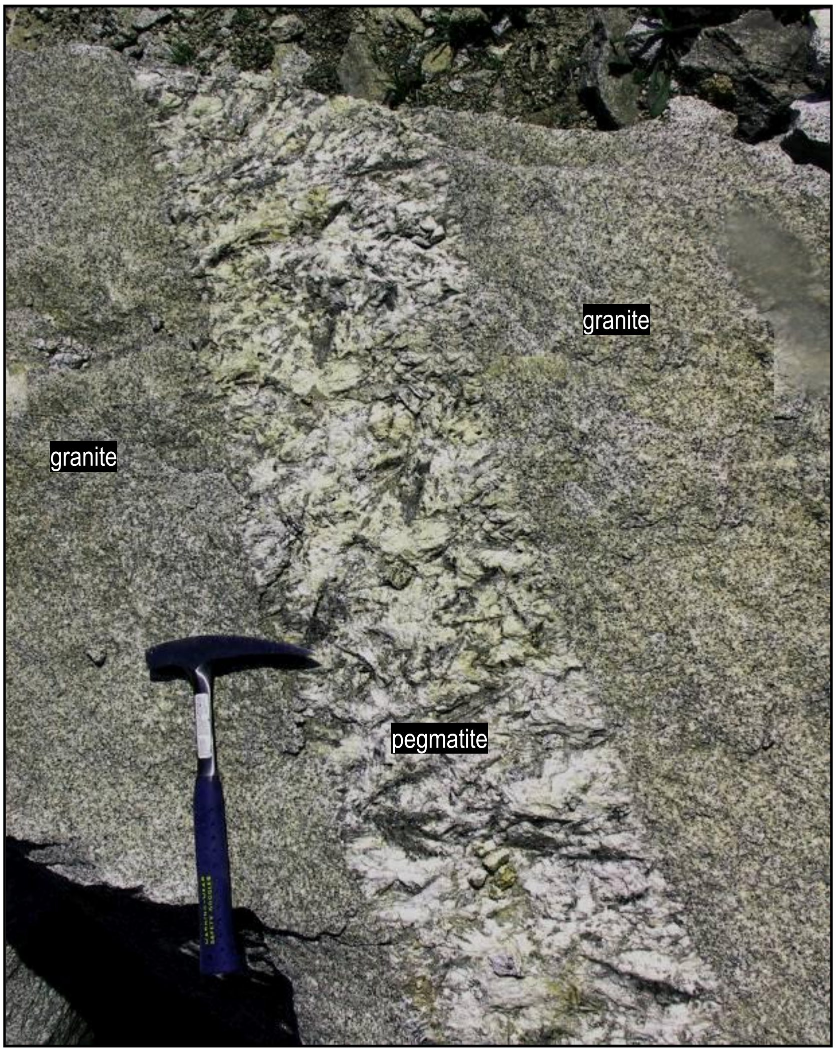


Fig. 94. Pegmatite vein in granite from Bukulja.

Pegmatites occasionally build their own massifs. Such appearance requires a high volatile-bearing magma, which allows the system to behave as pegmatitic melt during all stages of crystallization.

Some acid magma may finish crystallization without pegmatitic phase, although the volatile component is present. This happens when any of additional geological requirements, necessary for pegmatite formation, is not fulfilled: the depth and way of magma storage, composition of surrounding rocks, and a type of tectonic processes, which have significant impact on crystallization of igneous minerals.

In the final stage of crystallization of acid granitic magma, which has negligible amount of volatiles, or they are lacking, in the rest of melt remained only feldspar and quartz. Under low internal pressure such melt penetrate and cooled inside joints of already crystallized granite or along other mechanical discontinuities, fissures and faults, producing **aplite**. These rocks, just like pegmatites, occur in veins up to ten centimeters thick, are typically white in color, very fine-grained and consist of orthoclase and quartz only.

Veins of aplite and pegmatite are commonly found together in a nature (fig. 95), implying to multiphase and complex process of crystallization of granitic magma and on important role of volatile content, depth and way of magma storage, composition of surrounding rocks, and a type of tectonic processes.

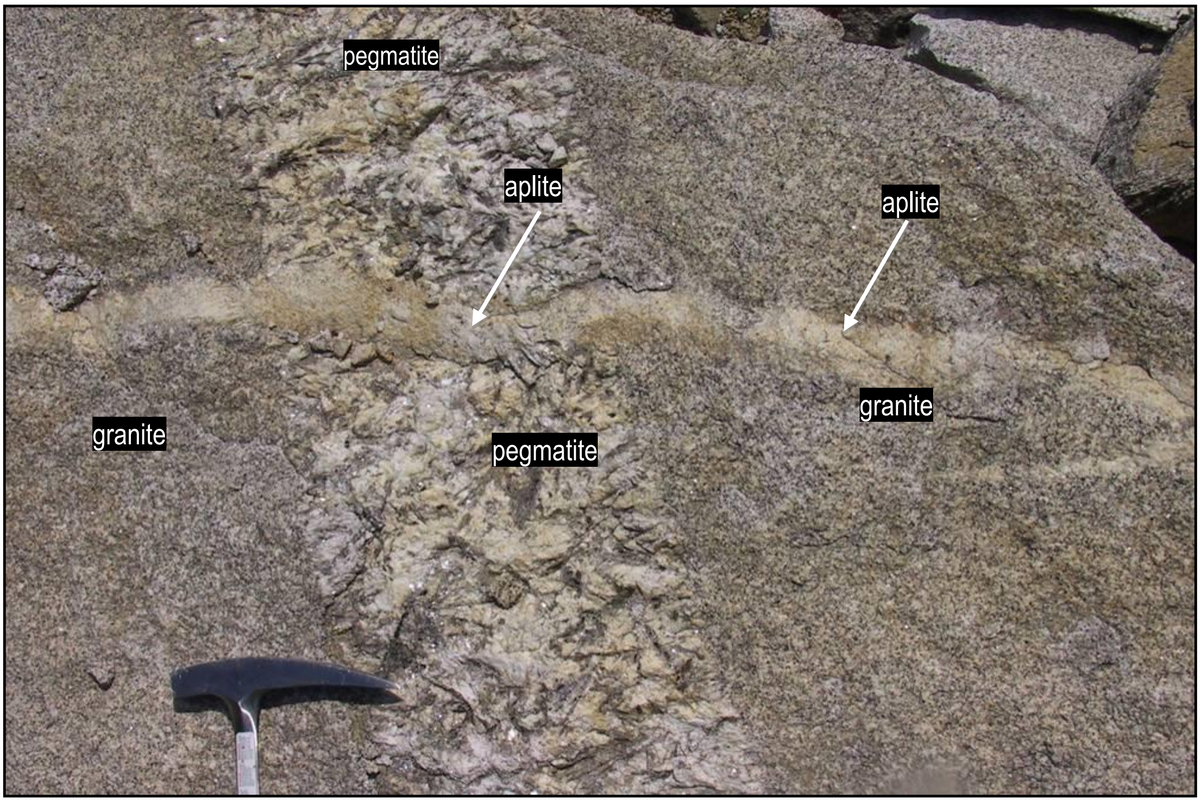


Fig. 95. Aplite vein cutting the pegmatite vein in granite from Bukulja.

6.1.2. POSTIGNEOUS MINERALS

6.1.2.1. Pneumatolitic minerals

Pegmatites are not the last products of crystallization of the granitic magma. Residual quartz, less abundant feldspar and volatile component, which dominates, at lower temperatures turns into overheated **gaseous state**, **pneumatolitic solution.** It is rather solution then melts due to insignificant amount of silicate in it. Although the temperature exceeds critical temperature of water (374.5 °C), giving rise to gaseous state, it is lower than in pegmatitic melt.

Volatile component includes water, fluorine, boron, sulphur-dioxide, carbon-dioxide and metals, which do not take part in silicate minerals that build granites and pegmatites: tungsten, tin and molybdenum. The mentioned metals are incompatible and of lower crystallization temperature then the silicate minerals in whose lattice do not enter. They concentrate after magmatic and pegmatitic stage, in pneumatolitic solution and occur as complex compounds with oxygen, or less frequently sulphur. They are only stable within a certain pressure/temperature intervals, as well as at confident pH and Eh of solution.

When the temperature drops down, the crystallization of the „remaining" silicates, feldspar and quartz, which react with boron and fluorine to create tourmaline, axinite and fluorite, took part. These minerals, including the excess of silica, quartz, which occur in any time and at every place associated with small amounts of carbonates, oxides, fluorides etc. compose the rock **greisen** (fig. 96).

Afterwards, the crystallization of metal-bearing minerals of the highest melting point under the established conditions: tungsten and tin oxides (wolframite, scheelite, cassiterite) or molybdenum sulphide (molybdenite), which is not petrogenic minerals (fig. 97). Both these species may locally concentrate and form ore deposits.

Pneumatolitic solution differs from pegmatitic melt having a low internal pressure, hence low intrusion ability. Crystallized minerals are commonly found in the host rock, along joints, fault zones or at contact with surrounding rocks that serve as „impermeable barrier” for their crystallization.

Fig .96. Greisen with axinite (left), and fluorite (right).

Fig. 97. Greisen with cassiterite.

Pneumatolitic solutions, as have been already mentioned, are related genetically to acid rocks, granite, quartzmonzonite and granodiorite. However, they are not always present.

There are authors that explain the development of greisens through interplay of pneumatolitic solution and surrounding, silica-rich rocks.

6.1.2.2. Hydrothermal minerals

The residual volatile component upon cooling and decerease the temperature below the critical temperature of water (374.5 °C) turns into **a liquid state**. These hot aqueous solutions consider **hydrothermal solutions.** Beside water, silica, sulphur dioxide and carbon dioxide, these solutions contain remaining metals, which did not enter in structure of silicates or were not deposited (crystallized) during pegmatitic or pneumatolitic phase due to much lower crystallization temperature. Such metals are: copper, gold, zinc, lead, silver, arsenic, mercury, antimony.

Hydrothermal solutions are genetically related to intermediate volcanic rocks (andesite, dacite, and quartzlatite, and their pyroclastic rocks) of shallow-seated magma reservoirs. During the final stage of crystallization of silicates, volatile component causes a high internal pressure, which exceeds the outer pressure and come to the surface where it rapidly cools and converts into liquid state producing **hydrothermal solutions**. In these environments a pegmatitic and pneumatolitic phases are lacking due to low outer pressure. Hydrothermal minerals most frequently precipitate within the host rock, as solutions percolate along a numerous cracks that penetrate a rock itself. Very rare these solutions „visit" rocks around. Hydrothermal minerals occur in veins from few centimeters to few meters thick (fig. 98).

Fig. 98. Hydrothermal vein (~ 10 cm thick) with lead and zinc minerals, sphalerite and galena (black) formed inside cracks in andesite (mine Rudnik at the Mountain Rudnik).

Hydrothermal solutions also bear quartz, sulphides and sulphosalts of copper, lead and zinc, as well as carbonates: calcite, rhodochrosite, siderite, sulphates and oxides, as the least abundant. Their content and mutual relationships are highly variable, depending on composition and temperature of hydrothermal solutions along with the velocity and place of deposition.

The highest temperatures, from 374.5 °C to approximatelly 300 °C, are considered in the geology of ore deposits, as the **kata zone.** As the first will be „deposited" copper sulphides (chalcopyrite, enargite, and bornite), gold, etc. At temperatures from 300 to 200 °C, in the **meso**

zone, a lead and zinc sulphides (galena, sphalerite) and silver „take part". At the lowest temperatures, within the so-called **epi** or **telethermal zone** from 200 to approximatelly 100 °C in the final phase of crystallization sulphide minerals of antimony, mercury and a part of arsenic minerals (stibnite, cinnabar, realgar, orpiment) precipitate from hot water solutions. All mentioned minerals are of **hydrothermal origin**.

The given order of crystallization is general, though the lack of some metals or different order is not uncommon.

When the hydrothermal solution infill large and wide fractures up to a few meters across (fractures are commonly from a few centimeters to 1 m across) the crystallization of minerals takes place in a vast empty, free space and the euhedral crystals or druses of amazing colors and shapes (fig. 99) will being precipitated.

Fig. 99. Crystal druse derived inside a fracture in the host rock where the minerals crystallized from hydrothermal solutions (Trepča).

This genetic group of minerals is very important because the majority of copper, gold, silver, lead and zinc-bearing minerals form hydrothermally.

Hydrothermal solutions seep through fissures and synchronously change minerals in country rocks. The intensity of such changes is a function of temperature and composition of hydrothermal solutions and of mineral composition of rocks around. The commonest types of alteration are: silification, kaolinitization of feldspars, chloritization of hornblende and biotite, alunitization (fig. 100).

Minerals formed by hydrothermal alteration of rocks with metal-bearing veins are good prospection criterions in discovering a new ore bodies. Such minerals, particularly in copper mineralization, are: neobiotite, adularia, kaolinite, sericite, alunite, diaspor, corundum, zunite, potassium sulphate (fig. 101).

Presented igneous, pegmatitic, pneumatolitic and hydrothermal origin of minerals is given for a general cases and summarized in figure 102. However, a lack of pegmatitic phase and the presence of pneumatolitic and hydrothermal phases are not uncommon in a nature even for magmas with volatile component.

In a certain cases pegmatites contain only feldspar, quartz and muscovite, while minerals with boron and beryllium are lacking. Similarly, pneumatolitic minerals may include only minerals of tungsten or tin-bearing minerals.

Fig. 100. Hydrothermally altered andesite, Lipa, Crni vrh (east Serbia), above right – the detail.

In intermediate volcanic rocks (andesite, dacite, quartzlatite), which underwent hydrothermal mineralization, commonly dominates one temperature phase (kata, meso or epi) with characteristic assemblage of metalliferous minerals.

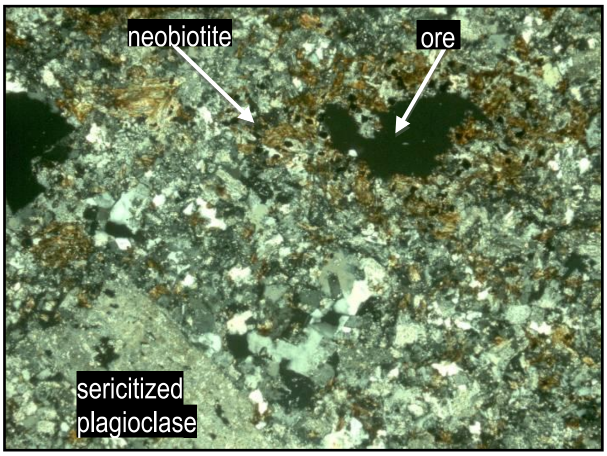


Fig. 101. Hydrothermally altered andesite with neobiotite. Microphotograph, XPL and magnification 100 ×.

Very important conditions in generation igneous, pegmatitic, pneumatolitic and hydrothermal minerals are: composition of magma, content of volatile component and the depth of magma storage, including a character of surrounding rocks and influence of tectonic motions. Almost every day the explorers get answers on numerous questions concerning the origin of mentioned minerals, but at the same time some new questions arise, waiting for answers. This is mineralogy, petrology or geology - the eternal inspiration and challenge, which sustains our job astonishing.

Hydrothermal phase	Not present	Not present	 Sulphides of Cu, Zn, Pb, Sn, Hg carbonates, quartz from 100-375° C	Rarely
Pneumatolitic phase	Not present	Not present	Rarely	 GREISEN Topaz, axinite minerals of Sn, W, Mo from 375-500° C
Pegmatitic phase	Not present	Rarely	Rarely	 PEGMATITE Orthoclase, muscovite quartz, beryl, topaz from 500-600° C
Magmatic phase	 Ultrabasic rocks < 45% SiO2 PERIDOTITE Main minerals OLIVINE, PYROXENE Accessory minerals chromite, magnetite T> 1000°C	 Basic rocks 45 do 52% SiO2 GABBRO Main minerals BAZ. PLAG, PYROXENE Accessory minerals ilmenite, sphene from 800-1000° C	 Intermediate rocks 52 do 66 % SiO2 DIORITE Main minerals INT. PLAG, PYROXENE, HORNBLENDE. Accessory minerals apatite, zircon,sphene from 700-900° C	 Acid rocks > 66 % SiO2 GRANITE Main minerals ORTHOCLASE, ALBITE BIOTITE, MUSCOVITE, QUARTZ. Accessory minerals zircon, apatite,sphene from 600-800° C

Fig. 102. Schematic presentation of genesis of certain igneous, pegmatitic, pneumatolitic and hydrothermal minerals from magmas of various composition. The average temperature of magmas is given in red color.

6.2. SEDIMENTARY MINERALS

All igneous, metamorphic and sedimentary rocks at the Earth`s surface are exposed to influence of atmospheric agents, wind, fluctuation of temperature, and impacts of vegetation. These processes associated with tectonic acivity guide to physical and chemical weathering of rocks. Decomposed rocks and minerals commonly are transported and will be accumulated under suitable conditions. New-formed minerals are genetically the sedimentary minerals. They form within the temperature range from –50 to 200 °C and pressures up to a few hundreds bars, which are significantly lower than conditions required for generation of igneous and metamorphic minerals. Sedimentary minerals are genetically divided into three broad groups: clastic, chemical and organic.

6.2.1. CLASTIC MINERALS

Physical (mechanical) weathering breaks large rocks into smaller ones, decomposes rocks producing boulders, fragments and clasts varying in size from few cubic meters to a few microns (clay). Smaller-sized clasts, a few millimeters in average, include grains of stable minerals that are resistant to physical and chemical weathering: quartz, muscovite, garnet, gold, cassiterite, and magnetite.

Fig. 103. A sand beach, right above a detail with quartz grains (white), which predominate.

Such minerals are the most frequent in a sea or river sand (fig. 103), and may concentrate in significant quantities, ready for exploitation. Pure quartz sand is the source for glass production. Gold and some gem minerals also are separating from sand.

6.2.2. MINERALS FORMED CHEMICALLY

Physical and chemical weathering of rocks commonly operates together in a nature altering its composition and mineral content. A part of components dissolved from minerals will being transported either as ionic (molecular or true) solution or as colloidal solution and will precipitate (deposit) upon suitable conditions: change in concentration, temperature, pH, etc. Elements, such as potassium and sodium, make ionic solutions and occur as hydroxides. Conversely, calcium and magnesium often are being transported in a form of carbonates. Silica, alumina and iron use to „travell” as both, hydroxides and oxides in colloidal solutions.

Precipitation, i.e. deposition of an mineral from a **ionic solutions** takes part due oversaturation of solution with a given component, evaporation of solvent, commonly water (fig. 104), addition or removal of some components that increase or decrease a solubility of other components (e.g. reducing CO_2 in solution the calcium-carbonate is less soluble), fluctuations in temperature and pressure. On such way form salts, gypsum and some carbonates.

Fig. 104. Table salt, formed troughout evaporation of sea-water; right above, halite.

Precipitation from ionic solutions had undergone also minerals that form from hot springs, geysers. Such minerals are aragonite and calcite that were dissolved in hot water, which originates from great depths. When it rises and seeps on a surface, a drop in pressure and temperature leads to precipitation of calcite and aragonite, commonly in the immediate geyser vicinity (fig. 105). These two minerals compose a rock, referred as travertine, which is a desirable decorative stone.

Submarine (underwater) volcanic eruptions emit a large amount of silica in a form of quartz, opal and chalcedony that will precipitate upon oversaturation of solution, changes in pH and Eh conditions, temperature drop or will be used for moulds of certain organisms (radiolarians). Iron is also emitted by these eruptions beside silica, either as hydroxide (limonite) or as oxide (hematite), which are often precipitated and associated with the mentioned silica minerals (fig. 106).

Fig. 105. Calcite (white), precipitated from hot springs. Right above is a detail.

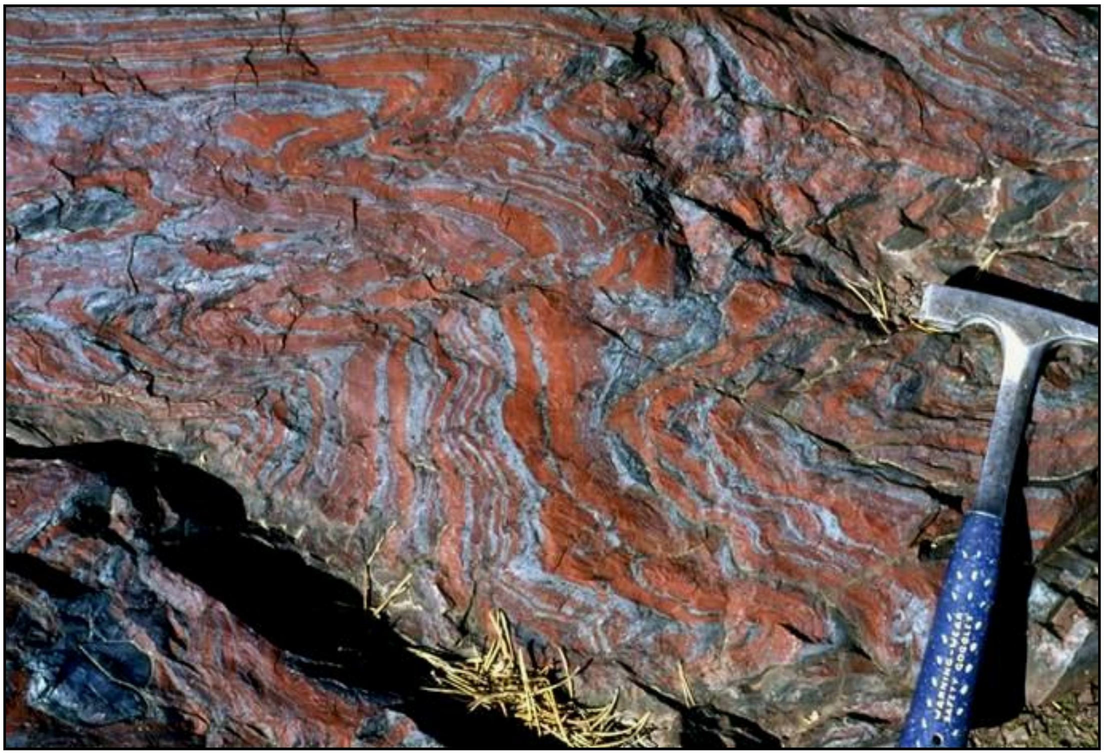


Fig. 106. Hematite and limonite (grey) and quartz (opal; red), precipitated from submarine eruptions.

Particles, dissolved in **colloidal solution** will precipitate (flocculate) when their electrical charge is removed, water molecule around colloidal particles. The action of strong electrolytes, if they are abundant in solution, as well as opposite charged colloidal particles, favours precipitation too. The commonest natural colloids are silica, aluminium, iron and manganese hydroxides (fig. 107).

Fig. 107. Colloidal solution of iron covers an area approximately 5 m in width, and 10 m in length. Left above, precipitated limonite.

6.2.3. MINERALS FORMED OF THE REMAINS OF PLANTS OR ANIMALS

Sedimentary minerals may originate from dead plants and animals, i.e. of their remains: calcite in corals, opal and chalcedony in radiolarians. The largest masses of sedimentary rock, limestone, made primarily of calcite, were formed by accumulation of remains of the coral species that thrive in huge colonies and build-up coral reefs near coastline at shallow depths (fig. 108). These animals use calcium carbonate, which is dissolved in sea water for their skeleton. Beside corals, in shallow depths close to shorelines, particularly in tropical seas snails and shells thrive also. Those species use similarly calcium-carbonate for their molds, which will accumulate to form huge masses of limestone.

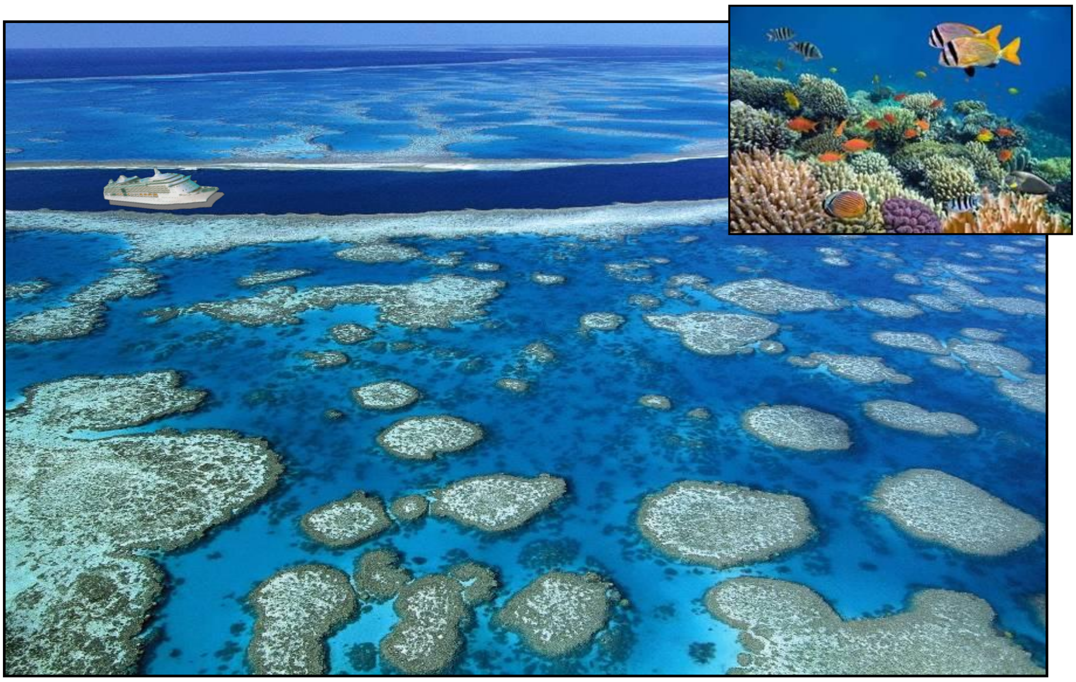


Fig. 108. Coral reef, right above is corals whose skeleton is of calcite.

Recall radiolarians, whose molds are generally of amorphous silica (chalcedony, opal) from sea water. Radiolarians thrive in deep sea environments and the required silica originates from submarine (underwater) eruption of basaltic lava. Their remains, along with fragments of radiolarian colonies that „float and wander" over the ocean, form cherts (fig. 109).

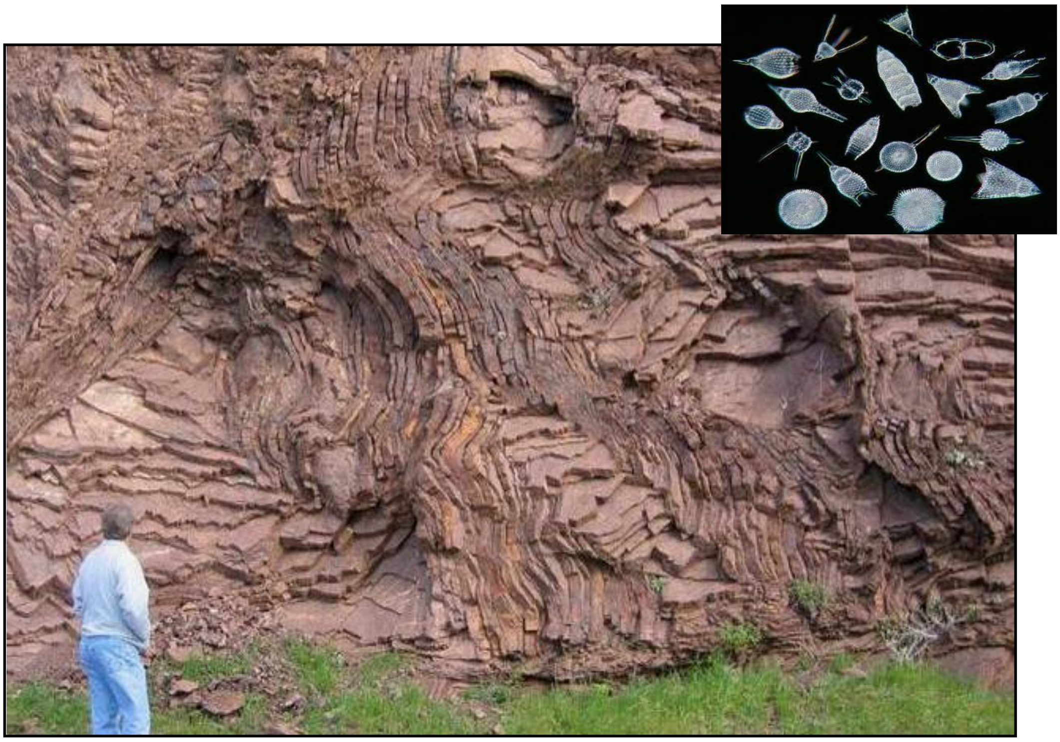


Fig. 109. Layers of chert are red in color due to impurities of limonite, originating from radiolarian fragments. Right above are radiolarian skeletons. Magnification 100×.

Precipitation or formation of minerals from solution may be favoured by plants that consume some components dissolved in water. On this way forms calcite which compose the rock tufa, common rock formed close to waterfalls (fig. 110).

When the drops of water fall on ground, they splash and the dissolved calcium bicarbonate breaks into insoluble calcium carbonate and carbon dioxide, which plants around waterfall breathe.

Accumulation of insoluble calcium carbonate forms the rock tufa with characteristic vesicular structure. Due to easy handling and exploitation, as well as it's pronouncing physical-mechanical properties (good sound and thermal isolator), the tufa had a significant role in construction of our Medieval monasteries.

Fig. 110. The formation of calcite, which makes the rock tufa around waterfall. Right above, the rock detail.

6.3. METAMORPHIC MINERALS

Tectonic movements, faulting, folding, transgression and regression, bring the existed igneous, sedimentary and metamorphic rocks in the PT conditions that are different from those during their formation, forcing them to adapt to new-formed environmental conditions through changes in mineral composition and texture, to undergo **metamorphism**. These processes lead to **metamorphic minerals**. Changes in mineral include morphological, structural and chemical changes, giving rise to new minerals that are stable in higher or lower PT conditions. Significant role in metamorphic processes has H_2O and CO_2.

Temperature and pressure rises with the depth causing different geological processes. The largest masses of metamorphic rocks form upon tectonic forces, when the huge rock masses sink in greater depths and adjust to new environmental conditions, i.e. undergo metamorphism. Metamorphism is isochemical when rocks or minerals do not change chemically, and conversely, allochemical if the original rock or mineral underwent chemical changes.

According to environment and conditions that cause metamorphism, the metamorphic minerals formed under regional and contact-metamorphism are distinguished.

6.3.1. REGIONAL METAMORPHIC MINERALS

Regional metamorphic minerals results from sediments buried by tectonic movements in a greater depths. It is widespread and affects large regions, hence the name.

Temperature rises gradually with a depth during regional metamorphism due to geothermal gradient. Pressure is rised by the weight of overlying rocks and by tectonic forces. Pressure is either stress, in shallower depths, or hydrostatic in deeper levels.

The rise of temperature and pressure leads to unstability of existed minerals and their replacement with another, metamorphic minerals that are stable in new conditions. The final product is the quite new, metamorphic rock, with its own mineral composition and fabric. The commonest structure is the schistose, and textures are lepidoblastic or granoblastic.

Regional metamorphic minerals form, depending on the depth, pressure, temperature and rock composition in a wide range of pressures, from 1 to over 20 Kb and temperatures from 200 to over 1000 °C, when rock partially to complete melt to form magma which forms igneous rocks when it solidifies. Regional metamorphic minerals are commonly in petrology distinguished on the basis of metamorphic grade:

LOW-GRADE REGIONAL METAMORPHISM expresses the changes that occur at temperatures from 200 °C (when sedimentary processes end and metamorphism begins) to 400 °C and at pressures up to 5 Kb, corresponding to depth of 5 km. In such conditions clays and tuffs, as the most sensitive rocks on pressure/temperature changes, develop: sericite, chlorite, albite, epidote, zoisite, tremolite and actinolite (fig. 111);

Fig. 111. Sericite, light grey in phyllite (left) and chlorite, green in chlorite schist (right).

INTERMEDIATE METAMORPHIC GRADE corresponds to changes that rock undergoes at temperatures from 400 °C to 600 °C and pressures of 5 to 10 Kb. Such conditions are found at depths from 5 to 20 km. Further transformation of clays, tuffs, sandstones and igneous rocks leads to: biotite, hornblende, garnets, kyanite, sillimanite, and staurolite (fig. 112). Most of these minerals remain stable during a high-grade metamorphism;

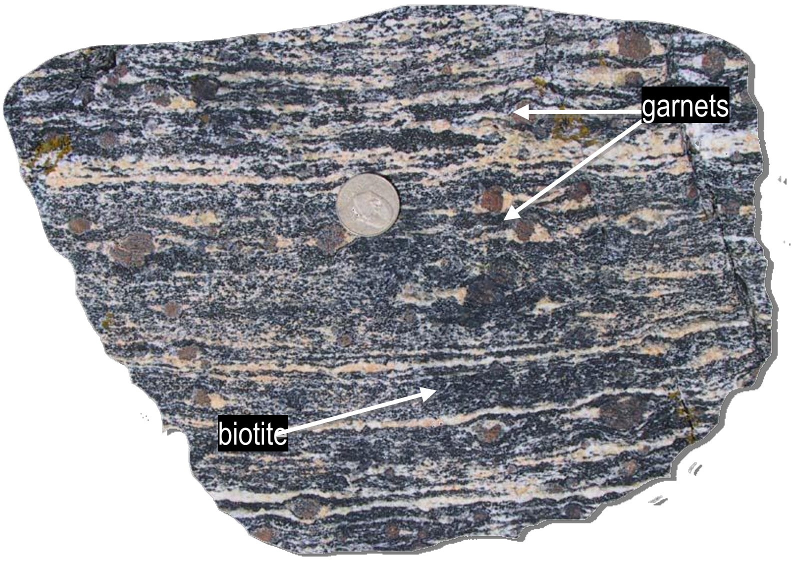


Fig. 112. Garnet (red grains) and biotite (black flakes), in gneiss.

HIGH METAMORPHIC GRADE considers to changes in rocks which take part at temperatures exceeding 600 °C and pressures over 10 Kb at depths beneath 20 km. Such conditions favor the anhydrous metamorphic minerals to be formed: alkali feldspar, garnet, omphacite, kyanite (fig. 113).

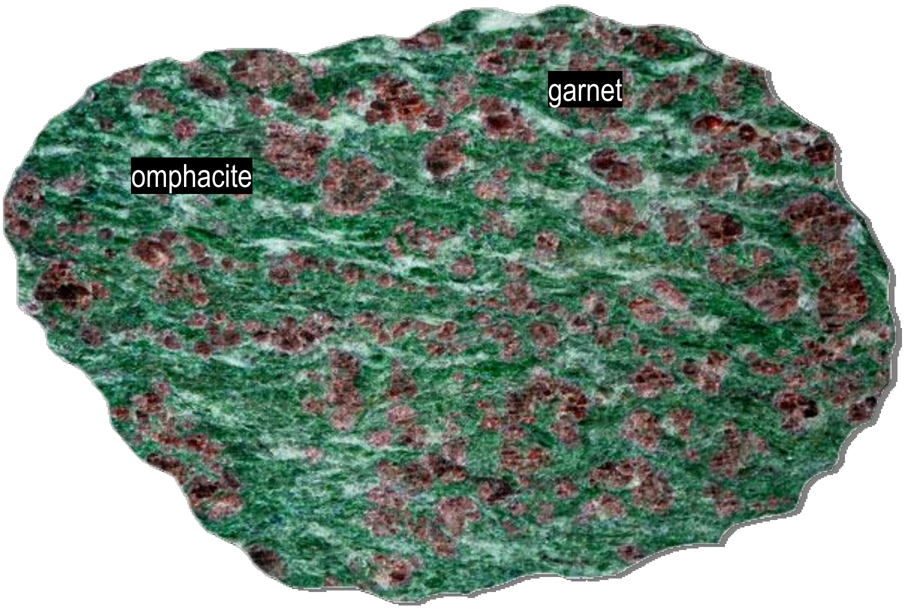


Fig. 113. Omphacite (green) and garnet (red) in eclogite.

Metamorphic minerals form in subduction zones where oceanic lithosphere is sinking beneath continental or oceanic lithosphere, too. In such regions pressures are very high (exceeding 10 Kb), whereas temperature is relatively low (up to 400 °C) and enable formation of distinct mineral assemblage: lawsonite, glaucophane, crossite and jadeite (fig. 114).

Fig. 114. Minerals formed in subduction zones: crystals of lawsonite in chlorite schist.

The figure 115 presents the commonest association of regional metamorphic minerals formed by metamorphism of clays, sandstone, tuff and igneous rocks in a certain pressure/temperature conditions. There are minerals that are stable in a wide range of P and T conditions: biotite above 400 °C until 800 °C (in closed system), garnet and kyanite from 500 °C to nearly 1000 °C (in dry system).

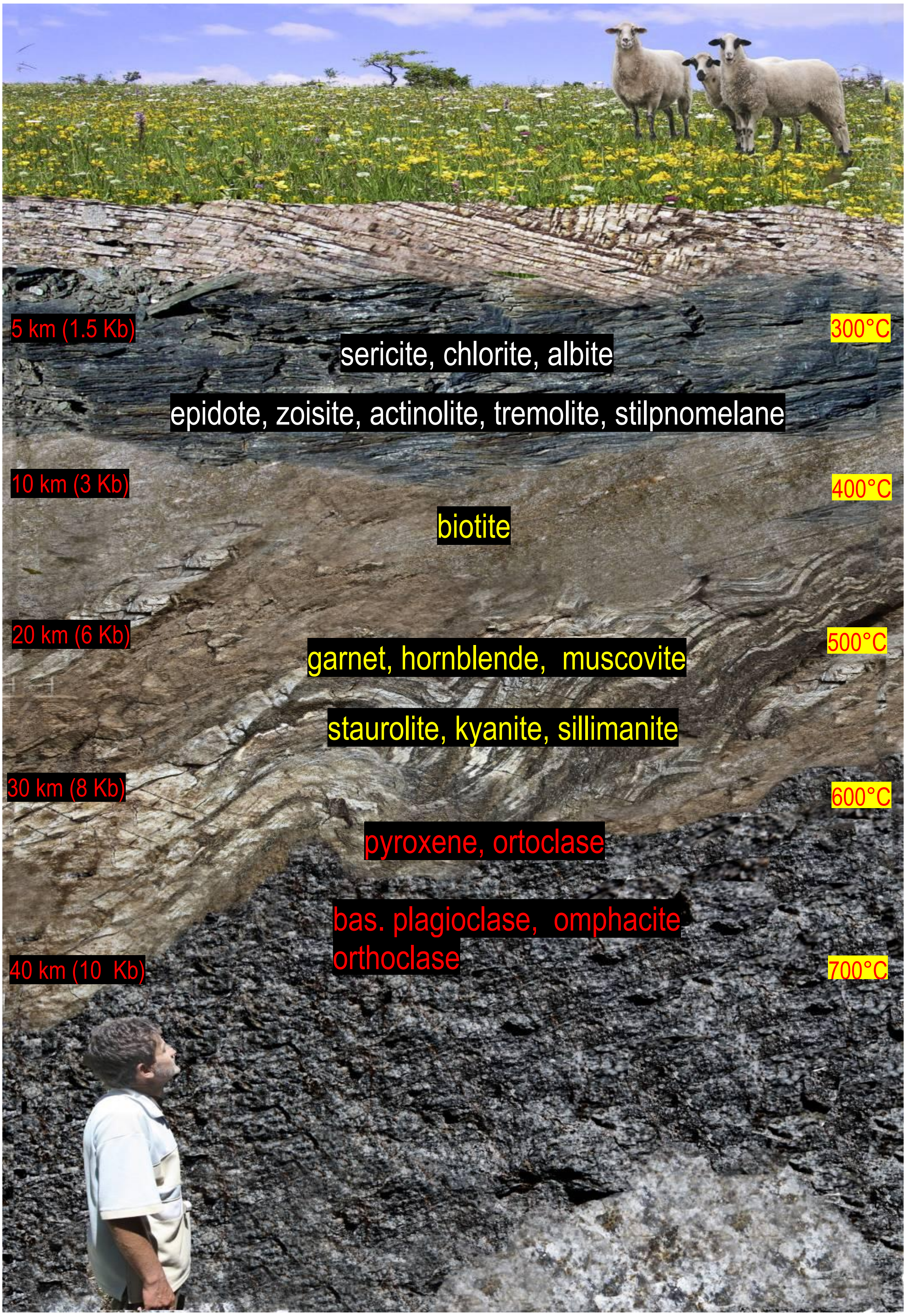


Fig. 115. The most frequent minerals in low-grade (white colored), intermediate (colored yellow) and in high-grade regional metamorphism (red colored).

6.3.2. CONTACT METAMORPHIC MINERALS

Contact metamorphic rocks, i.e. **contact metamorphic minerals** form at the immediate contact of hot magma and cooler country rocks. Volatile rich igneous intrusions release large amount of heat or interact with a country rocks.

Contact metamorphic changes, which include change in chemical composition, structure and texture, are the best developed at the contact between acid, granitic magma and sedimentary rocks.

The intensity of contact metamorphic changes depends on:

- size of intrusion, i.e. of magma, which causes contact metamorphic changes, its composition, crystallization degree and volatile content;
- depth of storage;
- composition of country rocks;
- type of the contact between magma and country rocks.

More intensive contact metamorphic changes cause large intrusions of silica and volatile rich magma.

Shallow-seated, up to 10 km, intrusions lead to more intensive contact metamorphism and formation of diverse mineral assemblages as country rocks are cooler and the difference in temperature is more pronounced.

The type of changes enables recognition of minerals that form during **thermal metamorphism** and **during contact metasomatism**.

6.3.2.1. Thermocontact minerals

Thermocontact minerals form under thermal influence of hot magma on surrounding, country rocks. The absence of chemical reactions considers such metamorphism to isochemical.

The most intensive thermocontact changes take place at the contact of acid, granitic magma and clastic sediments, particularly clays and fine-grained pyroclastic rocks, volcanic tuffs, that are the least resistant sedimentary rocks to temperature variations.

A thermometamorphic halo (aureole) develops around intrusion during these processes. It can range in width from few meters to hundreds of meters, depending on the already mentioned factors: the size and crystallization degree of intrusion, the type of contact, etc.

The rise of temperature leads to recrystallization of minerals in sedimentary rock and, commonly at depths around 10 km (fig. 116) forms the rock called hornfels, which consists of andalusite, cordierite, pyroxene, feldspar, and biotite (fig. 117).

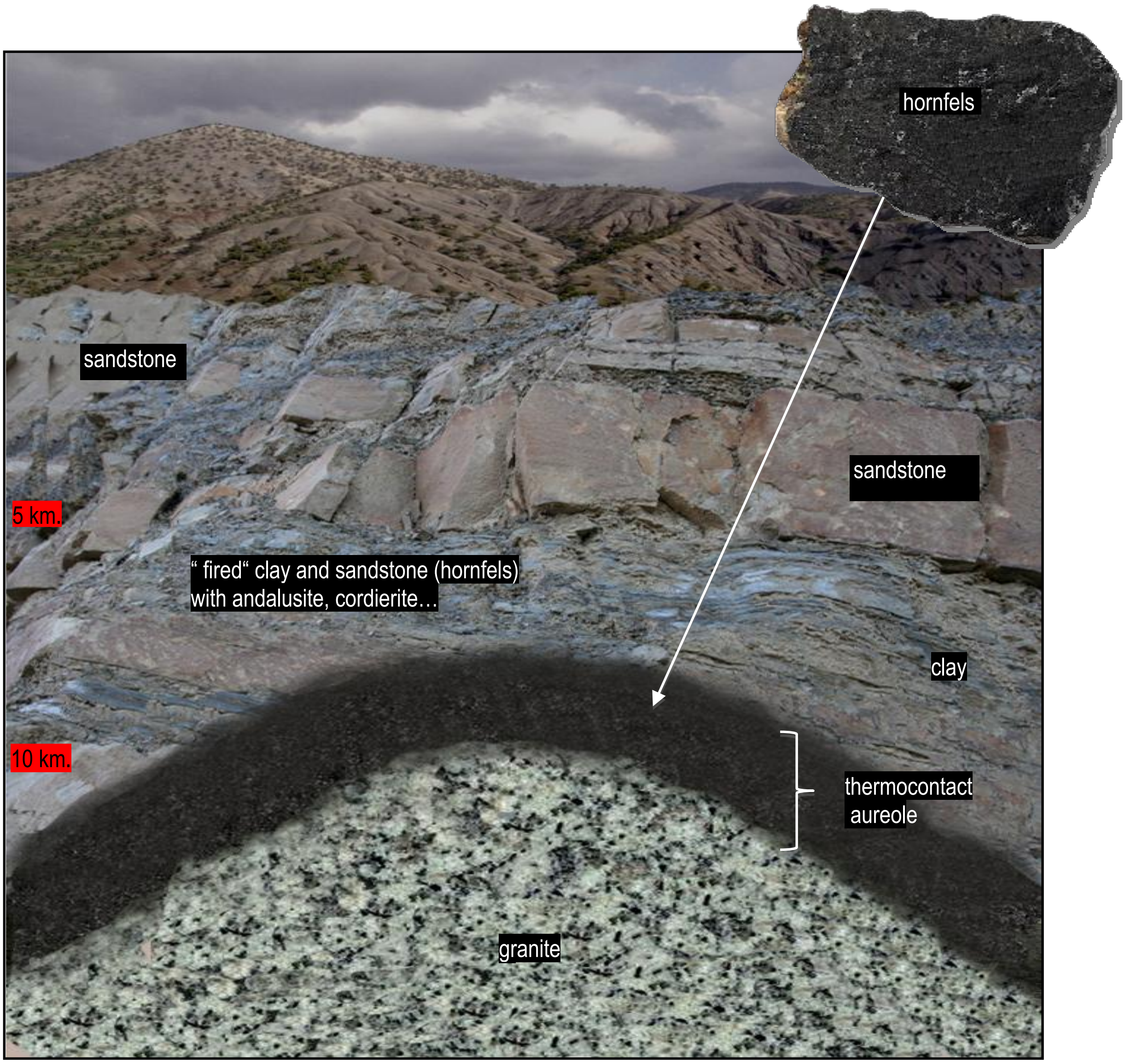


Fig. 116. Formation of thermocontact minerals. Right above, the rock hornfels.

Fig. 117. Andalusite (left), and cordierite (right) are typical thermocontact minerals.

6.3.2.2. Contact-metasomatic minerals

Contact metasomatic minerals form when magma interacts with a country rocks that intrudes. The most intensive reactions occur between **limestone and marlstone rocks** with **acid, wet granitic magma**.

The development of contact metasomatic minerals requires the „removal" of CO_2 from sedimentary rock (in petrology of metamorphic rocks known as an openned system), thus the reactions between Ca, Mg and Al in limestone and marlstone with quartz in granite will take part.

Metasomatic processes take part in both directions, thus the changes undergo marginal part of granitic magma, as well as the adjacent limestone or marlstone, leading to formation of skarn, the rock composed of contact metasomatic minerals (fig. 118).

This type of contact metamorphism is in respect to chemical changes, allochemical.

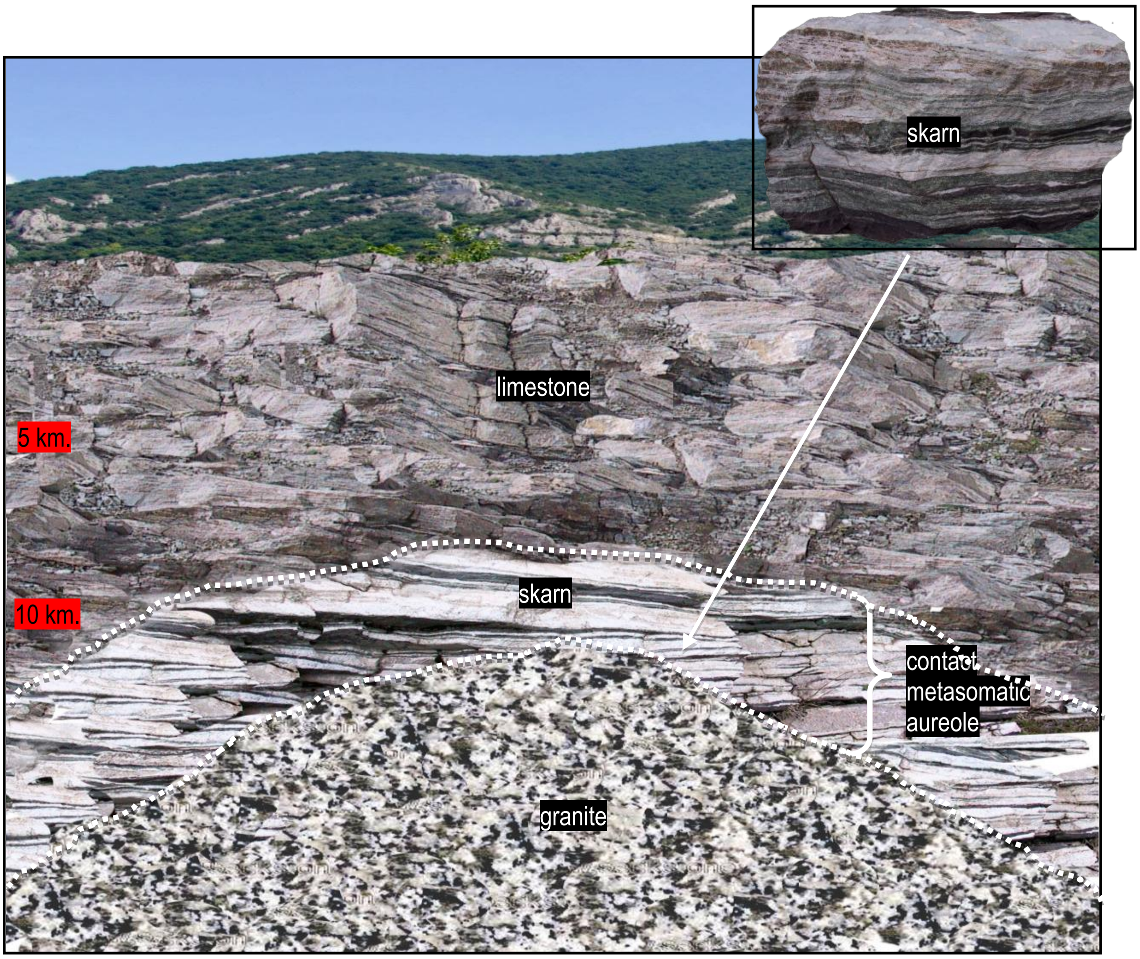


Fig. 118. Formation of contact metasomatic minerals, right above, the rock skarn.

Calc-silicate minerals are due to significant involvement of limestone and marlstone in metasomatic processes the most abundant in skarns: wollastonite, Ca-pyroxene: diopside, salite, hedenbergite, vesuvianite, Ca-garnets: grossular and andradite, basic plagioclase, etc. (fig. 119).

Fig. 119. Wollastonite (left), and vesuvianite (right), are typical contact metasomatic minerals.

These rocks bear important ore minerals of iron (magnetite), which is exploited when reserves are considerable (fig. 120).

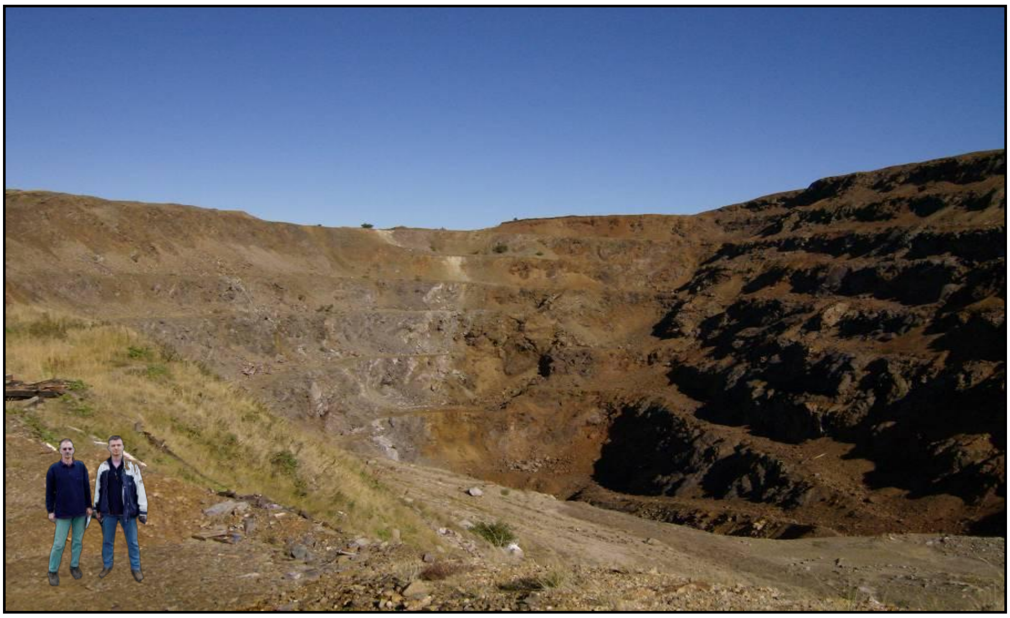


Fig. 120. The magnetite deposit in skarn, Kopaonik.

A numerous rock-forming minerals may form during more different processes, igneous, sedimentary and metamorphic. The most frequent are:

Quartz is the mineral that forms within all conditions. Igneous quartz is related to acid igneous rocks and is their essential. During metamorphic processes quartz derives through recrystallization of quartz-rich rocks. It also makes the rock quartzite, where is the only constituent. Quartz is resistant to physical-chemical weathering, hence is the very common and major constituent in sand or sandstone.

Feldspars are minerals of igneous and metamorphic rocks. Basic plagioclases are the essential minerals in basic igneous rocks but form also during regional metamorphism of high grade when being included in black granulite. Feldspars are present in contact metasomatic rock, skarn.

Orthoclase is the essential mineral in acid igneous rocks, forms also metamorphic and is found in gneisses, and white granulites. Monoclinic pyroxene and amphibole (hornblende) are igneous minerals and are mostly related to basic and intermediate rocks, gabbros, diorite, quartzdiorite and their volcanic equivalents. May be formed during regional metamorphism under intermediate or high grade conditions and represent the chief constituents of granulite, eclogite, amphibolite. Minerals, which form only igneous, metamorphic or sedimentary, are very rare in a nature as geological processes are interconnected and cyclic.

7. SYSTEMATIC MINERALOGY

Minerals, which build rocks, are rock-forming or petrogenic minerals. Their structure, chemical and physical properties, origin and the commonest associations will be presented in pages ahead.

According to chemical composition the essential rock-forming minerals are silicates, carbonates, oxides, hydroxides and native elements.

7.1. SILICATES

Minerals composed of silica and oxygen that bond other cations consider silicates. Electron configuration of silica and oxygen allows these two elements to form tetrahedra, which represent the main building blocks of the silicate group. Tetrahedra $(SiO_4)^{4-}$ is made of four-charged silicon atom with oxygen atoms on its corners (fig. 121). The oxygen serves for further bonding leading to more complex structures. Type of bonds is the base for classification of silicates.

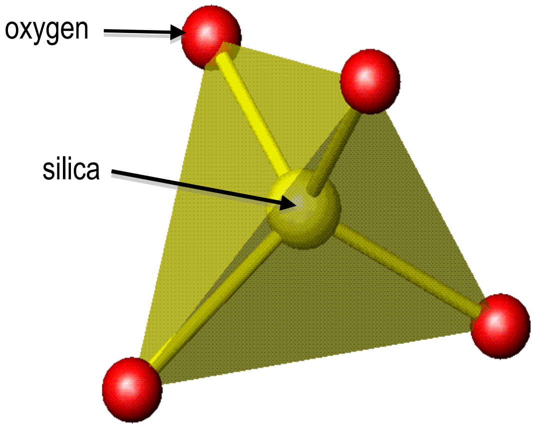


Fig. 121. The commonest graphic presentation of silica tetrahedra.

Aluminum is also forming tetrahedra with oxygen under limited mutual bonding. Minerals with alumina substituted silica in tetrahedra are alumosilicates. Alumina tetrahedra exist in feldspars, micas, amphiboles, and clay minerals.

Chemical composition of silicate minerals is very complex because a differently or same-charged elements may substitute each other and form solid solutions (isomorphic solutions). Silica and alumina tetrahedra may be linked on a few ways to form the "base" for incorporating certain cations: K, Na, Ca, Fe, and Mg. Water is, commonly as OH group, included in a structure of some silicates, as well as anions, such as: Cl, F, B, PO_4^{3-}, SO_4^{2-}, and CO_3^{2-}.

Although a small number of elements are taking part in building silicate minerals, the number of those minerals in a nature is pretty high, exceeding 2000, and the new one are constantly being discovered. They represent the most widespread minerals in the Earth`s crust and upper mantle, making 1/3 of all known minerals.

According to kind of bonds between the silica, $(SiO_4)^{4-}$ tetrahedra, are distinguished: **nezosilicates**, **sorosilicates**, **cyclosilicates**, **inosilicates**, **phyllosilicates and tectosilicates**.

7.1.1. NESO SILICATES

Nesosilicates have independent, isolated $(SiO_4)^{4-}$ tetrahedra linked mutually by other cations, iron, magnesium and calcium. Aluminum, if present, always occurs in a form of AlO_6 octahedra. Typical example of such minerals is garnets (fig. 122).

Nesosilicates have high specific gravity. They generally form under high P and T conditions: igneous, pegmatitic and during high-grade metamorphism. They crystallize variously, but most frequently isometric and triclinic, and display either poor or lack of cleavage. The hardness is great, from 6 to 8. The group includes garnet, olivine and kyanite.

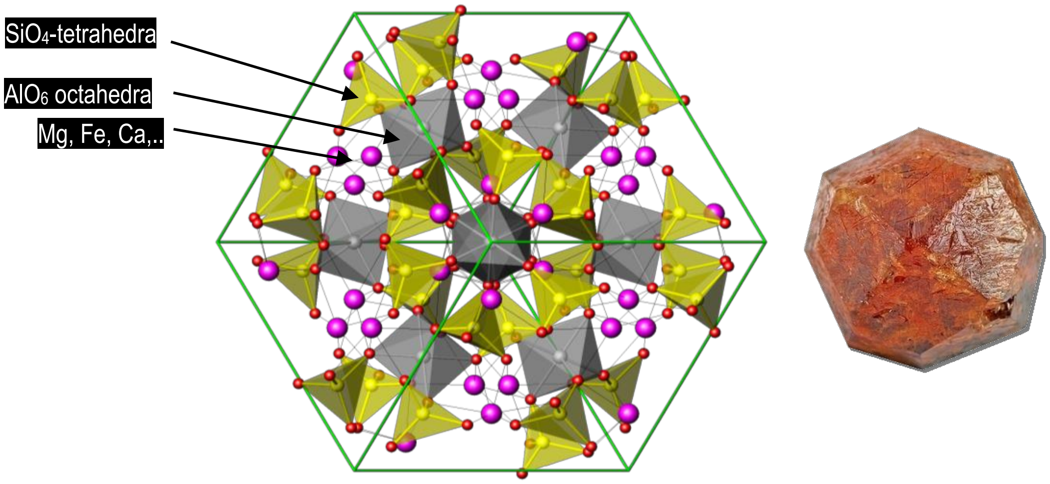


Fig. 122. The structure of garnet (left) and the crystal of garnet (right).

7.1.2. SOROSILICATES

Sorosilicates have two $(SiO_4)^{4-}$ tetrahedra sharing one oxygen (fig. 123). Minerals in this group often have „free“ tetrahedra, which are linked by certain cations: Ca, Fe, and Mg (epidote). The presence of OH group in the structure of this silicate group is not uncommon. Sorosilicates include beside epidote, zoisite, lawsonite, melilite and vesuvianite.

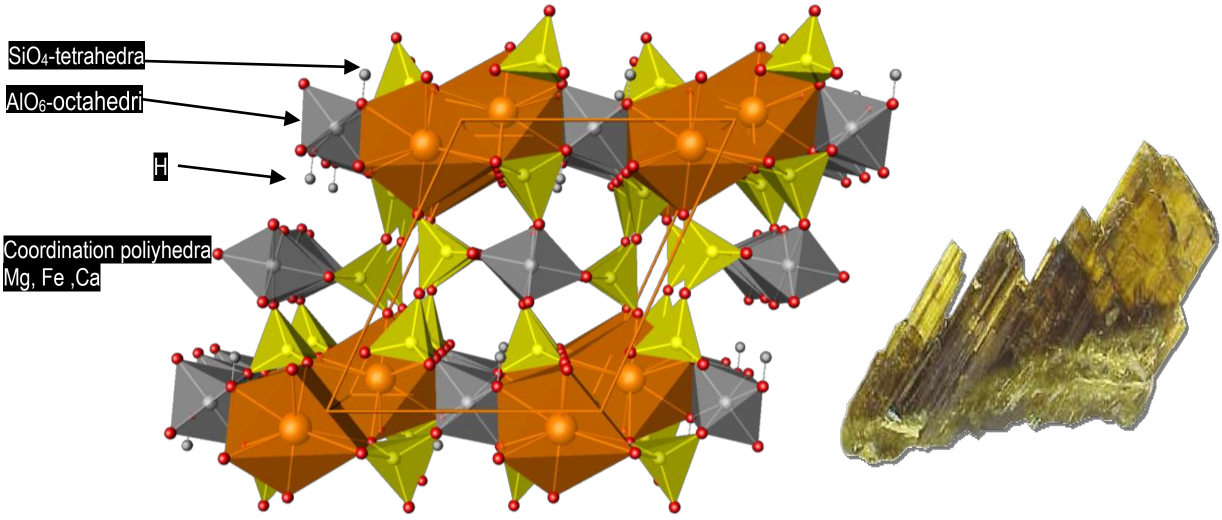


Fig. 123. The structure of epidote, left and the crystal of epidote, right.

7.1.3. CYCLOSILICATES

Cyclosilicates have $(SiO_4)^{4-}$ and $(AlO_4)^{5-}$ tetrahedras linked by two sharing oxygen atoms thus the first is linked with the last one, forming rings of three, four or six tetrahedra that are placed in planes perpendicular to vertical crystallographic axis c (fig. 124). Aluminum, like in sorosilicates, builds $(AlO_6)^{9-}$ octahedra.

Minerals in this group crystallize hexagonal, trigonal or orthorhombic, and are relatively hard, 7 to 8. This group includes beryl, tourmaline, cordierite and axinite.

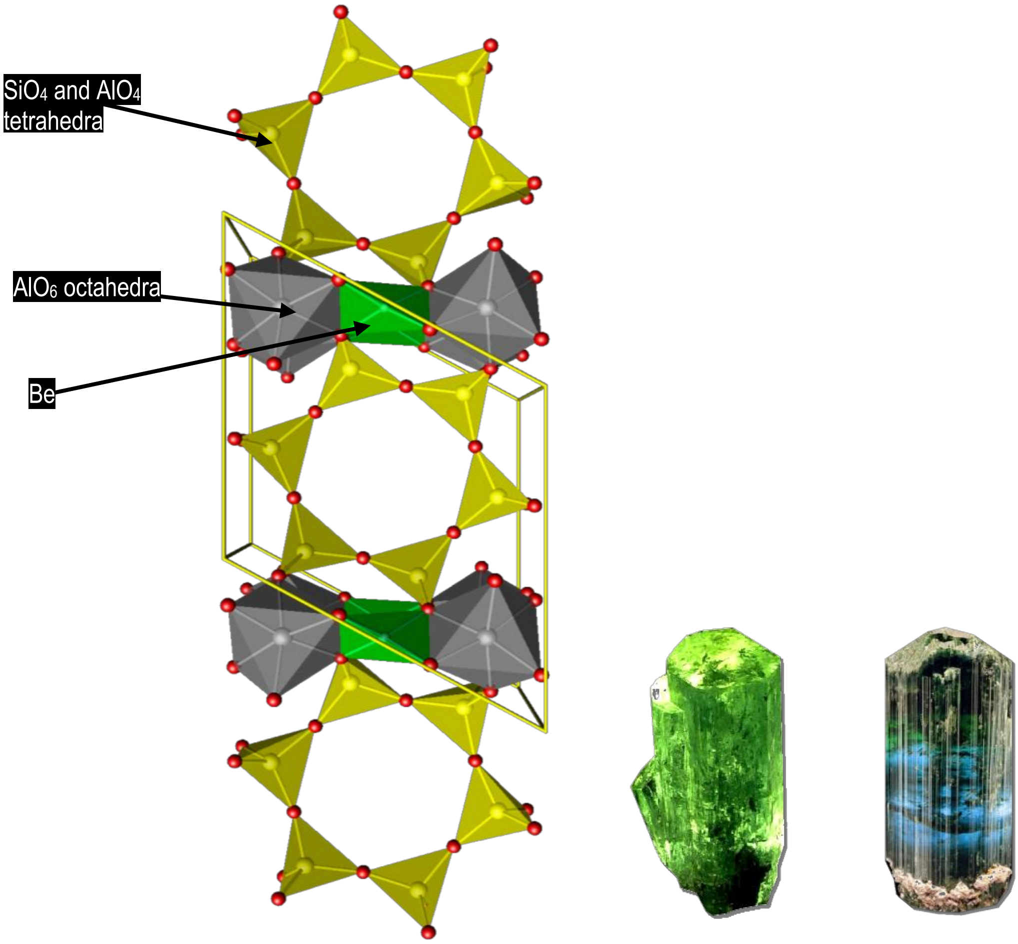


Fig. 124. The structure of beryl (left), and crystals of beryl and tourmaline (right).

7.1.4. INOSILICATES

Inosilicates have $(SiO_4)^{4-}$ tetrahedra linked together into indefinite $(Si_2O_6)^{4-}$ chains by sharing two oxygen ions. This structure is characteristic for pyroxene where silica tetrahedra are linked together to make a single chains (fig. 125) and for amphibole, where two chains are linked by oxygen ions to make double $(Si_4O_{10})^{6-}$ chains that may contain and tetrahedra of aluminum (fig. 126).

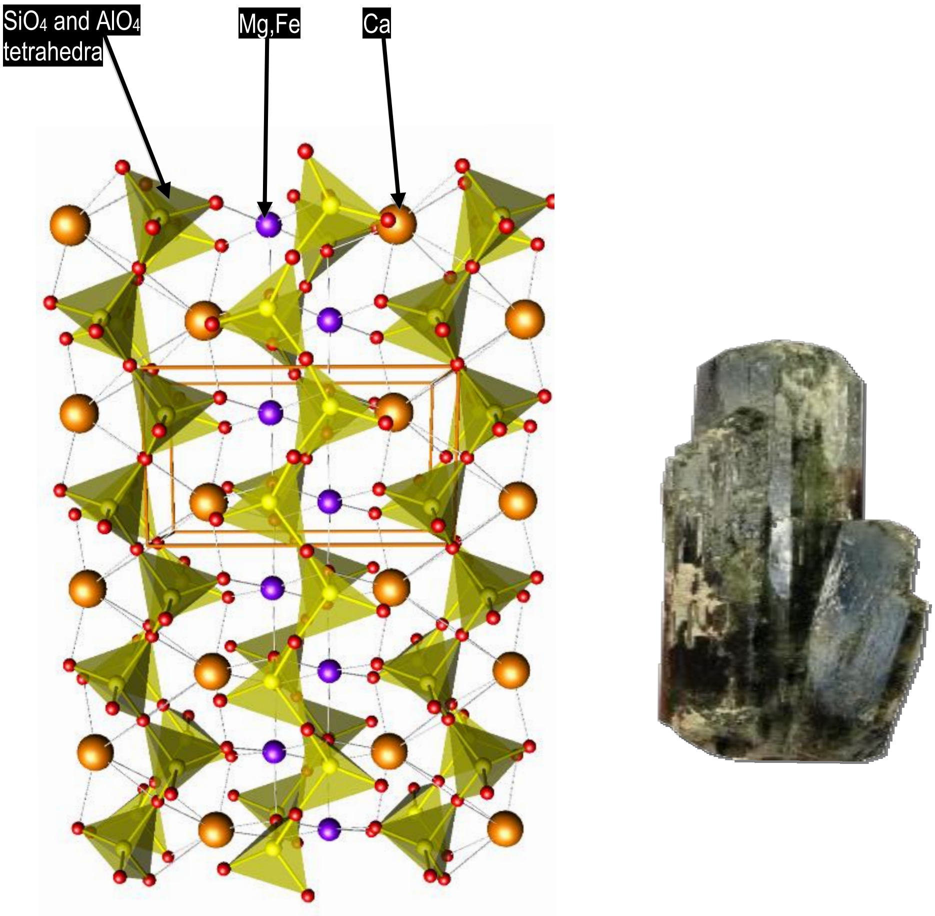


Fig. 125. The structure of pyroxene, the single chains (left), and the crystal of pyroxene, diopside (right).

Chains are arranged parallel and linked together by cations: Ca, Fe, Mg, and Na, which compensate negative electricity of additional anions, and OH group in amphiboles.

Minerals in this group crystallize monoclinic and orthorhombic and occur in crystals elongated along the vertical crystallographic axis, i.e. in the direction of the chain of $(SiO_4)^{4-}$ tetrahedra are arranged; hence occur in prismatic or columnar aggregates. Inosilicates display excellent cleavage in two directions. The cleavage in pyroxene group is between 87 and 90°, while in amphiboles intersect at angle near 124°.

Inosilicates develop at high temperatures, during igneous (orthorhombic and monoclinic pyroxene, alkali pyroxene) and regional or contact metamorphic processes (monoclinic Ca pyroxene, alkali pyroxene and hornblende). Some of them may be derived during low-grade metamorphism (tremolite, actinolite).

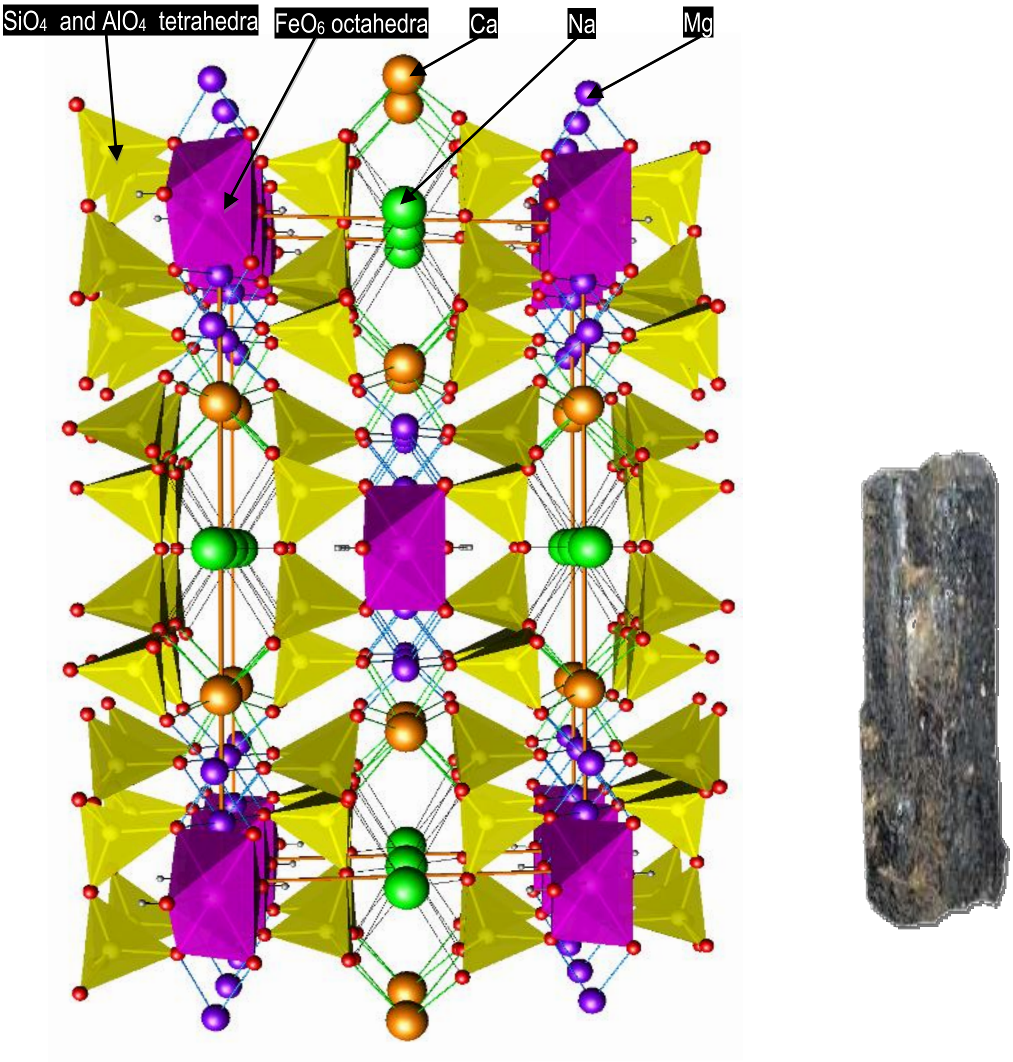


Fig. 126. The structure of amphibole, double chains (left), and hornblende (right).

7.1.5. PHYLLOSILICATES

Phyllosilicates have $(SiO_4)^{4-}$ and $(AlO_4)^{5-}$ tetrahedra held together by three sharing oxygen to form six-member rings at one plane, which is placed parallel to base building layers (sheets). Therefore, these minerals display perfect cleavage and occur in flakes or laths (fig. 127). Bonds between sheets are weaker than inside the sheet itself.

This group includes micas: muscovite and biotite, chlorite and clay minerals. Most of them crystallizes monoclinic or triclinic, are soft (low hardness) and has relatively low density. Laths are flexible, occasionally elastic.

Phyllosilicates generally form at low temperatures (clay minerals, chlorite) or at intermediate to high temperatures during igneous or metamorphic processes (muscovite, biotite, and lepidolite).

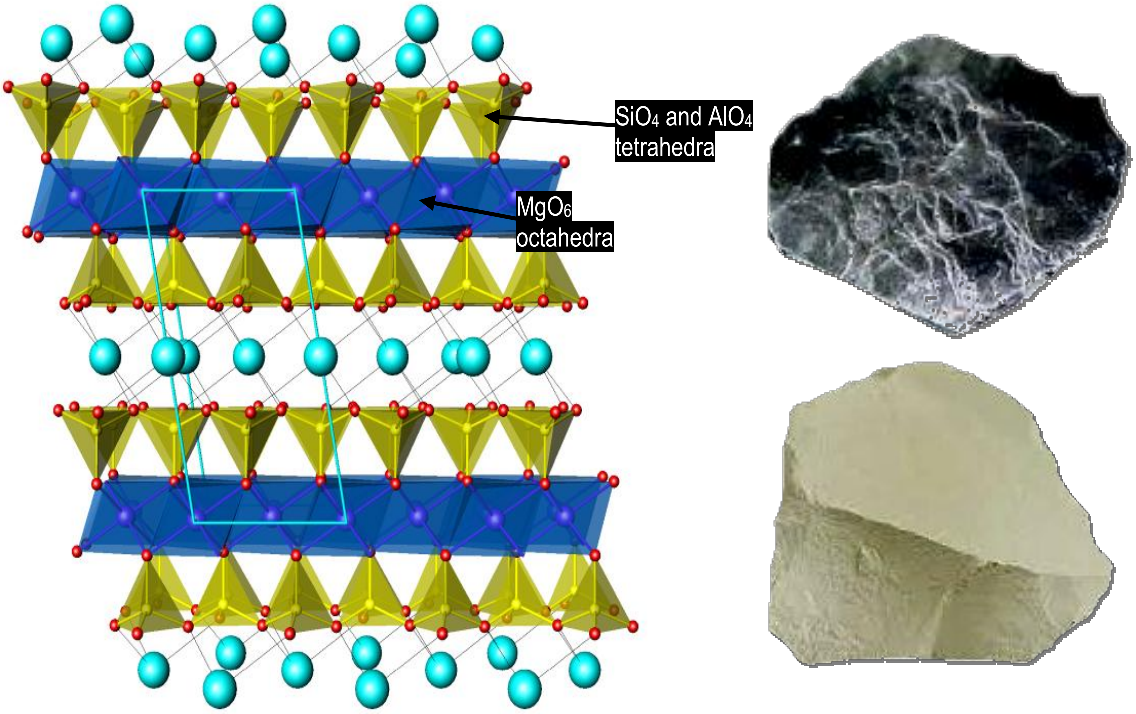


Fig. 127. The structure of mica, biotite (left), biotite flake right above, and kaolinite right down.

7.1.6. TECTOSILICATES

Tectosilicates have $(SiO_4)^{4-}$ tetrahedra linked together by oxygen into a three-dimensional framework (fig. 128).

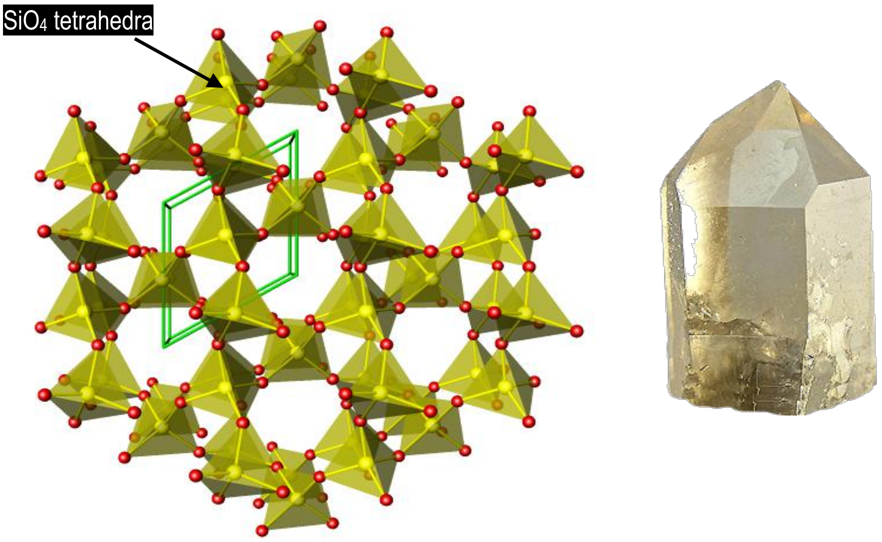


Fig. 128. The structure of quartz (left) and the crystal of quartz (right).

In the most of tectosilicates, excluding quartz, in a part of $(SiO_4)^{4-}$ tetrahedra is silica (up to half of it) substituted by tetrahedra of aluminum of smaller charge. On this way are producing free charges that may be compensated by ions of alkalis or earth alkaline elements. This includes feldspars, the essential minerals in numerous igneous, metamorphic and sedimentary rocks (fig. 129).

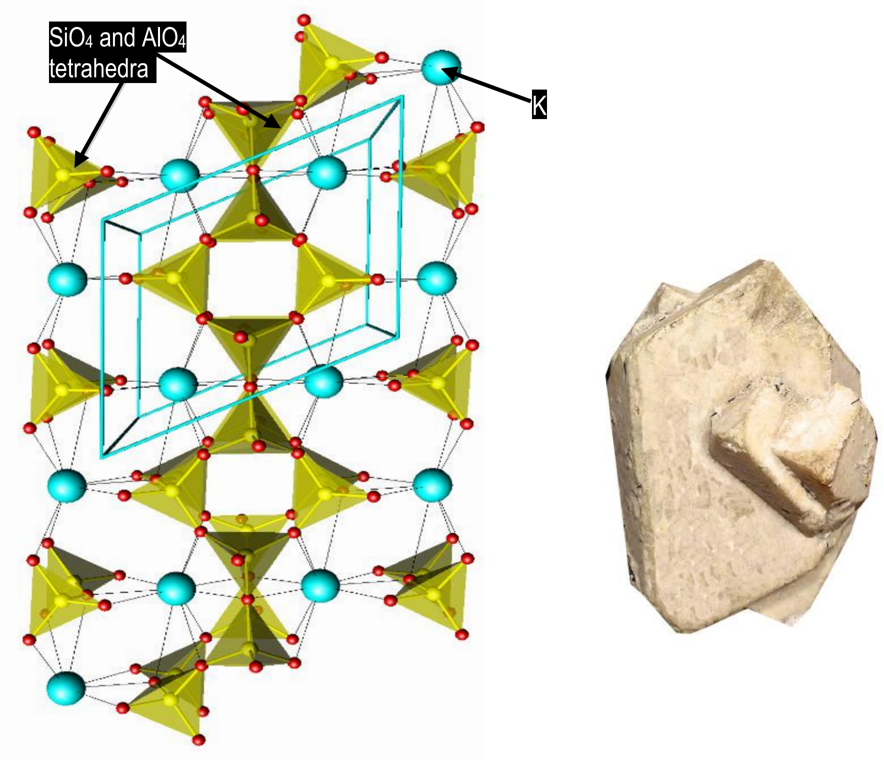


Fig. 129. The structure of orthoclase (left) and the twinned crystal of orthoclase (right).

Tectosilicates form in a wide range of pressures and temperatures during igneous and metamorphic processes. The most important minerals in this group are plagioclase, alkali feldspars and quartz, all being the essential constituents of basic, intermediate and acid igneous rocks, including most of metamorphic and sedimentary rocks.

Tectosilicates, alkali feldspars and plagioclase, excluding quartz, are not pure compounds. Many of them form isomorphic series with complete substitution (plagioclase).

Most tectosilicate minerals are of low density (from 2.1 to 2.8 g/cm^3) and display relatively low refractive indices. In polarizing microscope, these minerals commonly display low relief and colorless pattern under parallel nicols, while under crossed nicols are grey.

8. NESOSILICATES

Nesosilicates are structurally independent $(SiO_4)^{4-}$ tetrahedra held together by Mg, Fe, Al and Ca cations, but never with alkalis. Tetrahedrons are arranged like islands, hence the name nesosilicates (Greek word *nezos*-island). This group includes, with additional anions (neso-subsilicates) either pure aluminum silicates or aluminum silicates with another cations. The most important rock-forming minerals in this group are: olivine, garnet, zircon, pure aluminum silicates, staurolite and topaz.

8.1. OLIVINE $(Mg, Fe)_2SiO_4$

Olivine is a series of minerals with the least silica content, which crystallizes only from anhydrous and silica deficient melt (free quartz is lacking). Olivine is compositionally a solid solution of magnesium silicate, **forsterite** (Mg_2SiO_4) and iron silicate, **fayalite** (Fe_2SiO_4). Aluminum, calcium, manganese, chromium, and nickel are commonly present as impurities. It is named for its typically green color of olive. Complete combine between the last two end members results in natural appearance of olivine as mixed crystals. Higher content of forsterite than fayalite in olivine reflects on its higher temperature of crystallization. If SiO_2 is present in notable abundances, olivine converts into orthopyroxene.

Olivine crystallizes orthorhombic. Infrequently occurs in stubby prismatic crystals. Commonly builds granular masses of irregular shape (fig. 130). Cleavage is indistinct, hardness 6.5 -7, lustre vitreous or subadamantine at breaking surfaces.

Fig. 130. Crystals of olivine (left), and olivine in the rock dunite (right). Right above is an olive whose name is applied to this mineral.

Specific gravity of olivine varies between 3.2 and 4.4. Fresh olivine is light green or olive-green in color. With the increasing transformation (alteration) olivine receives dark green to almost black color. In polarizing microscope under crossed nicols olivine displays high interference colors (fig. 131), whereas is under parallel nicols colorless.

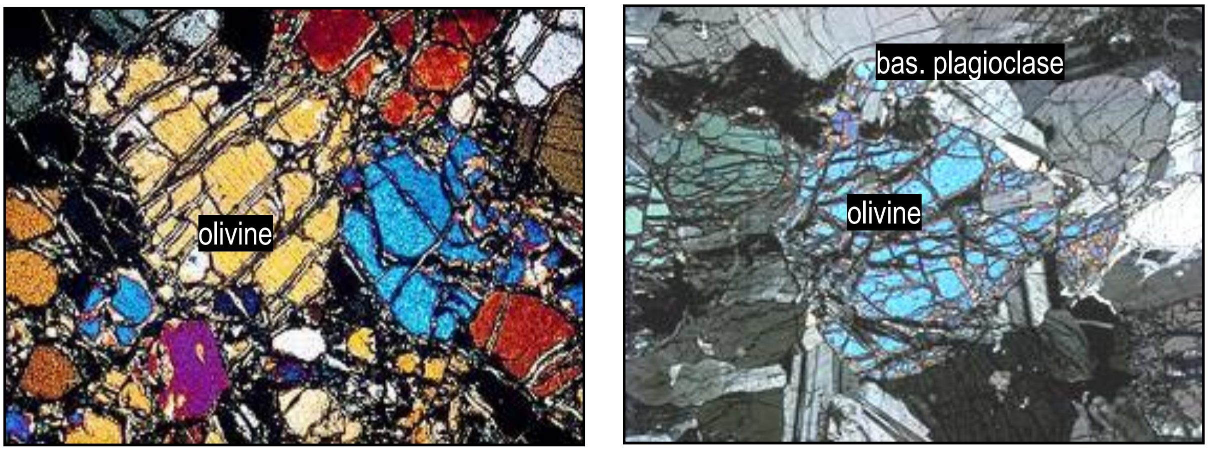


Fig.131. Microphotograph of olivine in dunite (left) and in gabbro (right). XPL, magnification 100x.

Olivine is **essential** mineral in ultrabasic igneous rocks, peridotites, commonly in association with ortho and monoclinic pyroxenes. These rocks are exposed in the Ibar River valley (fig. 132), at Zlatibor, Maljen, etc. Olivine is common in basic igneous rocks, olivine gabbro, and basalts, where it associates with pyroxene and basic plagioclase.

Fig. 132. Outcrop of peridotite with olivine, the Ibar River valley near Kraljevo.

Olivine is found at the contact of dolomitic rocks and granites when beside magnesium and iron is calcium present, too (calcium olivine – **monticellite** forms). Olivine is very rare in regional metamorphic rocks. Forsterite is the main constituent in stony meteorites.

Olivine is unstable mineral. At low temperatures, under the influence of hydrothermal solutions or atmospheric agents olivine turns into serpentine and iddingsite (fig. 133 and 134), rarely in talc, asbestos, dusty magnetite. With addition of CO_2 olivine converts into magnesite. During serpentinization the volume of olivine increases leading to easy-breaking of host rock (peridotite) and derivation of inappropriate environment (unstable ground) for road, tunnel or building constructions as well as for exploitation of chromite and magnetite that are common constituents of these rocks.

Fig.133. The sample of serpentine, formed by alteration of olivine.

Fig.134. Outcrop of serpentinized peridotite, Bubanj potok near Belgrade.

In polarizing microscope olivine displays low interference colors, commonly gray, bluish-gray, occasionally green. Under parallel nicols olivine is nearly colorless and display low relief. Olivine is commonly „marked“by dusty magnetite, oxides and hydroxides of Fe, which form during its alteration (serpentinization; fig. 135).

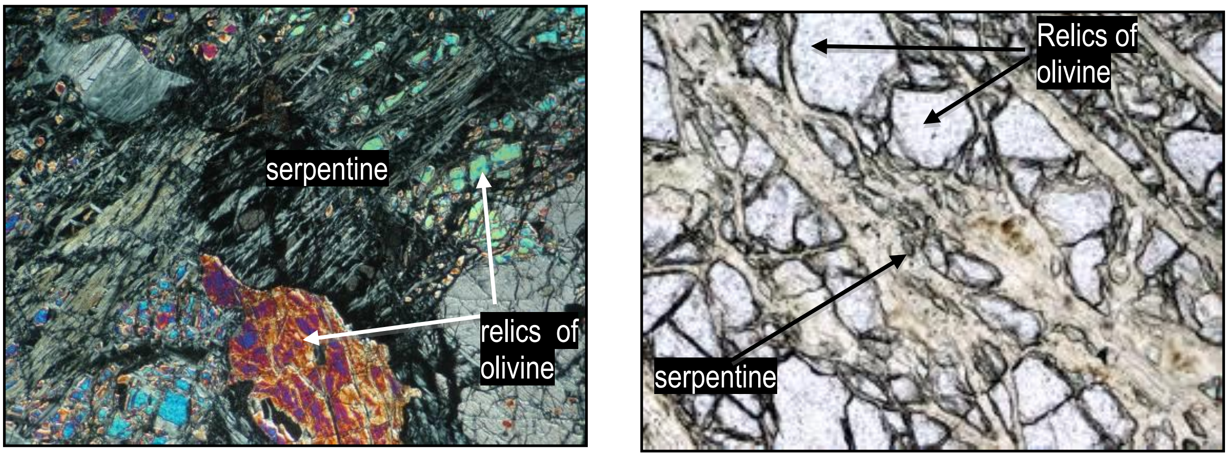


Fig. 135. Serpentinite formed by alteration of olivine. Microphotograph XPL (left), PPL (right), magnification 200×.

Iddingsite represents a mixture of several secondary minerals: chlorite, smectite, hematite and quartz. Such assemblage is referred as the product of transformation of olivine during early stage of the host rock consolidation. In microscope, under parallel nicols is iddingsite of characteristic red color (fig. 136).

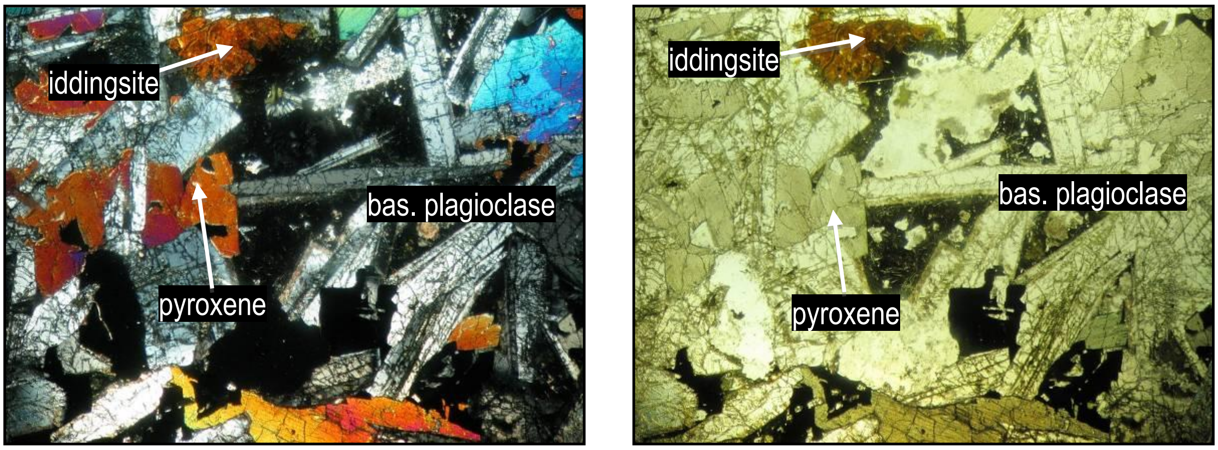


Fig. 136. Iddingsite, formed by alteration of olivine in gabbro. Microphotograph (left), XPL; the same mineral under PPL (right). Magnification 60×.

8.2. GARNETS

Garnets are characteristic regional and contact metamorphic minerals. Garnets are waterless aluminum silicates of Mg, Fe, Mn, and Ca, in respect of chemistry.

The name garnets come from a fruit-bearing plant, pomegranate, due to similar shape of garnet grains and fruit of this plant (fig. 137).

According to chemical composition garnets are classified in two groups: **pyralspite**, garnets with Mg, Fe and Mn and **ugrandite**, Ca garnets.

Fig. 137. Seeds of pomegranate, whose name is applied to garnets.

Pyralspite group includes:

- **PYROPE**, $Mg_3Al_2Si_3O_{12}$
- **ALMANDINE**, $Fe_3^{2+}Al_2Si_3O_{12}$
- **SPESSARTINE**, $Mn_3Al_2Si_3O_{12}$

Ugrandite group includes:

- **UVAROVITE**, $Ca_3Cr_2Si_3O_{12}$
- **GROSSULAR** $Ca_3Al_2Si_3O_{12}$
- **ANDRADITE** $Ca(Fe_2^{3+}Ti)_2Si_3O_{12}$

Garnets within these two groups, pyralspite and ugrandite, display complete substitution, whereas substitution between these two groups is partial, up to 20 %. The minerals are named according to the prevailing component, as garnets are always members of isomorphic series.

All garnets crystallize tesseral in well-developed, regular crystals, most frequent in rhombic dodecahedral; rarely ikositetrahedral crystal habits. Granular masses are also common.

Garnets are hard minerals, from 6 to 7.5, and lack of cleavage. Specific gravity varies with composition from 3.6 to 4.3 g/cm^3. The color of garnets depends on chemical composition and range from red to black (pyralspite), yellow and yellowish-green (grossular, andradite) and green (uvarovite). Zoned crystals are very common.

Garnets own high growth ability and intend to form euhedral crystals, therefore occur often as coarse grains, porphyroblasts, coarser than other constituents in rock.

Pyralspites are important regional metamorphic minerals. In a nature, this group always contains some percent of andradite and grossular components.

8.2.1. PYRALSPITE GROUP

PYROPE

Pyrope is magnesium garnet. Commonly occurs as accessory constituent in ultrabasic rocks and in alkali volcanic rocks. It forms at high pressures and high temperatures (fig. 138).

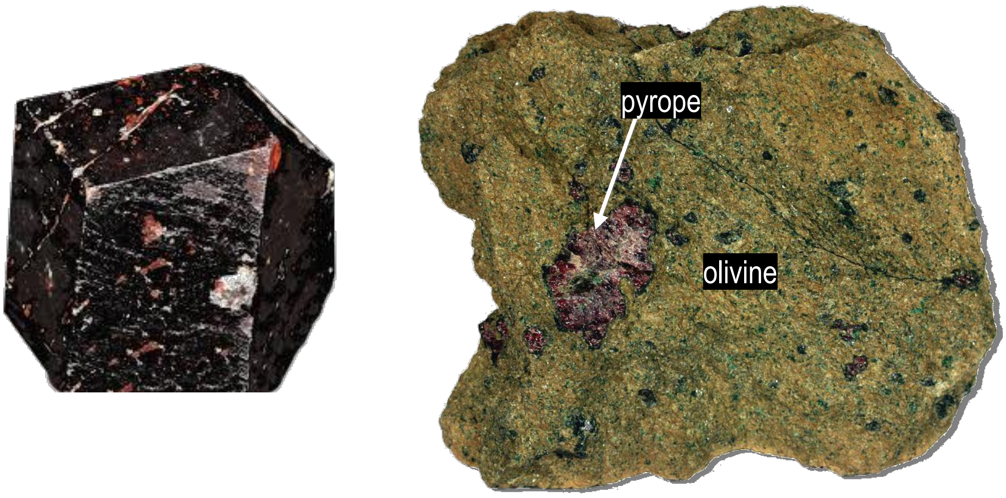


Fig. 138. Crystal of pyrope (left), and pyrope in dunite (right).

ALMANDINE

Almandine is iron-bearing garnet and the commonest mineral from the garnet group (fig. 139). It forms under regional metamorphism from clastic sedimentary rocks and from igneous rocks rich in aluminum, magnesium, iron and calcium, under intermediate to high PT conditions, temperature over 500 °C and at pressures exceeding 5 Kb.

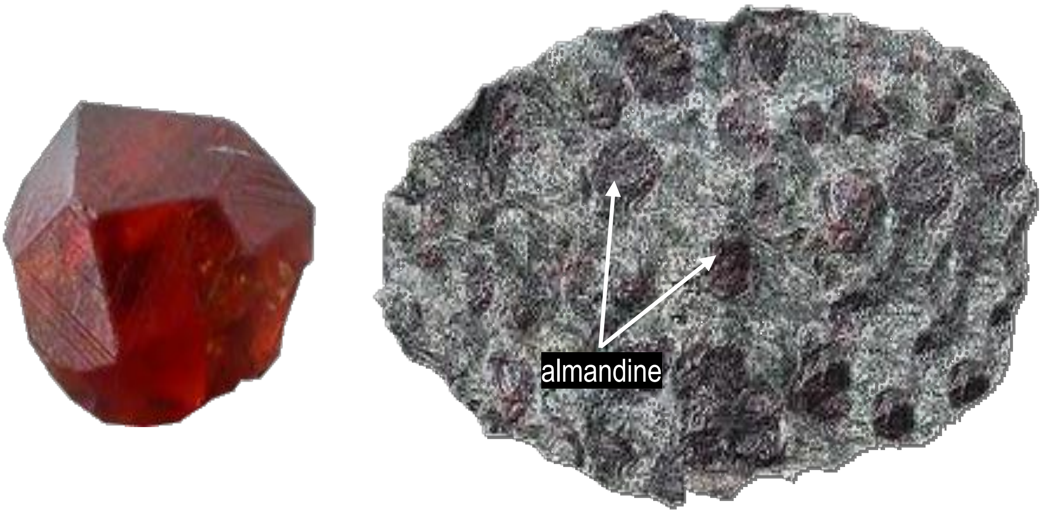


Fig. 139. Almandine crystal (left), and almandine in gneiss (right).

Almandine is isotropic under crossed nicols, whereas at parallel nicols displays high relief and colorless pattern (fig. 140).

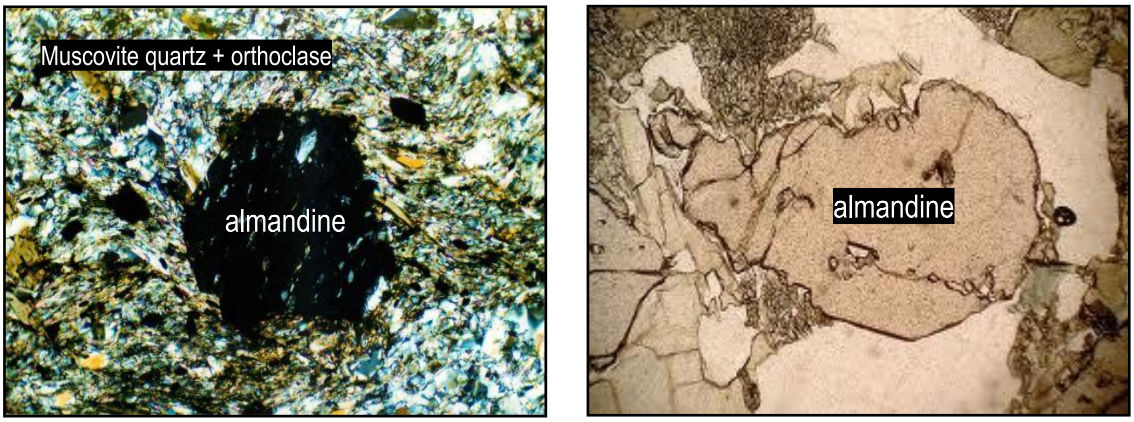


Fig. 140. Microphotograph of almandine crystals in gneiss (left,) XPL; same image in PPL (right). Magnification 200×.

Enclaves (inclusions) of other minerals that garnet enclosed during its growth in some stage of metamorphism when it was formed are common.

Almandine usually appears in grains from a few millimeters to a few centimeters (less frequent) in gneiss (fig. 141) and micaschists in which a kyanite, sillimanite and staurolite may appear, or in amphibolites where garnet associates with hornblende and intermediate to basic plagioclase. All mentioned rocks form during intermediate to high-grade metamorphism. Almandine could be found in pegmatites, less frequent in granites. In both cases is accessory mineral.

Fig. 141. Gneiss outcrop on the road Lebane–Medveđa..

SPESSARTINE

Spessartine forms at the lowest PT conditions in respect to all other garnets. It requires pressures from 3 to 5 Kb and temperatures of about 500 °C. It is very common in rocks formed through low grade regional metamorphism, by reaction of manganese bearing chlorite and quartz (fig. 142). May be present in pegmatite, too.

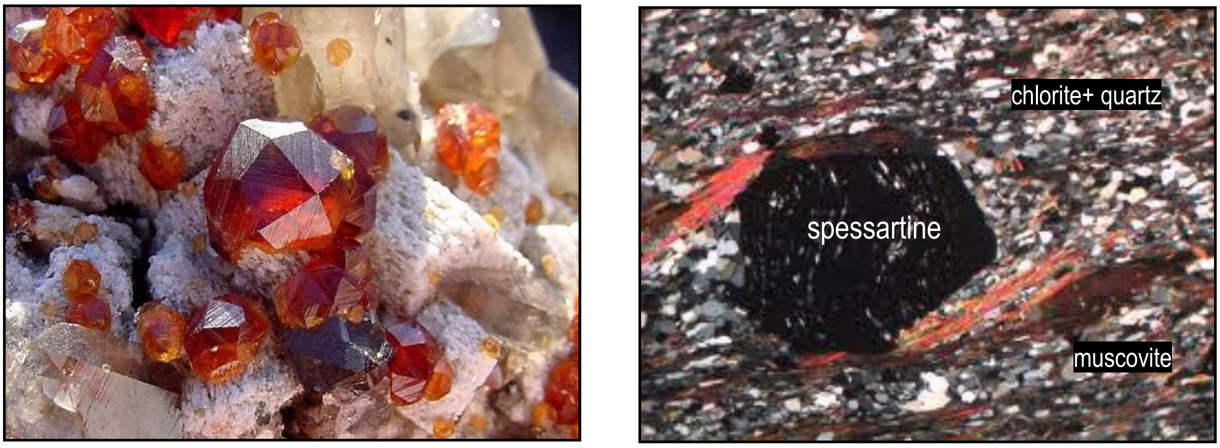


Fig. 142. Spessartine crystals, red (left) and the same mineral under the microscope in muscovite-chlorite schist (right), XPL, magnification 100×.

Almandine can be find in muscovite-chlorite schists originating from basic tuffs that underwent low-grade metamorphism. There it appears in small grains up to 1 mm and associates with sericite, albite, epidote, chlorite, and leucoxene (fig. 143).

Fig. 143. Outcrop of sericite-chlorite schist containing spessartine, Manastiriška River, near Vlasotince.

8.2.2. UGRANDITE GROUP

UGRANDITE group includes **grossular**, **andradite** and **uvarovite** (fig. 144). They form during contact-metasomatism process, i.e. at the contact of acid, granitic magma and marly or clayey carbonate rocks, when skarns take place (fig. 145).

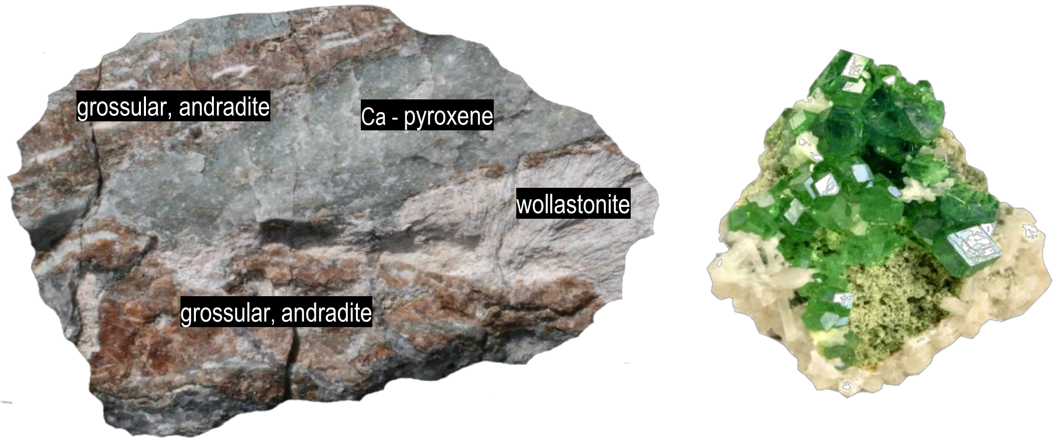


Fig. 144. Segregation of red grossular and andradite in skarn, red (left),and crystals of uvarovite with chromium (right).

Fig. 145. Skarns of Jaram (Kopaonik) contain andradite-grossular garnets.

Ugrandite forms at relatively low pressures, approximately 3 Kb, and at temperatures from nearly 550 to 700 °C. An „opened“ system is necessary for skarn to being formed, though the CO_2 could disappear from limestone leading to development of many other calcium-rich minerals, such as: vesuvianite, wollastonite, and calcium pyroxene, diopside and hedenbergite. Grossular and andradite are either isotropic under microscope or display sector zoning (fig. 146).

Fig. 146. Microphotograph of ugrandite in skarn (left), XPL; same mineral under PPL (right). Magnification 100×.

As garnets are durable minerals they could be often found in placer deposits (fig. 147). Under the influence of hydrothermal fluids or retrograde metamorphism, when rocks from greater depth come up to shallow levels, garnet transforms into chlorite and minerals of the epidote group.

Fig. 147. Garnet grains extracted from a sand (left), and chloritized garnet in a schist (right). Microphotograph, PPL, magnification 80×.

Garnets, occurring as coarse, pure crystals, particularly if red (almandine) or green colored (uvarovite), are used as gemstones (fig. 148).

Fig. 148. Jewelry made of garnets.

8.3. ZIRCON $ZrSiO_4$

Zircon is a silicate of zirconium, also containing: Hf, Th, Y, rare earth elements and uranium as impurities. Crystallizes tetragonal and occurs in crystals, commonly combination of prisms with bipyramids, or in granular masses (fig. 149). The color is brown to brownish-red, as well as yellowish-brown, and rarely green, blue or colorless. Lustre is adamantine; cleavage is lacking and the fracture is conchoidal. The hardness is 7.5, specific gravity from 4.6 to 4.7 g/cm^3. In polarizing microscope is colorless, displaying high relief and often a characteristic radioactive aureole when is enclosed by another minerals (fig. 150).

Fig. 149. Zircon crystal (left), and zircon in pegmatite (right).

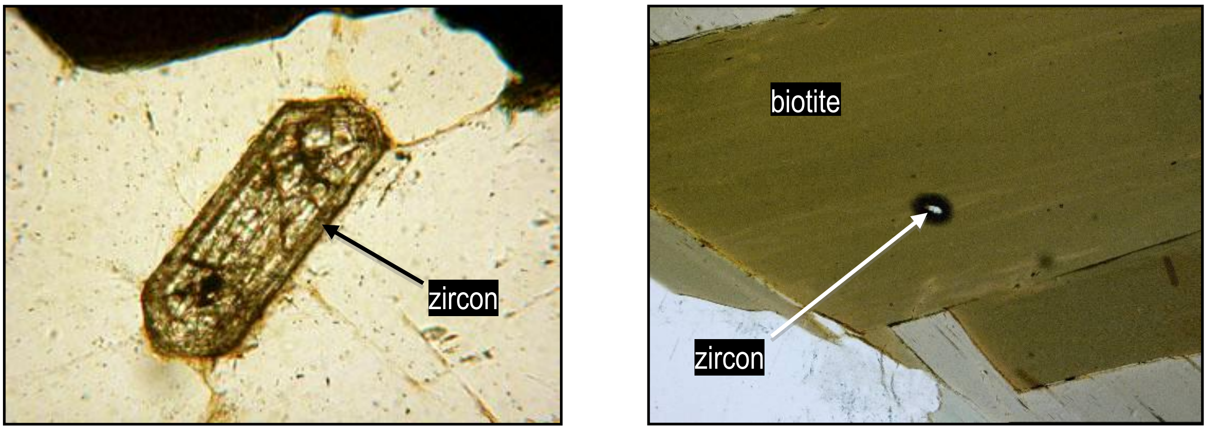


Fig. 150. Microphotograph of zircon crystal in granite (left), PPL, and of zircon enclosed in biotite (right), XPL. Magnification 200×.

Zircon is igneous mineral and occurs as an **accessory** constituent in igneous rocks of basic to acid composition, including their pegmatites. It is hardly recognizable in rocks due to small dimensions of grain, commonly a few millimeters, and its negligible abundance in a rock mass, i.e. just a few percents (fig. 151).

Fig. 151. The sample of granite with a zircon grains.

Zircon is often enclosed in biotite and hornblende in a form of inclusion. It can be used for the age determination (dating) of rocks and minerals, if contains radioactive elements. It is a common accessory mineral in Paleozoic granites (fig. 152).

Zircon is resistant to physical weathering thus is a common in clastic sedimentary rocks, sand and sandstone. Transparent zircon is a popular gemstone and also finds its application for zirconium and hafnium production and a special kind of ceramics. It is also produced synthetic, for jewelry.

Fig. 152. Granites of Gornjane (east Serbia) contain zircon as an accessory mineral. Right above, the detail of rock.

8.4. NESOSILICATES WITH ADDED ANIONS (NESO-SUBSILICATES)

This subgroup includes aluminum silicates, staurolite, topaz, titanite and chloritoid.

8.4.1. ALUMINUM SILICATES Al_2SiO_5

Aluminum silicates are three polymorph minerals of the same chemical composition:

- **KYANITE**, crystallizes triclinic;
- **ANDALUSITE**, crystallizes orthorhombic and
- **SILLIMANITE**, which is regarding structure inosilicate mineral, and also crystallizes orthorhombic.

These minerals in the structure contain $(SiO_4)^{4-}$ and $(AlO_6)^{-}$ octahedra.

Kyanite, sillimanite and andalusite form throughout regional and contact metamorphism of clays, rocks aluminum and silica-rich. Commonly occur as porphyroblasts in euhedral crystal shapes and much coarser than other rock constituents.

The formation of aluminum silicate minerals from clay minerals during metamorphism requires the removal of water from a system. Metamorphism of clays that usually contain smaller amounts of potassium, iron, calcium and magnesium from a closed system with water „captured” within, leads to development of hydrous aluminum silicates: muscovite, biotite, staurolite.

8.4.1.1. Kyanite

Kyanite, also called disthene, is aluminum silicate with very often impurities of ferric-iron, which reveals a blue color to it (fig. 153), or chromium, which gives a green color and allows it to be used as a gemstone.

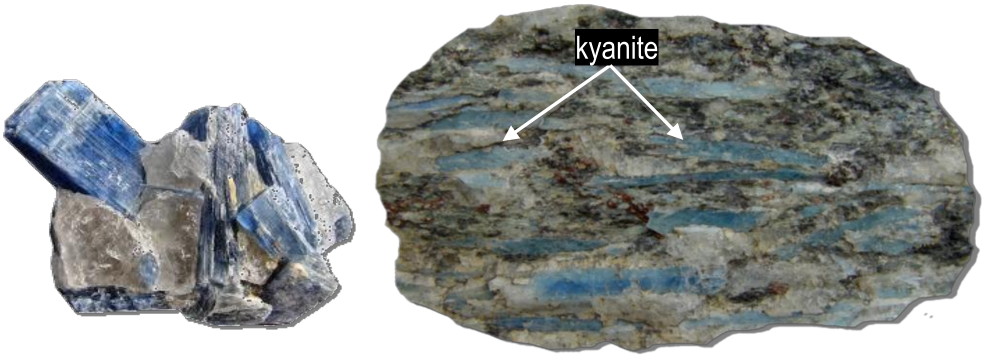


Fig. 153. Kyanite crystals (left), and a schist with kyanite (blue tabular crystals, right).

Kyanite occurs in tabular and elongated, occasionally very large crystals. Crystallizes triclinic. Different hardness from 5.5 to 7, vitreous to pearly lustre and perfect cleavage characterize a kyanite. It belongs to brittle minerals having specific gravity from 3.5 to 3.6 g/cm^3.

In superficial weathering processes is durable, thus could concentrate in alluvial detritus, but converts into sericite, i.e. into clay minerals when being exposed to influence of hydrothermal fluids.

Kyanite forms by regional metamorphism of clay and sandstone at moderate to high PT conditions, at temperatures exceeding 500 °C and at stress pressures above 5 Kb.

In polarizing microscope kyanite displays grey to high interference colors. Under parallel nicols is colorless, with apparent cleavage (fig. 154).

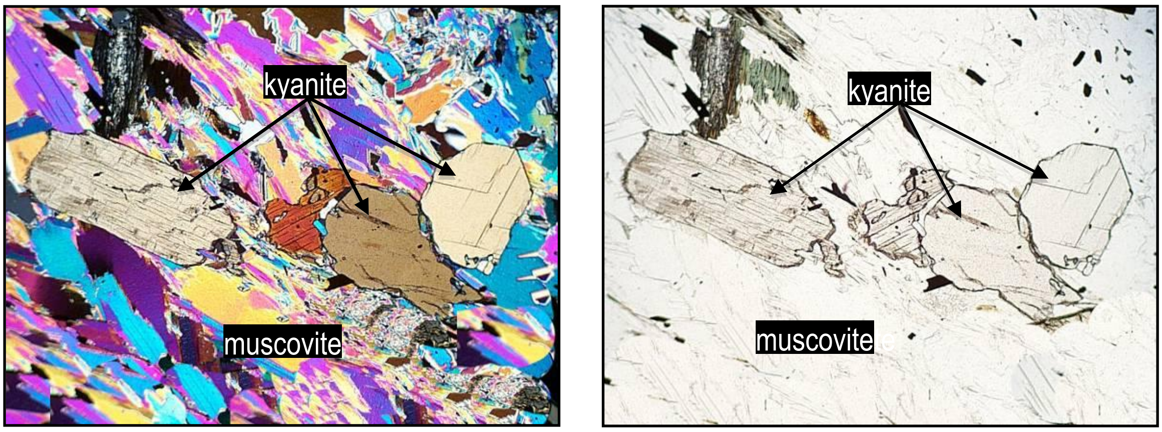


Fig. 154. Microphotograph of kyanite in micaschist (left), XPL, same mineral under PPL (right). Magnification 200×.

Kyanite is found in gneiss and micaschists (fig. 155) in association with garnets, staurolite, mica, sillimanite, occasionally in tiny grains visible only under the microscope.

Fig. 155. Outcrop of gneiss with kyanite, Golubinje, east Serbia.

8.4.1.2. Sillimanite

Sillimanite is also aluminum silicate and may contain up to 3 % of Fe_2O_3. Its name is applied to American professor B. Silliman (fig. 156).

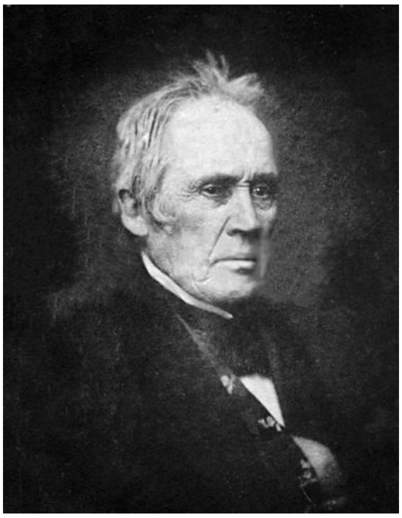


Fig. 156. B. Silliman 1779–1864.

This mineral is characterized by intermittent alternation of silica and aluminum tetrahedra. Crystallizes orthorhombic and occurs in fibrous, acicular to tabular aggregates, very rare in crystal habits (fig. 157). Its color is yellow to light green, the lustre vitreous to pearly. Cleavage is perfect, hardness from 6 to 7, and the specific gravity 3.2 g/cm^3.

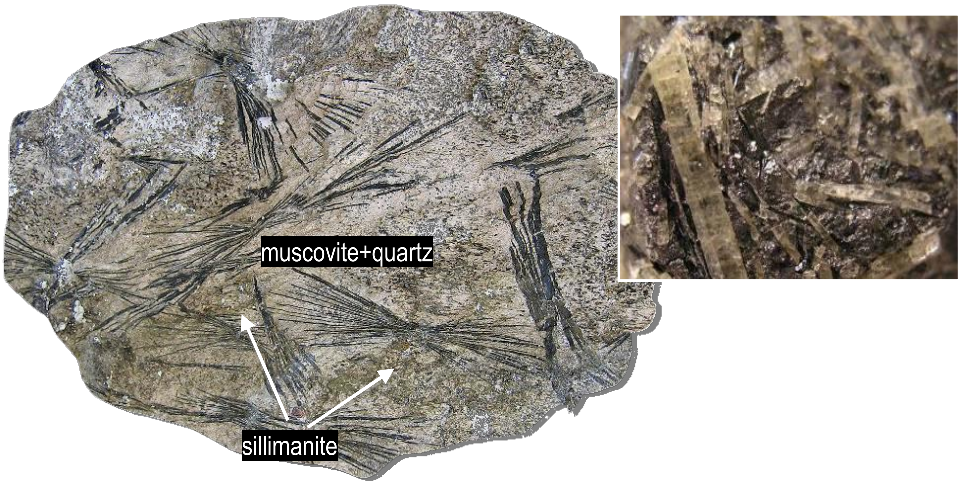


Fig. 157. Needles, i.e. crystals of sillimanite in micaschists. Right above, the detail of this mineral.

In polarizing microscope is sillimanite easy recognizable due to its typical elongated, acicular to fibrous masses. A coarser-grained sillimanite may occur as prismatic, even granular. With parallel polarizing prisms is colorless (fig. 158).

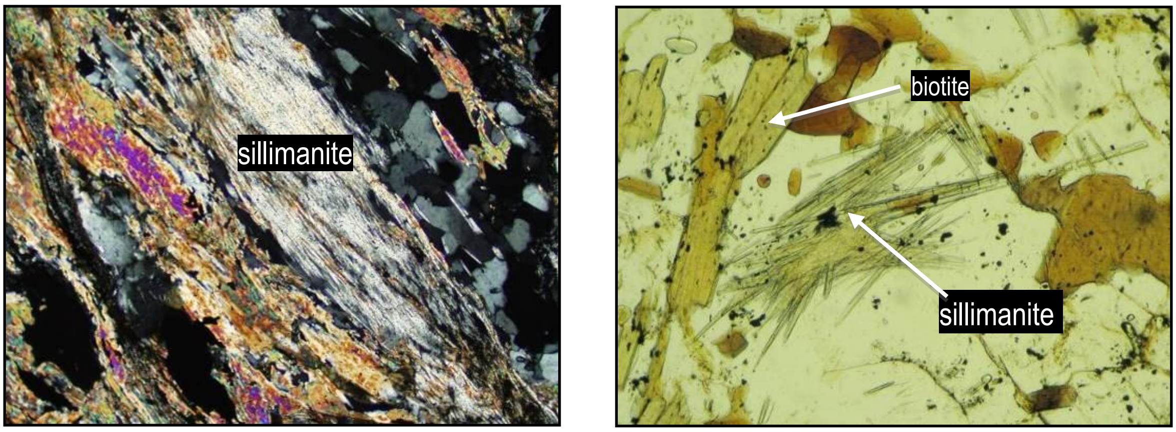


Fig. 158. Sillimanite under the microscope, XPL (left), and PPL (right). Magnification 200×.

Sillimanite forms by regional metamorphism of clays, at intermediate to high- metamorphic grade (fig. 159), within the same or similar conditions as kyanite with whom commonly associates. It may be generated during contact metamorphism, i.e. thermo contact metamorphism of clayey sediments, rarely. Alters to clay minerals and sericite.

Fig. 159. Outcrop of micaschist with sillimanite, Medveđa..

8.4.1.3. ANDALUSITE

Andalusite has a same chemistry as kyanite and sillimanite. It was named after the Spanish province Andalusia, where it has been found for the early first time. Common impurities in andalusite are iron and manganese oxides and organic matter. Crystallizes orthorhombic and occurs in prismatic crystals, commonly as porphyroblasts (fig. 160). It is colored yellow to brown, grey, rarely grayish green to green. The hardness is 6.5 to 7.5; specific gravity is from 3.1 to 3.2 g/cm^3. Cleavage is distinct, and the lustre vitreous.

Andalusite is grey in polarizing microscope (fig. 161), and colorless in parallel nicols. It commonly occurs in prismatic crystals with square, rhombohedral or prismatic cross-sections.

Fig. 160. Andalusite crystals (left), and spotted schist with andalusite, white crystals (right).

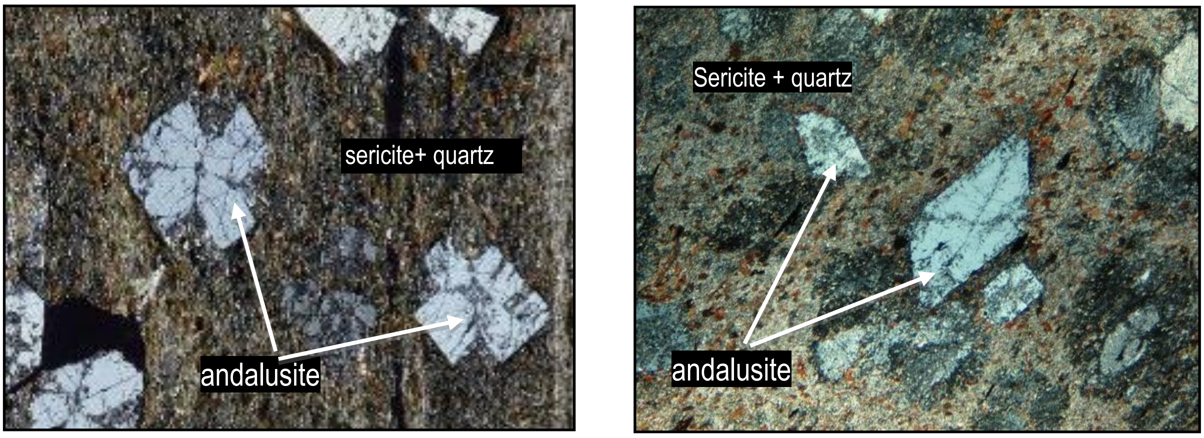


Fig. 161. Microphotograph of porphyroblasts of andalusite in spotted schist, XPL (left) and in altered contact metamorphic rock (right), XPL. Magnification 200×.

It forms in contact metamorphosed, i.e. thermal metamorphosed clayey sediments (fig. 162) at their contact with magma, most frequently with acid magma (granite), but is also found in pegmatite. Usually associates with cordierite, biotite and muscovite.

Andalusite alters to sericite and clay minerals when being exposed to influence of hydrothermal solution.

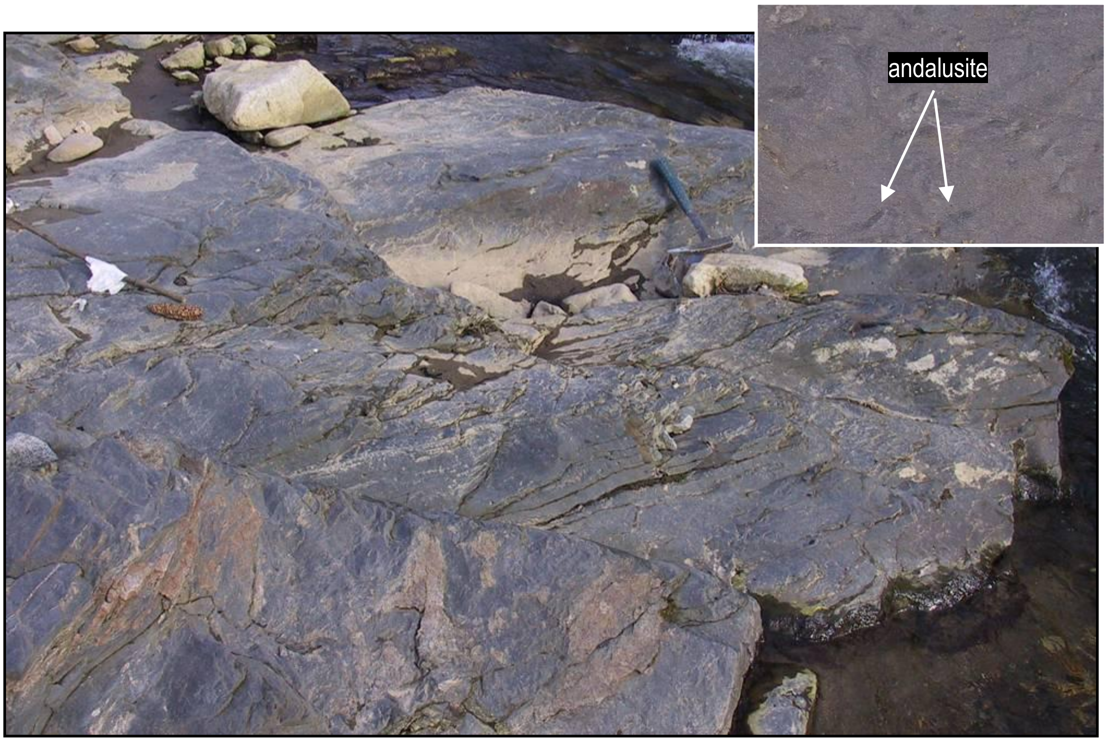


Fig. 162. Outcrop of spotted schist with andalusite, river Radaljska reka, Boranja, right above - a detail.

Although andalusite, sillimanite and kyanite are stable at certain PT conditions, only one of them may exist in rock following the physico-chemical law (phase rule). However, the association of two minerals (sillimanite and kyanite), or even of all three aluminum silicates occur in a nature as the consequence of their slow transformations to each other.

Aluminum silicates are significant and essential minerals in regional and contact metamorphic rocks and reflect on composition of the primary rock (protolith) and on PT conditions. They are mostly, as have been already mentioned, related to clayey, pelitic sediments composed of hydrous aluminum silicates that will loose water during metamorphism and transform into anhydrous aluminum silicates.

8.4.2. **STAUROLITE** $(Fe^{2+},Mg,Zn)_2(Al,Fe^{3+},Ti)_9O_6((Si,Al)O_4))_4(O,OH)_2$

Staurolite is hydrous iron aluminum silicate. Crystallizes orthorhombic and occurs in tabular, short stubby prismatic crystals or in granular masses. Porphyroblasts and cruciform penetration twins are common (fig. 163). Staurolite often encloses garnet, quartz and rutile grains.

Fig. 163. Twinned staurolite crystals (left) and micaschist with staurolite and garnet (right).

Staurolite is brown to brownish-red in color, with vitreous to resinous lustre. Cleavage is perfect to distinct; hardness is 7 and the specific gravity from 3.7 to 3.9 g/cm^3.

Staurolite forms during intermediate to high grade regional metamorphism of pelitic sediments (clay) that contain Fe and Mg. Under the same conditions form kyanite, sillimanite, almandine, micas and feldspars, minerals commonly associated with staurolite.

The relationship of Fe, Mg, Ca, Al, Na and K in a rock that takes part in metamorphism is important for the staurolite genesis. This mineral is in petrology referred as indicative for metamorphic grade, due to relatively narrow stability field.

Staurolite transforms to chlorite, sericite and iron oxides.

Under the microscope, in parallel nicols it displays pleochroism in yellow colors (fig. 164).

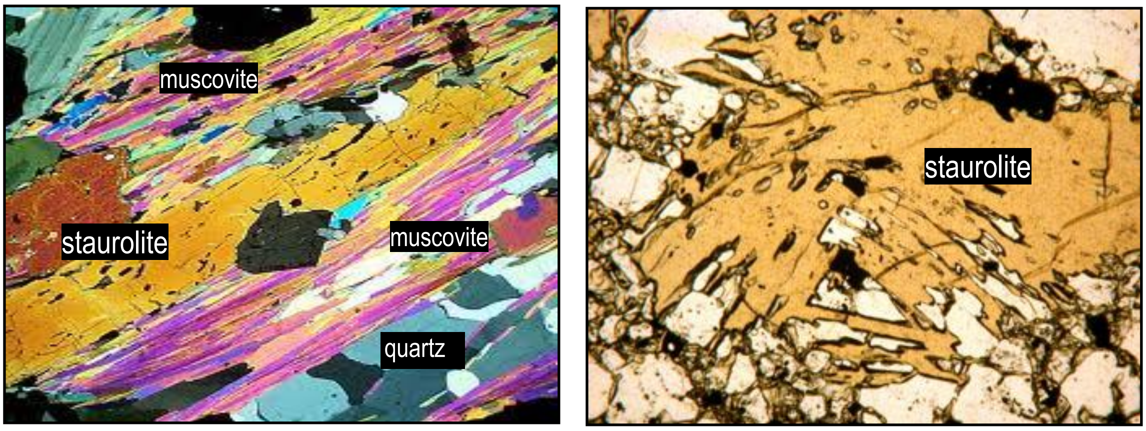


Fig. 164. Microphotograph of staurolite crystals in micaschist.
Left XPL and right PPL. Magnification 200×.

Staurolite is often found in huge grains (porphyroblast), up to a few centimeters in size, and is much coarser from other minerals in metamorphic rock, micaschist, less frequent in gneiss (fig. 165).

Fig. 165. Outcrop of micaschist with staurolite, Bobološ near Kragujevac. Above left, a detail.

8.4.3. **TOPAZ** $Al_2SiO_4(OH,F)_2$

Topaz is hydrous aluminum fluorosilicate, with the amount of fluorine exceeding the hydroxyl content. Common impurities are Fe, Mg and Ti.

It crystallizes orthorhombic and occurs in columnar, stubby prismatic to granular aggregates, very rare in huge crystals. It is white colored or colorless, also yellow and very rare blue or pinkish (fig. 166). It is transparent to translucent.

Fig. 166. Topaz crystals (left), and topaz in greisen (right).

Cleavage is perfect, lustre vitreous and fracture uneven to conchoidal. Specific gravity is from 3.4 to 3.6 g/cm^3, and hardness 8.

In polarizing microscope, under parallel nicols, is topaz whitish and displays moderate relief (fig. 167). Commonly is associated with other igneous minerals, tourmaline, feldspar, muscovite, biotite and beryl.

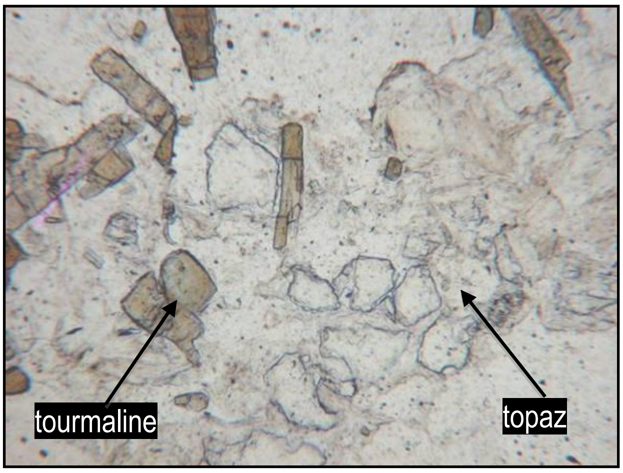


Fig. 167. Topaz associated with tourmaline in pegmatite, microphotograph PPL, magnification 100×.

Topaz forms in igneous, pegmatitic stage (fig. 168 and fig. 169) as well as by pneumatolitic action of volatile component with fluorine on already existed silicates. It is related to acid igneous rocks (granite), occurring as the **accessory** mineral.

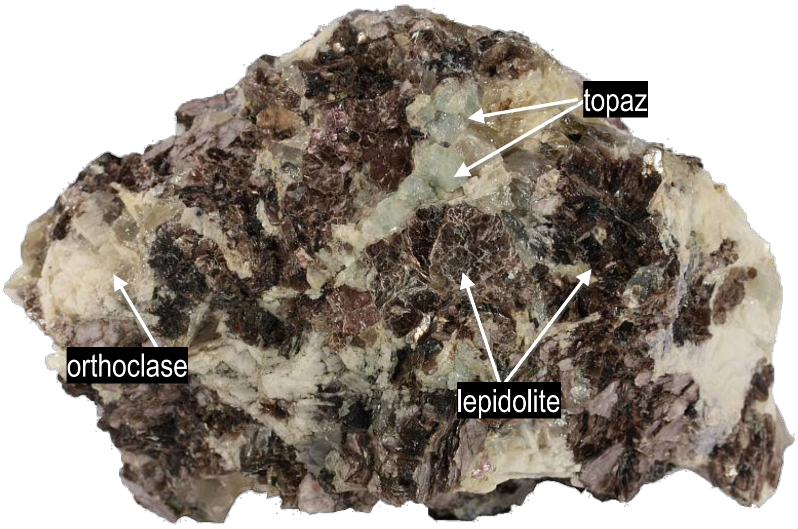


Fig. 168. Topaz, light blue, and lepidolite, pinkish, in pegmatite.

Fig. 169. Pegmatite vein in granite contains topaz.

The most beautiful topaz crystals were found in pegmatites (fig. 170) where they can reach one meter in size, and in greisens, when are associated with lepidolite, tourmaline, fluorite, muscovite, tungsten, tin and boron minerals.

Fig. 170. Topaz considering to gemstone.

Topaz is resistant at superficial conditions, hence is common in alluvial deposits. Clear and colored crystals are used for jewelry making. Topaz used to be formed synthetically, too.

8.4.4. SPHENE (TITANITE) $CaTi(SiO)_4(O,OH,F)$

Sphene, or titanite, is calcium titanium silicate. Common impurities are: Ce, Y, Fe, Nb, Ta and Cr. Substitution of Ca and Ti with other elements are common in sphene. Crystallizes monoclinic and is colorless, but may be yellow, brown, and rarely green.

It is transparent to translucent, displays vitreous, subadamantine or resinous lustre (fig. 171). It has white streak, perfect to distinct cleavage, specific gravity 3.5 to 3.6 g/cm^3, and hardness 5.

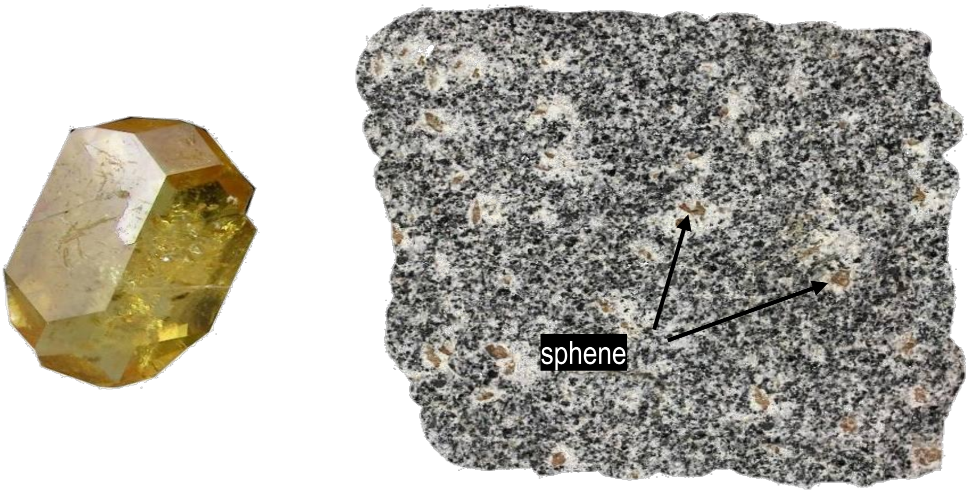


Fig. 171. Crystal of sphene (left), and grains of sphene in granite (right).

In polarizing microscope sphene occurs in wedge-shaped (letter-like) crystals with a distinctive high relief in granular, massive to radial and fan-shaped aggregates (fig. 172).

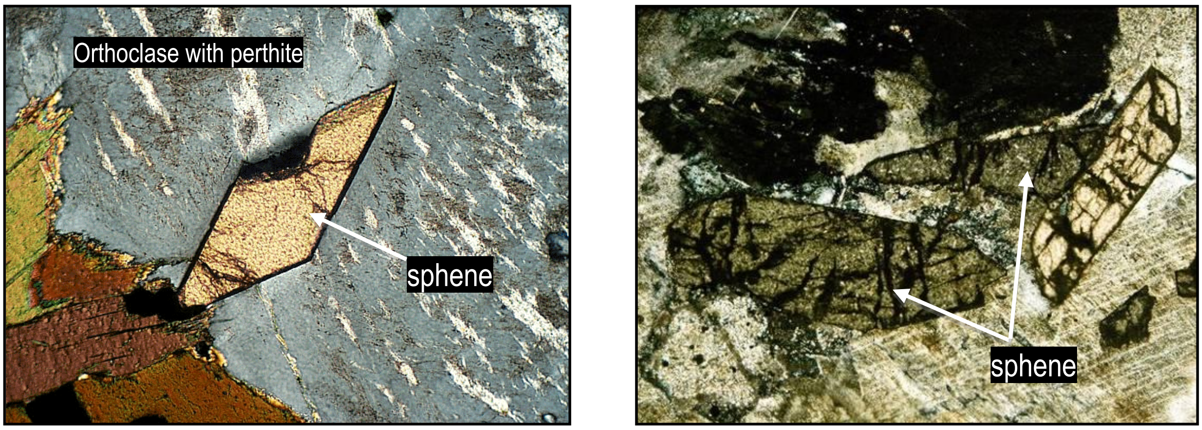


Fig. 172. Microphotograph of sphene crystals in granite, XPL (left),
and in amphibolite, PPL (right). Magnification 100×.

Sphene alters to leucoxene, which generally occur in earthy to grape-like, botryoidal accumulations (fig. 173).

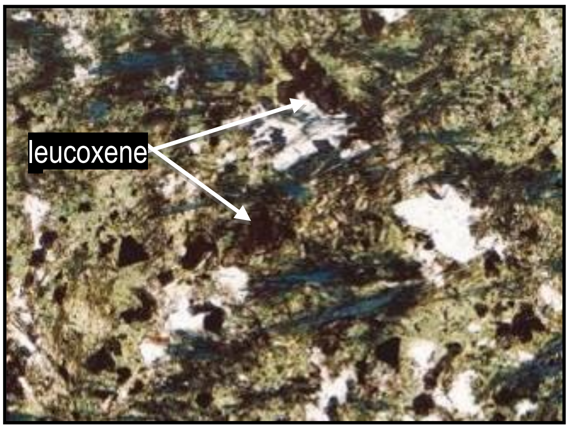


Fig. 173. Leucoxene formed over sphene in amphibolite. Microphotograph, PPL, magnification 100×.

Sphene forms igneous and pegmatitic. It is genetically related to acid (granite, granodiorite) (fig. 174), intermediate (diorite and quartzdiorite) and basic (gabbro) igneous rocks, where is present as an **accessory** (minor) mineral. It is also found in alkali igneous rocks, as well as in metamorphic, but is very rare as a hydrothermal mineral.

Fig.174. In granodiorite of Kopaonik is sphene accessory mineral.

8.4.5. **CHLORITOID** $(Fe^{2+},Mg,Mn)_2Al,Fe^{3+})(OH)_4Al_3O_2(SiO_4)_2$

Chloritoid is characteristic mineral for low and intermediate metamorphic grade. It actually represents a group of minerals: chloritoid, carboirite, magnesium-chloritoid and ottrelite, which are going to be present together.

Chloritoid is commonly present in porphyroblasts, which exceed other rock constituents in size (fig. 175).

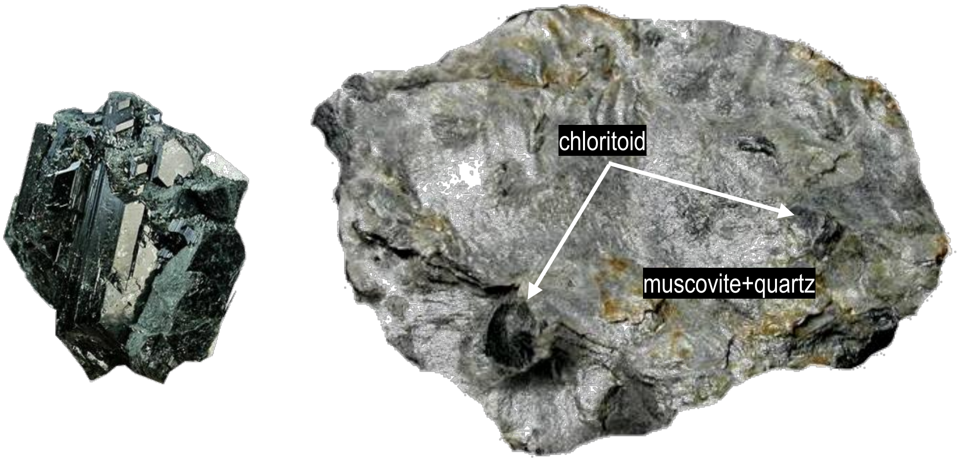


Fig. 175. Crystal of chloritoid (left) and chloritoid in schist (right).

The structure of this mineral is layered, similar to the structure of micas. The only difference is isolated, not linked $(SiO_4)^{4-}$ tetrahedra.

Chloritoid was named after chlorite, due to their similar mode of occurrence and color, especially. A common impurity are Mn, $Fe3^+$ and Ca. Crystallizes monoclinic and frequently occurs in pseudo hexagonal crystals or laths that may form radial and fan-shaped aggregates, which being coarser may be seen by naked eye.

Chloritoid is dark green to almost black in color. Lustre is vitreous to pearly; cleavage is distinct and belongs to brittle minerals. The hardness is 6.5 and specific gravity 3.5 to 3.8 g/cm^3. The streak is greenish.

In polarizing microscope displays moderate to high relief and very characteristic greenish-blue pleochroism under parallel nicols (fig. 176).

Fig. 176. Microphotograph of chloritoid with muscovite (left), XPL and the same mineral, PPL (right). Magnification 200×.

Chloritoid forms by low to intermediate grade regional metamorphism of clastic rocks, clays and sandstone or of conglomerate with clayey matrix aluminum and iron-rich (fig. 177). It commonly associates with pyrophillite and chlorite.

Fig. 177. Outcrop of quartzite originating from quartz conglomerate, which contains chloritoid. Left above, a detail, Kučevo, east Srbija.

9. SOROSILICATES

The crystal structure of sorosilicates, as have been mentioned already, have silica and aluminum tetrahedra linked together by one sharing oxygen atom, and are surrounded with magnesium, aluminum or calcium cations. Some of the minerals from this group play important role in certain rocks occurring either as the essential or accessory mineral, as well as the characteristic one.

9.1. MELILITE $(Ca,Na)_2((Mg, Fe^{2+}Al,Si)_3O_7)$

Melilite includes a complex solid solution series of akermanite and gehlenite as the end members, which can mix completely. Crystallizes tetragonal and occurs in short tabular or platy crystals (fig. 178).

Its color is white, yellow to brownish-yellow. Cleavage is distinct and lustre vitreous. The hardness is 5 to 6, and specific gravity 2.9 to 3.05 g/cm^3.

Melilite is seldom and occurs as the **accessory** constituent. Genetically is related to basic alkaline lava rich in alkalis and calcium, and deficient in silica. Extremely is rare in intrusive rocks. It was noted in some furnace slags and in antique pottery.

It may be formed during thermocontact metamorphism of carbonate rocks at high temperatures that correspond to sanidinite facies (temperatures exceeding 600 °C, pressures up to 3 Kb).

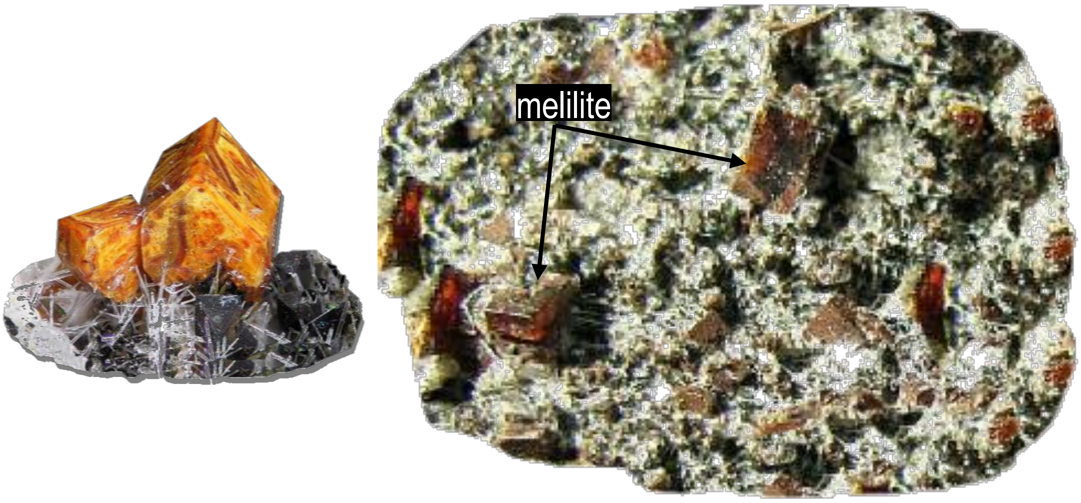


Fig. 178. Melilite crystal (left) and melilite in rock (right).

In crossed polarizing prisms, under the microscope, is melilite dark brown to brown. Under parallel nicols displays moderate to high relief and typical brown color, appearing in irregular or granular masses (fig. 179).

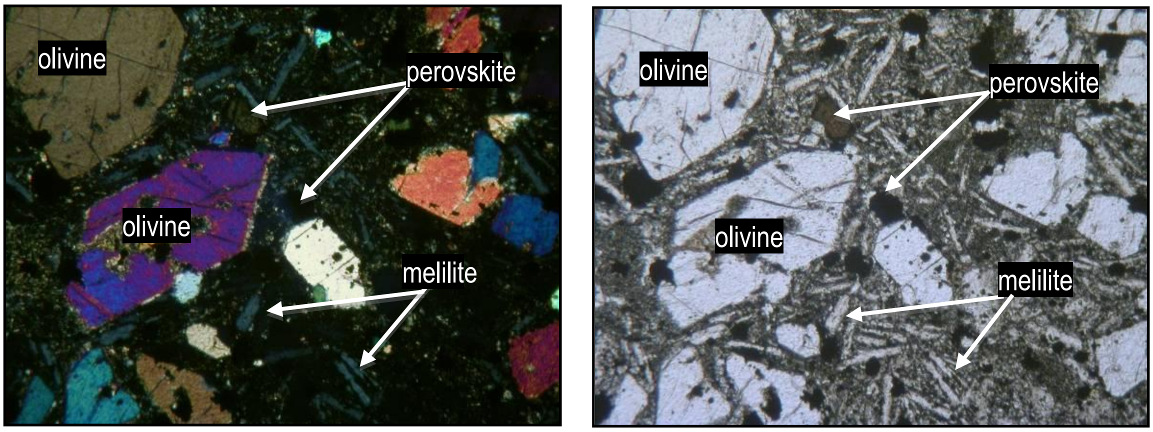


Fig. 179. Microphotograph of melilite in basalt (left), XPL, same mineral in PPL (right). Magnification 100×.

This mineral, as has been mentioned yet, occurs in volcanic rocks, too (fig. 180).

Fig. 180. Lava in volcano Nyiragongo (Congo) bears melilite and nepheline. Right above, a detail of cooled lava.

9.2. EPIDOTE GROUP

Epidote group includes several hydrous aluminum silicates with considerable amount of magnesium, iron or calcium. The most important petrogenic minerals are **epidote**, **zoisite, lawsonite** and **pumpellyite.**

9.2.1. EPIDOTE $Ca_2(Al,Fe)(Si_3O_{12})(OH)$

Epidote is a hydrous calcium aluminum iron silicate in which a part of aluminum may be replaced with Fe^{3+}. Chemical composition of it is not constant due to isomorph mixing between Fe^{3+} and Al, and a highly variable content of Fe^{2+}, Mg, Mn and Ti, additionally.

Manganese-rich variety is called **piedmontite**, and with considerable amount of Ce and U is **orthite** or **allanite**.

Crystallizes monoclinic and occurs as prismatic, slender, grooved crystals, occasionally acicular and tabular. May appears in granular, massive or earthy aggregates. Epidote's color ranges from yellowish-green to green (fig. 181). Manganese rich varieties display red or reddish-violet colors.

Fig. 181. Crystal of epidote (left) and epidote vein in dolerite (right).

Cleavage is perfect, hardness 6.5 to 7, lustre vitreous or greasy, specific gravity 3.2 to 3.6 g/cm^3. Yellowish-green color is very characteristic, while allanite displays brownish-black color and piedmontite violet to reddish-violet.

In polarizing microscope, under crossed nicols, epidote has high interference colors. Crystal forms display high relief at parallel nicols, and occasionally are weakly pleochroic in green (fig. 182).

Epidote forms at low grade regional metamorphism and is associating with albite, chlorite, zoisite, and actinolite (fig. 183). It is also common contact-metamorphic mineral and could be found in outer skarn and hornfels zones.

Epidote is also a secondary mineral, resulting from alteration of ferromagnesian minerals containing aluminum: hornblende, garnet, and basic plagioclase. The contribution of iron is required.

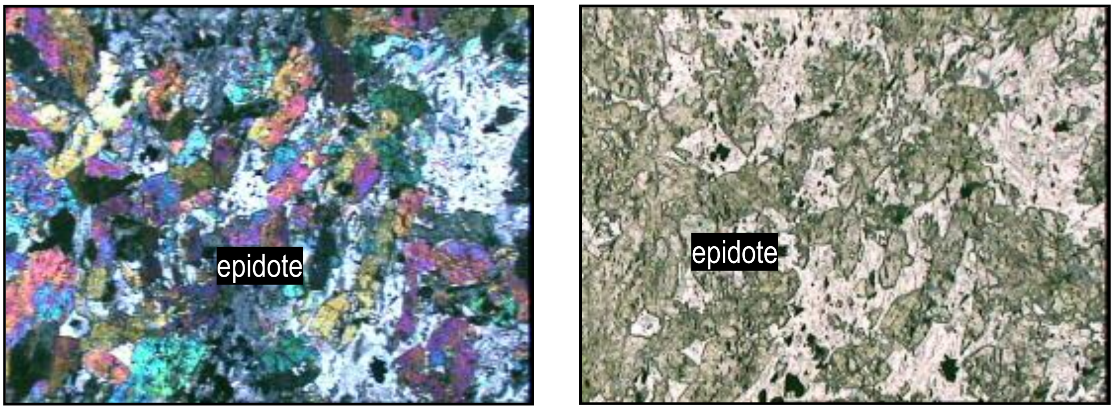


Fig. 182. Microphotograph of epidote in schist, XPL (left) and epidote in altered diabase, PPL (right). Magnification 100×.

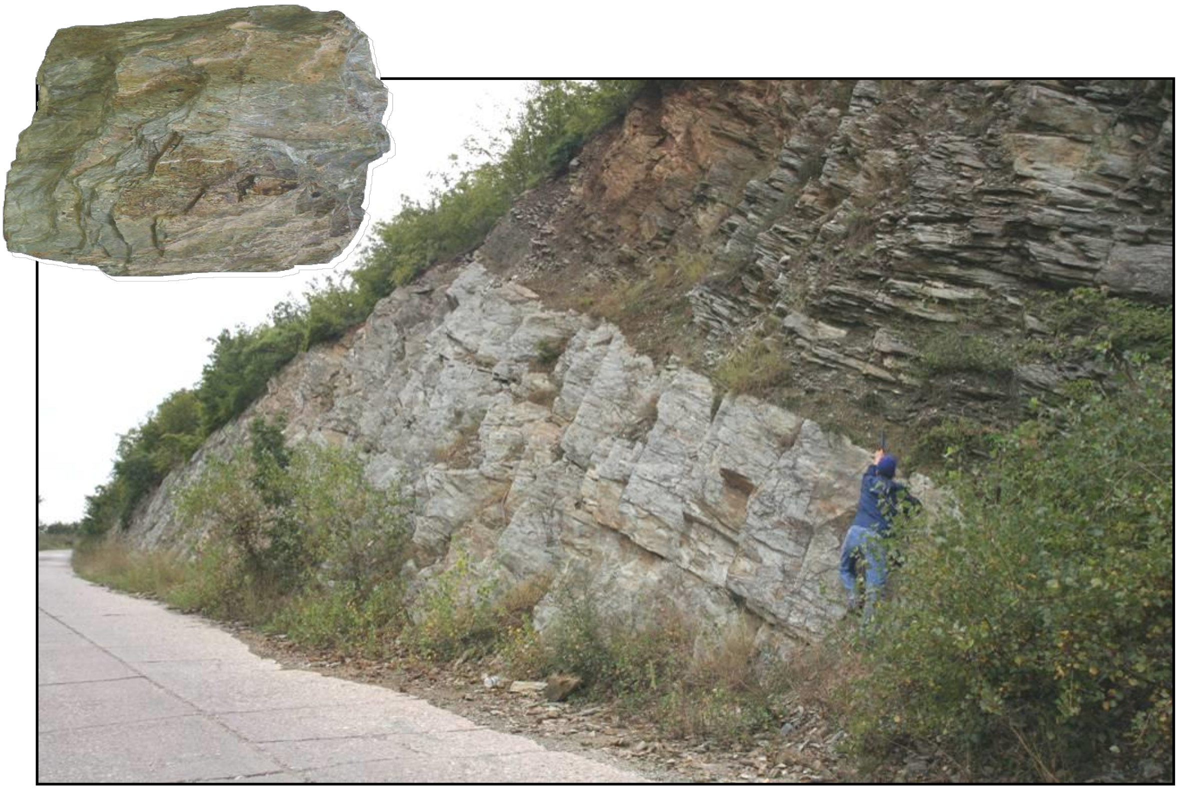


Fig. 183. Chlorite-actinolite schists at Glavica near Paraćin with epidote. Left above, a detail of rock.

As a primary igneous mineral, epidote is found in acid rocks, granites and their pegmatites. It is also hydrothermal mineral.

In weathering processes is resistant, thus could concentrate in alluvial deposits.

9.2.2. **ZOISITE** $Ca_2Al_3(SiO_4)(Si_2O_7)O(OH)$

Zoisite is hydrous calcium aluminum silicate. Small amounts of iron and manganese may be present. It was named after baron von Zois (fig. 184), a famous collector of minerals, from Ljubljana.

Fig. 184. Baron S. Zois (1747–1819).

Zoisite crystallizes either in orthorhombic system or in monoclinic, when is called **clinozoisite**. It occurs in tabular, prismatic to granular aggregates, very rare in regular crystal habits (fig. 185). Its color varies from white, grey, yellow, brownish to grayish-green and bluish. Considerable amount of iron resembles yellowish-green to green. Lustre is vitreous, a cleavage perfect, specific gravity 3.1 to 3.4 g/cm^3, and the hardness 6 to 7.

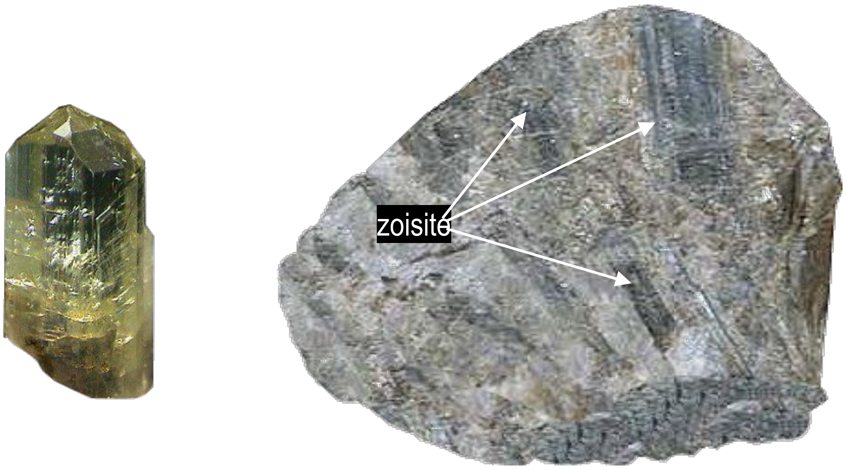


Fig. 185. Zoisite crystal (left) and zoisite in schist (right).

It results from alteration of basic plagioclase, but may occur as an accessory mineral in igneous rocks. It may form during low grade regional metamorphism at the lowest PT conditions (greenschist facies), when associates with epidote, chlorite, albite, and actinolite (fig. 186).

Fig. 186. Chlorite schists of Sena (near Kučevo) contain zoisite.

Zoisite displays blue to grayish-blue color in polarizing microscope in crossed nicols, and is colorless with moderate relief in parallel nicols (fig. 187).

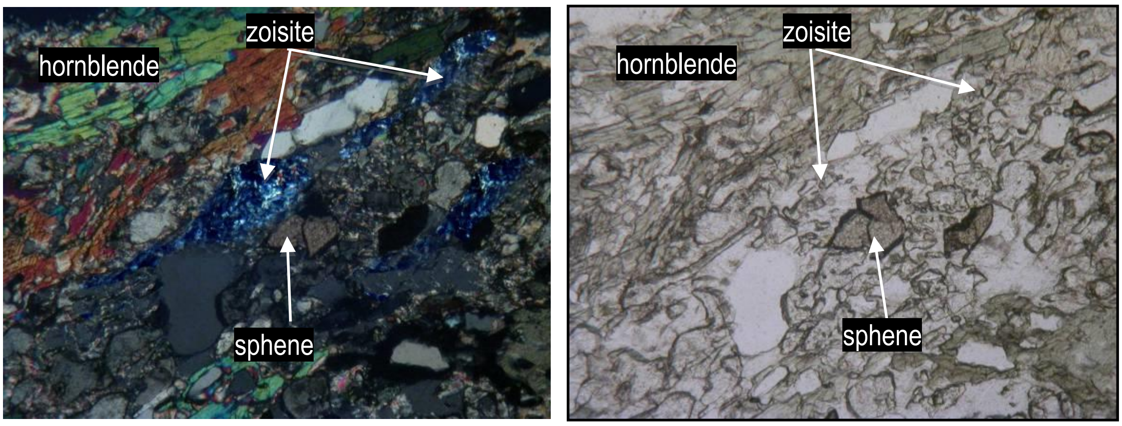


Fig. 187. Microphotograph of zoisite in schist (blue granular aggregates), XPL (left) and the same image in PPL (right). Magnification 100×.

9.3. LAWSONITE $CaAl_2Si_2O_7(OH)_2\times H_2O$

Lawsonite is named after American professor of geology Andrew Lawson (fig. 188). Lawsonite crystallizes orthorhombic, has perfect cleavage and conchoidal to uneven fracture. Hardness is 6, and specific gravity from 3 to 3.1 g/cm^3.

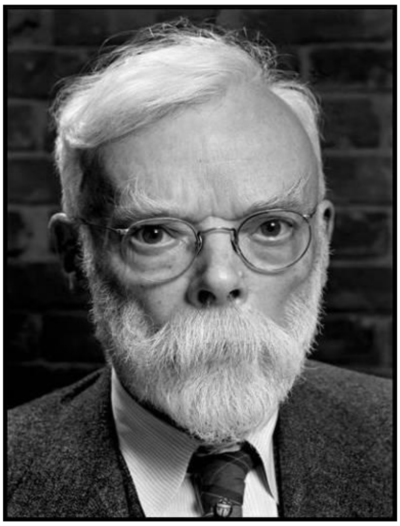


Fig. 188. A. Lawson (1861–1952).

Lawsonite appears in prismatic to tabular crystals, or in granular to massive aggregates. It displays vitreous lustre and grayish-blue, white, pink and grey colors (fig. 189). Colorless varieties are very rare. Streak is white.

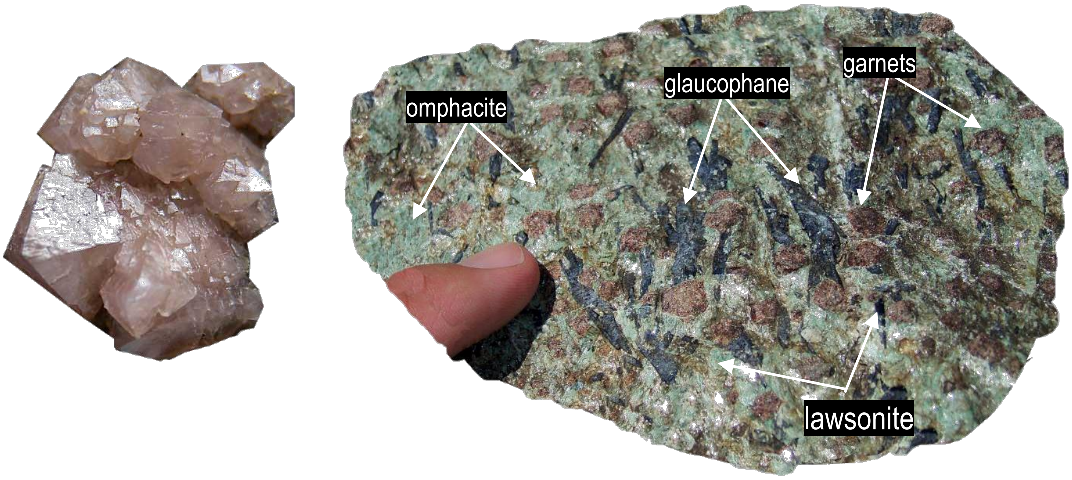


Fig. 189. Crystal of lawsonite (left) and lawsonite in eclogite, grey (right).

In polarizing microscope is lawsonite, in terms of optical properties, very similar to epidote and zoisite. Interference colors may be high. In parallel nicols is lawsonite colorless and of moderate relief (fig. 190).

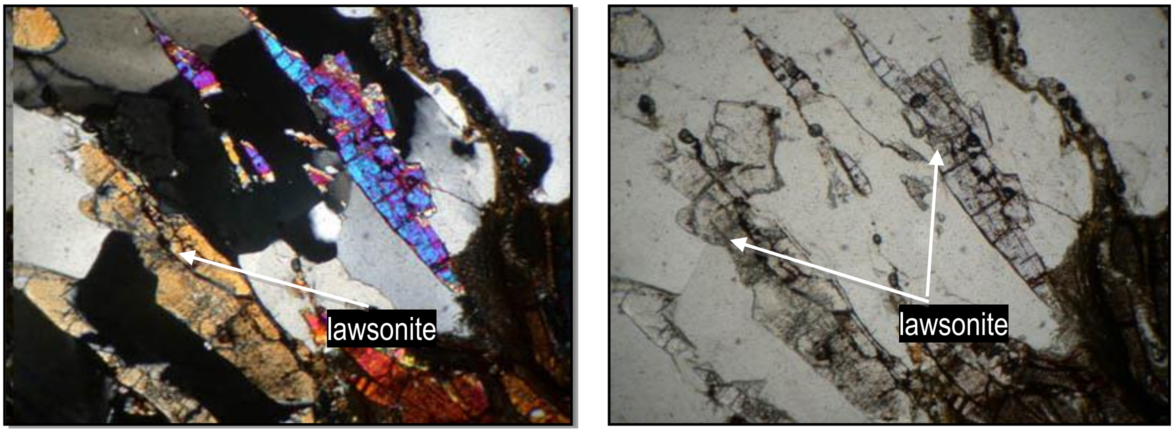


Fig. 190. Microphotograph of lawsonite in schist (left), XPL, and the same image in PPL (right). Magnification 200×.

It is particularly important mineral in the studies of metamorphism that takes part in high pressure-low temperature zones where the oceanic lithosphere is sinking beneath continental, or oceanic beneath oceanic lithosphere (subduction zones) (fig. 191). In petrology of metamorphic rocks is lawsonite very important mineral, as being formed in a very narrow PT conditions defining a distinctive facies.

Fig. 191. Schist with lawsonite outcropping in the stream, Piljevački potok, Brezovica.

9.4. PUMPELLYITE $Ca_2,Al_2(Al,Fe^{3+},Fe^{2+},Mg)_{1.0}(Si_2(O,OH)_7)(SiO_4)(OH,O)_3$

Pumpellyite is hydrous aluminum silicate with calcium, magnesium, and iron. The above given formula refers to end member of prehnite-pumpellyite series (Fe^{3+}).

Pumpellyite crystallizes in monoclinic system. It occurs in acicular or tabular aggregates that often build radiating aggregates. Hardness is 5 to 6, and specific gravity from 3.2 to 3.4 g/cm^3 (fig. 192).

Fig. 192. Crystals of pumpellyite (left), and pumpellyite in a rock mass (right).

According to optical properties and a mode of occurrence is pumpellyite very similar to epidote, commonly associating with it (fig. 193).

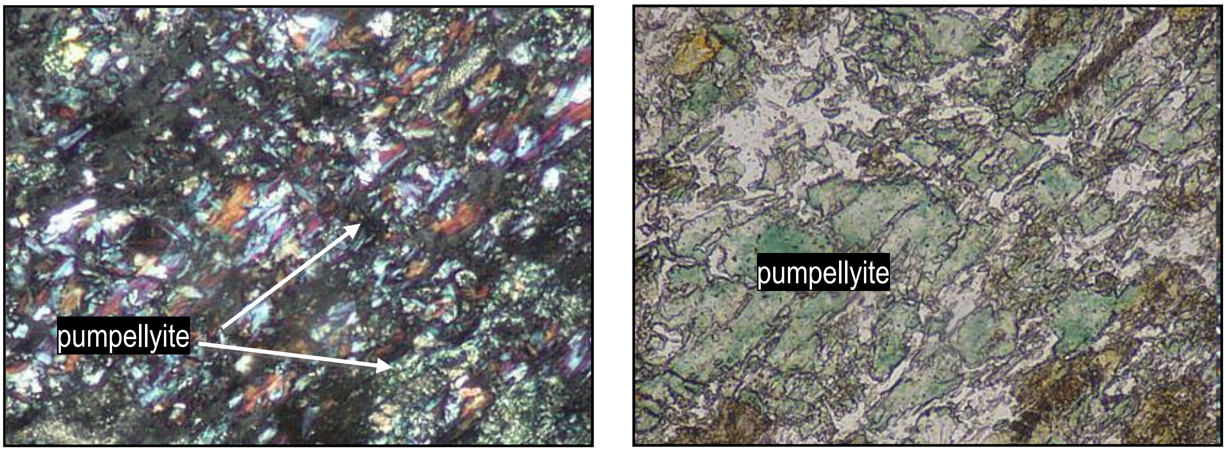


Fig. 193. Microphotograph of pumpellyite, XPL (left), and the same mineral in PPL (right). Magnification 100×.

Pumpellyite is regionally-metamorphic mineral and forms at low metamorphic grade. It associates with glaucophane and lawsonite, minerals that are characteristic for subduction zones and for low temperature (up to 400 °C) and high pressure (over 10 Kb) conditions.

Pumpellyite is also secondary mineral resulting from alteration of basic, submarine volcanic rocks where it replaces basic plagioclase after contribution of iron (fig. 194).

Fig. 194. „Pillow" lavas of basic rocks that contain the assemblage of alteration minerals including pumpellyite. Above right, a detail.River Zlatarska reka, Nova Varoš.

9.5. VESUVIANITE $Ca_{19}(Al, Fe)_{10}(Mg,Fe)_3(Si_2O_7)_4(SiO_4)_{10}(O,OH,F)_{10}$

Vesuvianite is named for the volcano Vesuvius, above Naples in Italy, where it was initially discovered (fig. 195). The older synonym is **idocrase**. It is hydrous calcium magnesium aluminum silicate. Quite common substitution of Mg with Ca and Fe^{2+}, Al with Fe^{3+} results in its very variable composition. Some species may contain considerable amount of B and CO_2. It crystallizes in tetragonal system. Its color differs from yellowish-green, yellowish-brown to green.

Fig. 195. Volcano Vesuvius, close to Naples, Italy.

Vesuvianite occurs in crystals that is combination of prism and one or two bipyramids, but also occurs in prismatic, acicular or radiating to compact, granular masses (fig. 196).

Cleavage is lacking, fracture is uneven and the lustre vitreous. Specific gravity is 3.3 to 3.5 g/cm^3, and the hardness ranges from 6 to 7.

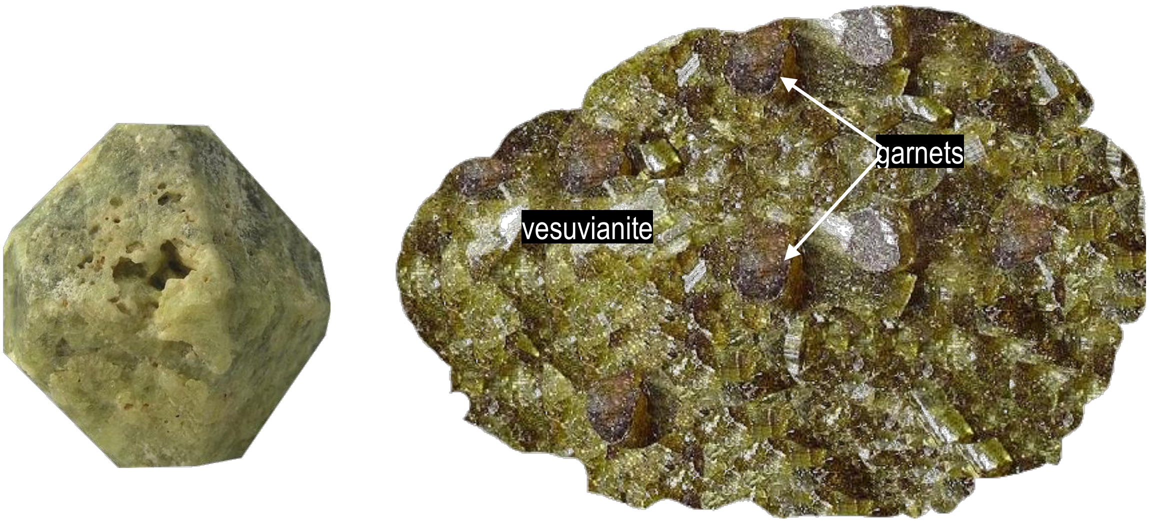


Fig. 196. Vesuvianite crystal (left), and vesuvianite in a rock mass (right).

In polarizing microscope, when nicols are crossed, vesuvianite displays typical dark blue color and could be easily identified in the sample (fig. 197).

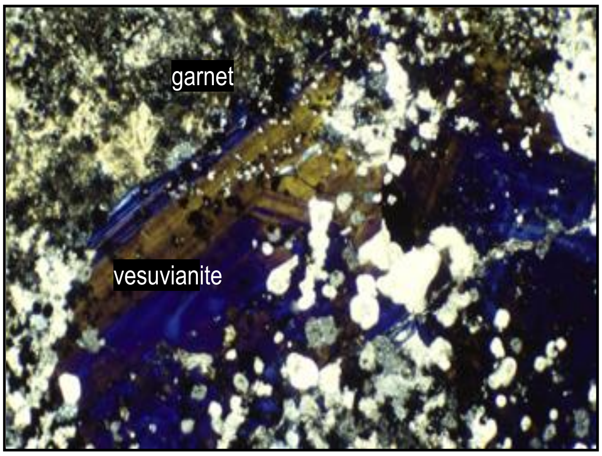


Fig. 197. Microphotograph of vesuvianite in skarn; XPL, magnification 200×.

Vesuvianite is contact-metasomatic mineral and forms by addition of Si, partly and Mg from acid magma (granite to granodiorite) into limestone and marlstone, when skarns are formed. Skarns, closest to the contact, consist of vesuvianite, Ca-garnets (grossular, andradite), Ca pyroxene (diopside), wollastonite, etc. (fig. 198).

Fig. 198. Vesuvianite in skarn at Valja Strž (east Serbia). Above right are crystals of vesuvianite.

10. CYCLOSILICATES

In cyclosilicates, as have been indicated already, the $(SiO_4)^{4-}$ tetrahedra forms ring structures with anion groups OH, BO_3 and BO_4. This group includes beryl, tourmaline, cordierite and axinite.

10.1. BERYL $Be_3Al_2(Si_6O_{18})$

Beryl is beryllium aluminum silicate in composition. Common impurities are: Na, K, Li, Rb, Cs, Fe, and Cr.

The beryl group occurs as well-developed hexagonal crystals, often very large and elongated, prismatic. Pure beryl is colorless. When is colored by certain impurities it takes on a number of colors: yellow, yellowish-green, green (fig. 199).

Beryl does not have cleavage. Its hardness is 7.5 to 8, specific gravity 2.6 to 2.9 g/cm^3. It is transparent to translucent, thus of vitreous lustre.

The green beryl is recognized as **emerald**, and the blue one is **aquamarine**. These two varieties refer to gemstones.

Fig. 199. Crystals of beryl, left above; beryl in pegmatite (in the middle) and ring with emerald (right).

In polarizing microscope is beryl grey under crossed nicols, and colorless when nicols are parallel (fig. 200).

It is resistant to weathering; however a pretty long exposure to atmospheric agents makes it muddy and finally leads to transformation into kaolinite.

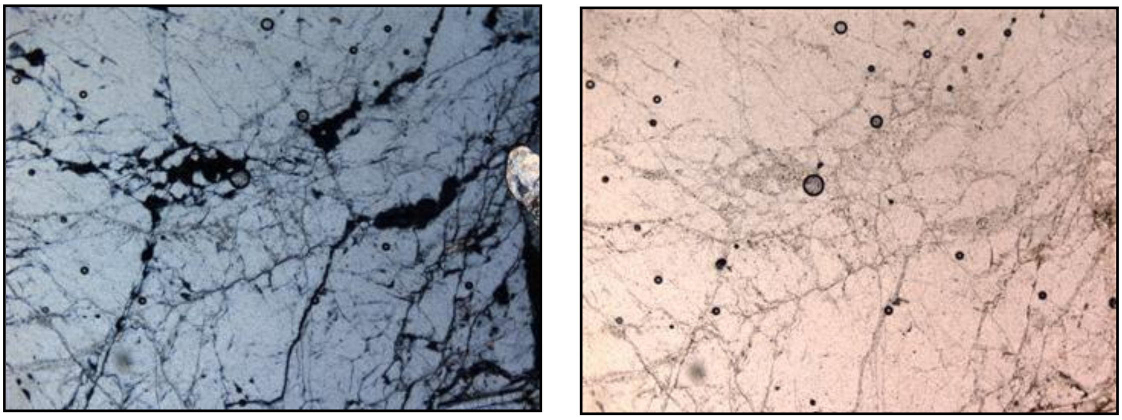


Fig. 200. Microphotograph of beryl (left), XPL, and the same mineral in PPL (right). Magnification 100×.

Beryl occurs in pegmatite and is related to acid igneous rocks, which bear some of the most beautiful and regular crystals of beryl (fig. 201).

In pegmatite, common granitic, is associated with tourmaline, garnets and with lithium pyroxene and micas, occasionally.

Beryl is also contact metamorphic mineral, pneumatolitic (in greisen), rarely hydrothermal.

Fig. 201. Pegmatites of Cer contain beryl, above right – the crystal of beryl.

10.2. TOURMALINE

$(Na,Ca)(Mg,Fe,Mn,Li,Al)_3(AlMg,Fe^{3+})_6(Si_6O_{18})(BO_3)_3(O,OH)_3(OH,F)$

Tourmaline has very complex composition and is able to include as much as 15 different elements. Its composition may be simply defined as Na, Ca, Mg, Fe borosilicate of aluminum and OH group.

It crystallizes in orthorhombic system and commonly occurs in prismatic crystals (fig. 202). Acicular, sticky or granular appearance is less common. Its color varies with composition from colorless over pinkish, to green, brown and black.

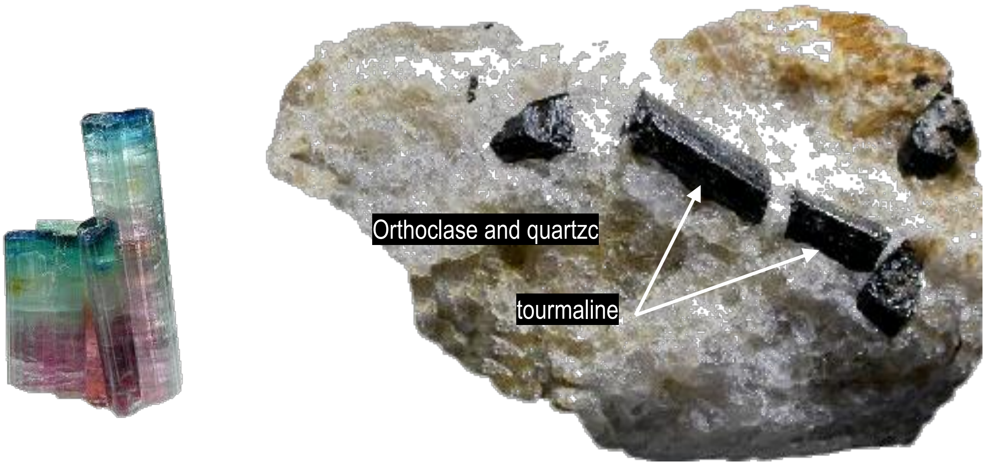


Fig. 202. Tourmaline crystals (left), and tourmaline in pegmatite (right).

Tourmaline is of vitreous lustre and absent cleavage. Its fracture is uneven or conchoidal. Specific gravity ranges from 2.9 to 3.3 g/cm^3, and hardness from 7 to 7.5. When rubbed and warmed becomes piezoelectric. Tourmaline may be semi-precious (gemstone) and a precious stone.

In polarizing microscope in parallel nicols is pleochroic displaying green and blue colors (fig. 203).

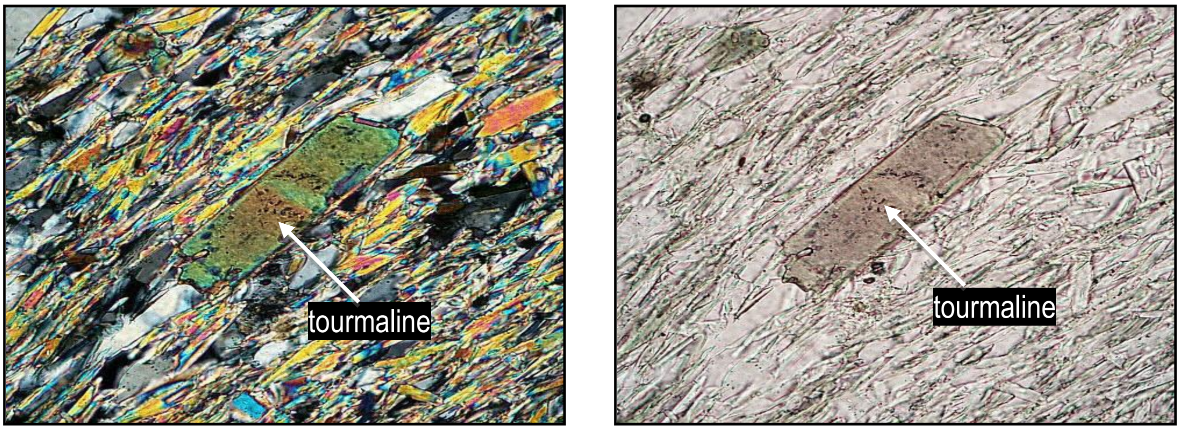


Fig. 203. Microphotograph of tourmaline in schist, XPL (left), and of the same mineral in PPL (right). Magnification 200×.

Tourmaline is igneous mineral and is abundant in acid rocks, granites, where represents an accessory constituent. The most beautiful crystals, commonly large and well-developed, are found in pegmatites accompanying granites (fig. 204). Tourmaline also forms pneumatolitic and hydrothermally, when star-shaped aggregates of the dravite variety develop. During regional metamorphism tourmaline forms by addition of boron into sediments that take part in metamorphic processes. It is resistant in atmospheric conditions and concentrates in detrital, sandstone sediments.

When transparent to semi transparent crystals take on a number of colors, tourmaline is recognized as a gemstone.

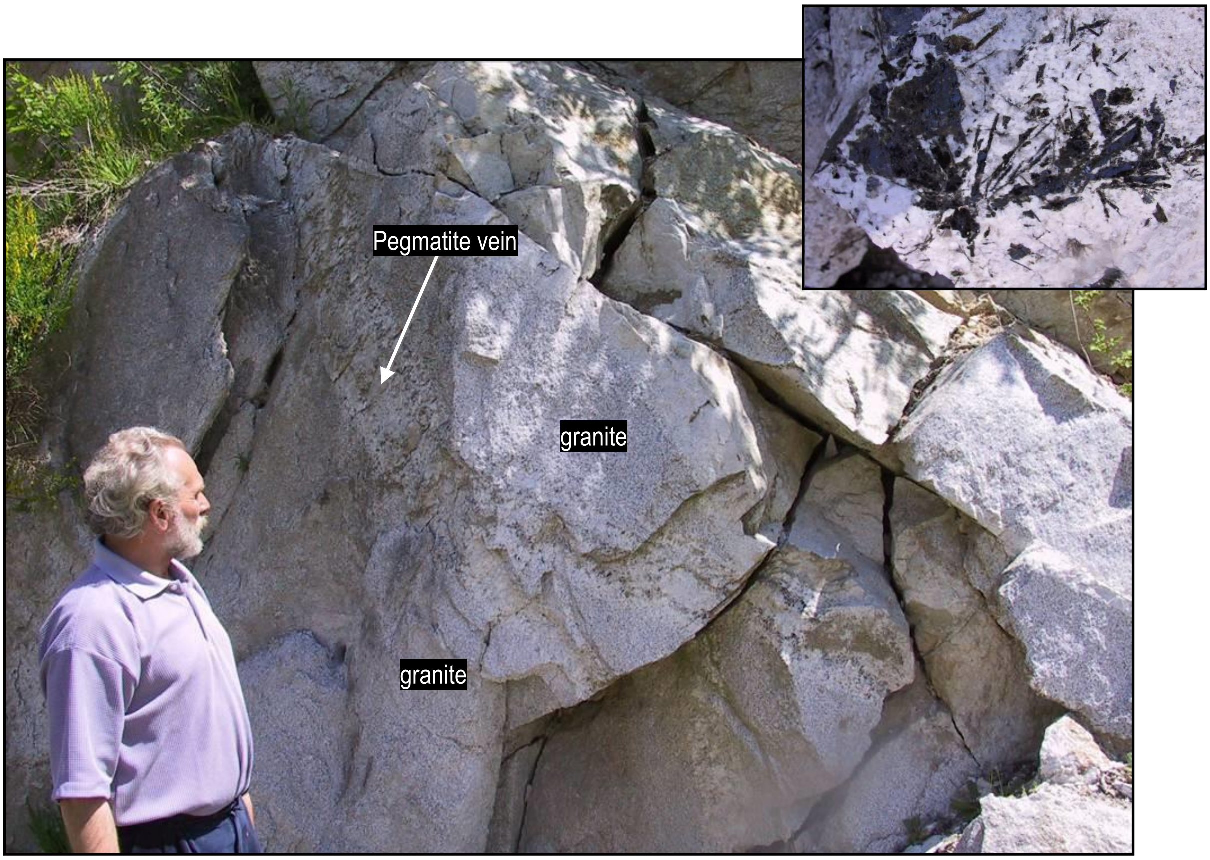


Fig. 204. Granites on Bukulja contain tourmaline. Right above, a detail of the sample with biotite and tourmaline.

10.3. CORDIERITE $(Mg,Fe)_2(Si_5Al_4O_{18})$

Cordierite is named for the French mineralogist Cordier (fig. 205). In composition is hydrous aluminum silicate with magnesium and iron. May contains Na, K, Mn, Ca, Fe, Ti and CO_2 as impurities. Structure of cordierite is similar to the structure of beryl.

Fig. 205. L. Cordier (1777–1861).

Cordierite crystallizes orthorhombic, but also produces the high-temperature, hexagonal modification. It occurs in granular masses, rarely in short prismatic crystals, which are commonly twinned.

Its color is light blue, grayish-blue to blue, but colorless variety exists also. Cleavage is distinct and broken surfaces display resinous lustre. Specific gravity is 2.5 to 2.8 g/cm^3, and hardness from 7 to 7.5 (fig. 206).

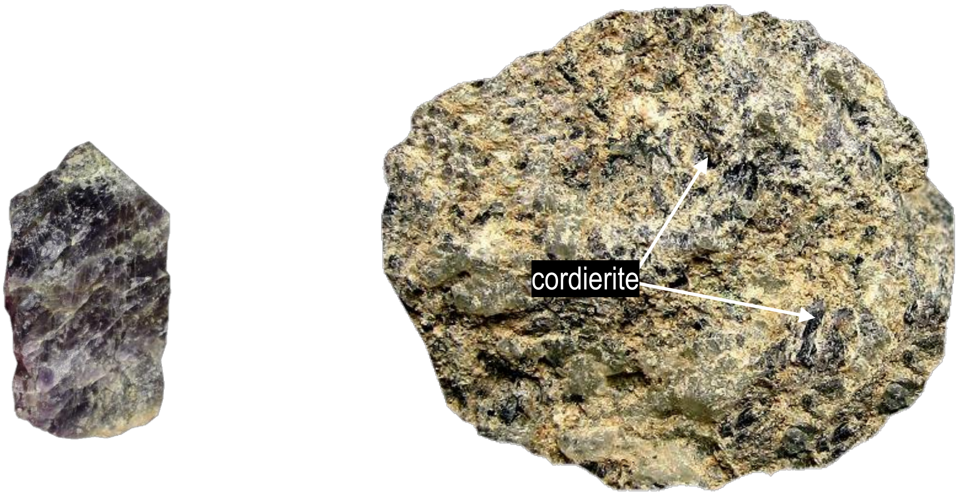


Fig. 206. Crystal of cordierite (left) and cordierite in hornfels (right).

In polarizing microscope looks like alkali feldspar and quartz, particularly when is present in granite or gneiss. May be confused with andalusite in hornfels (fig. 207).

Cordierite is primarily thermometamorphic mineral, which forms at the contact of acid magma and clayey sediments, when metamorphism is caused only by higher temperature.

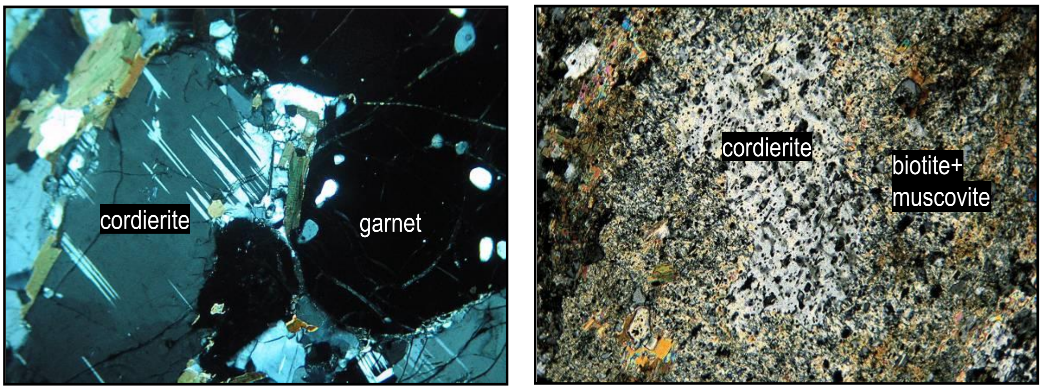


Fig. 207. Microphotograph of cordierite in garnet gneiss (left), and in hornfels (right). XPL, magnification 100×.

Cordierite is usually found at the immediate contact or very close to it as a result of the highest influence of hot magma on surrounding rocks (fig. 208). In those zones cordierite associates with andalusite, but alkali feldspars, biotite, even pyroxene, may be present too. These metamorphic processes give rise to rock named hornfels.

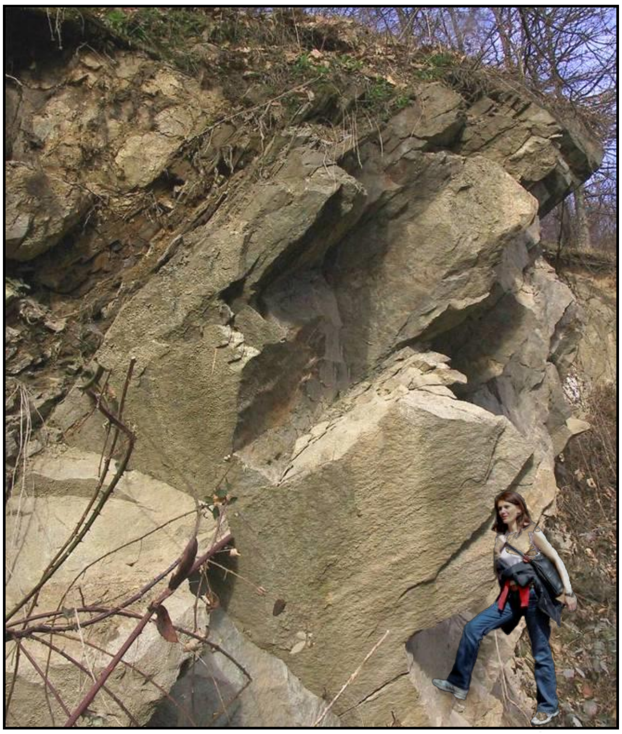


Fig. 208. Hornfels at Boranja bears cordierite.

Cordierite may be found in regionally metamorphosed psammitic and pelitic rocks that were exposed to moderate and high PT conditions, temperatures above 500 °C and pressures exceeding 5 Kb. This mineral has been noted in some igneous, acid intrusive rocks (granites), where it occurs as major mineral and formed through crystallization of magma of certain composition (Mg exceeding Fe) and negligible amount of water.

The influence of hydrothermal solutions and atmospheric agents converts cordierite into fine-grained aggregate of chlorite and sericite, pinite.

10.4. AXINITE $(Ca,Fe,Mn,Mg)_3(Al_2Si_4O_{12})(BO_3)(OH)$

Axinite is the solid solution of ferrous-axinite to tinzenite. It was named after the Greek word "*axine*" (ax) because its sharp, wedge-shaped crystals are common.

It crystallizes in triclinic system and occurs in tabular to prismatic wedge-shaped crystals with sharp edges. This mineral builds granular and massive aggregates, also.

Its color is violet to purple-brown, and lustre is vitreous (fig. 209). Some crystals display fluorescence in red-orange color under ultraviolet emission. Axinite has distinct cleavage, specific gravity 3.2 to 3.3 g/cm^3, and hardness from 6.5 to 7.

Fig. 209. Crystals of axinite (left) and axinite occupying a cavity in rock (right).

In polarized microscope axinite displays moderate to high relief and is colorless or purple under parallel nicols, thus could be easily identified in thin-section (fig. 210).

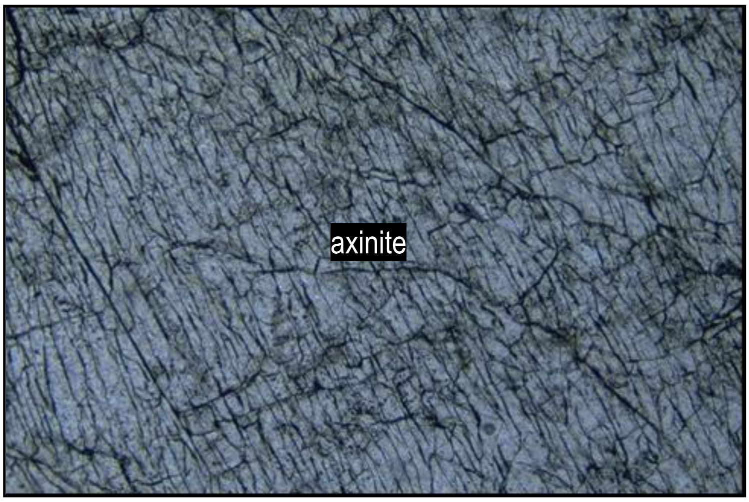


Fig. 210. Microphotograph of axinite. PPL, magnification 200×.

Axinite forms as metasomatic mineral, in contact zones of acid igneous rocks and carbonate rocks by a certain amount of boron contribution (fig. 211). It forms in pneumatolitic stage when associates with tourmaline, quartz, sometimes with tin, tungsten and molybdenum ore-minerals. Axinite is noted in association with hydrothermal minerals.

Fig. 211. Axinite occurs in the lead-zinc mine at the mountain Rudnik. Above left, crystals of axinite taken from ore vein approximately ten centimeters thick.

11. INOSILICATES

Inosilicates are the group of silicate minerals whose silica and aluminum tetrahedra compose unlimited single or complex chains that are linked together by Ca, Fe, Mg, and Na cations, including OH group in amphiboles. According to basically structural type within the inosilicates are recognized:

- **pyroxene group** with $(SiO_4)^{4-}$ tetrahedra arranged in one single, continuous chain;
- **amphibole group** with $(SiO_4)^{4-}$ tetrahedra linked together in two rows (double chains).

Such type of bonding reveals the appearance of inosilicates in prismatic, tabular, acicular and fibrous aggregates.

11.1. PYROXENE

The pyroxene group forms single chains and compositionally represents anhydrous calcium, magnesium, iron and sodium silicates. Complex chemistry results from isomorphism and composing of solid solutions (isomorphic series). Pyroxene occurs in short, stubby prismatic aggregates, either as single crystals or twins. Crystals are characterized by a good prismatic cleavage at 87 and 90°. This property allows the identification of the pyroxene group in the microscope. They crystallize in orthorhombic and monoclinic system.

11.1.1. ORTHOPYROXENES $(Mg,Fe^{2+})SiO_3$

Orthorhombic pyroxene or, also designated as orthopyroxene, comprise a solid solution series with extreme composition of enstatite, $MgSiO_3$ and ferrosilite, $FeSiO_3$. These minerals have incongruent melting point and form through reaction of olivine and rest of melt. In complex natural systems, orthopyroxene crystallizes at some lower temperatures directly from magma. The important rock-making members of the series are:

enstatite	0-12 % $FeSiO_3$
bronzite	12-30 % $FeSiO_3$
hypersthene	30-50 % $FeSiO_3$

They are going to be presented together as have similar or same properties. Orthopyroxene occurs in stubby prismatic crystals (fig. 212) or as prismatic and granular aggregates.

Their color depends on their composition, and is commonly white, grey to yellowish. The increasing iron gives green color to enstatite. Bronzite has very characteristic bronze-yellowish shine, hence the name. Hypersthene is green to dull green.

Orthopyroxene displays vitreous lustre and a good to perfect cleavage in two directions at 87–90°. Fracture is uneven, specific gravity from 3.2 to 3.9 g/cm^3, hardness 5 to 6. Bronzite has characteristic bronze lustre (fig. 213).

Fig. 212. Crystal of enstatite (left), and enstatite in a rock mass (right).

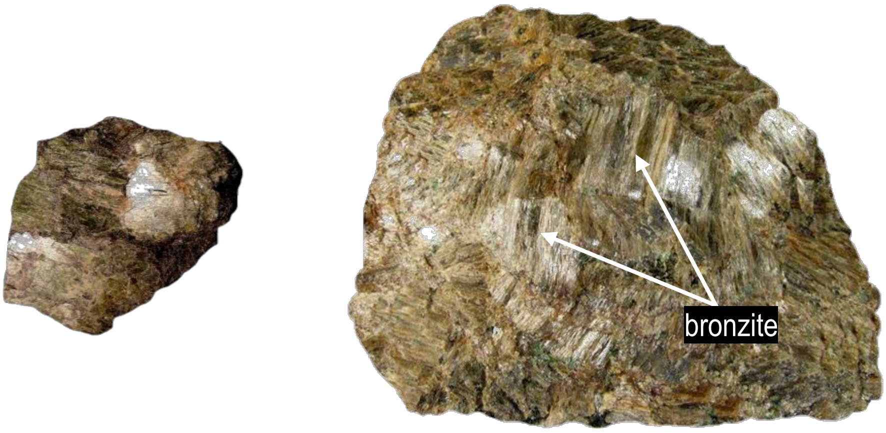


Fig. 213. Crystal of bronzite (left), and bronzite in a rock (right).

In polarizing microscope pyroxene displays moderate relief and high interference colors under crossed nicols. In parallel nicols are colorless (fig. 214). Their parallel extinction permits them to be distinguished from clinopyroxene, which displays the extinction angles.

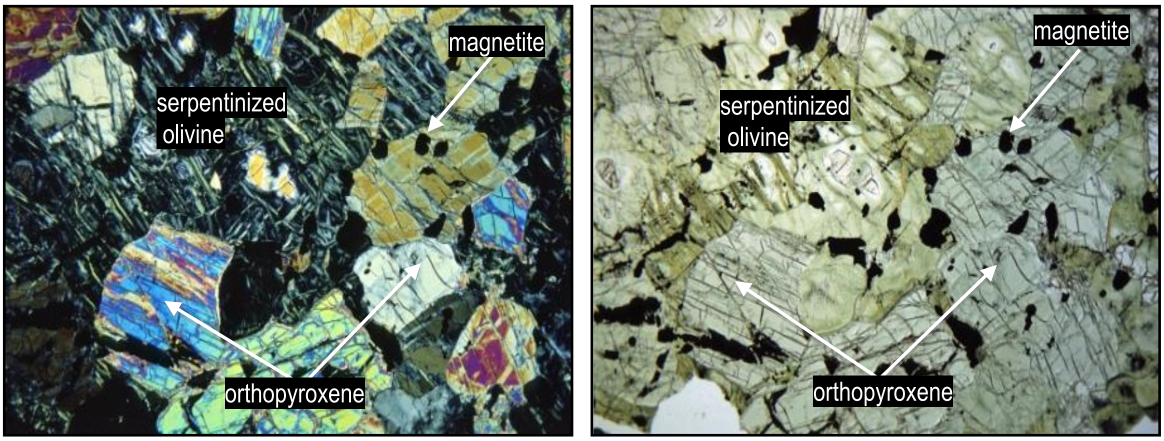


Fig. 214. Microphotograph of orthopyroxene in peridotite (harzburgite). XPL (left), the same image in PPL (right). Magnification 100×.

Deformations formed during tectonic motions are sometimes obvious on coarse grains of orthopyroxene (commonly in ultrabasic rocks).

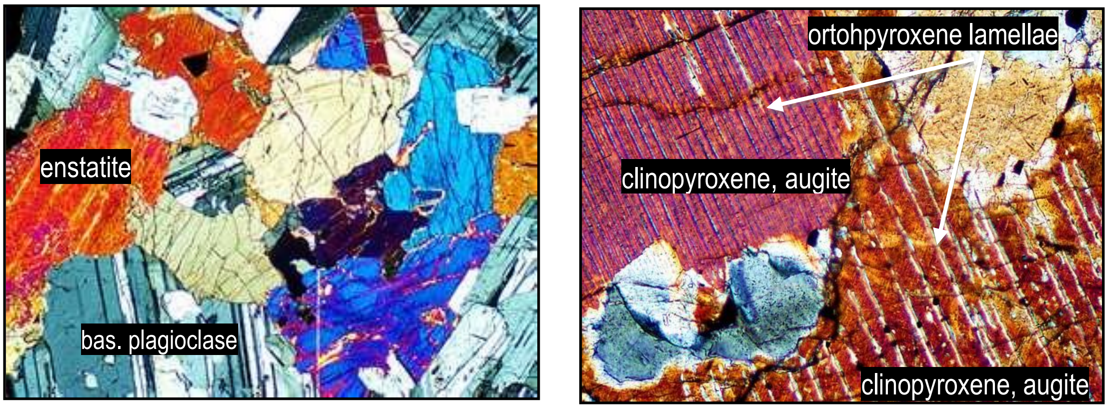
Orthopyroxene is formed typically in igneous rocks and is one of the principal minerals in ultrabasic rocks where associates with olivine (fig. 215). It builds also a monomineral veins up to ten cm thick (pyroxenite).

Orthopyroxene may be macroscopically (by naked eye) recognized in peridotites on account the apparent cleavage in contrast to olivine, with who is associated in these rocks.

Fig 215. Peridotites at Divčibare, contain orthopyroxene beside olivine. Above right, a detail of rock sample with grains of orthopyroxene.

Orthopyroxene, found in basic intrusive rocks, gabbros as well as in basic volcanic rocks, basalts, usually displays zoned pattern. Exsolutions lamellae (lamellae of separated phase) of clinopyroxene, or contrary, of orthopyroxene in monoclinic pyroxene, resulted from the reduced miscibility of two different phases with slow lowering temperature of magma (fig. 216).

Orthopyroxene in mantle peridotite displays lamellae of magnesium ilmenite and of garnet.



Figl. 216. Microphotograph of enstatite in gabbro (left), and exsolutions lamellae of orthopyroxene (thin lines) in clinopyroxene (right). XPL, magnification 100×.

Orthopyroxene may be present in granite variety called charnockite. Some authors consider this rock metamorphic.

Orthopyroxene forms during regional metamorphism at high temperatures and pressures (dry granulite facies). Very rare are contact metamorphic minerals, formed close to the contact of magma and surrounding sedimentary rocks, either of dolomitic marlstone or of Mg and Fe rich clays.

At atmospheric conditions and when imposed to hydrothermal fluids, orthopyroxene transforms into minerals of the serpentine group.

11.1.2. MONOCLINIC PYROXENE

Monoclinic pyroxene is calcium-magnesium-iron silicate in composition that like orthopyroxene represents isomorphic series. They crystallize directly from the melt of matching composition. Crystallization takes part from magnesium rich to iron rich members.

The most important igneous and metamorphic rock-making monoclinic pyroxenes are: pigeonite, diopside-hedenbergite, augite, alkali pyroxene and spodumene.

11.1.2.1. Pigeonite $(Mg,Fe^{2+},Ca)(Mg,Fe^{2+})(Si_2O_6)$

Pigeonite is magnesium-iron-calcium silicate in composition, calcium poor and with Na, Mn, Cr and Al as impurities. It occurs in prismatic (fig. 217) to granular aggregates, very rare in crystal habits.

Pigeonite is green, dark-green, occasionally brownish in color, transparent to translucent, of vitreous lustre, sometimes even opaque. Cleavage is perfect in two directions at 87–90°. This property has been already mentioned as the distinctive feature for the whole group. Specific gravity of pigeonite ranges with composition from 3.2 to 3.5 g/cm^3, and hardness is 6.

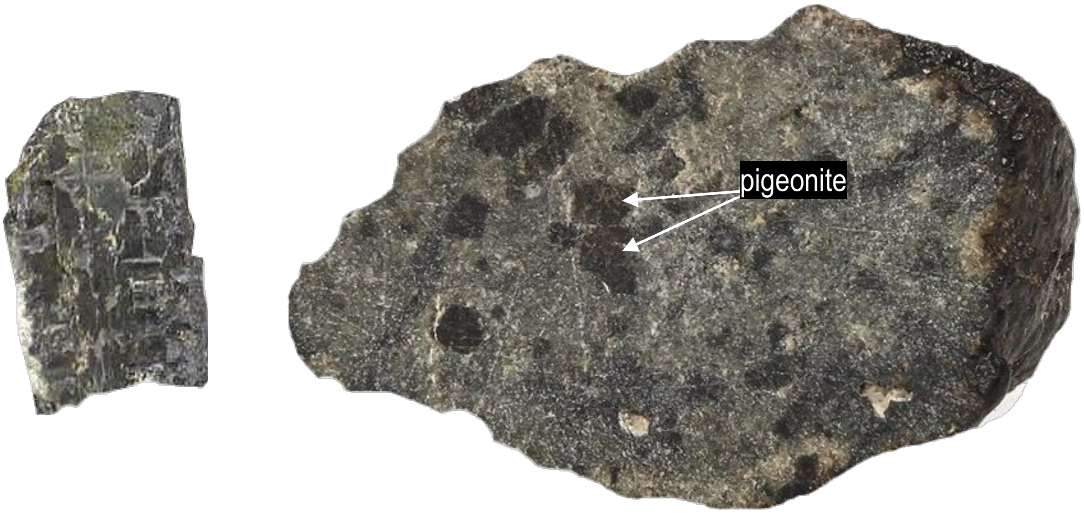


Fig. 217. Crystal of pigeonite (left), and pigeonite (black) in andesite (right).

Pigeonite displays interference colors of the first and second order in polarizing microscope at crossed nicols and is colorless or faintly pleochroic under the parallel nicols (fig. 218).

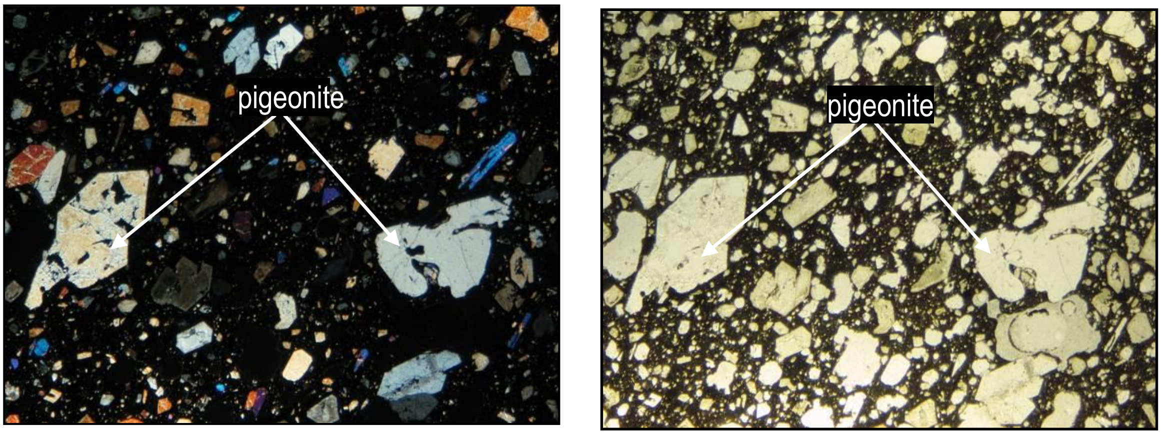


Fig. 218. Microphotograph of pigeonite in basalt, XPL (left), and the same mineral in PPL (right). Magnification 80×.

Pigeonite is igneous mineral, and is a common constituent in intermediate volcanic rocks, andesite and dacite (fig. 219). May be found in basalt, too.

Fig. 219. In andesites of Šumnik (near Raška) is present pigeonite. Above right, the sample of these rocks.

Pigeonite also forms during regional metamorphism, at high temperatures and pressures (granulite facies). This mineral is found in certain meteorites composed of silicates: olivine, pyroxene, basic plagioclase (fig. 220).

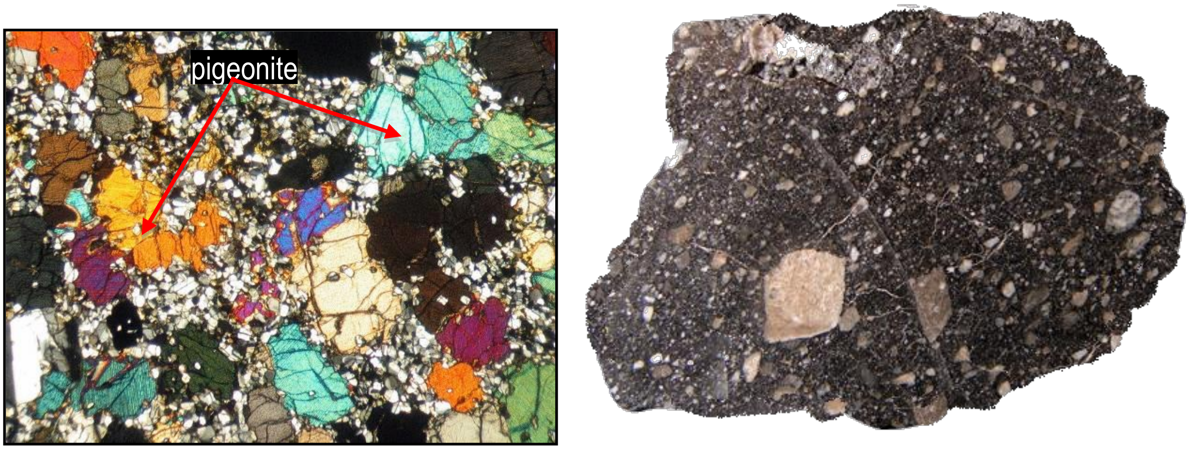


Fig. 220. Pigeonite in meteorite, XPL (left), magnification 100×, and the sample of meteorite of the achondrite class, where it was found (right).

Pigeonite alters under the action of hot water solutions (hydrothermal fluids), into aluminum-lack amphibole, actinolite, and is called uralite, as well as into chlorite and iron oxides and hydroxides.

11.1.2.2. Diopside $CaMgSi_2O_6$
Hedenbergite $CaFeSi_2O_6$

Diopside is calcium-magnesium silicate, and the hedenbergite is calcium-iron silicate. Between these two minerals occur the complete mixing and all transitions.

Diopside contains Al, Fe and Cr as impurities and occurs in short prismatic, columnar, and tabular to granular aggregates. Diopside is generally white or grey. The depth of color is a function of the iron content, thus the iron presence colors it from pale green to dark green.

It is transparent to translucent, of vitreous lustre. Cleavage is perfect, fracture uneven, specific gravity 3.3 to 3.5 g/cm^3, and the hardness 5.5 to 6.5.

Diopside and hedenbergite are contact metamorphic minerals and are related to skarn, a rock formed at contact of granite and limestone (fig. 221).

Diopside is forming through the reaction of quartz and calcite, yet at 250 to 300 °C and at pressures up to 3 Kb in an opened system, while other Ca pyroxenes, salite and hedenbergite form at higher temperatures, approximately 500 °C.

Diopside and hedenbergite are in skarns commonly associated with wollastonite, Ca-garnet (grossular and andradite), vesuvianite, basic plagioclase, and calcite.

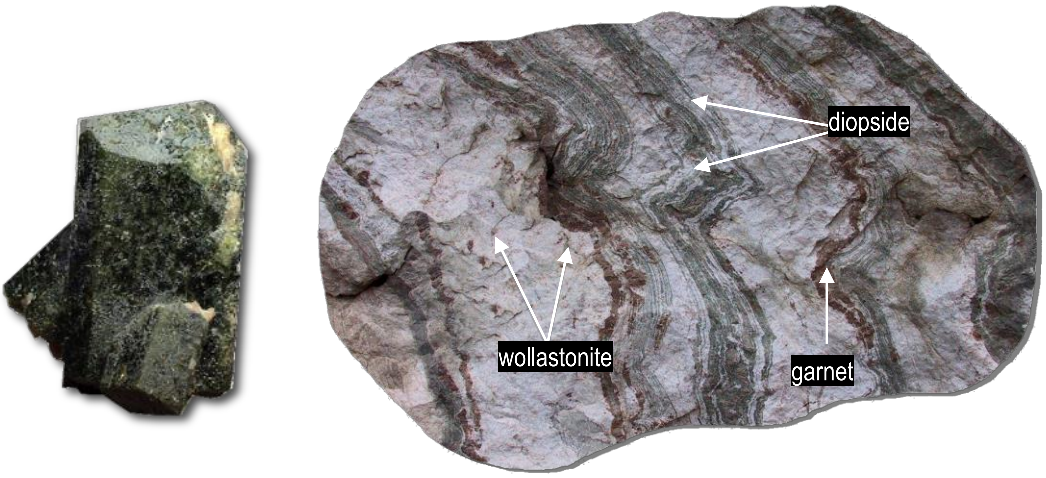


Fig. 221. Crystal of diopside (left), and diopside in skarn (right), occurring in granular aggregates that compose bands alternating with wollastonite (white) and garnets (red).

Skarns in the mine at the mountain Rudnik contain diopside and bear lead-zinc mineralization (fig. 222).

Diopside is a common constituent of many kinds of igneous rocks, gabbro, basalts and related pegmatites, and in the high grade regional metamorphic rocks.

Diopside alters into the aluminum-lack amphibole, actinolite and tremolite (uralite) under the action of hot water solutions.

Fig. 222. Skarns in the mine at the mountain Rudnik are with diopside (photo from the mine shaft). Above right, a detail of skarn with diopside (grey).

In polarizing microscope, at parallel nicols is diopside white (fig. 223). The perfect cleavage at 87–90°, which is characteristic for this group, commonly may be observed at diopside crystals.

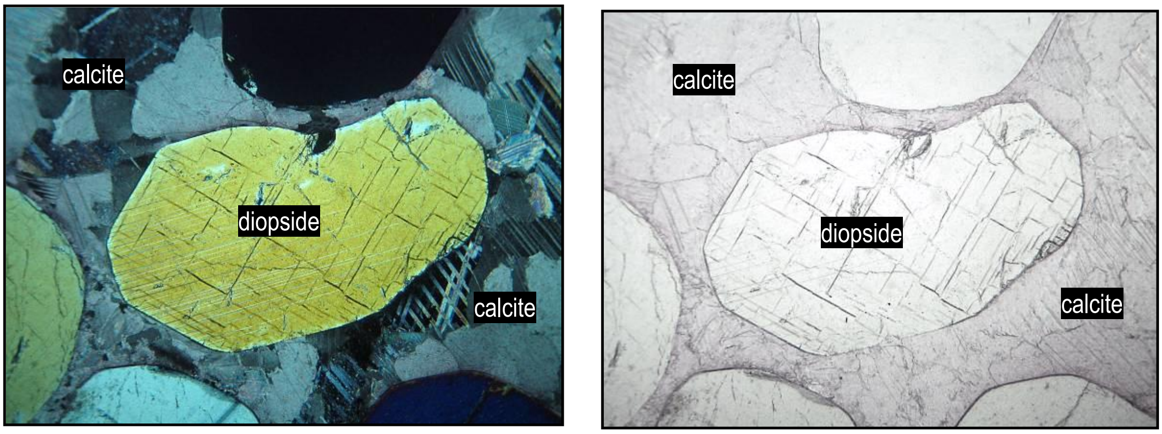


Fig. 223. Microphotograph of diopside crystals in skarn, XPL (left), and the same mineral in PPL (right). Magnification 200×.

11.1.2.3. Augite $(Ca,Mg,Fe^{2+},Fe^{3+},Ti,Al)_2((Si,Al)_2O_6))$

Augite is aluminum calcium-magnesium-iron silicate. The above given formulae refers to a mixture augite-ferroaugite. Chemistry varies considerably in compare with other minerals from the pyroxene group. Impurities are Al, which partly substitutes Si, and Ti, Cr, Mn and Ni. Iron-poor augite is called **diallage.**

Considerable amount of titanium, up to 5 %, is characteristic for **titanaugite,** which displays purple-brownish color. The presence of sodium, leads to transitions towards alkali pyroxene. Such chemical properties cause a common zoned pattern of augite grains.

Augite occurs in stubby prismatic crystals (fig. 224) or in granular to massive aggregates. It is green to dark green colored, rarely brown.

Lustre is vitreous, cleavage perfect. Fracture is uneven to conchoidal, specific gravity 3.2 to 3.5 g/cm^3, and hardness 5 to 6.

Fig. 224. Crystal of augite (left), and augite in gabbro, black grains (right).

Augite is important rock-forming mineral. It forms during igneous processes and plays important role in basic intrusive rocks, gabbros (fig. 225) and their volcanic equivalents, basalts. It is one of the most widespread femic mineral.

Gabbro, as has been noted already, composes the lower levels in oceanic crust and is overlying cumulate feldspar peridotites and tectonite peridotites of the upper mantle. Between the last two is the Moho discontinuity. Diabase, which is placed in the “roof” of gabbro zone, also contains augite as a major constituent.

Fig. 225. Gabbro of Deli Jovan (east Serbia) builds the lower part of oceanic crust and contains augite. Above right, the rock sample.

In polarizing microscope augite displays high interference colors and high relief at parallel nicols, when is colorless, rarely grey or pinkish if contains titanium (fig. 226).

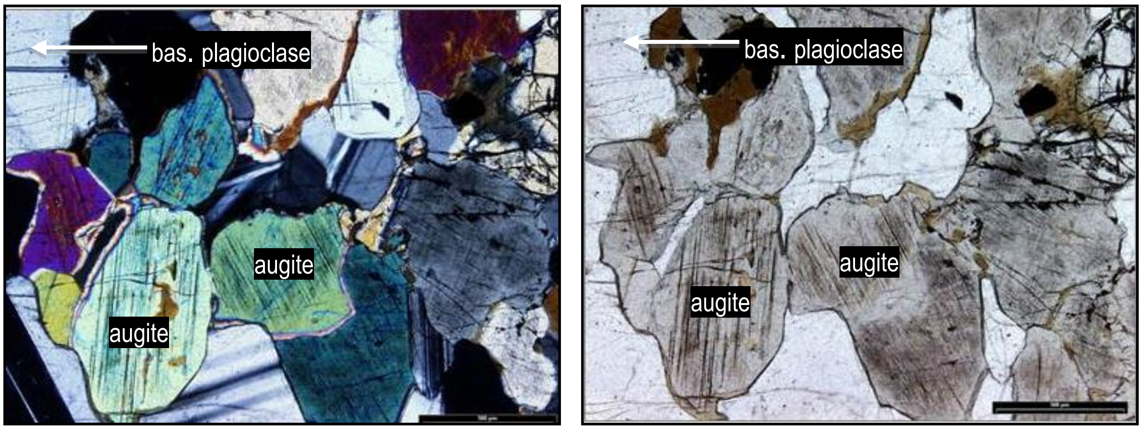


Fig. 226. Microphotograph of augite in gabbro, XPL (left), and the same mineral under PPL (right). Magnification 100×.

Augite is significant femic mineral in basalt, a volcanic rock of the gabbroic magma. Vast masses of basalts were erupted on the sea floor (submarine eruptions) in very characteristic form of pillows, known as „pillow" lava (fig. 227) covering an area of few thousands square kilometers (in Pacific, Atlantic ocean). In continental regions basalts are present, but in much lesser extent.

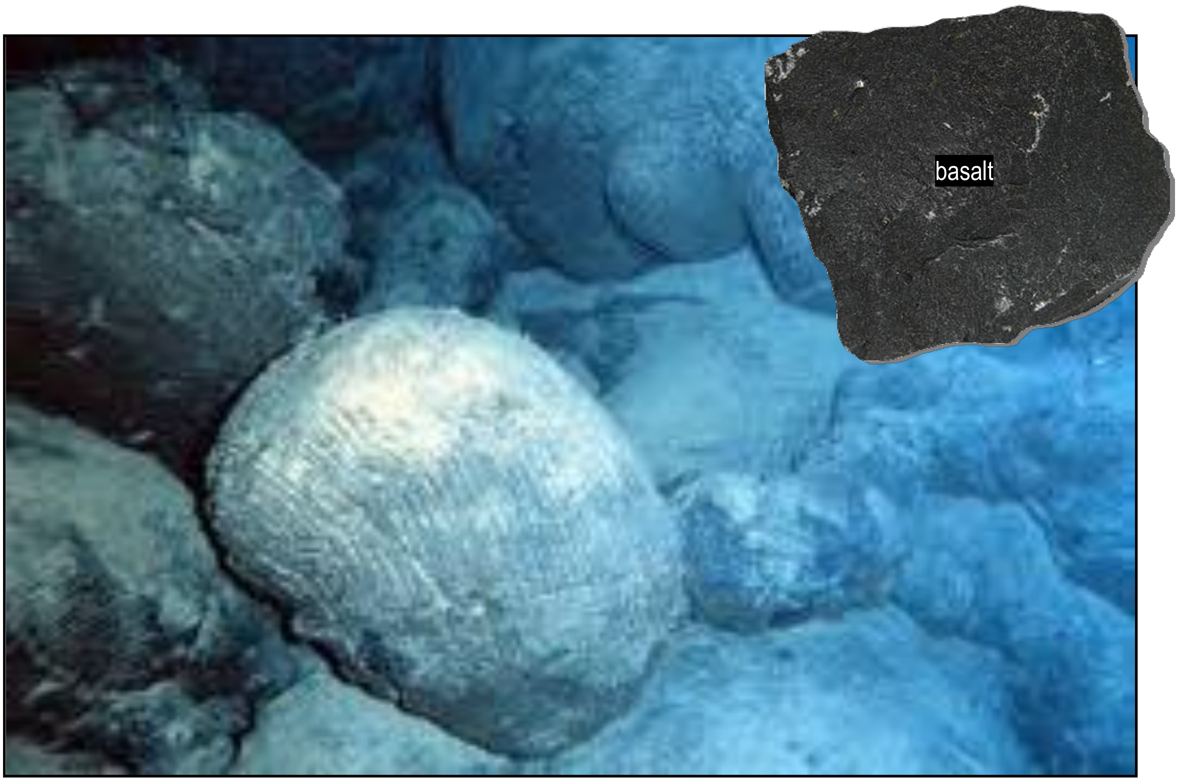


Fig. 227. Erupted basaltic pillow lava in Pacific. Above right, is a sample of basalt.

Augite occurs as phenocrysts in basalts, along with basic plagioclase, and olivine sometimes. All of them are commonly lying in a fine-grained groundmass as the consequence of rapid cooling (fig. 228).

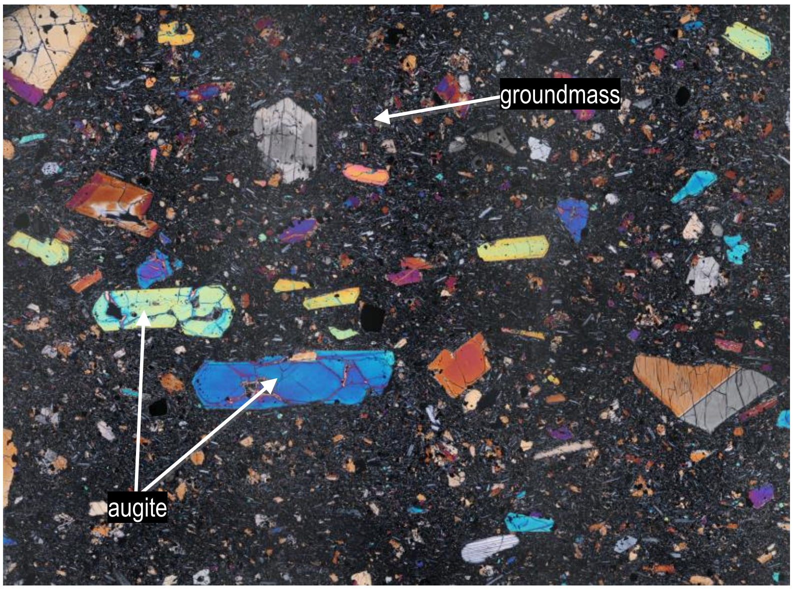


Fig. 228. Augite phenocrysts in basalt, XPL, magnification 200×.

A hot water solutions (hydrothermal fluids) convert augite into amphibole lack of aluminum (uralite, which is compositionally actinolite (fig. 229) or into chlorite, i.e. epidote and calcite when aluminum and calcium are present in the system. That is a common case in a nature due to the regularly presence of basic plagioclase as the essential mineral in gabbro and basalt.

Such processes often lead to segregation of titanium minerals, as this element was primarily present in augite.

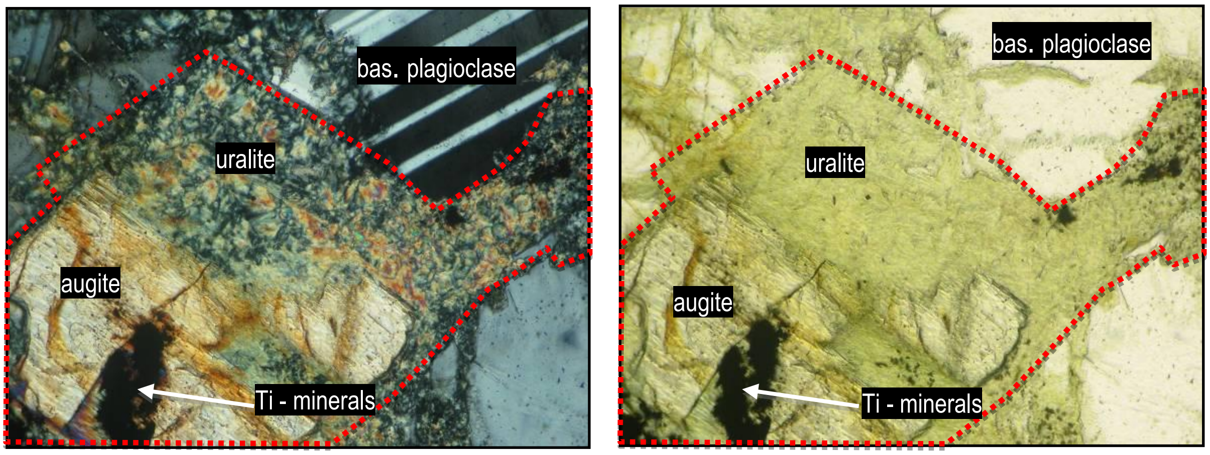


Fig. 229. Uralitized augite in gabbro, microphotograph, XPL (left), and in PPL (right). Magnification 100×. Dotted red lines envelope relic augite grain.

11.1.2.4. **Spodumene** $LiAl(Si_2O_6)$

Spodumene is lithium-bearing pyroxene. Common impurities are Na and Ca, while Fe, Cr and Cs are rarely present. It occurs in stubby prismatic crystals (fig. 230) or in granular aggregates.

Its color is grey, sometimes green and violet-pink or yellow. Spodumene is transparent to translucent, with vitreous lustre and perfect cleavage. Specific gravity is 3.1 to 3.2 g/cm^3, hardness 6 to 7. Alters into mica or clay minerals.

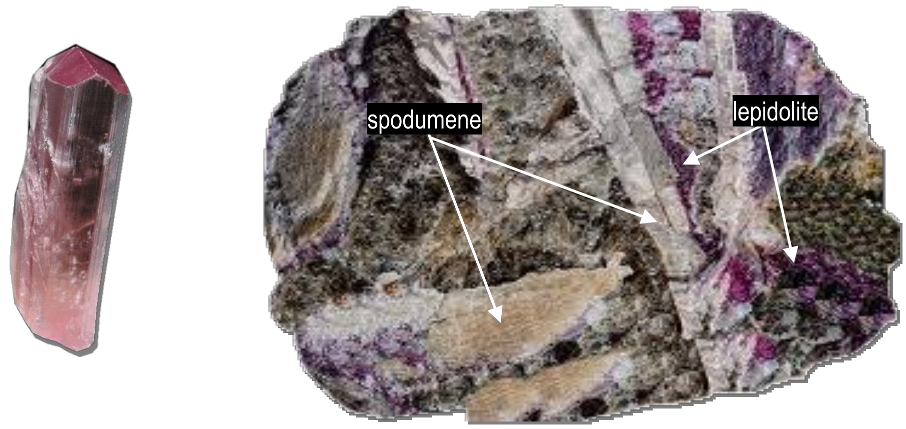


Fig. 230. Crystal of spodumene (left) and Spodumene in pegmatite (right).

Spodumene relates genetically with lithium-bearing granite and pegmatite (fig. 231). It associates with beryl, tourmaline, and lithium-bearing micas.

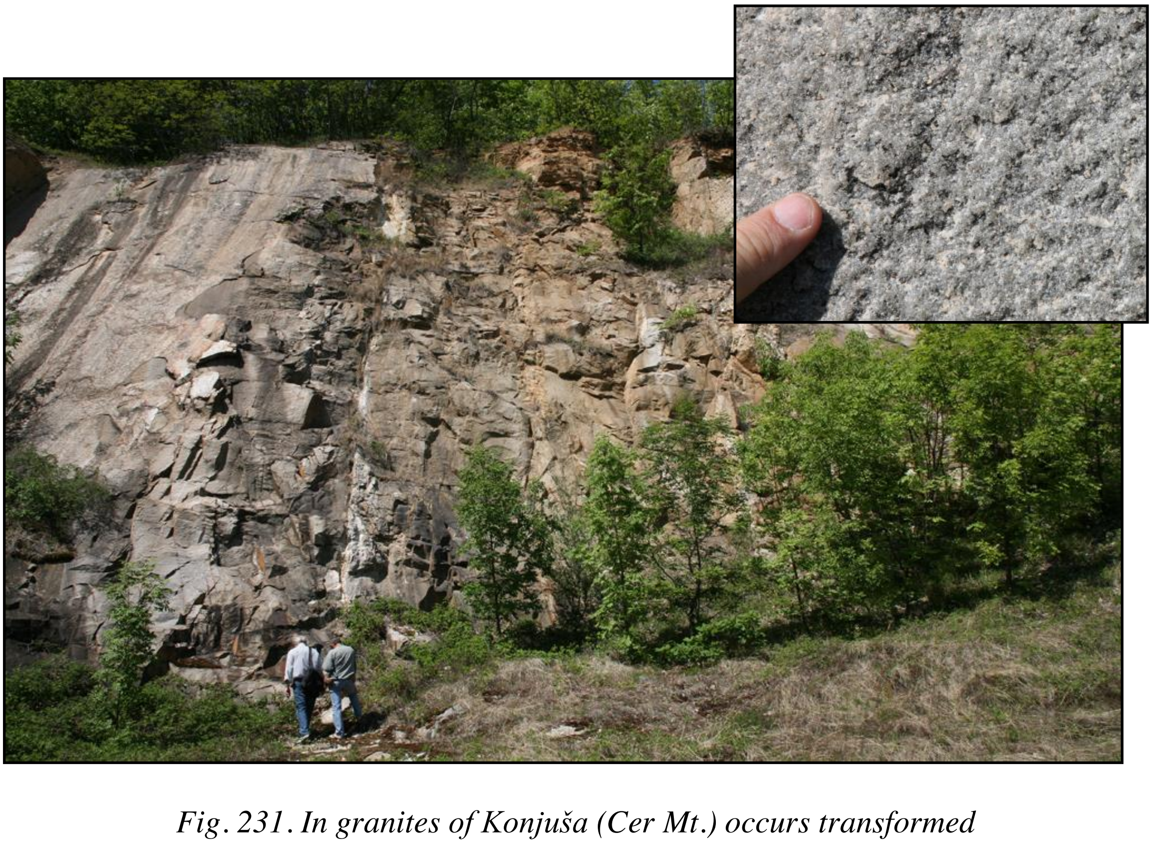


Fig. 231. In granites of Konjuša (Cer Mt.) occurs transformed lepidolite. Above right, a rock detail.

11.1.2.5. Alkali pyroxene

Alkali pyroxene derives from a melt in which the amount of alkalis exceeds aluminum content. Physical properties of these minerals are similar to those of augite. When being formed during igneous processes they play an important role in alkali intrusive and volcanic rocks, while their formation through high grade metamorphic processes requires water to be removed from a system.

The most frequent alkali pyroxenes are **omphacite**, a**egirine** and **jadeite**.

11.1.2.5.1. Omphacite $(Ca,Na)(Mg,Fe^{2+},Fe^{3+},Al)(Si_2O_6)$

Omphacite is calcium-sodium pyroxene with small aluminum content. It represents a mixture of augite and jadeite with a part of calcium substituted by sodium, and a part of magnesium by aluminum. This mineral occurs very rare in stubby prismatic crystals (fig. 232), while granular aggregates and massive accumulations are frequent.

Omphacite has perfect to good cleavage, and appears in green, dull green to almost black color. Specific gravity is 3.2 to 3.5 g/cm^3, and hardness 5 to 6. Lustre is vitreous. Omphacite forms in subduction zones at high pressures and low temperatures when associates with glaucophane, lawsonite, and garnet.

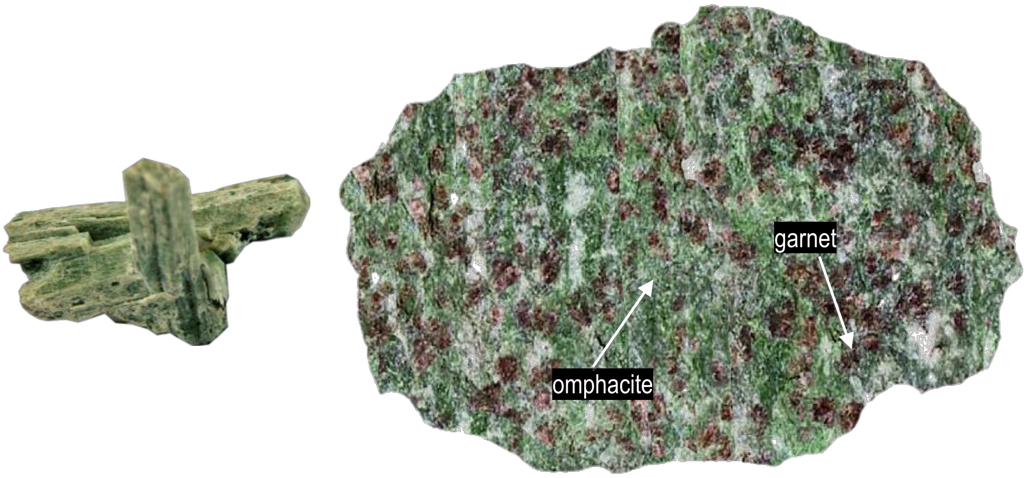


Fig. 232. Crystal of omphacite (left), and omphacite in eclogite, green (right).

Omphacite is also a regionally metamorphic mineral and forms at high pressures and temperatures. In such cases compose together with garnet the rock eclogite (fig. 233), which commonly outcrops in a form of lenses or intercalation (interlayers) in gneisses reaching up to a few meters in thickness.

Fig. 233. Omphacite is found in eclogite at Bojnik (near Leskovac). Above right, the rock sample.

Omphacite may be found in kimberlites (diamond bearing rocks), as well as in metamorphic rocks within ophiolites. The later case includes omphacite which has been formed tectonically, during the emplacement of basic and ultrabasic rocks.

In polarizing microscope omphacite displays high interference colors at crossed nicols and is colorless or pleochroic in light green with the parallel nicols (fig. 234).

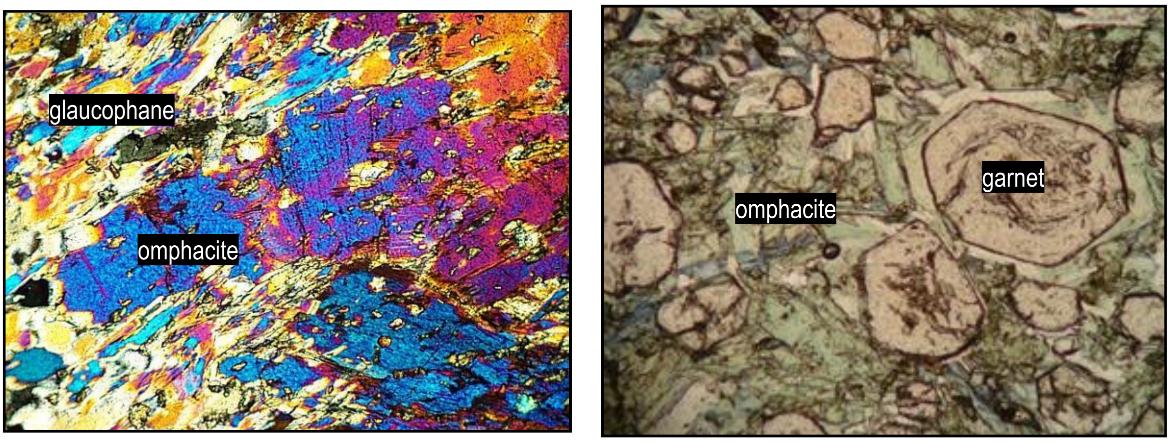


Fig. 234. Microphotograph of omphacite associated with glaucophane, XPL (left), and omphacite with garnet, PPL (right). Magnification 100×.

11.1.2.5.2. **Aegirine** $NaFe^{3+}(Si_2O_6)$

Aegirine (synonym is acmite) is compositionally the sodic-iron pyroxene. Common impurities are Ca, Al, Mg, and Mn. Rarely occurs as crystals (fig. 235). In rocks appear in short prismatic, granular, tabular or acicular aggregates (fig. 236).

Color is different, from green to reddish-brown, brown to almost black. Cleavage is good to perfect, in two directions. Specific gravity is 3.4 to 3.6 g/cm^3, hardness 6.

Fig. 235. Crystal of aegirine (left), and aegirine in syenite, black grains (right).

Aegirine is igneous mineral and occurs typically in alkali basic rocks where is associated with feldspathoid, nepheline, and alkali amphiboles. It may be found in pegmatite, granite, and syenite, as well as in contact-metamorphic rocks when derives at the immediate contact of alkali magma and limestone.

Fig. 236. Aegirine, black, radiating needles in alkali pegmatite, Greenland.

In alkali igneous rock, syenite and its volcanic equivalents may be also present aegirine-augite, which is a solid solution of aegirine and augite.

Under the microscope aegirine has high interference colors with the crossed nicols, and is strongly pleochroic in green, light green to yellowish-brown, displaying moderate relief with parallel nicols (fig. 237).

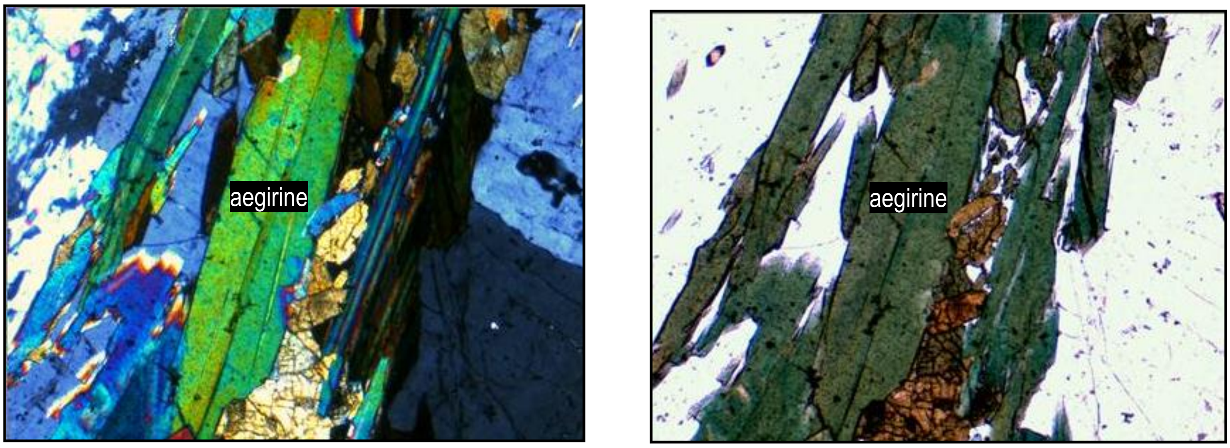


Fig. 237. Microphotograph of aegirine, XPL (left), and the same mineral with PPL (right). Magnification 60×.

11.1.2.5.3. Jadeite $NaAl(Si_2O_6)$

Jadeite is sodium aluminum silicate. The substitution of calcium and magnesium with sodium and aluminum is often. Partial substitution of ferric iron leads to **omphacite**.

Jadeite occurs in columnar to granular or massive aggregates (fig. 238). The color is a function of composition and varies from light green, greenish-blue, rarely lavender (violet) or pink. Cleavage is good to perfect, lustre vitreous. Specific gravity varies with composition from 3.25 to 3.35 g/cm^3, and hardness 6.

Fig. 238. Jadeite crystals (left), jadeite in rock (middle) and a rock mass consisting of jadeite (right).

Jadeite derives either at high pressures and temperatures in regional metamorphism (granulite facies) through replacement of albite and release of silica, or at high pressures and relatively low temperatures (beneath 400 °C), when associates with lawsonite. It was additionally noted in rocks associated with ultrabasic rocks, i.e. peridotites. In polarizing microscope is jadeite colorless, may be slightly pleochroic in green to bluish-green (fig. 239).

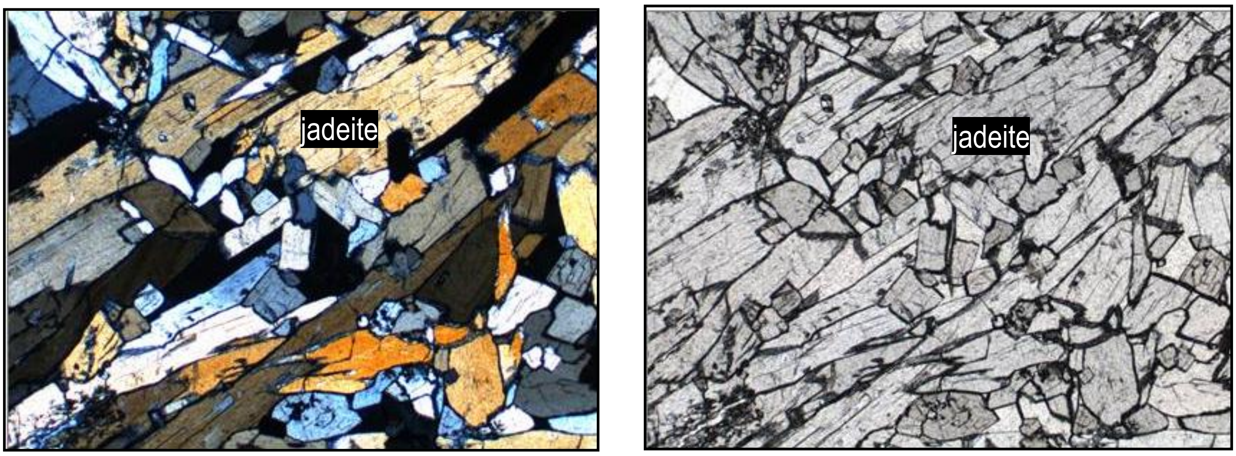


Fig. 239. Microphotograph of jadeite, XPL (left), and the same mineral with PPL (right). Magnification 100×.

Jadeite may be exploited for lapidary use (fig. 240) when considers **jade**. It has been and is still a particularly popular in China as an exceptional carving material for ornamental objects, sculpture and jewelry making (fig. 241).

Fig. 240. Uncut rough piece of jade.

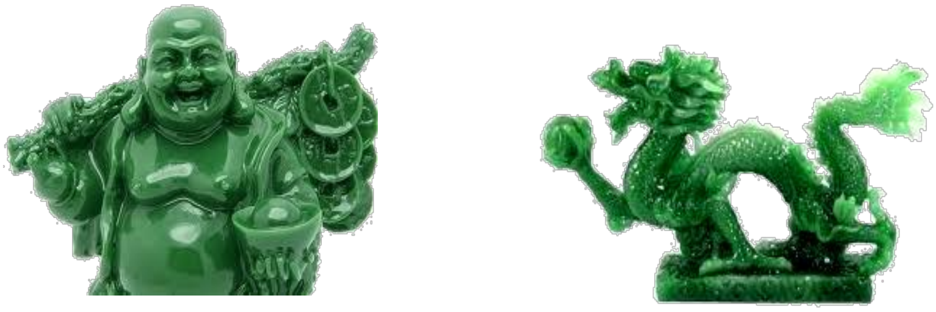


Fig. 241. Carved and polished items of jade.

According to archeological data the jade has been used since prehistoric times for tools and primitive weapons as its hardness, durability and easy carving and polishing are best suited for those purpose. The same name, jade, is applied to another mineral, to very compact, flexible and fibrous amphibole, nephrite.

11.2. WOLLASTONITE $CaSiO_3$

Wollastonite is included in the pyroxenoid group, which has very similar properties and composition with the pyroxene group. It is named after the English chemist Wollaston (fig. 242).

Fig. 242. W.H.Wollaston (1766–1828).

Wollastonite is calcium silicate mineral that may contain small amounts of Mg, Mn, Fe and Al as impurities. It has perfect cleavage, vitreous lustre and specific gravity from 2.9 to 3.1 g/cm^3. Its hardness is 4.5 to 5.

Crystallizes triclinic and occurs in very typical radiating and fibrous aggregates (fig. 243). Wollastonite is white or grayish-white. With an increase in manganese becomes pinkish. It is most commonly found in skarns and associated with calcium pyroxenes (diopside and hedenbergite), Ca-garnets (grossular and andradite) and scapolite.

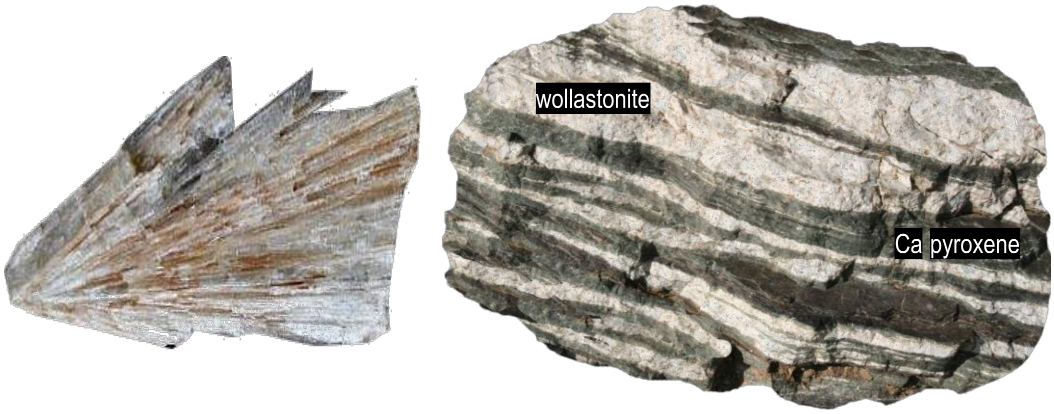


Fig. 243.Wollastonite crystal (left), and wollastonite (white bands) in skarn (right).

Wollastonite is very rare found in regional metamorphic rocks and in basic alkali lavas.

This mineral is the resource for ceramics and for fire resistant tiles. Wollastonite has also being synthesized for industrial purpose.

Under the microscope is wollastonite commonly in radiating and fan-shaped crystal aggregates of low relief and without pleochroism (fig. 244).

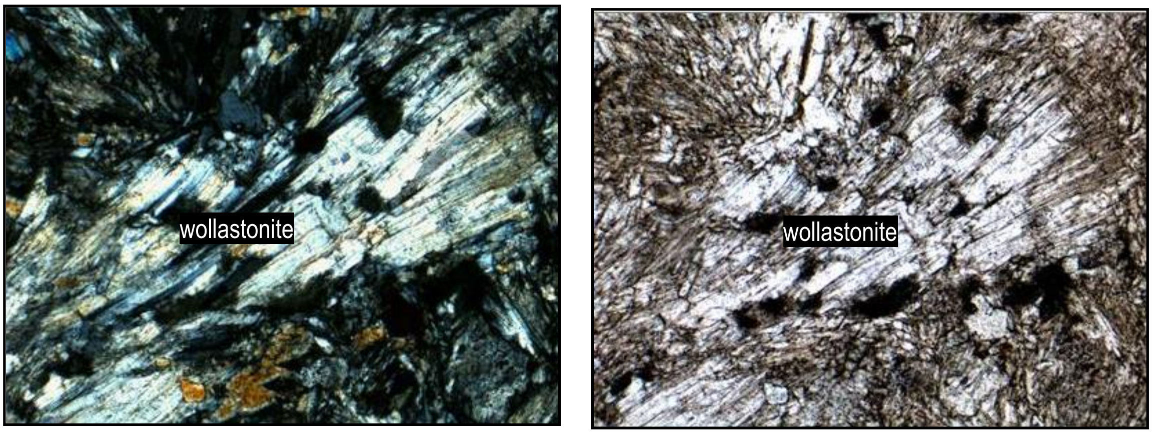


Fig. 244. Microphotograph of wollastonite, XPL (left), and with PPL (right). Magnification 120×.

Wollastonite is contact metasomatically formed mineral. It develops at the granite and limestone contacts through reaction of silica, which is coming from magma, and calcite inherited from mentioned carbonate rocks and includes the removal of CO_2 from the system giving rise to skarn formation (fig. 245). Temperature for its development depends on pressure and ability of carbon dioxide to migrate. The most frequent association is with Ca garnets, Ca pyroxene and epidote.

Fig. 245. Skarns at Kopaonik contain wollastonite beside Ca garnet and Ca pyroxene.

11.3. RHODONITE $MnSiO_3$

Rhodonite is the member of the same group as wollastonite. Rhodonite is a silicate of manganese and occasionally contains impurities of Fe, Ca and Mg.

Commonly occurs in granular and massive aggregates, but may be tabular (fig. 246). Crystallizes triclinic. It is colored pinkish or purple-pink. Cleavage is perfect, lustre vitreous and fracture uneven, occasionally semi-conchoidal. Specific gravity is from 3.4 to 3.7 g/cm^3, hardness 5.5 to 6.

Rhodonite forms during regional metamorphism of manganese rich sediments at low to intermediate PT conditions (up to 6 Kb and 600 °C). It may be found in contact-metamorphosed and hydrothermally derived rocks, too. Usually associates with manganese oxides and hydroxides.

Fig. 246. Crystal of rhodonite (left), and rhodonite in the rock (right).

Rhodonite is very rare mineral. Under the polarizing microscope displays moderate relief and moderate to high interference colors, being colorless with parallel nicols (fig. 247).

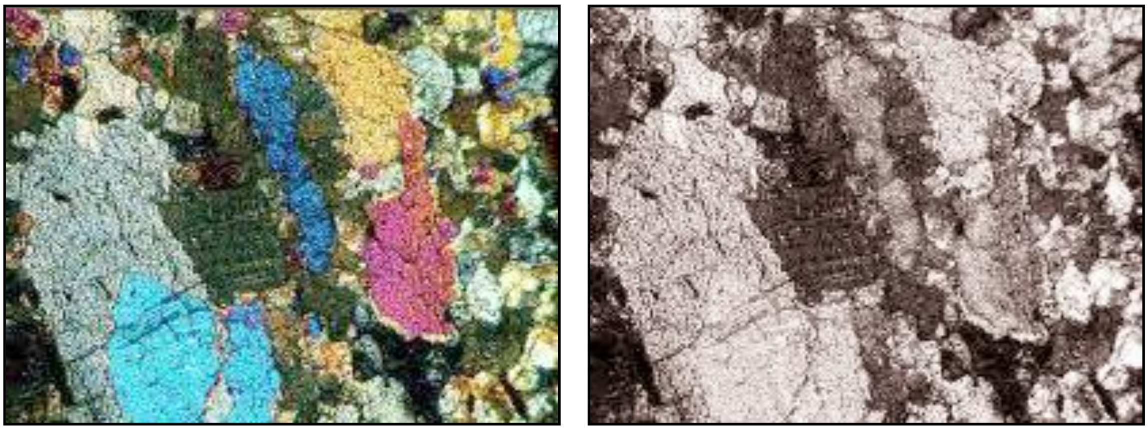


Fig. 247. Microphotograph of rhodonite, XPL (left), and with PPL (right). Magnification 100×.

11.4. SAPPHIRINE $(Mg, Fe^{2+}, Fe^{3+}Al)_8O_2(Al,Si)_6O_{18})$

Sapphirine is magnesium-iron silicate with aluminum. Its composition is highly variable and may contain chromium sometimes. Crystallizes in monoclinic system. Color is light blue, green, occasionally grey or pinkish-grey. Cleavage is good, specific gravity from 3.4 to 3.6 g/cm^3, hardness 7.5. It occurs in prismatic crystals or granular masses (fig. 248).

Sapphirine is rare mineral. It is regionally metamorphic mineral, which forms at high pressures and temperatures (granulite facies), associating with kyanite, spinel, garnet, cordierite. In a certain circumstances may be igneous.

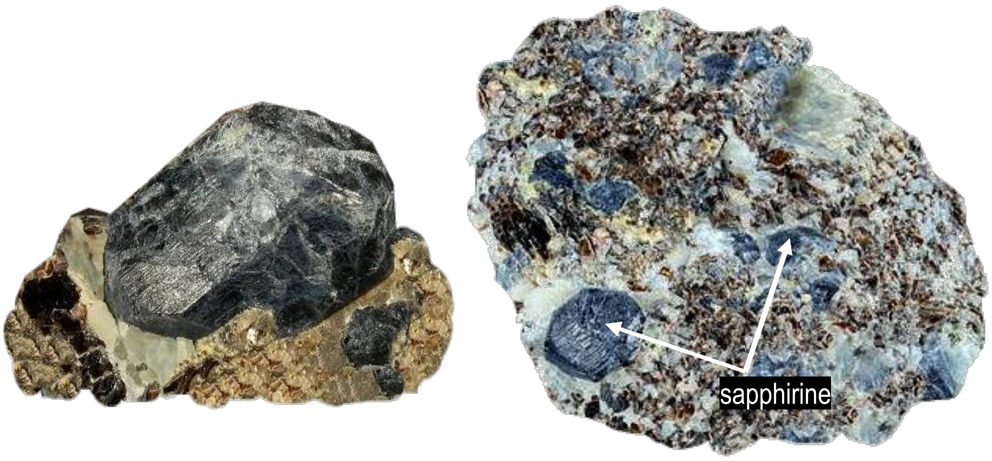


Fig. 248. Crystal of sapphirine (left), and sapphirine in a rock mass (right).

The distinguishing properties of sapphirine under the microscope are high relief and characteristic green to greenish-blue pleochroism (fig. 249).

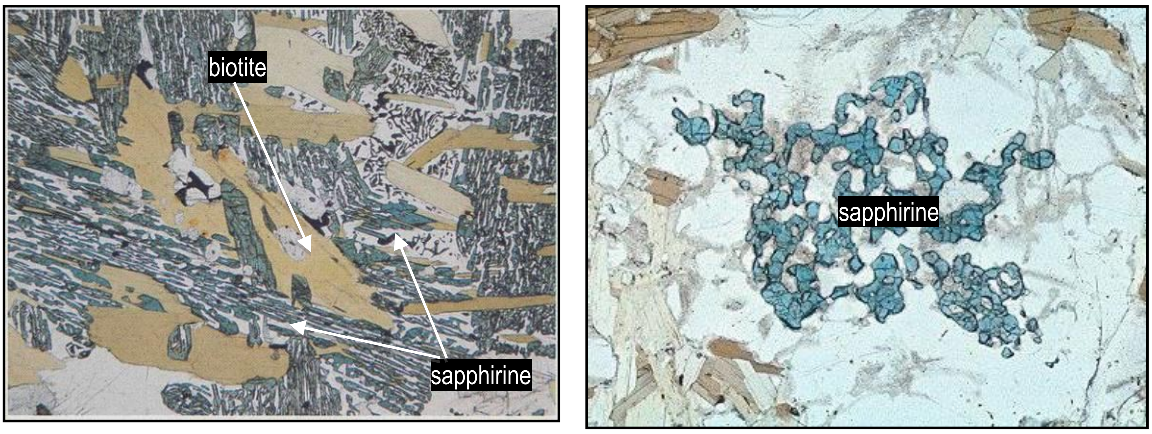


Fig. 249. Microphotograph of sapphirine with biotite (left), and of the same mineral with PPL (right). Magnification 80×.

11.5. AMPHIBOLES

Amphiboles are important group of minerals that are the essential constituents of many igneous and metamorphic rocks. Amphiboles are structurally the double chain inosilicates and compositionally represent hydrous aluminum silicates of Ca, Mg, Fe, and Na. The presence of (OH)-group reflects that igneous amphiboles derived from water-bearing magma (wet magma).

This group includes a large number of minerals. Mineralogy offers a few classifications of amphiboles that are based on different criterions. Petrologists commonly use the classification proposed in 1997 by Lake and co-authors, which relies on the position of cations in a crystal lattice of amphibole.

Amphiboles occur in columnar to acicular aggregates. The cleavage is good to excellent prismatic and intersects 124° enabling their easy recognition under the microscope. Amphiboles crystallize in o**rthorhombic** and **monoclinic** system. Orthorhombic amphiboles, anthophyllite and gedrite, and monoclinic tremolite, actinolite, hornblende and alkali tremolite are going to be present.

11.5.1. ORTHORHOMBIC AMPHIBOLES

ANTHOPHYLLITE $(Mg,Fe^{2+})_7(Si_8O_{22})(OH,F)_2$
GEDRITE $(Mg, Fe^{2+})_5,Al_2(Si_6Al_2O_{22})(OH,F)_2$

Anthophyllite is hydrous magnesium silicate that composes isomorphic series with ferro-anthophyllite, whereas the gedrite contains aluminum.

Small amounts of Mn, K, Ca, and Na may be present and a part of (OH) group may be replaced with fluorine.

Orthorhombic amphiboles occur in acicular, fibrous or asbestiform aggregates (anthophyllite asbestos). They are colored white to whitish-grey (fig. 250); however the iron-bearing species are brownish to almost black.

Fig. 250. Fan-shaped crystals of anthophyllite (left), and anthophyllite in schist (right).

Anthophyllite may be distinguished by its perfect cleavage, in addition to its vitreous or pearly lustre. Specific gravity depends on composition and varies from 2.8 to 3.3 g/cm^3, hardness is 5 to 6.

These minerals form at low to intermediate grade of regional metamorphism from magnesium-rich rocks.

Orthorhombic amphiboles may be formed during contact metamorphism, rarely during secondary processes that enclose igneous rocks, through transformation of pyroxenes.

It should be noted that anthophyllite was found in pegmatite of Bukulja in Serbia (fig. 251).

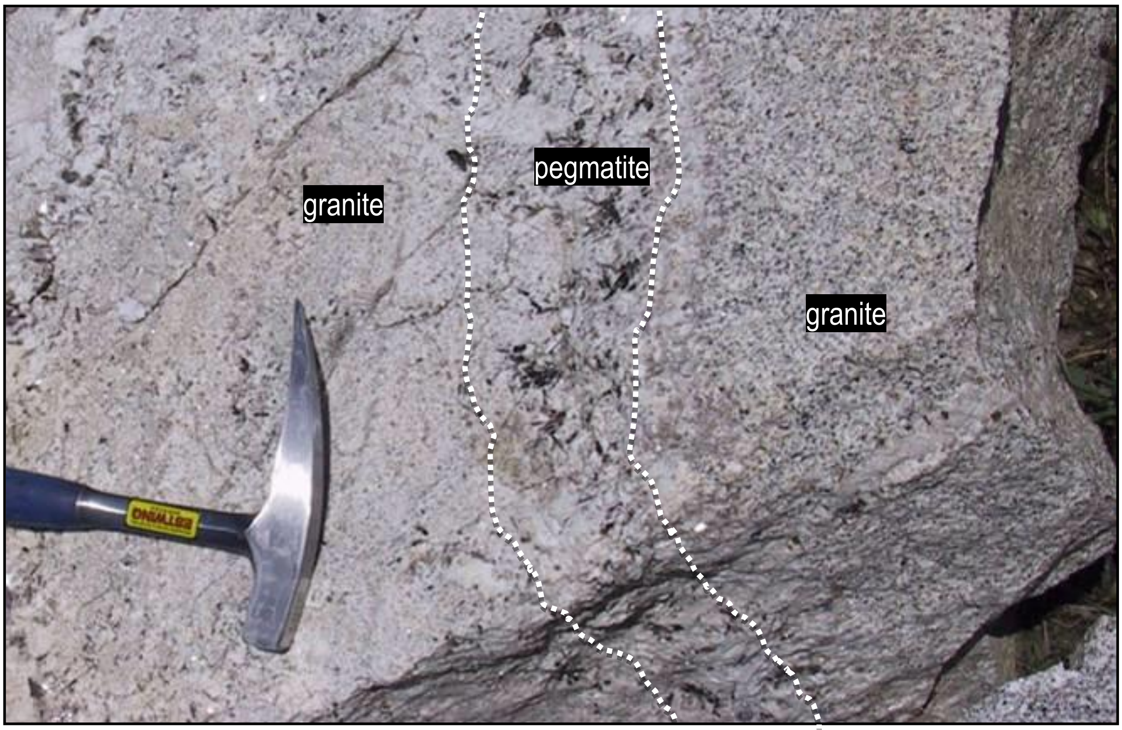


Fig. 251. Anthophyllite was found in pegmatite vein in granites of Bukulja.

Under the influence of hydrothermal fluids the anthophyllite will turn into serpentine when rocks are poor in Ca and Fe, or in talc if rocks contain Mg and Al.

In polarizing microscope anthophyllite could be identified by its tubular aggregates or faintly pleochroism in brownish-yellow to yellow, occasionally green (fig. 252).

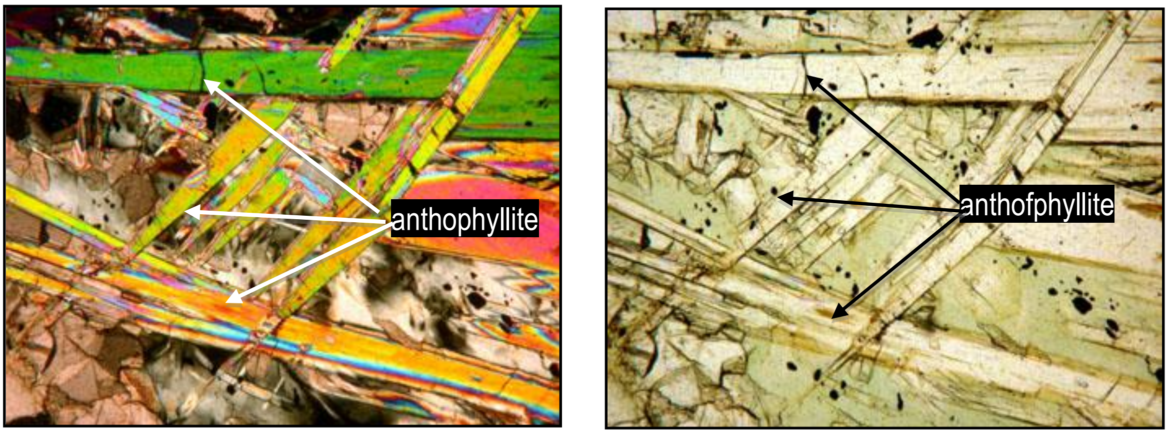


Fig. 252. Microphotograph anthophyllite, XPL (left), and the same mineral with PPL (right).Magnification 60×.

There is a possibility for some part of magnesium in gedrite to being replaced with iron (ferrogedrite) like in anthophyllite (fig. 253). Substitution of silica by aluminum allows sodium to „enter“ in the crystal lattice of gedrite.

Fig. 253. Fan-shaped crystals of gedrite (left), and gedrite in granite (right).

Gedrite is also forming in alteration processes, serpentinization of ultrabasic rocks (peridotite) at their contact with aluminum-bearing rocks.

Under the polarizing microscope, the gedrite like anthophyllite occurs in tabular or shortened prismatic crystals (fig. 254). With parallel nicols is white or displays weak pleochroism in brown color.

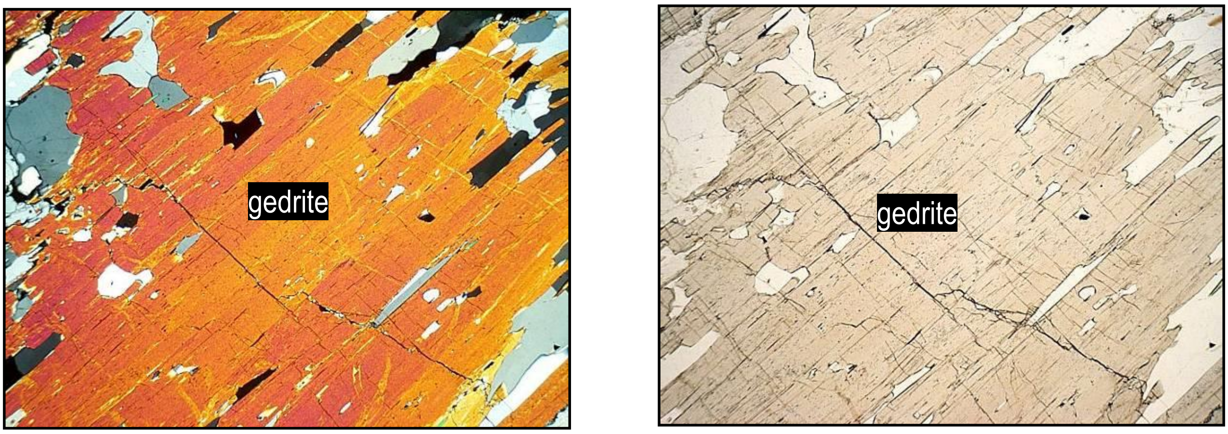


Fig 254. Microphotograph of gedrite, XPL (left), and the same mineral with PPL (right). Magnification 60×.

11.5.2. MONOCLINIC AMPHIBOLES

Monoclinic amphiboles are more frequent then orthorhombic. The most important are: **tremolite**, **actinolite**, **hornblende** and **alkali amphibole**.

11.5.2.1. Tremolite $Ca_2Mg_5Si_8O_{22}(OH,F)_2$

Tremolite is hydrous silicate of calcium and magnesium. Small amounts of Fe and Al may be present. The increasing Fe leads to transitions towards actinolite, while the higher Al approaches it to Ca-hornblende.

Tremolite occurs in prismatic to tabular aggregates, rarely acicular, radiating and fan-shaped (fig. 255) or as fibrous accumulations forming tremolite asbestos. A fine-grained cryptocrystalline mass of tremolite refers to nephrite.

It is colorless, white or grey. May be green when contains some iron. Cleavage is perfect in two directions, which intersect at angle 124°. This is the characteristic and distinguishing feature of the whole group of monoclinic amphibole. Tremolite has vitreous lustre, specific gravity 2.9 to 3 g/cm^3, and hardness 5.5 to 6.

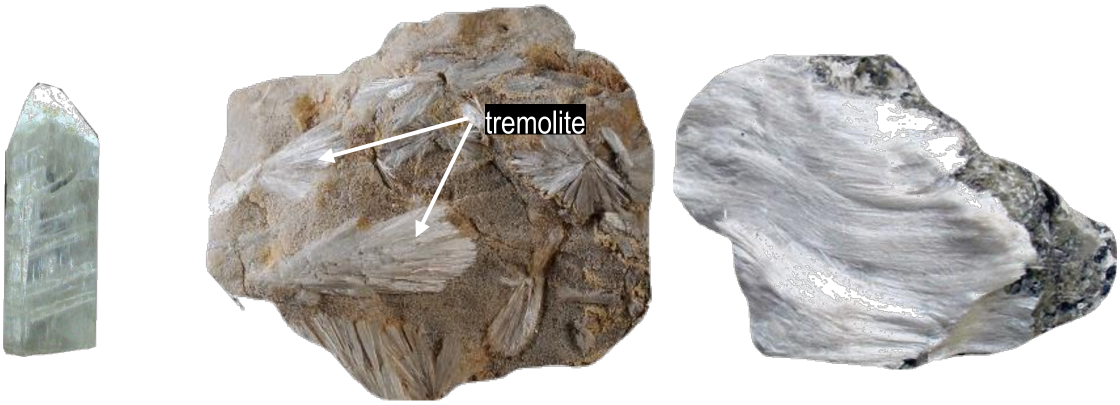


Fig. 255. Crystal of tremolite (left), tremolite in a rock-mass (middle), and tremolite asbestos (right).

Under the polarizing microscope is tremolite recognizable by its characteristic prismatic aggregates and the lack of color with parallel nicols (fig. 256).

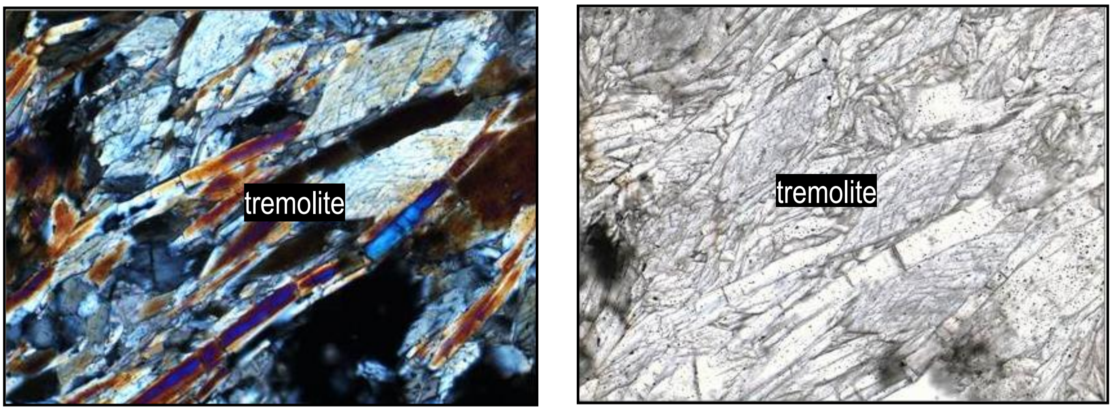


Fig. 256. Microphotograph of tremolite in schist, XPL (left), and the same mineral with PPL (right). Magnification 60×.

Tremolite forms by low grade regional metamorphism of dolomitic marlstone at temperatures from 350 to maximally 500 °C and at pressures up to 5 Kb (fig. 257 and fig. 258) or from basic igneous rocks and their pyroclastic equivalents (volcanic ash and dust).

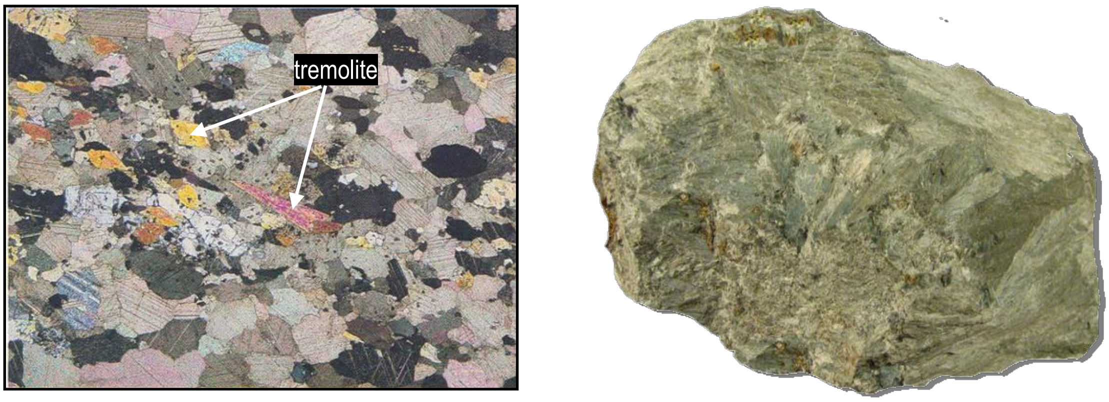


Fig. 257. Microphotograph of tremolite in marble (left), XPL, magnification 100×, a rock sample with calcite and tremolite (right).

Fig. 258. Tremolite is found in marbles of Batočina. Above right, the sample of rock with tremolite.

It could form during contact metasomatism at certain distance from the contact, and may be additionally formed as secondary product from pyroxene weathering within the igneous rocks.

11.5.2.2. Actinolite $Ca_2(Mg,Fe^{2+})_5Si_8O_{22}(OH,F)_2$

Actinolite is hydrous calcium-magnesium-iron silicate. The iron is prevailing over magnesium in actinolite in respect to tremolite. Varieties containing only iron and lack of magnesium are known as ferro-actinolites. May contains some Na and K as impurities.

Actinolite appears very similar to tremolite, in tabular or prismatic aggregates, rarely in needle-shaped radiating forms (fig. 259). Fibrous aggregates refer to actinolite asbestos. Its color is green to dark-green, lustre vitreous and pearly in fibrous aggregates. Actinolite has perfect or good cleavage, specific gravity from 3.1 to 3.3 g/cm^3, hardness 6.

Fig. 259. Crystal of actinolite (left), and actinolite in schist (right).

Under the microscope occurs in prisms and is colorless or green with parallel nicols (fig. 260).

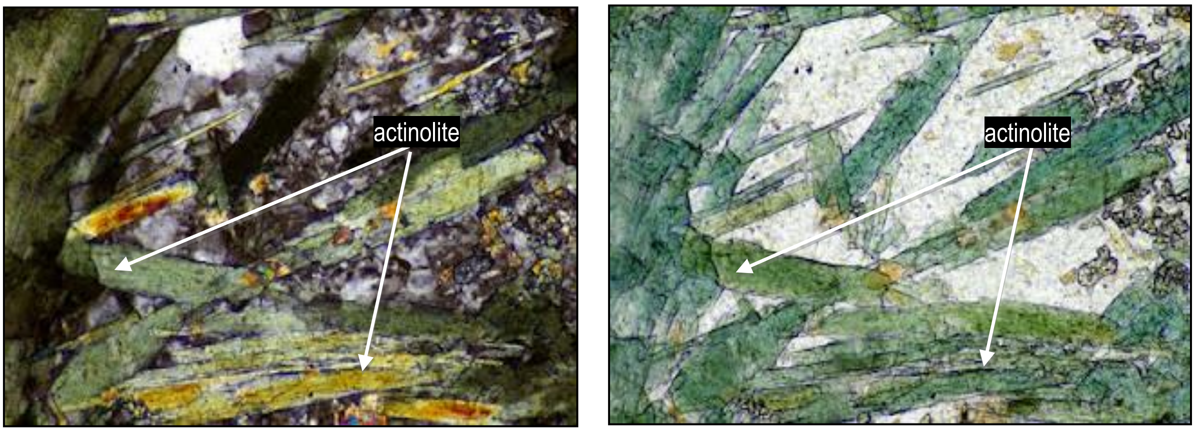


Fig. 260. Microphotograph of actinolite with XPL (left), and the same mineral with PPL (right).Magnification 60×.

Actinolite forms in same or similar conditions as tremolite and is common in green schists formed by regional metamorphism at low PT conditions (fig. 261).

It develops in metamorphosed dolomitic, magnesium marlstone. With the increasing metamorphic grade, particularly temperature, actinolite incorporates aluminum and converts into hornblende.

Fig.

261. Actinolite in actinolite schist in Brezovica.

Actinolite may be formed as secondary mineral, under the action of hydrothermal solutions or hot water from pyroxene in gabbro, when is called **uralite** (fig. 262).

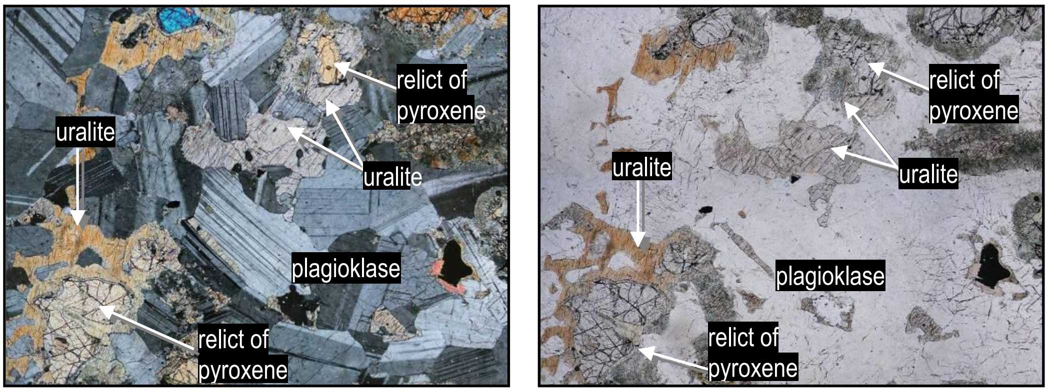


Fig. 262. Uralitized pyroxene in gabbro, XPL (left), and the same sample with PPL (right). Magnification 100×.

11.5.2.3. Hornblende $Ca_2((Mg,Fe^{2+})_4Al,Fe^{3+})(Si_7AlO_{22})(OH)_2$

Hornblende is one of the most widespread and the most abundant amphibole. It is of very complex composition: hydrous calcium-magnesium-iron aluminum silicate and comprises a gradational series, which has composition between ferrous- and magnesio-hornblende.

Crystallizes monoclinic and occurs in prismatic aggregates, sometimes tabular (fig. 263), acicular or twinned grains. Its color is dark green to almost black, lustre vitreous and the cleavage is perfect. Specific gravity is 3.1 to 3.5 g/cm^3, and hardness from 5 to 6. It displays green pleochroism under the polarizing microscope with parallel nicols and the excellent cleavage in two directions at 124° (fig. 264).

Fig. 263. Hornblende crystal (left), and prisms of hornblende in andesite (right).

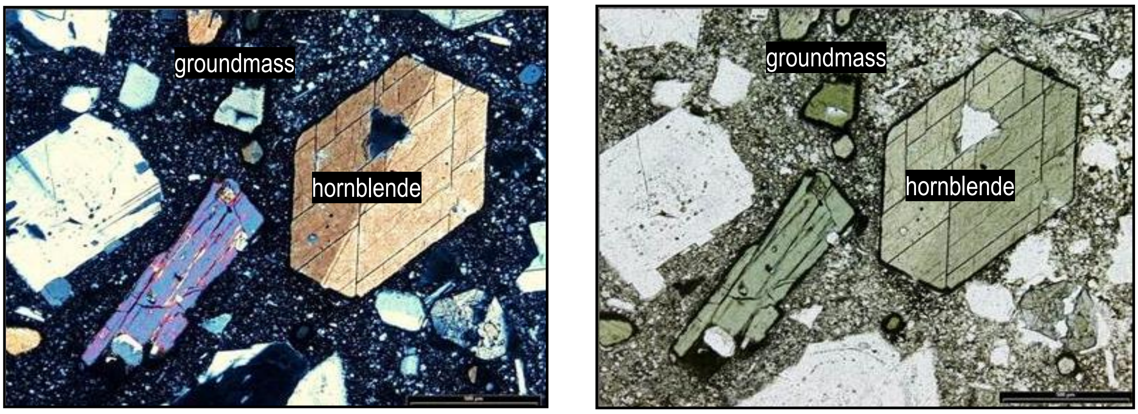


Fig. 264. Microphotograph of hornblende in andesite, XPL (left), and the same mineral with PPL (right). Magnification 60×.

Contents of Fe, Mg and Al vary in hornblende, and the OH group is often substituted with F, sometimes with Cl. The increasing sodium converts hornblende into alkali amphiboles.

Hornblende is igneous and metamorphic mineral. It is the chief constituent of acid, intermediate and basic igneous rocks (fig. 265). In igneous rocks (commonly volcanic) that have been solidified in the presence of high oxygen, a ferrous iron (Fe^{2+}) oxidized into ferric iron (Fe^{3+}), and a „common" hornblende converts into **oxyhornblende**. The earlier crystallized grains as well as the core in grains are with higher magnesium content in respect to later formed, iron-rich grains.

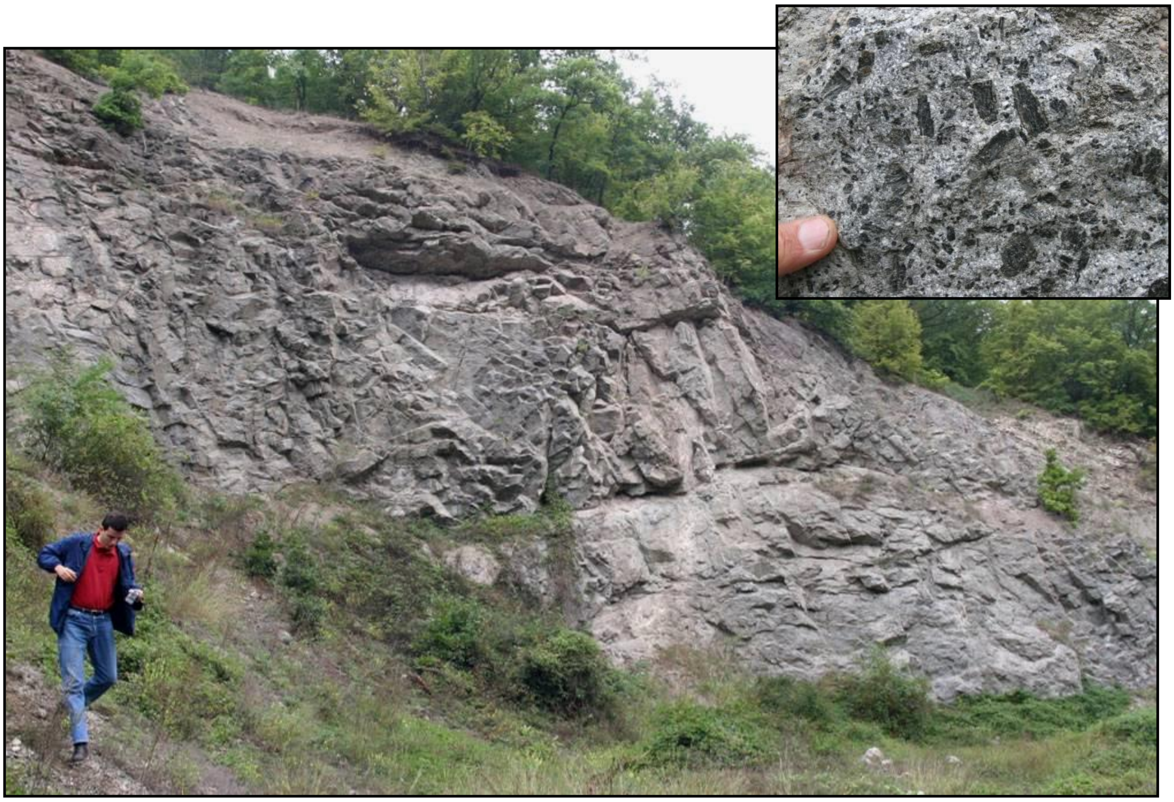


Fig. 265. Andesites of Veliki Krivelj (Bor) contain hornblende. Right above are crystals of hornblende (black) in a rock sample.

Fig. 266. Hornblende and intermediate plagioclase are the most abundant constituents in amphibolites (Tulare near Lebane). Above right is the sample of rock with hornblende (black).

Hornblende is a common in basic rocks, gabbros, diabase, basalt and their pyroclastic equivalents (tuff) or in a magnesium-rich marlstone that were regionally metamorphosed at moderate to high PT conditions. On this way the rock amphibolite, consisting of hornblende, intermediate to basic plagioclase and a certain metamorphic minerals, garnet, epidote, zoisite and biotite, should be formed (fig. 266).

Hornblende within amphibolites occurs under the polarizing microscope in oriented tabular grains resulting in nematoblastic texture of the given rock (fig. 267).

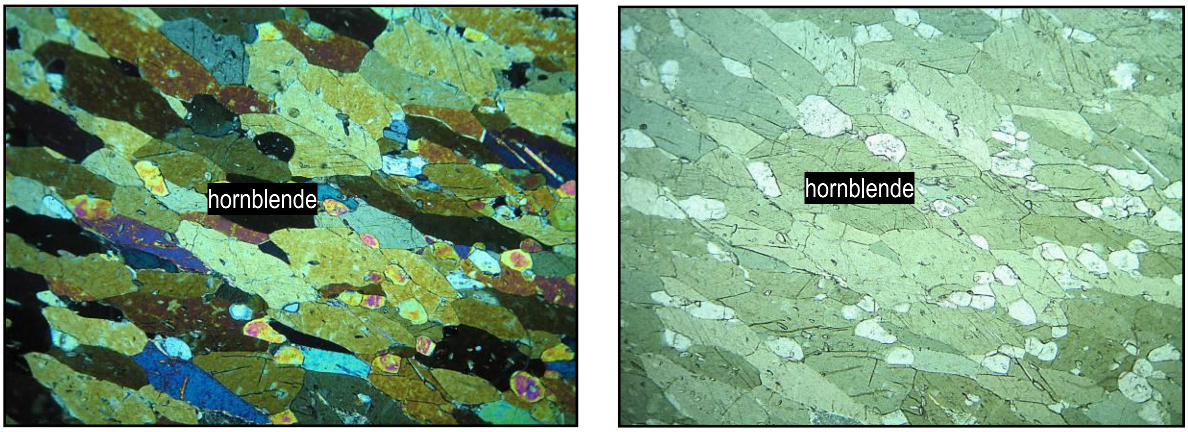


Fig. 267. Microphotograph of oriented prismatic hornblende crystals in amphibolite, XPL (left), and with PPL (right). Magnification 100×.

Hornblende is stable during metamorphism at moderately to high temperatures and pressures within the water-bearing systems. The removal of water during metamorphism (if the system is opened) results in formation of pyroxene and garnets.

Hydrothermal solutions, depending on their composition along with composition of hornblende, alter it into chlorite, epidote, calcite with frequent segregation of dusty magnetite and Fe-hydroxides that represent opaque minerals under the polarizing microscope (fig. 268).

In superficial processes the hornblende transforms into calcite, limonite and clay minerals.

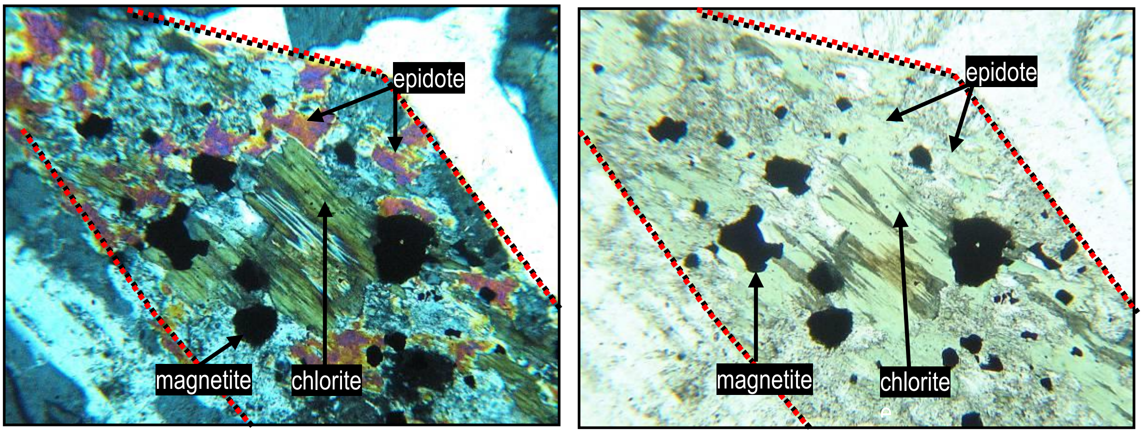


Fig. 268. Altered grain of hornblende is marked with dashed red line. Left, XPL, and the same mineral with PPL (right). Magnification 100×.

11.5.2.4. Alkali amphiboles

Alkali amphiboles contain sodium. They are found in metamorphic rocks in which sodium was brought or in alkali, sodium-rich igneous rocks. The most important alkali amphiboles as the petrogenic minerals are **glaucophane**, **riebeckite** and **crossite**.

11.5.2.4.1. Glaucophane $Na_2,Mg_3,Al_2(Si_8O_{22}(OH)_2$

Glaucophane is a hydrous sodium, magnesium-iron silicate with small amount of aluminum. When is Mg substituted with Fe, this mineral is $Na_2(Fe_3^{2+}Al_2)(Si_8O_{22})(OH)_2$ in composition and is named ferro-glaucophane. These two minerals build isomorphic series.

Glaucophane has characteristic grayish-blue to blue color and commonly occurs in columnar to acicular aggregates, extremely rare as crystals (fig. 269).

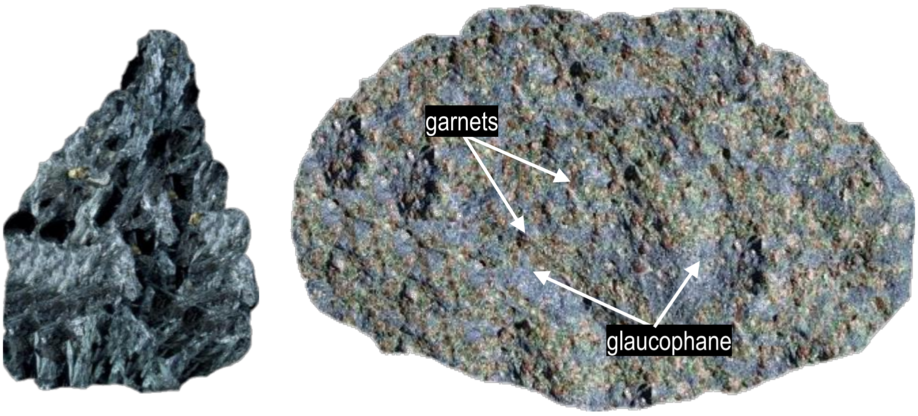


Fig. 269. Crystals of glaucophane (left) and glaucophane in the schist, grayish-blue (right).

Cleavage is perfect, lustre vitreous to pearly and the streak is typically grayish-blue to blue.

Specific gravity is 3.1 to 3.4 g/cm^3, hardness 6 to 6.5. In polarizing microscope with parallel nicols glaucophane displays characteristic greenish-blue pleochroism like all alkali amphiboles (fig. 270).

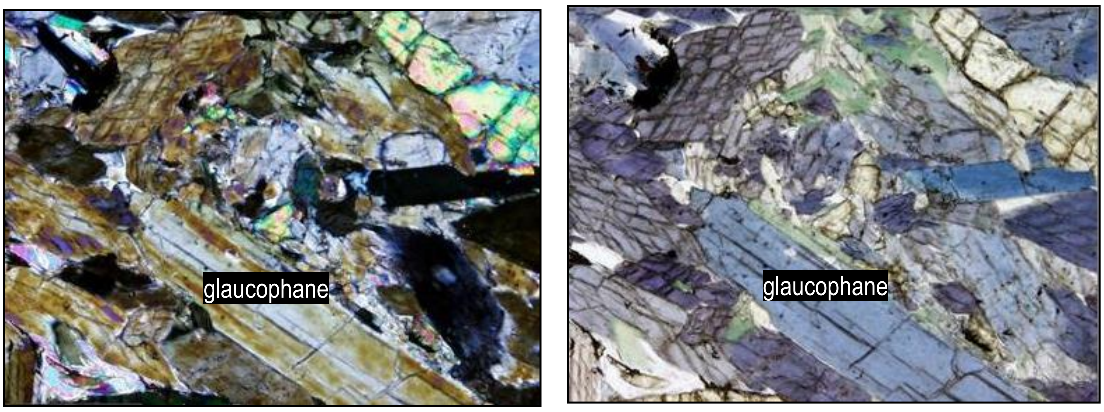


Fig. 270. Microphotograph of glaucophane, XPL (left), and the same mineral with PPL (right). Magnification 100×.

Glaucophane forms in specific conditions. It correlates with regionally metamorphosed rocks formed at low to moderate metamorphic grade with contribution of sodium or under the extremely high pressures (exceeding 10 Kb) and low temperatures, up to 400 °C, such as conditions in subduction zones are.

It commonly associates with lawsonite, occasionally with garnets and epidote, etc. Glaucophane may be formed in biotite and amphibole-bearing rocks with contribution of sodium.

11.5.2.4.2. Riebeckite $Na_2(Fe_3^{2+}Fe_2^{3+})(Si_8O_{22})(OH)_2$

Riebeckite is a hydrous sodium-iron silicate.

Crystallizes in monoclinic system and appears in prismatic, columnar to acicular aggregates.

Riebeckite is dark-green to black in color (fig. 271). It displays vitreous to pearly luster, a perfect cleavage and characteristic blue streak. Specific gravity is from 3.0 to 3.4 g/cm^3, hardness 6.

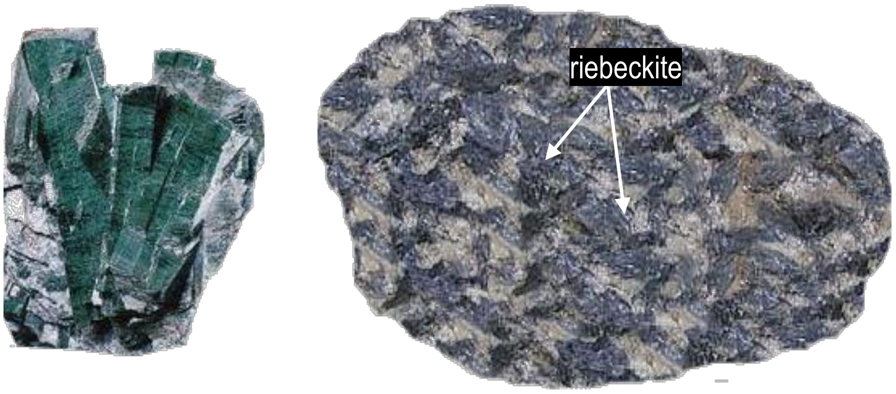


Fig. 271. Crystal of riebeckite (left), and riebeckite in schist (right).

Under the polarizing microscope riebeckite should be, just like glaucophane, recognized by its columnar aggregates and very characteristic pleochroism in greenish-blue (fig. 272).

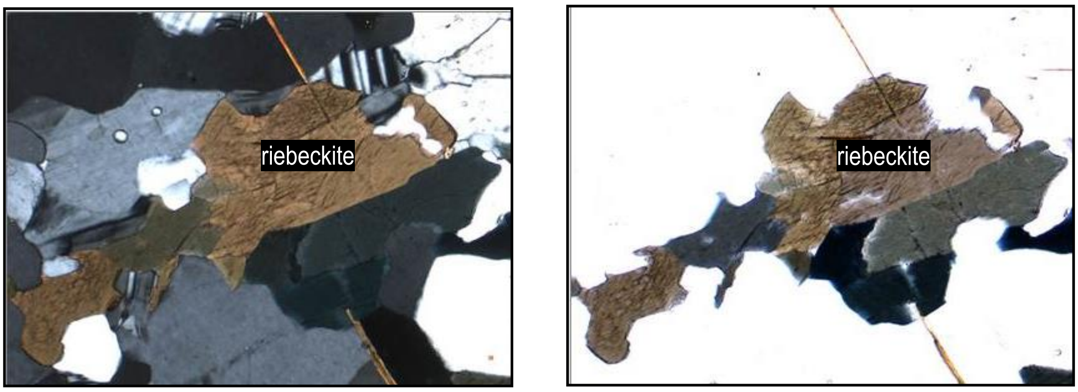


Fig. 272. Microphotograph of riebeckite, XPL (left), and the same mineral with PPL (right). Magnification 60×.

Riebeckite is found in alkali igneous rocks of acid to intermediate composition, granite, and syenite. It also forms as regional metamorphic mineral at low temperatures (up to 400 °C) and at pressures up to 5 Kb (greenschist facies), when is associated with albite, chlorite, epidote, zoisite, etc.

When a part of Fe in riebeckite is replaced with Mg, a **magnesium-riebeckite** is going to be formed. It is: $Na_2(Mg_3^{2+}Fe_2^{3+})(Si_8O_{22})(OH)_2$ in composition and is the most frequent in low-grade metamorphic rocks where is accompanied with actinolite, chlorite, epidote, zoisite, and albite (fig. 273).

Fig. 273. Outcrop of chlorite schists with Mg-riebeckite (stream Tmuša, River Seča Reka, at Kosjerić). Above right, a detail of rock.

Riebeckite commonly builds isomorphic series with glaucophane and is called **crossite** (fig. 274). It is a mineral of alkali igneous rocks, as well as of regionally metamorphic rocks, which have been formed at low temperatures and high pressures, and in which is associated with lawsonite, alkali pyroxene and glaucophane.

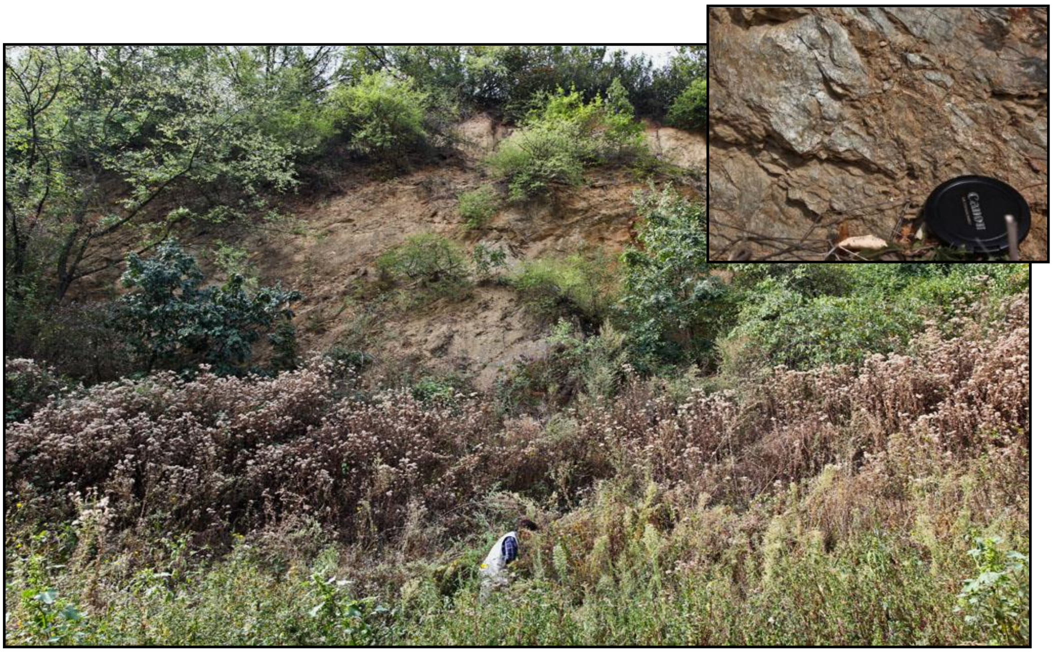


Fig. 274. Outcrop of crossite schists, Selište near Sremski Karlovci. Above right, a detail of rock.

Alkali amphiboles are very similar and could be hardly recognized on a field, as well as under the polarizing microscope due to their similar optical properties. Because of that, their identification requires a chemical analysis (microprobe) for calculating a crystallochemical formula, needed for their classification.

12. LAYERED CHAIN SILICATES

Layered chain silicates or hetero phyllosilicates are the group of minerals with a transitional ino-phyllosilicate structure. One of the most important mineral in this group is prehnite.

12.1. PREHNITE $Ca_2(Al,Fe^{3+})(AlSi_3O_{10})(OH)_2$

Prehnite gets the name after a colonel H.P. Prehn, (1733-1785) who discovered it at the Cape of Good Hope.

It crystallizes orthorhombic and occurs in thin, platy crystals or builds rosette, radiating, and fanlike, ball- or kidney-shaped aggregates. Color is white, light-green, yellow and pinkish to grey (fig. 275).

Prehnite has perfect cleavage, uneven fracture and vitreous lustre. Its hardness is 6 to 6.5, and specific gravity from 2.8 to 3 g/cm³.

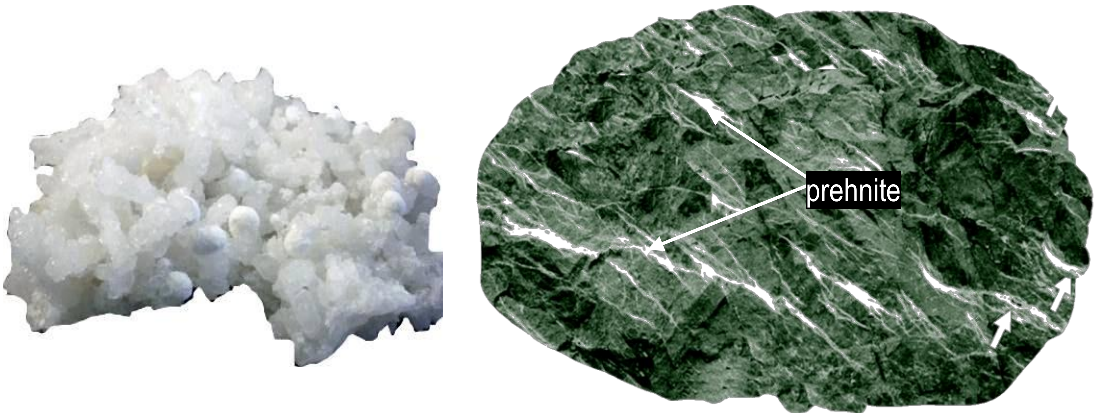


Fig. 275. Crystals of prehnite (left), and white prehnite veins in diabase (right).

In polarizing microscope may be recognized by its characteristic fan-shaped aggregates with low relief and without pleochroism (fig. 276).

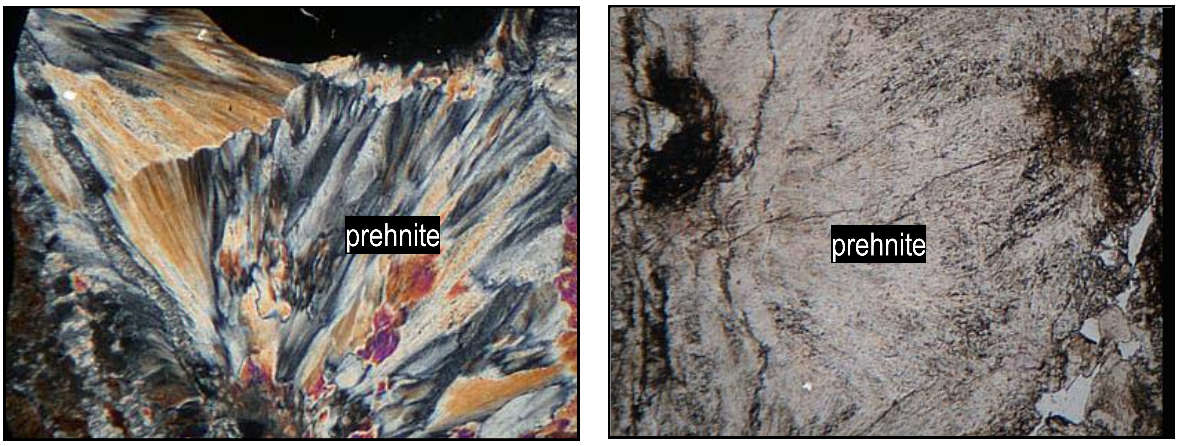


Fig. 276. Microphotograph of prehnite, XPL (left), and prehnite with PPL (right). Magnification is 60×.

Prehnite is secondary mineral, formed by alteration of basic plagioclase. Its pseudomorphs after analcite and basic plagioclase are common. Prehnite could be found in veins and amygdales in basic igneous rocks (fig. 277).

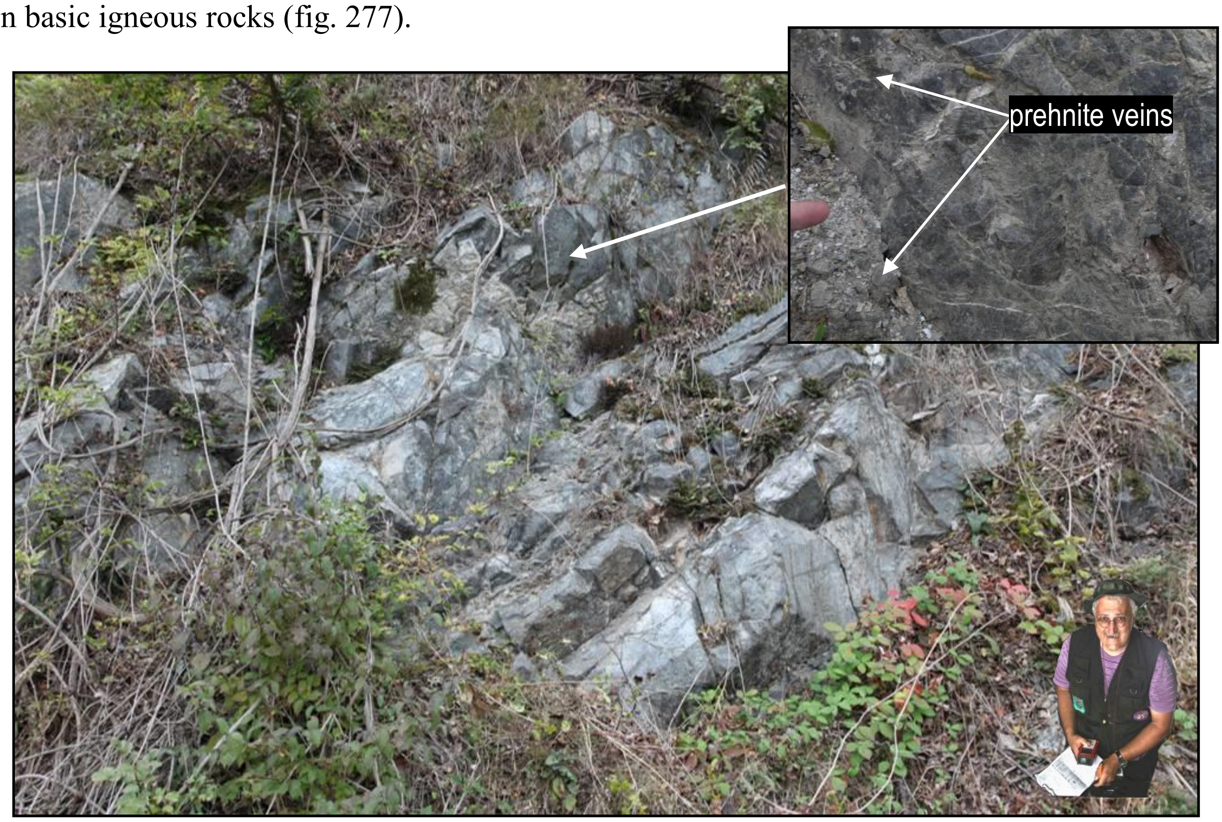


Fig. 277. Gabbro from Glavica, near Donji Milanovac is with veins of prehnite.
Above right is the detail of rock with veins of prehnite.

Prehnite forms in rodingites or gabbros by calcium metasomatism, commonly in association with hydrated garnet (hybschite).

Prehnite forms as metamorphic mineral at low metamorphic grade, usually below the limit of the greenschist facies, at temperatures below 400 °C and pressures up to 5 Kb, when is associated with pumpellyite, actinolite, chlorite, albite, and zeolites.

13. PHYLLOSILICATES

Phyllosilicates are the group of silicate minerals in which silica and aluminum tetrahedra are linked together to form continuous frameworks, sheets in one plane producing layered or sheet structure. Most of the phyllosilicate minerals consist of hexagonal rings (phyllosilicates with hexagonal sheet structure) when a tetrahedra peaks are on a same side and their bases are positioned in a same plane. Oxygen atoms at peaks of tetrahedra are linked with silica ions and with cations. These atoms are inactive in the base as their charges were spent for building a downward ring structures. A part of silica is substituted with aluminum. Two frameworks of phyllosilicates are turned to each other with their active sides and mutually connected by K, Na, Mg, and Fe cations, or by OH group.

Phyllosilicates represent chemically hydrated aluminum silicates of K, Na, Mg and Fe. A part of hydroxyl group may be substituted with fluorine, rarely chlorine. This group includes important petrogenic minerals, such as micas, chlorite and clay minerals.

13.1. MICAS

Micas are among the most widespread minerals in the Earth's crust. They are essential minerals in acid igneous rocks (granite and granitoids), metamorphic rocks (gneiss and micaschist) and sedimentary rocks (sandstone). They are igneous minerals and crystallize from wet magma (water-rich magma). They are metamorphic minerals, too.

Minerals from the group of micas are of different chemistry, but of similar physical and morphological properties.

They crystallize monoclinic and occur in micaceous and leaf-like aggregates. Cleavage is perfect, flakes and leafs very flexible and elastic. Hardness is about 2.5. In the sense of chemistry could be distinguished:

MUSCOVITE	$K_2,Al_4(Si_6\,Al_2O_{20})(OH,F)_4$
PARAGONITE	$Na_2,Al_4(Si_6\,Al_2O_{20})(OH)_2$
BIOTITE AND PHLOGOPITE	$K_2(Mg,Fe^{2+})_{6\text{-}4}(Fe^{3+},Al,Ti)_{0\text{-}2}(Si_{6\text{-}5}Al_{2}\text{-}O_{20})(OH,F)_4$
LEPIDOLITE	$K_2(Li,Al)_{5\text{-}6}\,(Si_{6\text{-}7}\,Al_{2\text{-}1}O_{20}\,)\,(OH,F)_4$
MARGARITE	$Ca_2Al_4(Si_4Al_4O_{20})(OH)_4$
STILPNOMELANE	$(K,Na,Ca)_{0.6}(Mg,Fe^{2+}Fe^{3+})_6Si_8Al(O,OH)_{27}x2\text{-}4\ H_2O$.

13.1.1. MUSCOVITE

Muscovite is hydrated potassium aluminum silicate. Small amounts of Na, Mg, Fe, as well as of Rb, Ba and Cs may enter into their composition. A part of OH group may be substituted with F and Cl. Its name derived from Latin term *vitrum* (glass) and from one Russian province (Muscovy) from where a huge transparent sheets have being imported in Europe, under the commercial name „Russian glass“.

Muscovite crystallizes monoclinic, has specific gravity 2.8 to 3.0 g/cm^3, and hardness 2 to 2.5. It occurs in flaky aggregates of various dimensions. Thin flakes of muscovite are transparent.

Displays perfect cleavage and is colorless. Muscovite laths are flexible and elastic. At cleavage planes is lustre pearly (fig. 278). The powder of it is white in color.

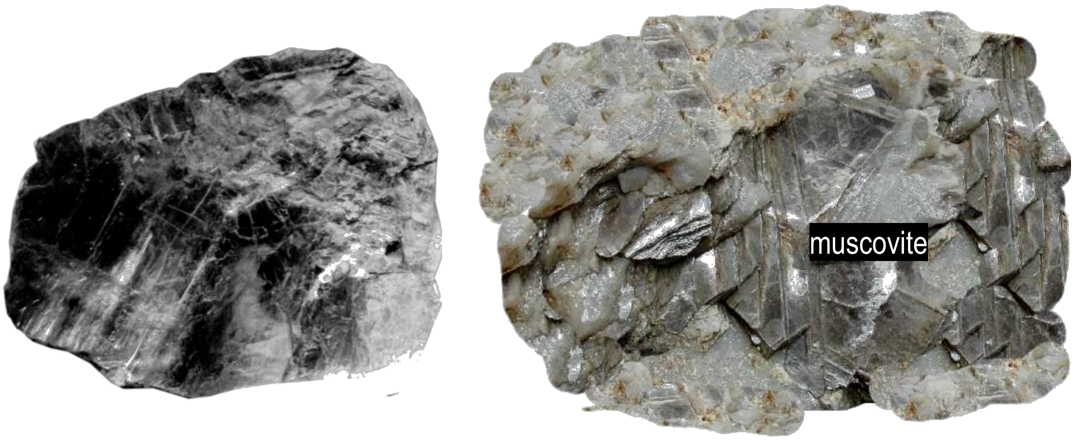


Fig. 278. Muscovite flake (left), and muscovite in pegmatite (right).

Under the microscope is muscovite distinguishable after its bright interference colors, low relief and lack of pleochroism (fig. 279).

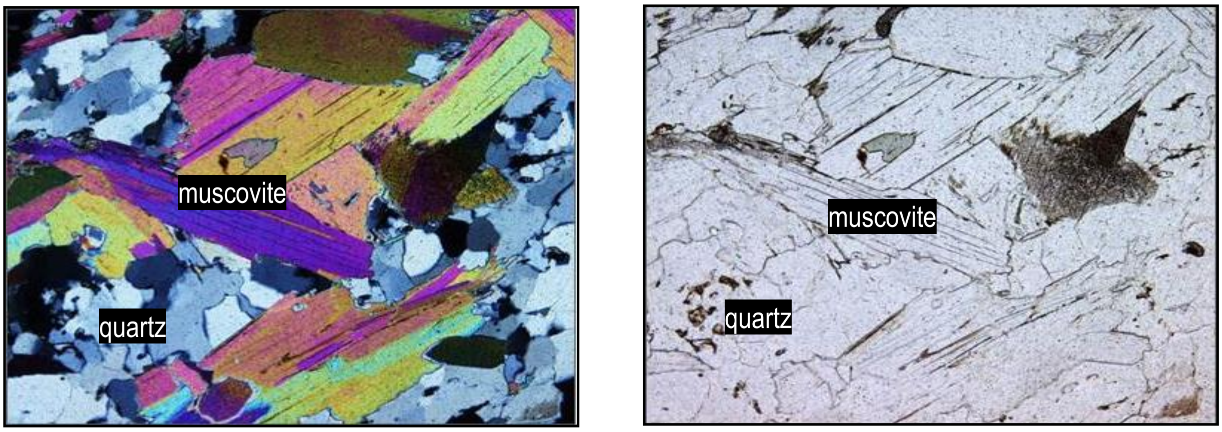


Fig. 279. Microphotograph of muscovite in granite, XPL (left), and the same mineral with PPL (right). Magnification 100 x.

Muscovite forms:

- **igneous**, from acid, water-rich magma (granite) and commonly is the last crystallizing mineral; pegmatitic, under reaction of vapor phase (water) and previously crystallized potassium feldspar or throughout reaction of the rest of a melt, feldspar in composition, and water (fig. 280 and fig. 281). Flakes of muscovite can reach 1 m in size in pegmatite. It is commonly associated (in paragenesis) with biotite and another minerals that occur in these rocks: tourmaline, beryl, garnets.

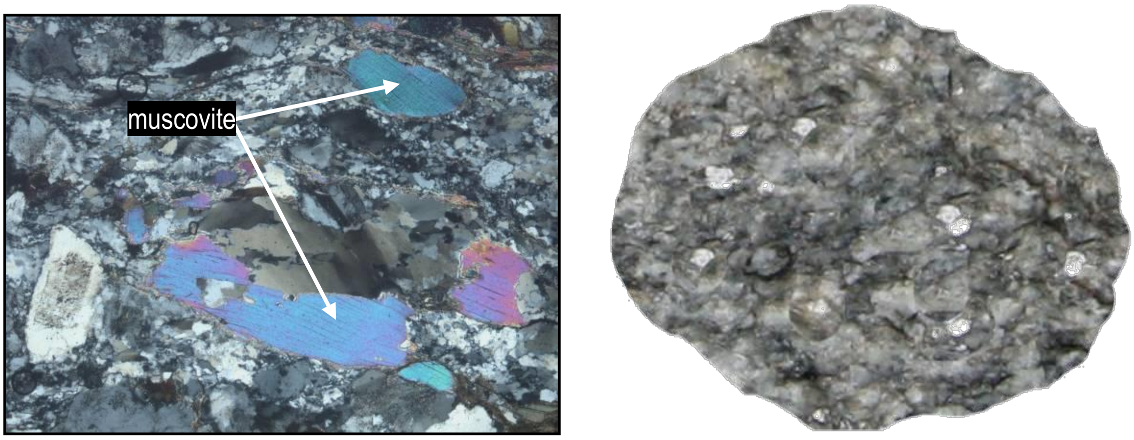


Fig. 280. Microphotograph of muscovite in granite (left), XPL, magnification 100×.; The sample of muscovite-bearing granite (right).

Fig. 281. Granites of Polumir are with muscovite. Above right is a detail of rock.

- **metamorphic**, by transformation, i.e. recrystallization of the clay mineral illite (clay mineral with potassium), which converts into sericite at low metamorphic grade (laths up to 2 mm in size) and builds the rock phyllite. With the increasing metamorphic grade (amphibolite facies) sericite turns into muscovite (laths exceeding 2 mm). It commonly contains more Al, Mg and Fe, than the igneous-formed muscovite. It is the essential mineral in gneisses and micaschists (fig. 282 and fig. 283). At high temperatures, muscovite loose water (if the system is opened) and turns into orthoclase or into sillimanite, either by loose of potassium or in excess of aluminum.

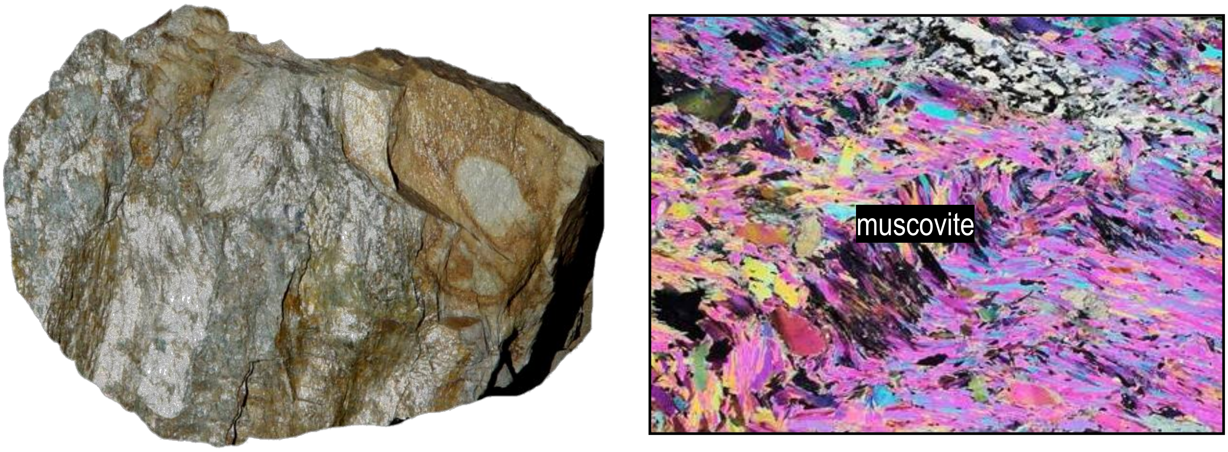


Fig. 282. Micaschist with muscovite (left), and microphotograph of the same rock, XPL (right). Magnification 100×.

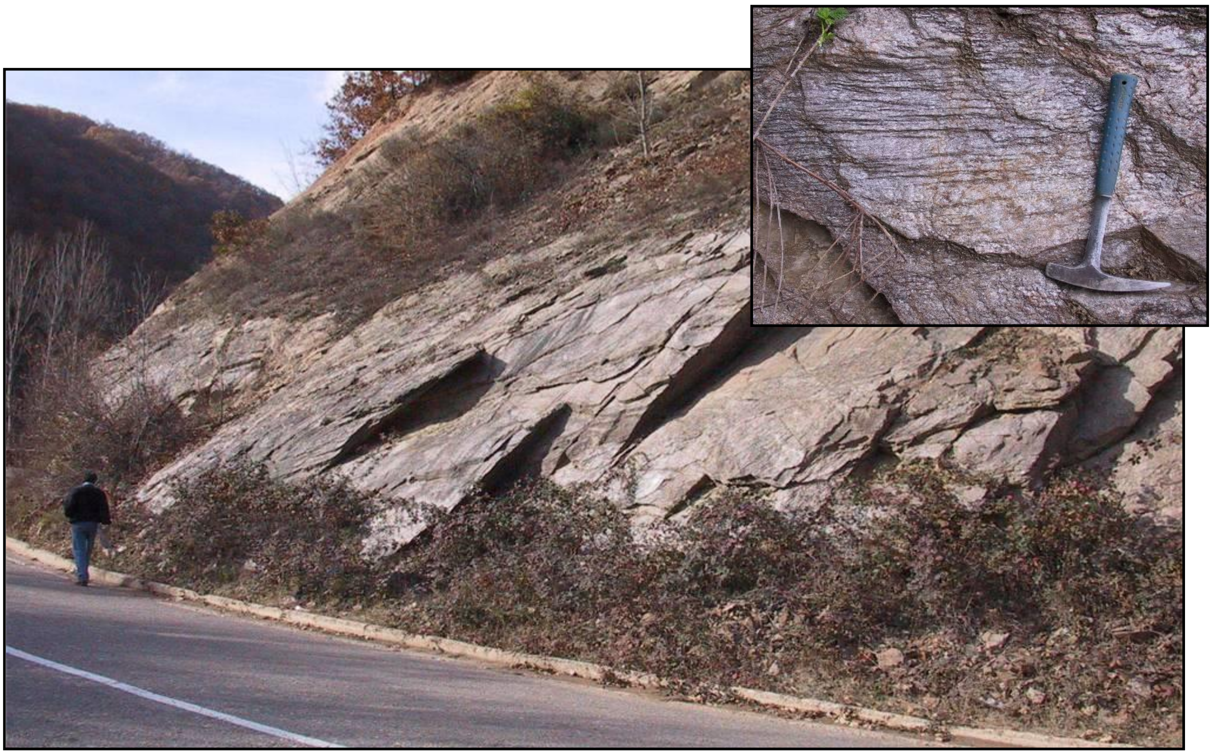


Fig. 283. The chief mineral in micaschists of Lebane is muscovite. Above right, a detail of rock.

- **under alteration processes**, from alkali feldspar (orthoclase, sanidine) or hydrothermally, when is the commonest mineral of wall-rock alterations related to mineralization of copper, gold, lead and zinc. It occurs in lathlike aggregates and accumulations of considerable smaller laths than those of sericite, hence are often called illite (fig. 284).

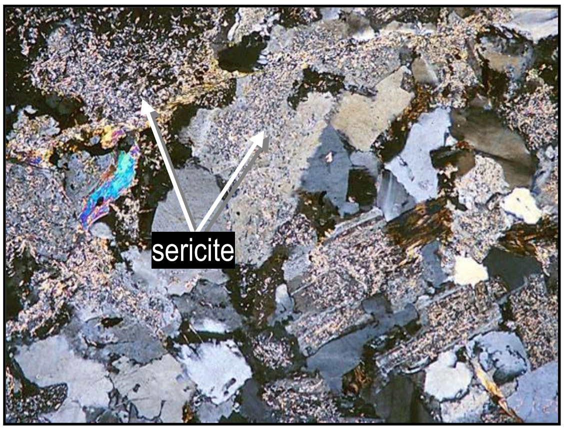


Fig. 284. Orthoclase partly replaced by sericite (illite), XPL, magnification 100×.

Muscovite is resistant during physical-chemical weathering, thus could be transported on large distances from the place of birth. It is the essential mineral in loose or bonded clastic sediments, sand and sandstone (fig. 285). Large muscovite flakes found their application in electro industry as isolator.

Fig. 285. Muscovite in sand, above right is accumulation of muscovite, a detail.

Compaction of sand leads to formation of sandstone, rock in which is muscovite one of the chief minerals (fig. 286 and fig. 287). There it occurs in flakes (clasts) up to 2 mm in size, that could be easily recognized due to its characteristic vitreous lustre resulted from "shining" muscovite.

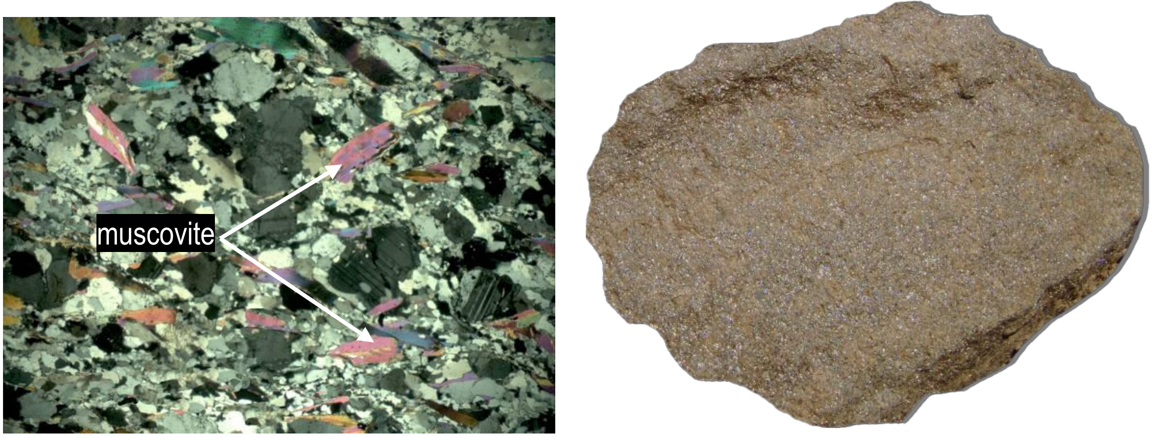


Fig. 286. Microphotograph of muscovite in sandstone, XPL (left), magnification 60×, and the sample of sandstone with muscovite, light flakes (right).

Fig. 287. Flysch of Ljig is dominantly composed of sandstone with muscovite. Above right, a detail of rock.

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13.1.2. PARAGONITE

Paragonite is sodium mica. Considerable amount of sodium may be substituted with potassium. It is significantly less abundant in rocks than muscovite.

Paragonite is white colored, sometimes light yellow, greenish to grey. Like muscovite, occurs in lathlike aggregates (fig. 288). It has perfect cleavage and pearly lustre.

Specific gravity of this mineral is 2.8 to 2.9 g/cm^3, and hardness is 2.5 to 3.

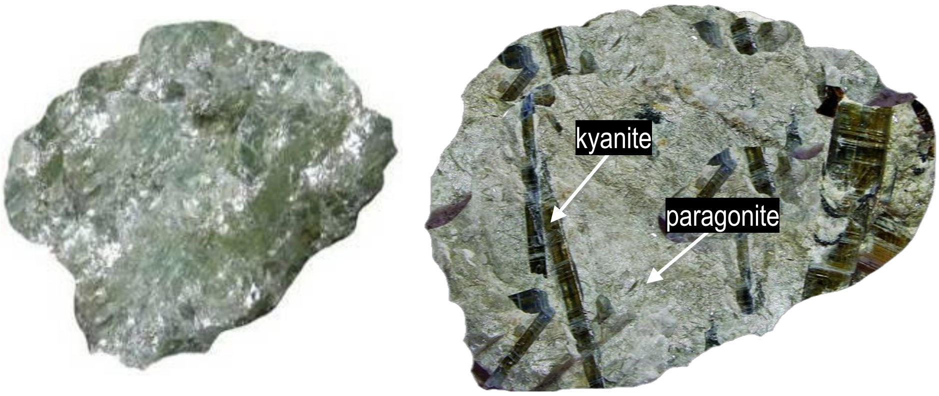

Fig 288. Laths of paragonite (left), and paragonite, white flakes in kyanite schist (right).

Paragonite forms as metamorphic mineral, at low to moderate grade, in sodium or aluminum-rich rocks or by addition of sodium. Pressure supports the formation of it. Regarding its optical properties is similar to muscovite.

It occurs in association with muscovite, chlorite, kyanite and staurolite.

This mineral was noted in metamorphic rocks that were formed in subduction zones, when associates with glaucophane and garnets. In polarizing microscope is, like muscovite, resembling flakes of low relief (fig. 289).

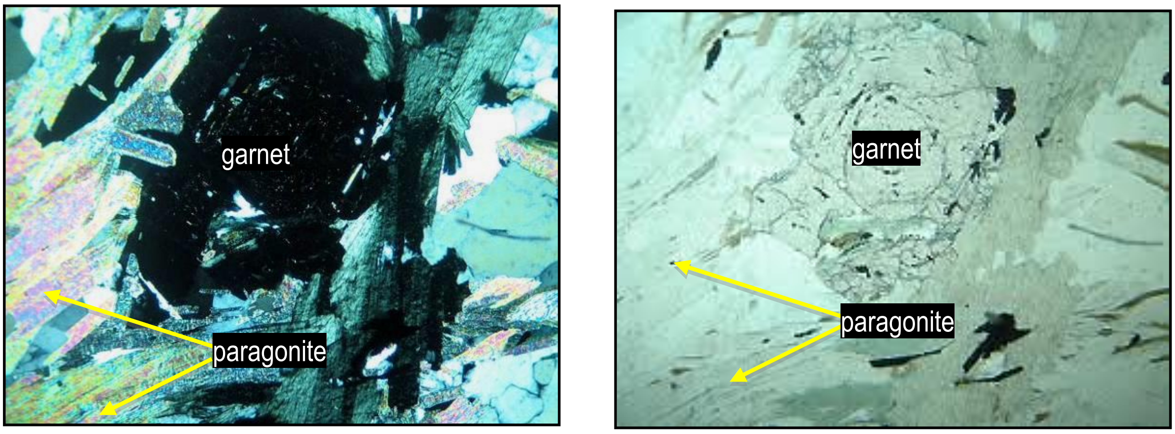

Fig. 289. Microphotograph of paragonite in garnet-bearing gneiss (left), XPL, and the same mineral with PPL (right). Magnification 100×.

13.1.3. BIOTITE

Biotite is named in honor of the French physician Biot (fig. 290). This mineral is compositionally isomorph mixture of hydrated potassium iron-rich aluminum silicate, annite, and potassium-magnesium aluminum silicate, phlogopite.

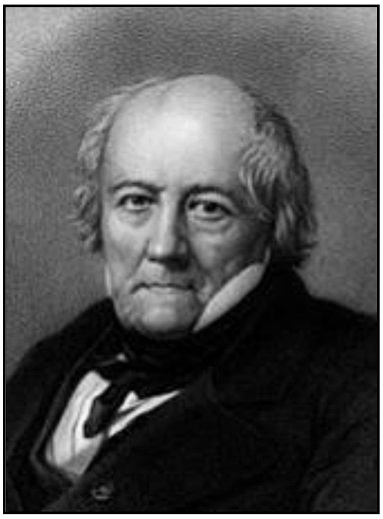

Fig. 290. G. Biot (1774–1862).

Mg-content in biotite increases with the temperature of crystallization. Impurities in biotite are Mn, Ti, Ba and Na.

It crystallizes monoclinic, has specific gravity 2.7 to 3.4 g/cm^3, hardness 2-3. Its color is brownish-yellow, greenish-brown to black, and it occurs in flakes of perfect cleavage, vitreous to pearly lustre (fig. 291). Flakes are flexible and elastic. Thin laths are semi-transparent to transparent.

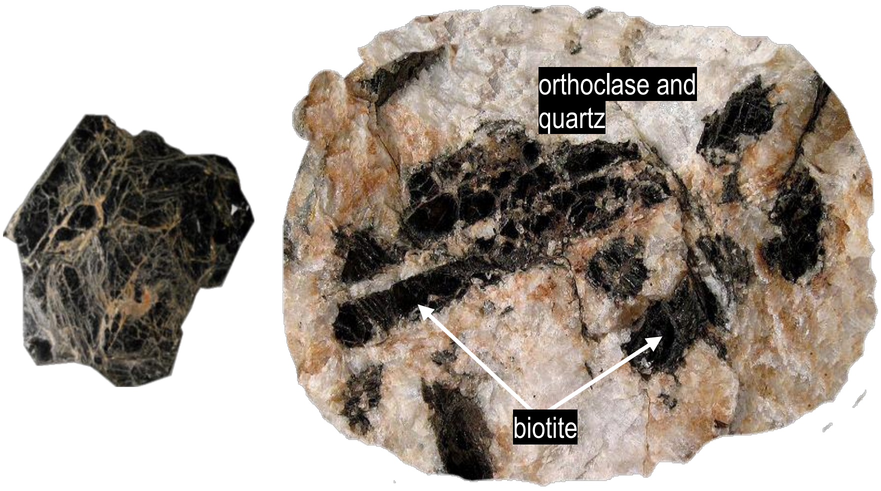

Fig. 291. Flake of biotite (left), and biotite in pegmatite (right).

In polarizing microscope is biotite recognizable by its mode of appearance, flakes in characteristic brown to reddish-brown pleochroism with parallel nicols, which is a function of Fe content (fig. 292).

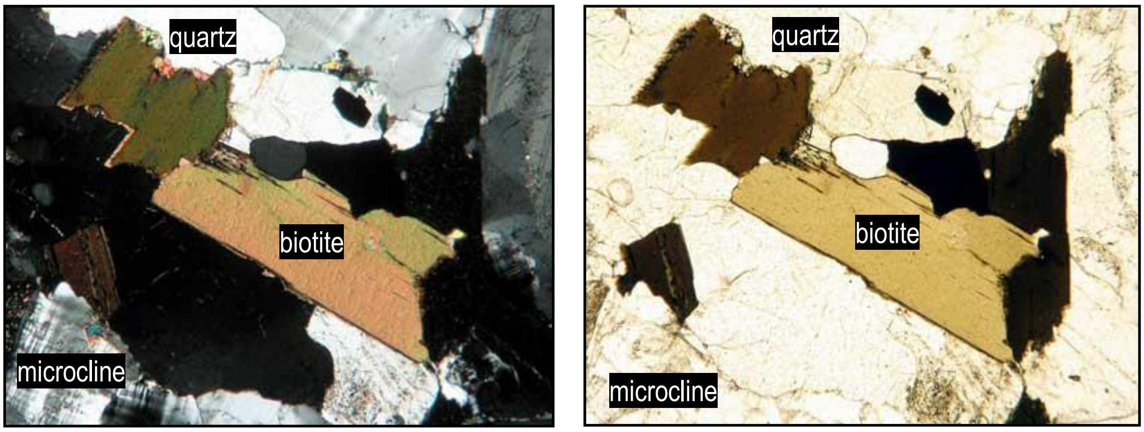

Fig. 292. Microphotograph of biotite in granite, XPL (left), and the same sample with PPL (right). Magnification 100×.

Biotite forms igneously, metamorphic and hydrothermally.

Within the **igneous cycle** is genetically related to acid and intermediate rocks, granite, quartzmonzonite, granodiorite, quartzdiorite, diorite and their volcanic equivalents, representing their major colored (femic) mineral (fig. 293).

Fig. 293. Granodiorite from Boranja contains biotite. Above left, a detail of rock.

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It could be easy identified in rocks by its mode of appearance, lath-like aggregates, brownish to almost black color and glittering.

It could be found in pegmatite, commonly together with muscovite. In basic igneous rocks and their volcanic equivalents is rare and commonly present as characteristic minor mineral, and suggests on composition of magma from which the given rock crystallized (considerable amount of potassium and water).

In volcanic rocks biotite occurs as phenocrysts (fig. 294 and fig. 295), up to a few millimeters in size, rarely coarser. In vein rocks (particularly lamprophyres or alkali effusive rocks) is fine-grained, about 1 to 2 millimeters.

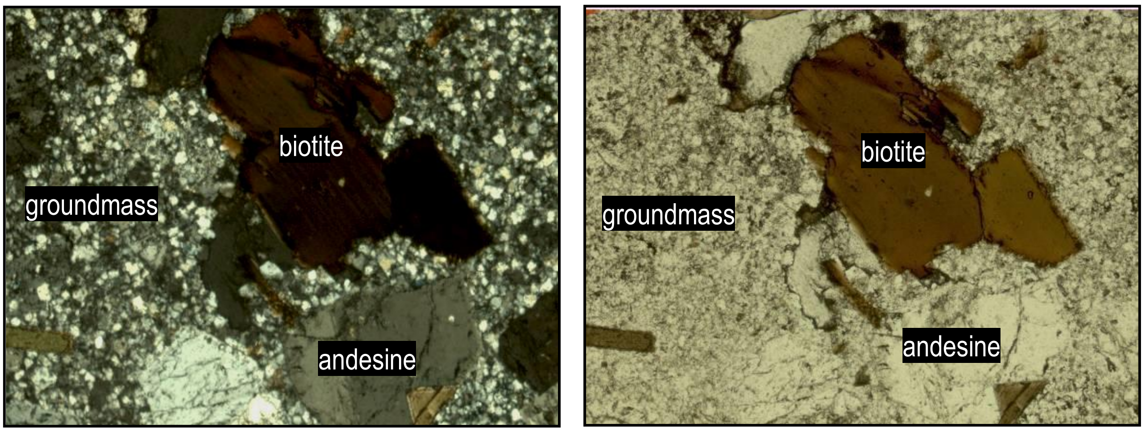

Fig. 294. Microphotograph of biotite phenocrysts in dacite from Slavkovica, XPL (left) and the same sample with PPL (right). Magnification 100×.

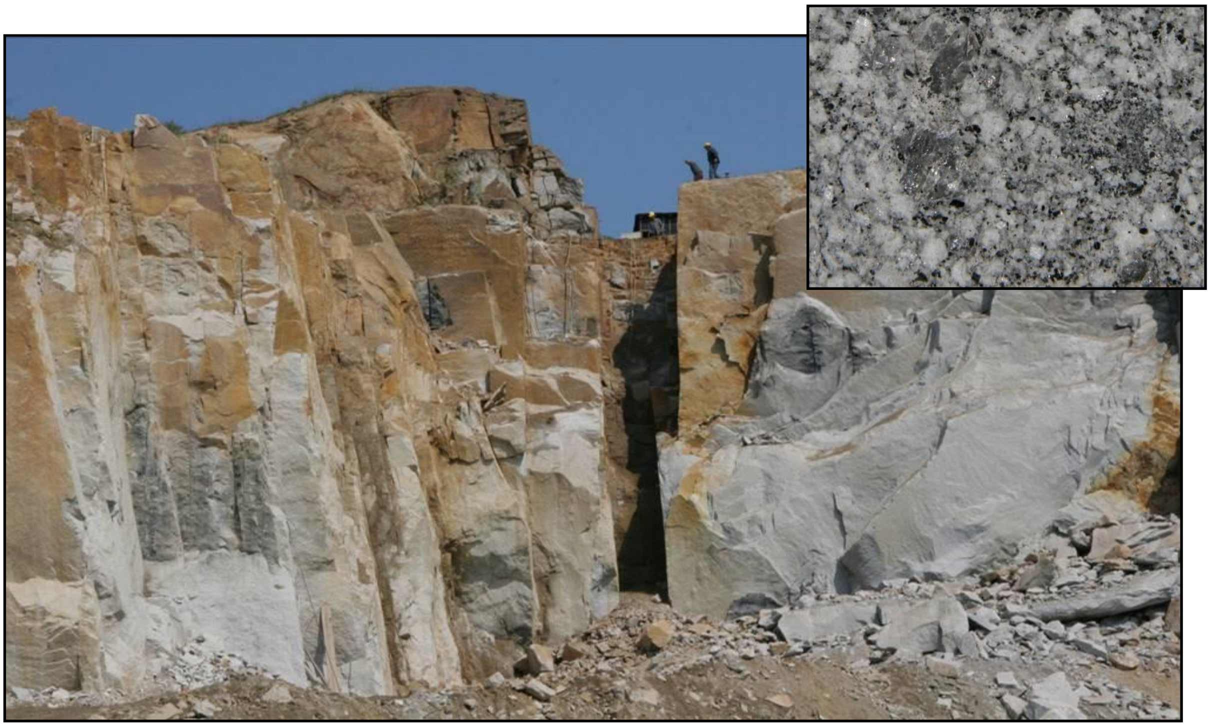

Fig. 295. Dacites from Slavkovica near Ljig contain biotite as phenocrysts, above right is a sample of rock.

Biotite is also **metamorphic** mineral. It is a constituent of numerous regional and contact metamorphic rocks, gneisses (fig. 296 and fig. 297), micaschists, and hornfelses. Biotite commonly forms under reaction of muscovite (sericite) and chlorite or by recrystallization from illite (mineral of the clay group) if Fe and Mg are contributed at moderate metamorphic grade (temperature above 400 °C). It is stable in a wide pressure-temperature range. Biotite would decompose at high metamorphic grade when water is able to leave and in reactions with other minerals will „give" orthoclase and garnets.

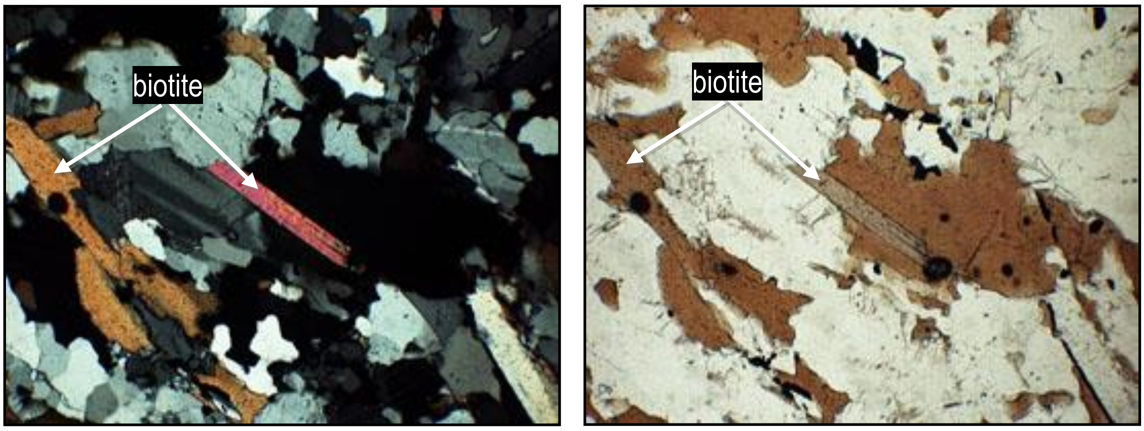

Fig. 296. Microphotograph of biotite in gneiss, XPL (left), and the same sample with PPL (right). Magnification 100×.

Fig .297. Gneisses from Batočina contain biotite. Above right is a detail of rock.

This mineral forms also during contact metamorphism, under the influence of hot magma (commonly granitic) on clastic sediments, sandstone, siltstone and clays. On this way develop hornfelses and spotted schists (fig. 298 and fig. 299), rocks that compose „aureole“ around granite reaching in width from a few meters to maximally few hundred meters. Biotite is present in tiny laths (up to a few mm) without any orientation, revealing a brownish color to rock. Commonly is associated with orthoclase, pyroxene, cordierite, and garnets.

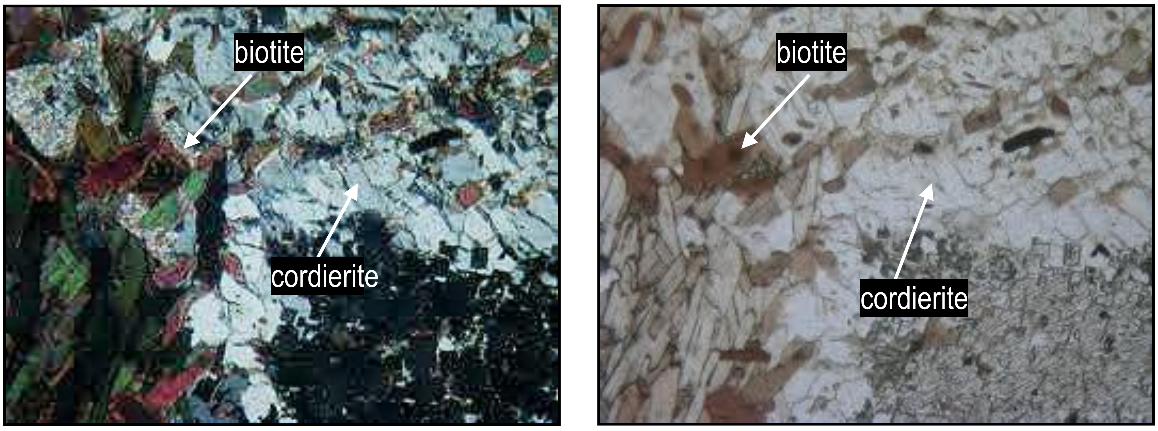

Fig. 298. Microphotograph of hornfels composed of garnet, cordierite and biotite, XPL (left), and the same sample with PPL (right). Magnification 100×.

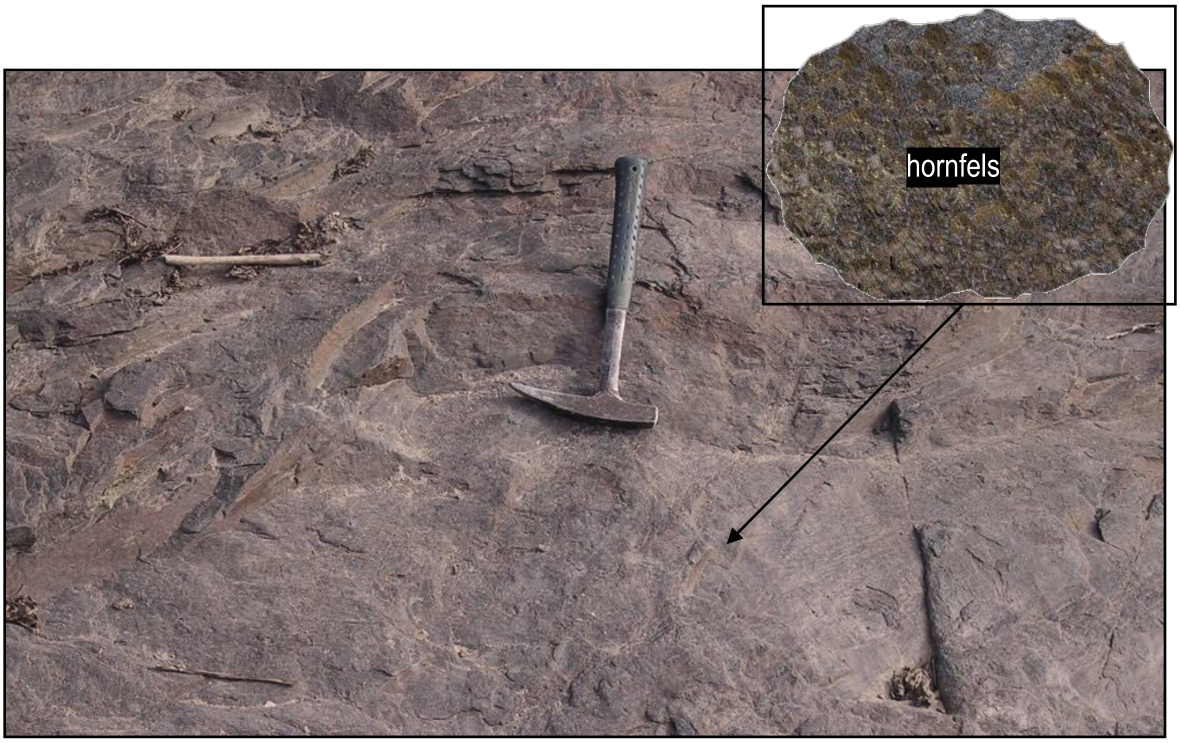

Fig. 299. Hornfels from Boranja with biotite beside cordierite and andalusite. Above right is a detail of rock.

Biotite is also hydrothermal mineral, when occurs in tiny lath-like aggregates and is named **neobiotite**. It commonly associates with sericite, alunite, and kaolinite, i.e. with characteristic minerals for wall-rock alterations related to copper, gold, lead and zinc mineralization (fig. 300).

Fig. 300. Hydrothermally altered rocks in Lipa at Crni Vrh (east Serbia). Above right are altered andesite with neobiotite (tiny brownish leafs), PPL, magnification 100×.

Biotite, contrary from muscovite, is not stable and experiences physical-chemical weathering. In the presence of water, atmospheric agents or hydrothermal fluids it converts into chlorite, fine-grained magnetite, iron hydroxide and needle-shaped rutile occasionally. These processes are easy recognizable in the polarizing microscope, particularly with parallel nicols (fig. 301).

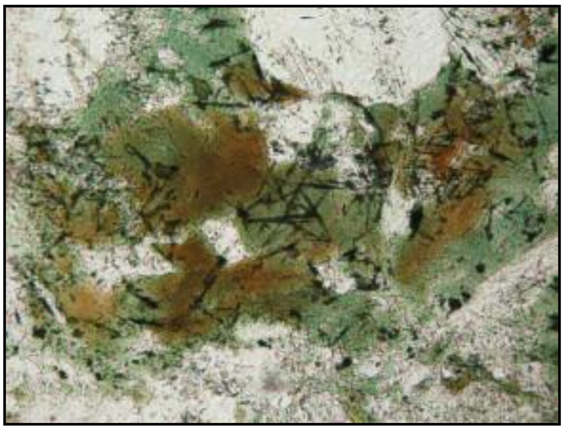

Fig. 301. Microphotograph of chloritized biotite with needles of rutile and secondary magnetite and limonite. PPL, magnification 100×.

13.1.4. PHLOGOPITE

Phlogopite is hydrated aluminum silicate of potassium and magnesium. With elevated Fe, it converts into biotite. This mineral rarely occurs in crystal forms, usually is present in lathlike aggregates that are flexible, even elastic. Thin laths are translucent to transparent (fig. 302).

Fig. 302. Flakes of phlogopite (left) and phlogopite in rock (right).

Crystallizes monoclinic and is green, brownish-green or fire-red. Lustre is vitreous or opaque; cleavage is perfect as in other micas. Specific gravity varies from 2.8 to 3.0 g/cm^3, and hardness is 2–3. In polarizing microscope is phlogopite very similar to almost same with biotite. It is igneous mineral and occurs in ultrabasic rocks suggesting on the presence of water and higher alkalis. These data are important in determination the genesis of mentioned rocks and conditions during their creation (fig. 303).

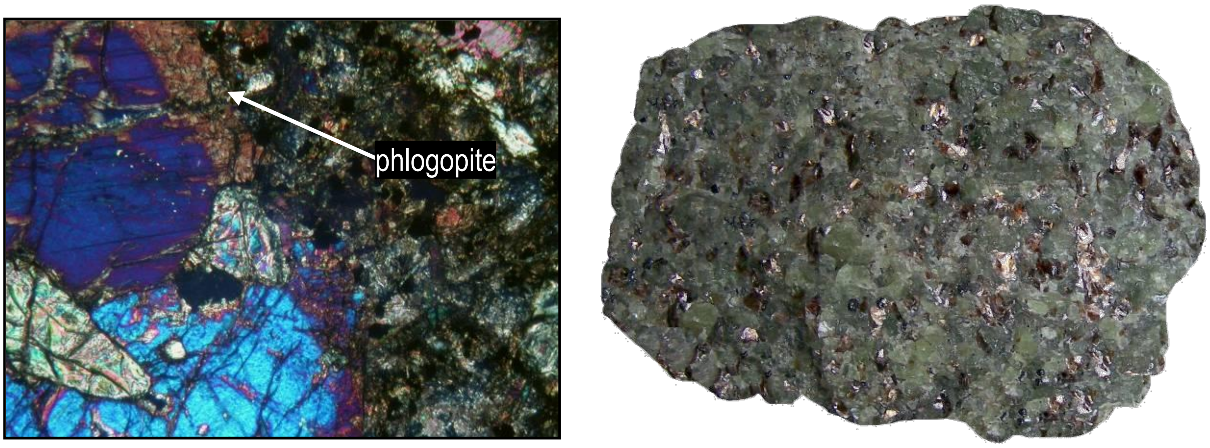

Fig. 303. Microphotograph of phlogopite in peridotite (left), XPL, magnification 100× and the sample of peridotite with phlogopite, dark laths (right).

Phlogopite is present in alkali and basic volcanic rocks, too, as well as in kimberlites, which bear diamonds (fig. 304 and fig. 305).

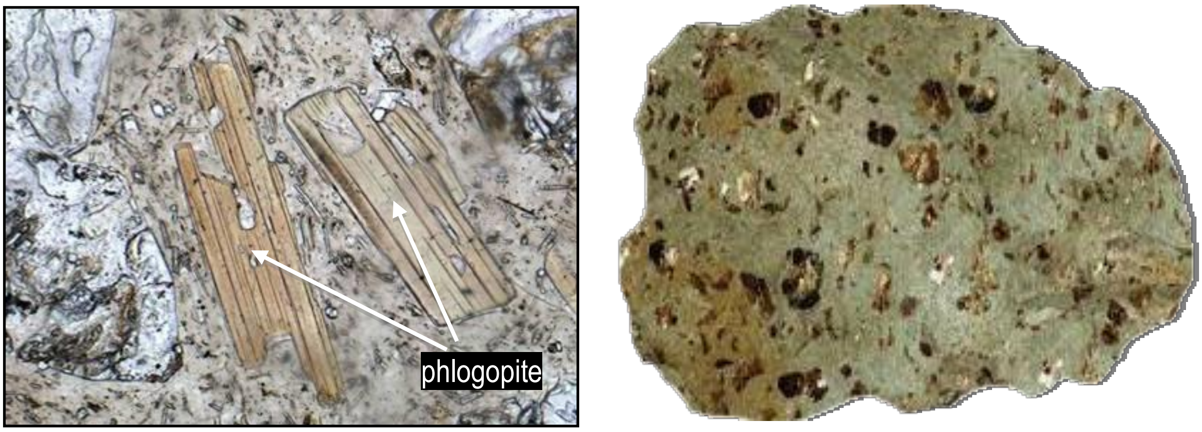

Fig. 304. Microphotograph of phlogopite in lamprophyre, XPL (left), and the same mineral in alkali rock, lamrpoite (right), dark brown laths. Magnification 100×.

Phlogopite is extremely rare found in granites, pegmatites and in contact metamorphic (metasomatic) rocks when silica, aluminum and potassium were contributed from magma into the host dolomite. In such cases is phlogopite enriched with fluorine. It forms hydrothermally, too. Alters into chlorite.

Fig. 305. Alkali basalts of Koritnik (near Sjenica) contain phlogopite. Above right is the sample of given rock.

13.1.5. LEPIDOLITE

Lepidolite is hydrous potassium-lithium aluminum silicate, which builds an isomorphic series of variable potassium and lithium contents. A part of potassium may be substituted with sodium, rubidium, cesium, and iron. Crystallizes monoclinic. Laths of it are elastic and flexible, of typical pinkish color (fig. 306) and often transparent. Lepidolite has vitreous to pearly lustre and a perfect cleavage. Specific gravity is from 2.8 to 2.9 g/cm^3, hardness 3–4.

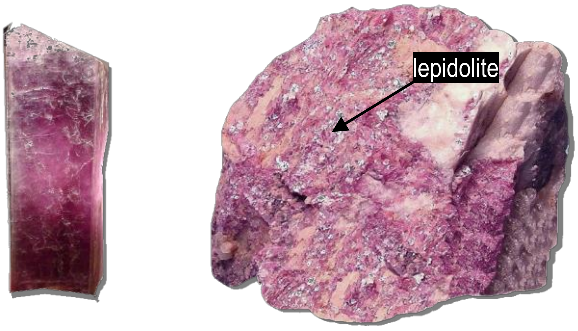

Fig. 306. Crystal of lepidolite (left), and lepidolite in pegmatite (right).

In polarizing microscope is lepidolite similar to muscovite (fig. 307). With crossed nicols displays high interference colors and is colorless with low relief when nicols are parallel.

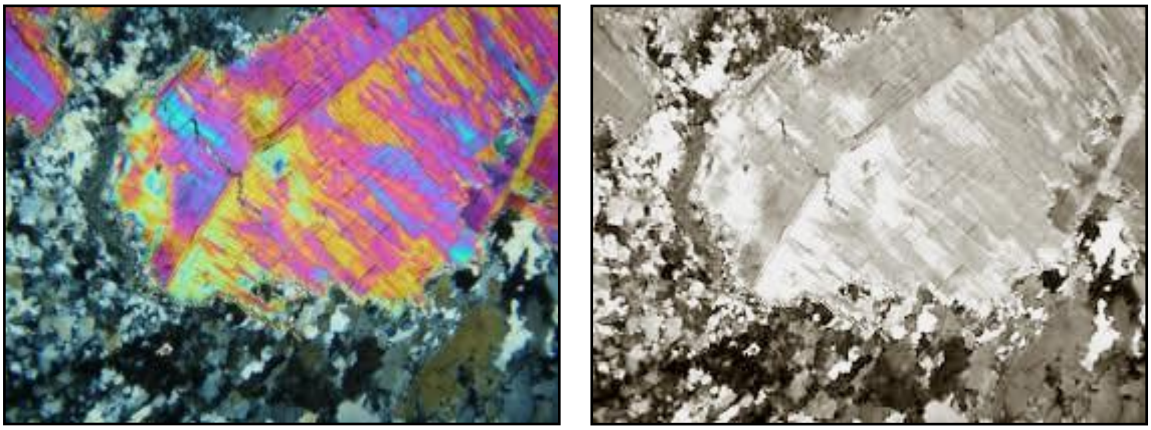

Fig. 307. Microphotograph of lepidolite (left), XPL, and the same mineral in PPL (right).Magnification 200×.

Lepidolite is most often found in pegmatites and is genetically related for acid igneous rocks and their pegmatites. It is frequently associated with muscovite, tourmaline, beryl, and lithium pyroxene. When fluorine and lithium is added affecting feldspars it may be formed pneumatolytic. At atmospheric conditions alters into clay minerals.

13.1.6. MARGARITE

Margarite was named after the Greek word meaning "pearl" due to its notable pearly lustre. A part of aluminum may be substituted by ferric iron.

Margarite is white to grimy yellow or brown colored (fig. 308). It occurs as flakes or lathlike aggregates, has a perfect cleavage and a pearly lustre. Its hardness varies from 3.5 to 4, and its specific gravity is 3 g/cm^3. Laths of it are poorly flexible or brittle, unlike those of muscovite and biotite.

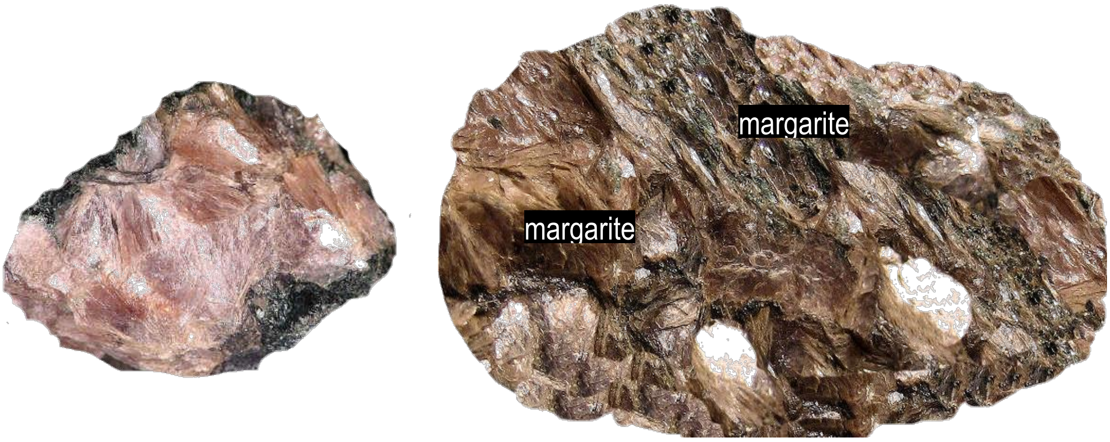

Fig.308. Laths of margarite (left), and margarite in schist (right).

Margarite is metamorphic mineral and forms at low to moderate grade metamorphism from pelites with carbonate component (carbonate, marly clays) or is a product of hydrothermally alteration of basic plagioclase and aluminum silicates. In the later case is associated with zoisite, calcite and quartz. It has similar optical properties to biotite and muscovite (fig. 309).

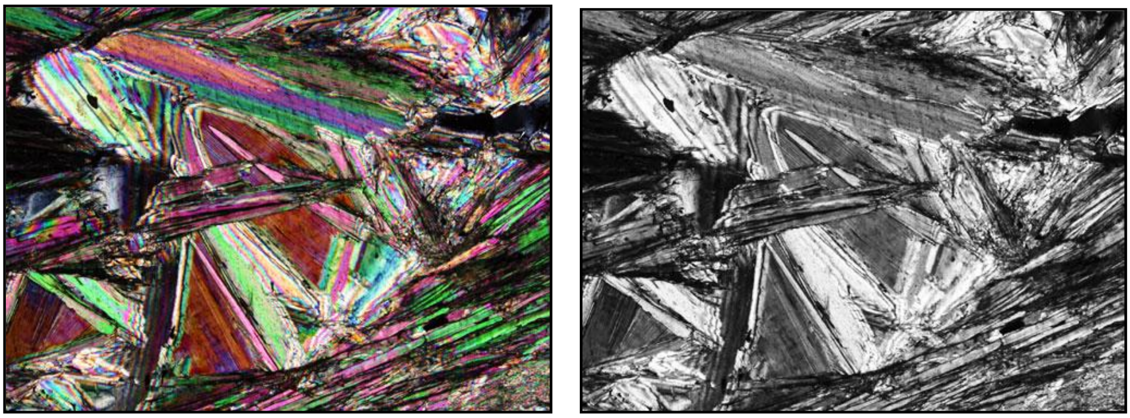

Fig. 309. Microphotograph of margarite in a schist, XPL (left), and the same mineral in PPL (right). Magnification 100×.

13.1.7. STILPNOMELANE

Stilpnomelane has complex chemical composition and considerably modified phyllosilicate structure. It crystallizes triclinic and has perfect cleavage. Specific gravity is 2.6 to 2.9 g/cm^3, and hardness 3 to 4.

It occurs in tabular to columnar or lathlike aggregates. In optical properties is similar to biotite (fig. 310). Color is brown to reddish-brown, dark brown, rarely red.

Fig. 310. Crystals of stilpnomelane (left), and stilpnomelane in the rock mass (right).

In polarizing microscope is stilpnomelane similar to biotite. With crossed nicols it displays interference colors of second order, whereas is characteristically pleochroic in brown and of low to moderate relief with parallel nicols (fig. 311).

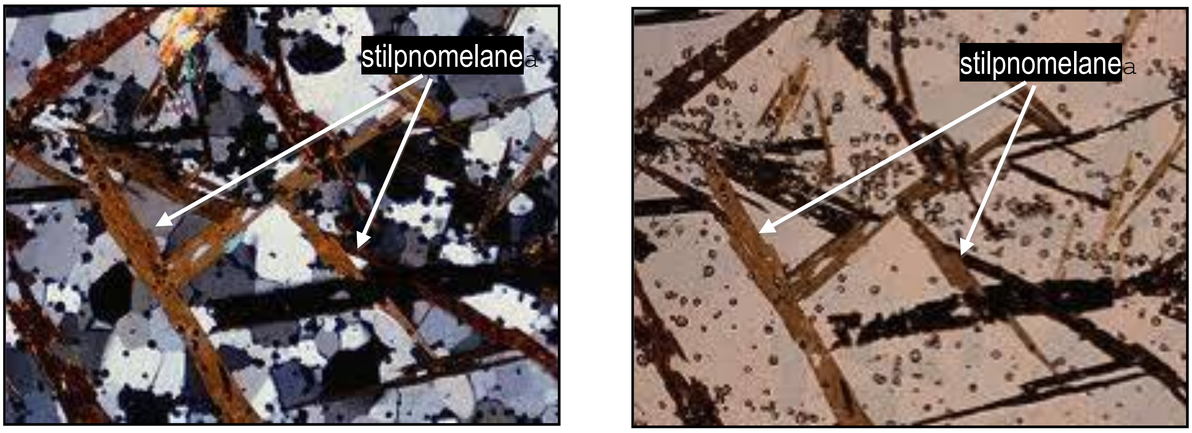

Fig. 311. Microphotograph of stilpnomelane in a schist, XPL (left) and stilpnomelane with PPL (right). Magnification 100×.

It comes in regional-metamorphic rocks, which derived at low grade (temperatures up to 400 °C and pressures up to 5 Kb) from basic pyroclastic rocks (tuff). The most frequently is associated with albite, chlorite, actinolite, and leucoxene (fig. 312).

Fig. 312. In chlorite schists, exposed in the stream Tmuša by Seča Reka (Kosjerić), are found Mg-riebeckite and stilpnomelane. Above right is the sample of rock with stilpnomelane.

The generation of stilpnomelane requires the higher presence of oxygen (oxidizing environment) and a certain ratio between alkalis, magnesia and iron in a host rock.

13.2. CHLORITES $(Mg,Fe^{2+},Fe^{3+},Mn,Al)_{12}(Si,Al)_8O_{20}(OH)_{16}$

Chlorites are hydrous aluminum silicates included in isomorphic series with end members: **clinochlore,** magnesium member, and iron member, **chamosite.** They have complex and variable chemistry and structure. A part of aluminum may be replaced with Fe^{3+} and Cr, and a part of Mg, Fe^{2+} and Mn with Ni.

The new classifications of chlorites are based on the dominant cations, Mg, Fe, and Mn. However, they will be here taken together.

Chlorites crystallize monoclinic, commonly in flake or lathlike aggregates. Laths are flexible but not elastic. Chlorites appear in all shades of green color, display vitreous lustre and a perfect cleavage (fig. 313). Specific gravity of chlorite is 2.6 to 3.3 g/cm^3, hardness from 2 to 3.

Fig. 313. Crystals of chlorite (left), and the chlorite in chlorite schist (right).

Chlorites are found in igneous, metamorphic and sedimentary rocks, and are common secondary minerals. It is extremely rare the primary mineral in igneous rocks. It forms at low temperatures from water-enriched magma.

In polarizing microscope, with crossed nicols is chlorite with the first order interference colors, such as dark green, brown to dark blue. It displays green pleochroism with parallel nicols, as well as low relief and lathlike aggregates that makes it easy recognizable and distinguishable from other minerals (fig. 314).

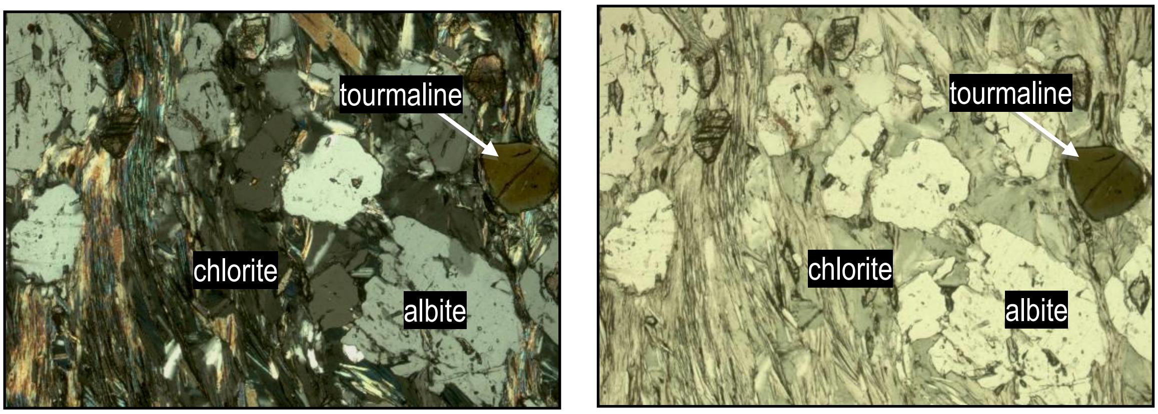

Fig. 314. Chlorite in chlorite schist, XPL (left), and the same mineral with PPL (right).Magnification 60×.

This is regional metamorphic mineral, too. It forms at low PT conditions (temperature ranges from 200 to 400 °C and pressures from 3 to 5 Kb) from basic rocks and their pyroclastics (basalt, spilite, diabase, and their tuffs). There is associated with albite, epidote, zoisite, sericite (fig. 315). At temperatures above 450 °C, chlorite interacts with other minerals giving rise to biotite, garnet, and hornblende.

Fig. 315. Outcrop of chlorite schists near Aleksinac. Above left, the rock sample.

Chlorite is a secondary mineral, formed by decomposition of biotite, hornblende and pyroxene (fig. 316).

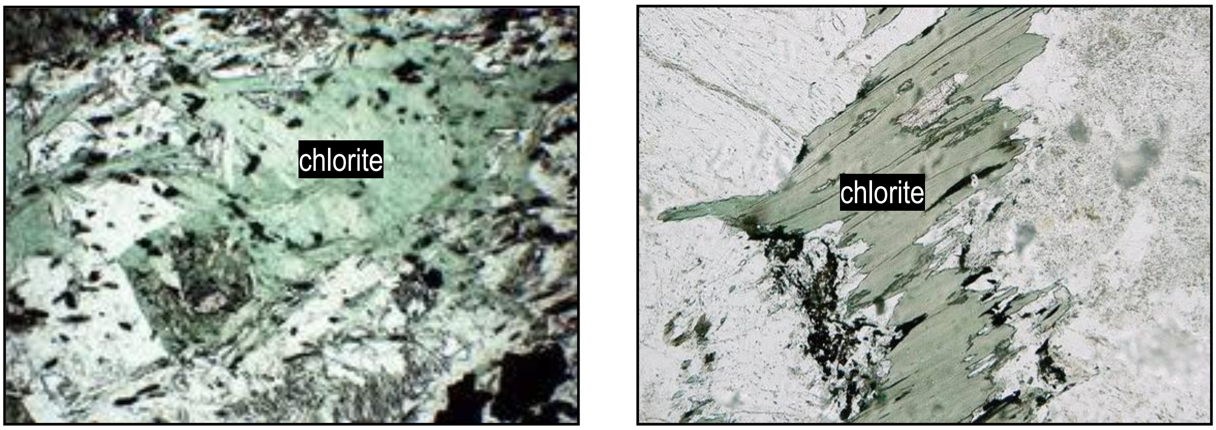

Fig. 316. Microphotograph of chlorite accumulations in chlorite schist, PPL (left) and the same mineral formed by decomposition of biotite, PPL (right). Magnification 60×.

Iron-rich chlorites may form in sedimentary cycle, during diagenesis of iron and magnesium rich clays. The increasing temperature enlarges the laths of chlorite. In such cases also forms schamosite, which may be ore of iron. It usually occurs in compact, oolitic masses (fig. 317). Its color is green to greenish-gray. Most frequently it associates with siderite and fine-grained to amorphous quartz. Schamosite is often followed by turingite, which is Mg-Fe chlorite. Iron-rich chlorites (schamosite) precipitates from basic solutions enriched with ferrous iron and magnesium.

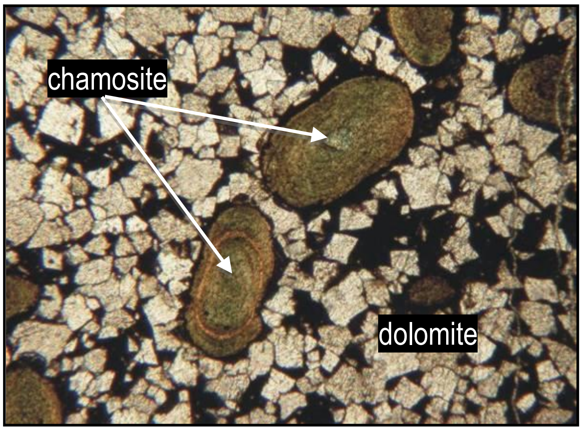

Fig. 317. Oolites of schamosite in carbonate (dolomite) mass. Magnification 40×.

In superficial conditions chlorite looses iron and converts into clay minerals of which is montmorillonite the most frequent.

13.3. SERPENTINE $Mg_3Si_2O_5(OH)_4$

Serpentine belongs to the group of clay minerals lack of aluminum. Compositionally they represent hydrous magnesium silicates. Small amounts of Fe, Cr and Ni are commonly present. Their name is after the Latin word *serpent* meaning snake.

The most important minerals are **lizardite**, **antigorite** and **chrysotile**.

Antigorite crystallizes monoclinic, may be hexagonal and orthorhombic, whereas lizardite and chrysotile are exclusively monoclinic.

Lizardite is the most frequent and the most abundant mineral in the serpentine group (fig. 318). It occurs in compact masses or flakes that are visible only under the electron microscope. It is green in color. In this mineral Al^{3+}, sometimes and Fe^{3+} may replace Mg and Si.

Fig. 318. Crystals of lizardite (left), and lizardite in vein (right).

Antigorite may be found in characteristic platy aggregates or compact masses (fig. 319). Its color depends on content of iron and varies from green and yellowish-green, to brownish and grey, even grayish-brown.

Fig. 319. Antigorite (left), and antigorite in vein (right).

Chrysotile appears in fibrous aggregates and is commonly identified as chrysotile-asbestos (fig. 320). Fibers are of silky lustre and yellowish-green to gold iridescence. It commonly occurs in veins that cut a host rock.

Density of these minerals is about 2.6 g/cm^3, and their hardness varies from 2.5 to 3.

Fig. 320. Chrysotile-asbestos (left) and chrysotile-asbestos in vein (right).

The mentioned serpentine minerals are autometamorphic minerals and form under action of vapor phase or hot water solutions on olivine and orthorhombic pyroxene, which are the essential constituents in ultrabasic rock, peridotite (fig. 321). During serpentinization of olivine a part of Mg and Fe **migrate,** and silica **being contributed**. The serpentinization of orthorhombic pyroxene **involves** Mg and Fe and **loose** silica. All mentioned processes take part inside the rock itself. Weathering of olivine in the presence of CO_2, which originated mostly from atmospheric water, the magnesite may be formed.

Antigorite is the only serpentine mineral that may form in regional metamorphism.

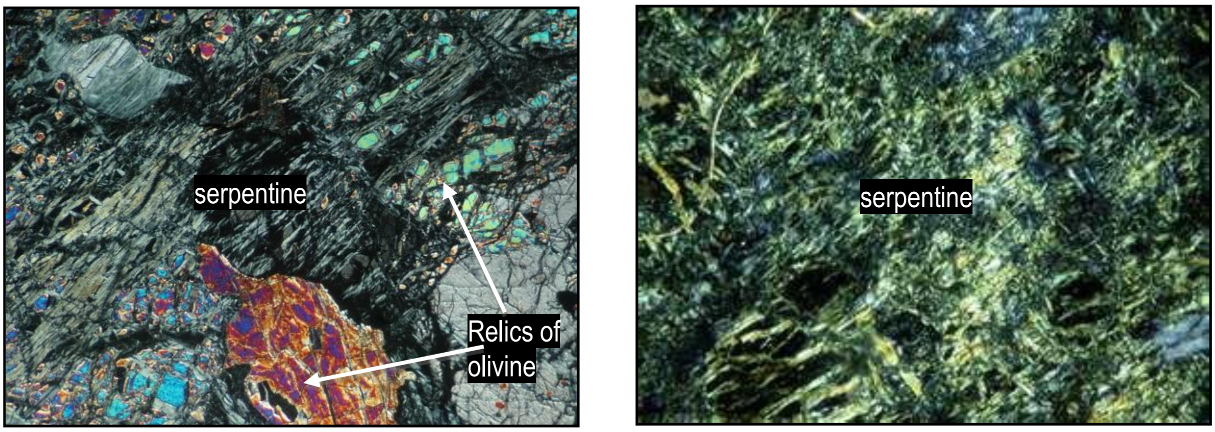

Fig. 321. Microphotograph of serpentinized olivine, XPL (left),and serpentine in the mass of peridotite, XPL (right). Magnification 100×.

Majority of ultrabasic rocks, peridotite is partly to completely serpentinized as they arrived at the surface from the great depth of the upper mantle and beside a strong tectonic activity undergone fracturing, crushing and foliating (fig. 322).

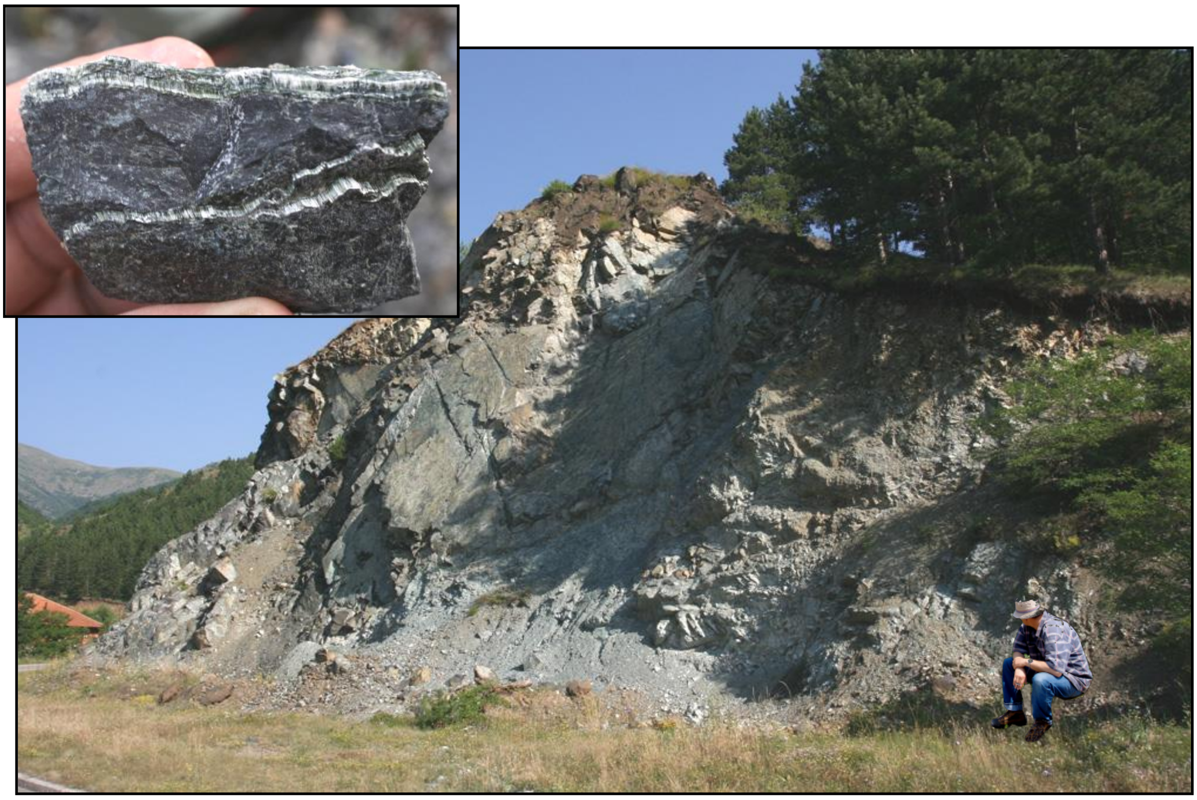

Fig. 322. Serpentinized peridotite at Kopaonik. Above left, the sample of rock with vein of asbestos.

Chrysotile asbestos finds its application as isolator, a raw for production of fire-resistant materials. Distinct antigorite species may be used as a facing stone, rarely as a gemstone.

13.4. **TALC** $Mg_6(Si_8O_{20})(OH)_4$

Talc is hydrous magnesium silicate. Small amounts of iron, aluminum, manganese, calcium and nickel is usually present.

It crystallizes monoclinic and occurs in platy or massive aggregates. Laths are of pearly-silky to resinous lustre, of perfect cleavage and flexible or weakly elastic. Dense masses of it are known as steatite.

Color is whitish-gray to white, rarely light green to yellow (fig. 323). It has greasy touch and is one of the softest mineral in a nature, having hardness 1. Specific gravity is 2.7 to 2.8 g/cm^3.

Fig. 323. Talc in vein (left) and in the rock mass (right).

In polarizing microscope is talc micaceous with high interference colors, low relief and without pleochroism (fig. 324). In thin section resembles muscovite.

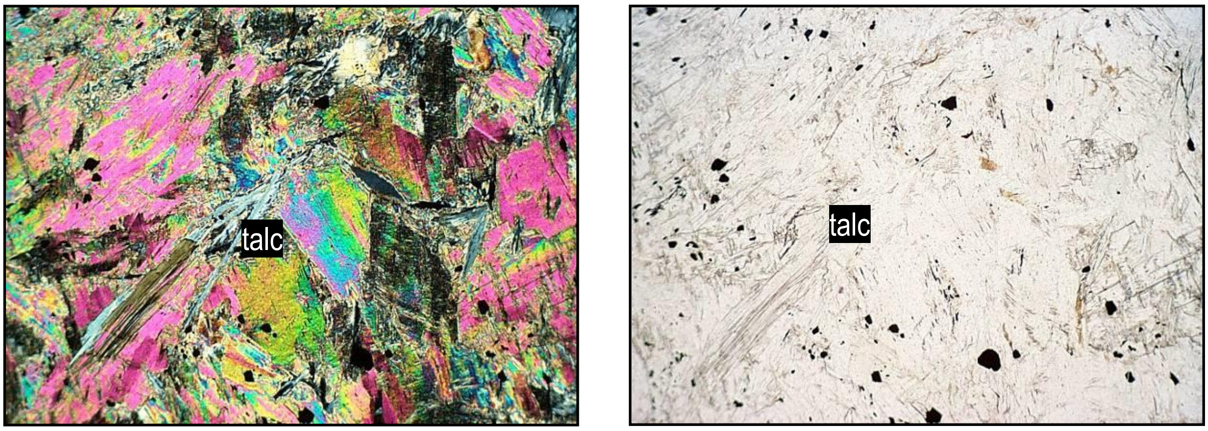

Fig. 324. Microphotograph of talc, XPL (left) and in PPL (right). Magnification 100×.

Talc formed after alteration of olivine and other Mg silicates aluminum lack, hence accompanies serpentines (fig. 325).

Secondary talc in altered ultrabasic rocks (peridotites) derives usually after an olivine undergone serpentinization. In the presence of carbon dioxide (CO_2) during serpentinization a magnesite, common accompanied with talc, would form, also.

Fig. 325. Serpentinized peridotites on Maljen contain talc. Above right, a detail of rock with talc vein.

Talc forms during the moderate to high metamorphism grade through reaction of dolomite and quartz, or chlorite and quartz resulting in new mineral assemblage: talc, kyanite, garnet, chloritoid.

It builds its „own"metamorphic rock, talc schist.

Talc finds big application in paper production, cosmetics and medicine for powder, as mineral filler in tooth paste, for flame-resistant materials.

13.5. PYROPHILLITE $Al_4(Si_8O_{20})(OH)_4$

Pyrophillite is hydrous aluminum silicate. Common impurities are Fe, Mg, Ca, K and Na. It crystallizes monoclinic, occurs in micaceous to fan-shaped aggregates or in cryptocrystalline, firn masses (fig. 326). Laths are flexible but not elastic.

It is white or whitish-grey colored, may be light green or grayish-green. Its cleavage is perfect, lustre pearly to resinous. Specific gravity is 2.60 to 2.80 g/cm^3, hardness 1 to 1.5, greasy touch. Pyrophillite separates on distinct fan-shaped sheets when heated

Fig. 326. Radiating crystals of pyrophillite (left), and pyrophillite in a rock mass (right).

In polarizing microscope (fig. 327) pyrophillite resembles muscovite in its optical properties. It occurs in laths that often build monomineral accumulations, spurs or radiating and fan-shaped "nests". With crossed nicols displays the third order colors and is with low relief and without pleochroism with parallel nicols.

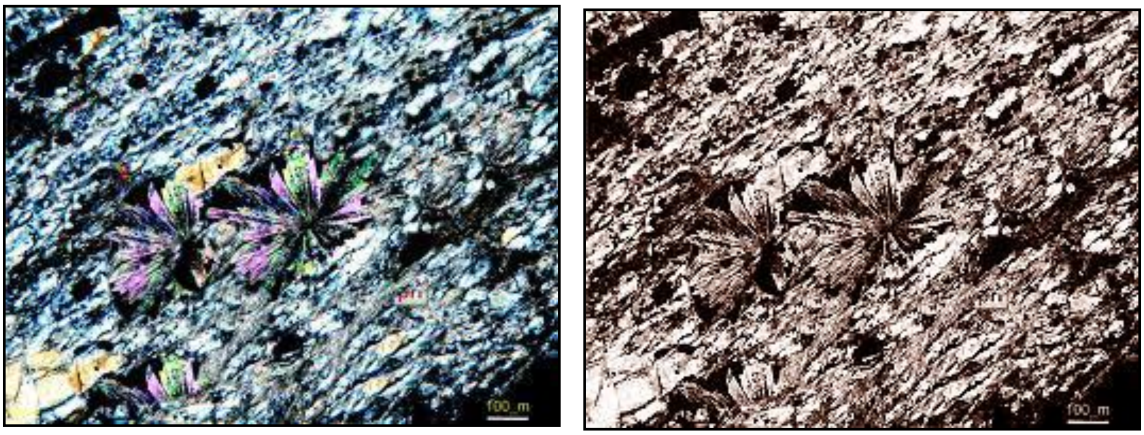

Fig. 327. Pyrophillite in a rock mass (left), XPL, and the same mineral with PPL (right). Magnification 200×.

It forms under the action of hydrothermal fluids on feldspars when kaolinite and other hydrated aluminum silicates accompanied to it.

Pyrophillite is metamorphic mineral, too. It forms during the low to medium metamorphic grade from clay minerals that lost a part of water (fig. 328).

When pyrophillite interacts with calcite and dolomite, during the low metamorphism, margarite, chloritoid and chlorite derives.

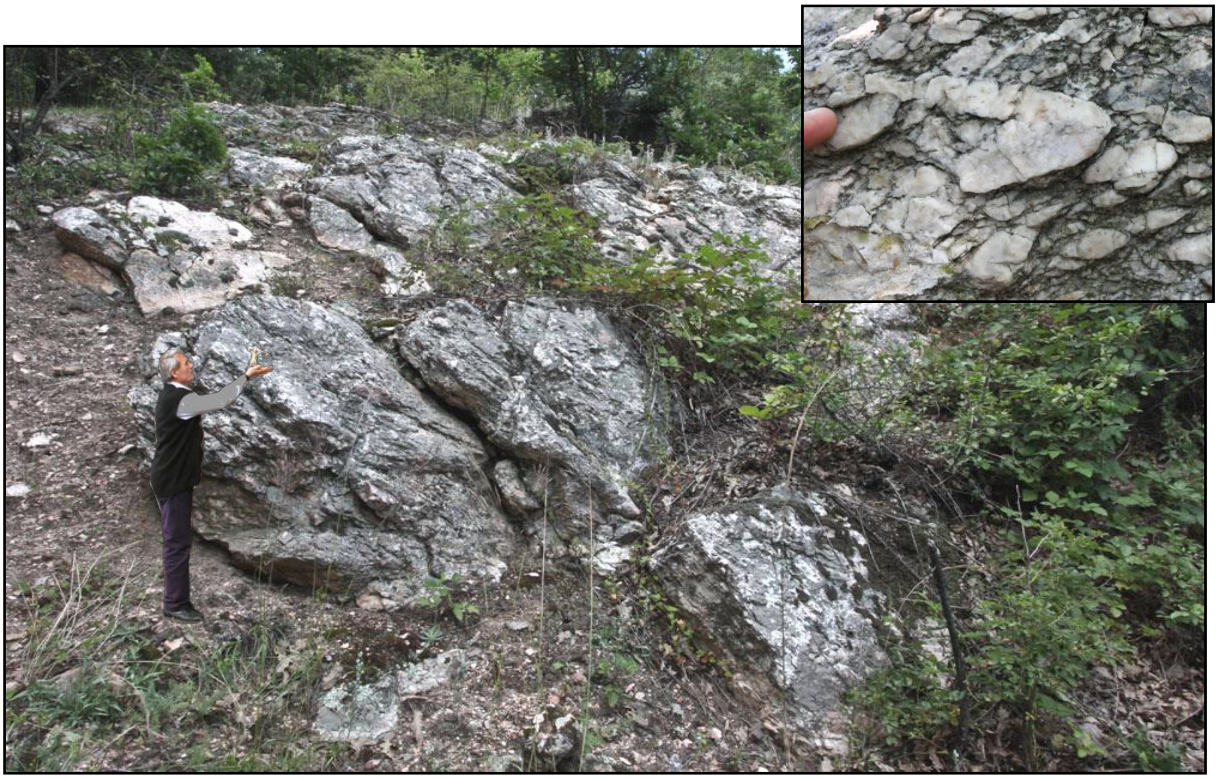

Fig. 328. In quartzite (quartz meta-conglomerates) near Kučevo pyrophillite occurs in recrystallized bonding material and is occasionally associated with chloritoid. Above right, a detail of rock.

Kyanite, andalusite, and accompanied calcite, dolomite and garnet form in rocks (systems) with pyrophillite as the dominant constituent at the higher metamorphic grades (temperatures above 550 to 600 °C and pressures exceeding 5 Kb).

13.6. CLAY MINERALS

Minerals of the clay group are the most abundant in sedimentary rocks, weathering crust and soil. Compositionally, they are hydrous aluminum silicates with negligible difference from the composition considered as the ideal. The most important rock-making clay minerals are kaolinite, motnmorillonite and illite.

13.6.1. KAOLINITE $Al_4(Si_4O_{10})(OH)_8$

Kaolinite is hydrated aluminum silicate. Ions of Si and Al do not substitute each other in the crystal lattice yet are building their own alternating tetrahedral and octahedral sheets. Dense ion packing in the crystal lattice disables the entrance of water and other substances; hence kaolinite does not change its volume, i.e. does not swell and does not have ion-exchange capacity. This group includes dickite, nacrite and halloysite.

Kaolinite crystallizes triclinic. It appears in very thin lathlike or platy aggregates, which are apparent only under the electron microscope (fig. 329). This mineral naturally composes earthy masses, clays. Dry kaolinite could be easily crushed with fingers into very fine-grained powder, which becomes plastic with water. Specific gravity is 2.6 g/cm^3, hardness 1 to 2.

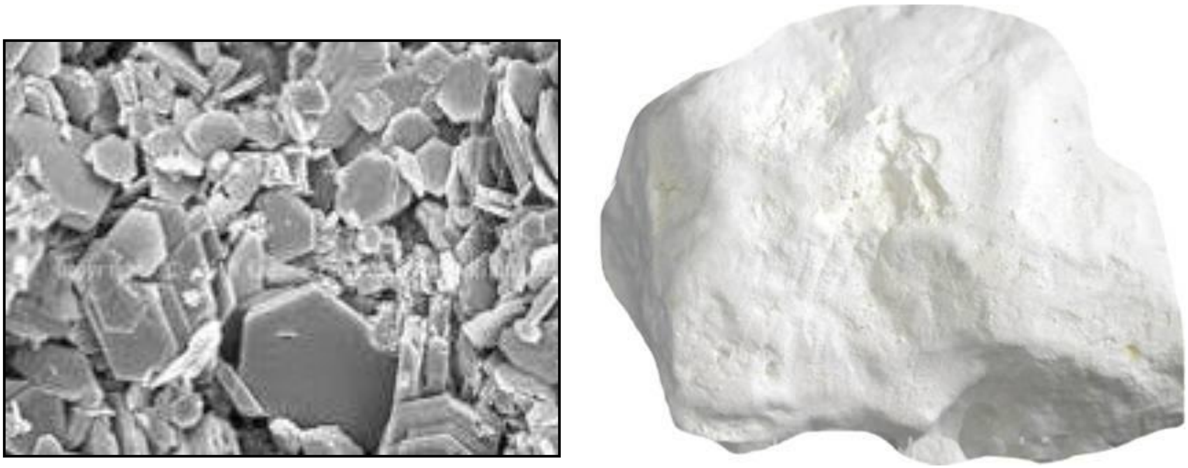

Fig. 329. Kaolinite under the electron microscope (left), and kaolinite in a rock mass (right).

Pure kaolinite is **porcelain white.** The presence of impurities, such as iron, bauxite and organic matter, colors it grey, yellow and brown.

Kaolinite forms by weathering of feldspars, feldspatoids and micas, which are the essential minerals in many igneous (granite, quartzmonzonite, granodiorite) and metamorphic rocks (gneisses). This happens under the influence of hydrothermal solutions or atmospheric agents.

It occurs in hydrothermally altered rocks that bear mineralization of copper and gold, less frequent in those carrying lead and zinc (fig. 330).

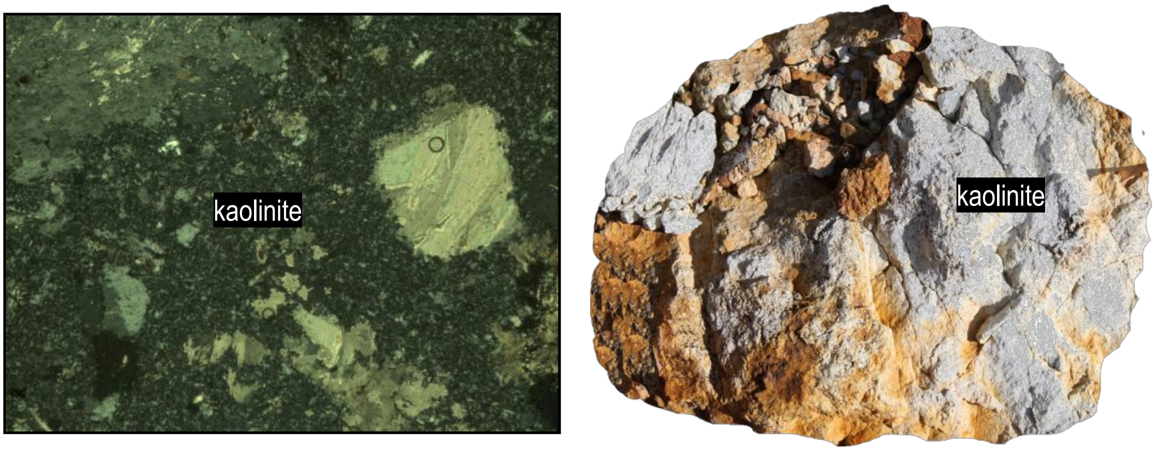

Fig. 330. Accumulations of kaolinite in hydrothermally altered andesite (left), XPL, magnification 100×, and the sample of a given rock (right).

The largest masses of kaolinite develop sedimentary, under the wet climate conditions in acid environment from the oxygen-rich solutions and of low sodium, magnesium and ferrous-iron contents (fig. 331). Oxidation environment supports the kaolinite formation.

Deposits formed by superficial weathering of acid igneous rocks, mostly granite, are particularly important.

Fig. 331. Kaolinite deposit near Aranđelovac.

When wet, kaolinite builds plastic masses. It is important raw material for ceramics, and paper industry.

13.6.2. MONTMORILLONITE $(Al_{2-y}Mg)Al_xSi_{4-x}O_{10}(OH)_2X^+_{x+y} \times nH_2O$.

X^+ is interlayered cations, x and y are tetrahedral and octahedral exchanges.

Montmorillonite is chemically hydrous silicate of magnesium, and is structurally a member of the dioctahedral smectite clays. A part of Al ions (almost a half) may be substituted by Mg and/or Fe^{3+}.

Montmorillonite is structurally different from kaolinite. Two layers in its crystal lattice are of SiO_4 groups with a layer of Al, Mg and Fe ions sandwiched between. Fe, Mg, Na, or organic cations are placed between these two layers as well as weakly bonded water molecules, which may be loose by heating at 100-200 °C without disturbing structure, and may be received again. The ability to expand or reduce a space with water molecules enables montmorillonite to swell and increase its volume up to three times.

It crystallizes monoclinic. Commonly occurs in earthy to clayey aggregates, rarely in crystals that are visible only under the electron microscope (fig. 332).

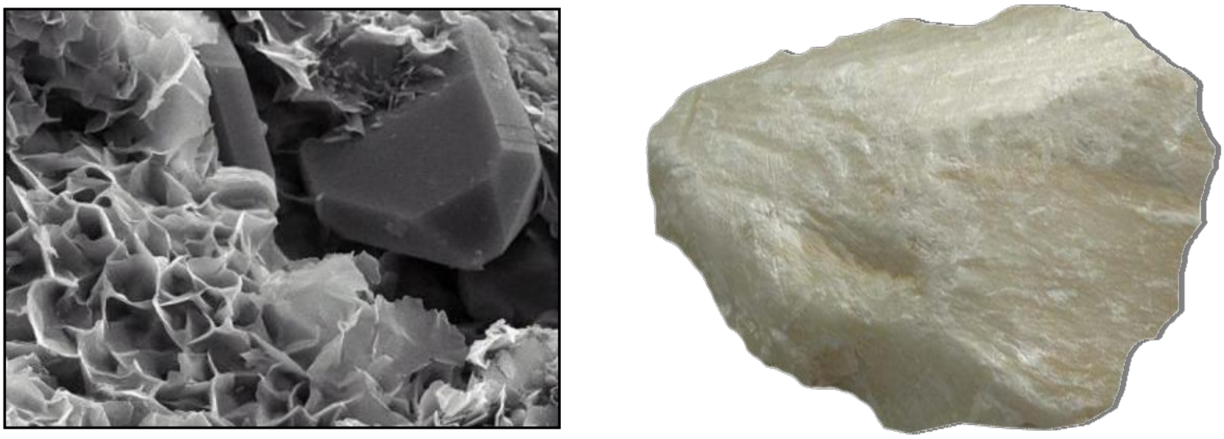

Fig. 332. Montmorillonite crystals under the electron microscope (left) and montmorillonite in a rock mass (right).

Pure montmorillonite is porcelain white or grayish-white in color. The presence of chromium and nickel, colors it bluish-green or green. Specific gravity is variable, from 2.0 to 2.8 g/cm^3, hardness from 1 to 2. Touch is greasy, swells in contact with water increasing its volume for a few times.

Montmorillonite derives from basic, neutral, rarely weakly acidic solutions rich in magnesium, and with more abundant silica than aluminum. It develops in deeper parts of weathering crust, particularly from magnesium and calcium rich rocks, i.e. from andesitic and basic tuffs.

This mineral is the chief constituent of bentonite (fig. 333).

Montmorillonite is used in deep drilling fluids, as filler in iron and steel foundries, absorbent material, for pesticides.

Fig. 333. Bentonite occurs in hanging-wall layers of coal in Vrdnik.

13.6.3. ILLITE $K_{1.5-1}Al_4(Si_{6.5-7}Al_{1.5-1}O_{20})(OH)_4$

Illite has structure similar to micas, but is chemically closer to clays. It is often called hydromica or hydromuscovite. It was named after the American state Illinois where it has been discovered and analyzed many times.

According to chemistry illite refers to the group of hydromicas. It contains less K in respect to muscovite. Although it has been analyzed for many times and widely studied, it remains unclear.

Crystallizes monoclinic and occurs in thinly lath aggregates.

Color is white to grayish-white, or yellow, brown from impurities of iron oxides (fig. 334). Cleavage is perfect. Specific gravity is 2.6 to 2.9 g/cm^3, hardness 1 to 2.

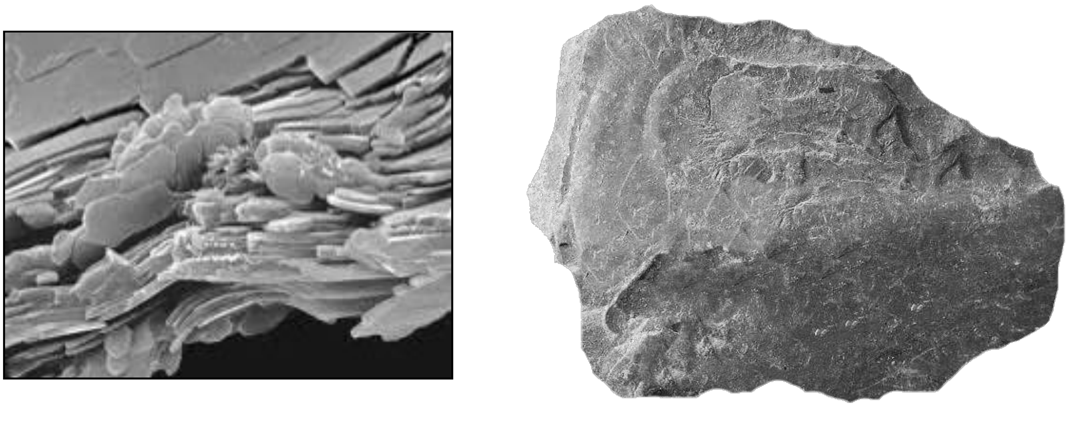

Fig. 334. Illite crystals under the electron microscope (left) and illite in a rock mass (right).

Contrary of montmorillonite, illite does not absorb water and does not swell.

The largest masses of it form during diagenesis or metamorphic processes by involving potassium in crystal lattice of kaolinite. Those conditions mostly considered to the boundary of sedimentary processes and metamorphism (temperature from 150 to 200 °C and pressures of 1 Kb) until the beginning of the greenschist facies (temperature from 400 °C and pressures of about 3 Kb) when illite recrystallizes into sericite, or into chlorite if contains magnesium.

Illite may be authigenous mineral, when it precipitates from moderately basic, potassium rich solutions. It also forms by leaching of potassium from feldspars (fig. 335). It is common in hydrothermally altered rocks where is associated with kaolinite and sericite.

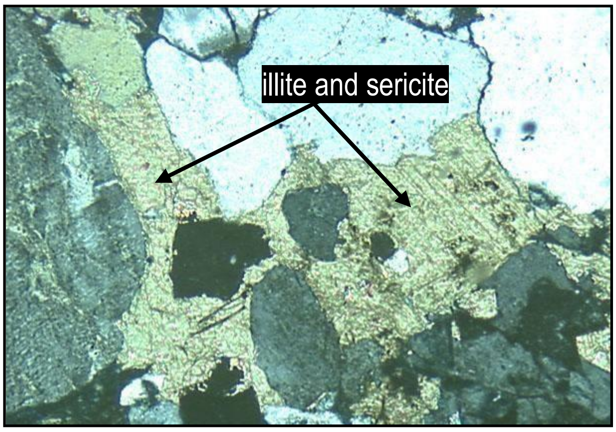

Fig.335. Microphotograph of illite and sericite replacing (altering) orthoclase in granite. XPL, magnification 100×.

Some authors believe that illite forms by capturing of K ions in smectite. Illite is the dominant mineral in recent clayey sediments (fig. 336).

Fig. 336. Illite is the dominant mineral in deposits of clay and is exploited as raw material for bricks.

13.6.4 GLAUCONITE $(K,Ca,Na)_{\sim 1.6}(Fe^{3+},Al,Mg,Fe^{2+})_{4.0}Si_{7.3}Al_{0.7}O_{20}(OH)_4$

According to new classification the glauconite represents the series of iron-rich clay minerals.

It occurs in granular aggregates, which derive by glauconitization, a chemical exchange or precipitation in solutions with microfossil remains, pelet, bioclast and rock or mineral fragments. Glauconite grains are yellowish-green green, dark green to bluish-green (fig. 337).

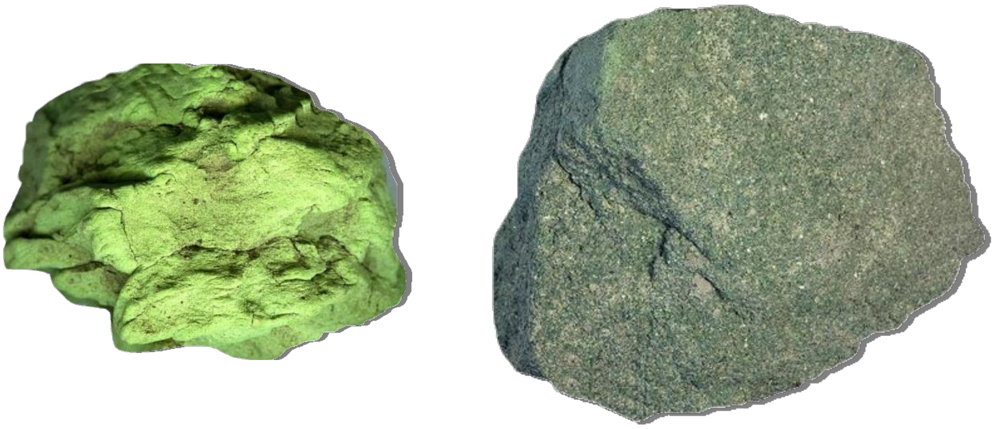

Fig. 337. Glauconite, monomineral aggregates (left), and glauconite in a rock mass (right).

Glauconite is a shallow-marine mineral. It is found in limestones, sandstones, siltstones as nodules in the groundmass. Its presence reveals the rock names: glauconite limestone, sandstones, and siltstones. It requires reduction conditions and a presence of organic matter, probably.

Glauconite occurs as impregnation or thin coating on carbonate clasts, or covers (coats) surfaces of carbonate rocks. Its appearance in nodules, oval grains up to a few millimeters in size suggests on its origin from shallow water environments.

It occasionally accompanies pyrite, reflecting on its origin from reduction conditions.

In polarizing microscope, with parallel nicols is glauconite easy recognizable due to its characteristic green to greenish-blue pleochroism (fig. 338).

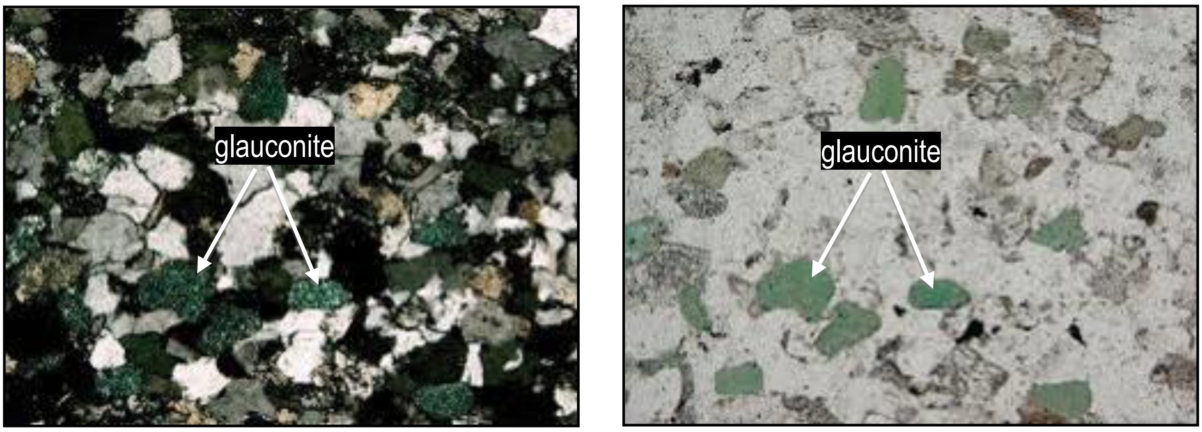

Fig. 338. Microphotograph of glauconite in a sandstone, XPL (left) and the same mineral with PPL (right). Magnification 100×.

Glauconite also occurs in detrital, clastic sediments as a clast inside a bonding material of rock (fig. 339).

Fig. 339. Glauconite is found in the sandstones near Novi Pazar

13.7. CELADONITE $KFe^{3+}(Mg,Fe^{2+})Si_4O_{10}(OH)_2$

Its name develops from the French word *seladon,* meaning light green. This mineral occurs in minute crystals or as fine-grained aggregates, of green or bluish-green color (fig. 340). It is most frequently found in amygdales, cavities or voids in volcanic rocks where has been formed under transformation of colored minerals. Crystallizes monoclinic, has hardness 1 to 2, specific gravity from 2.5 to 3 g/cm^3. Discussions regarding its composition, structure and origin, as well as for glauconite, are common.

Fig. 340. Crystals of celadonite (left), and celadonite in amygdale, void in trachyte (right).

In polarizing microscope, with parallel nicols, displays characteristic green to greenish-blue color (fig. 341).

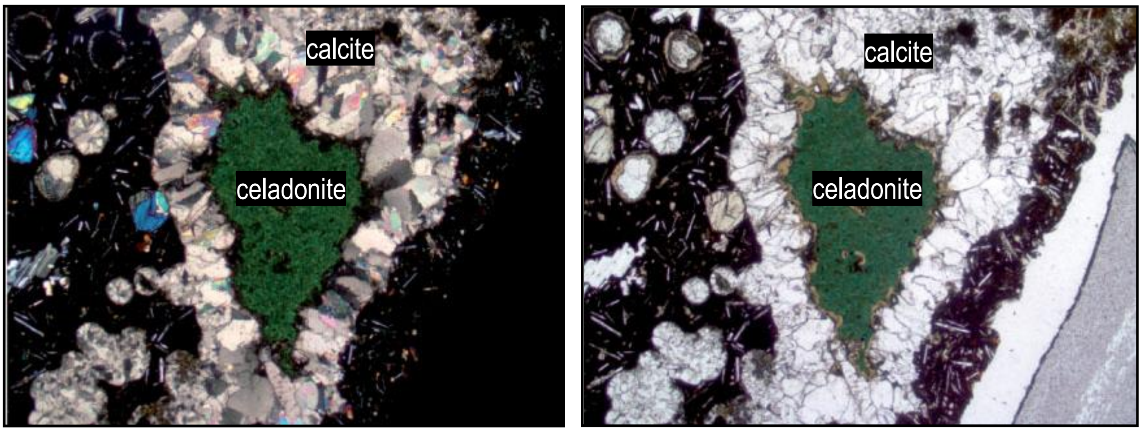

Fig. 341. Microphotograph of celadonite in amygdale, XPL (left), and the same image with PPL (right). Magnification 40×.

14. TECTOSILICATES

Tectosilicates are very widespread rock-forming minerals and most of them represent the essential minerals of rock. Tectosilicates are a "three-dimensional framework" with all corners in tetrahedra (oxygen atoms) being shared with the adjacent tetrahedra. A part of silica in tetrahedra, up to a half of it, in the crystal lattice may be replaced by aluminum and the resulting negative charge is going to be compensated by cations: K, Na, Ca, Ba. Water (OH or H_2O) also enters into the crystal structure of tectosilicates and is important constituent of minerals from the zeolite group. Presence of F, SO_4 and CO_2 is also possible. This group includes SiO_2 minerals, feldspars, feldspatoids and zeolites.

14.1. SiO_2 MINERALS

SiO_2 minerals, depending on the temperature of crystallization, occur naturally in several crystal modifications. In the sense of petrology, cristobalite, tridymite, alpha and beta quartz are of particular importance.

14.1.1. CRISTOBALITE

Cristobalite crystallizes at the highest temperature (1713 °C) and converts as it cools into tridymite (~ 1470 °C). It is extremely rare mineral in the nature. It crystallizes tetragonal, commonly in octahedral or hexahedral forms, although a spherical masses and skeletal crystals are more commonly observed (fig. 342). Under the polarizing microscope is very similar to quartz.

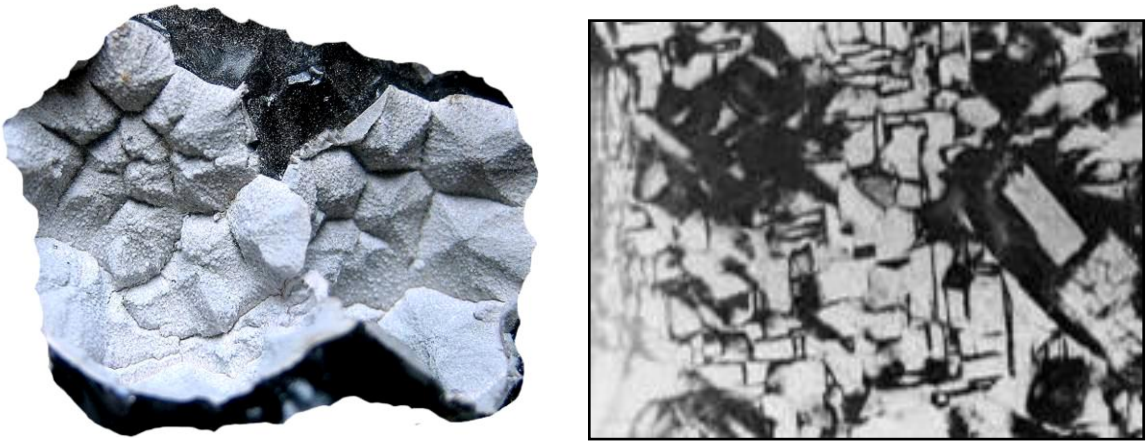

Fig. 342. Crystals of cristobalite in obsidian (volcanic glass) (left), and the same mineral in polarizing microscope (right); parallel nicols, magnification 1000×.

Luster is vitreous and the commonest color is milky white. Cristobalite is often transparent and without cleavage. Specific gravity is 2.32 g/cm^3, hardness 6.5 do 7. It occurs in cavities inside volcanic rocks where derived from high-temperature gasses. In artificial products, ceramics and glass, is also present. Converts into tridymite when cools.

14.1.2. TRIDYMITE

Tridymite crystallizes hexagonal and appears in crystals in combinations of base and prism (fig. 343). It forms, similar as cristobalite, from volcanic gasses inside cavities in porous volcanic rocks or in fragments of rock that have been enclosed by lava, throughout transformation of SiO_2 minerals at high temperatures (1470 °C).

The stability field of cristobalite and tridymite decreases along with the pressure and water content in magma with the depth, though these minerals could not be formed at depths exceeding 15 kilometers.

Fig. 343. Crystals of tridymite (left), and tridymite in cavity (right).

When temperature decreases to 870 °C, it converts to α-quartz.

14.1.3 α-QUARTZ

α-quartz is a high-temperature quartz, which is stable above 573 °C. It crystallizes hexagonal, commonly in combinations of bipyramids and weakly developed prism (fig. 344).

It is igneous, pegmatitic (related for acid igneous rocks, granite) and contact metamorphic mineral. In the last case it usually occurs next to the contact. During regional metamorphism occurs rarely if the temperature exceeds stability of beta quartz.

Physical properties are like of already mentioned SiO_2 minerals.

At temperatures below 573 °C α-quartz should instantly inverse to β quartz, naturally the commonest one.

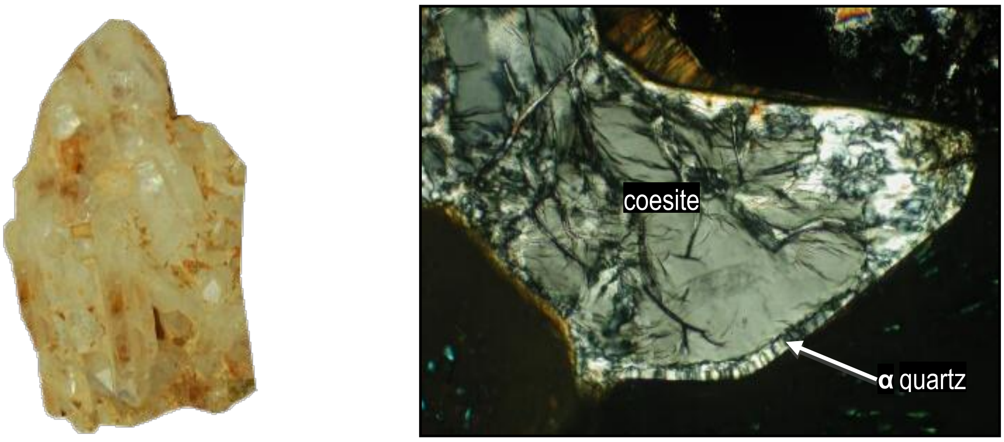

Fig. 344. Crystals of α-quartz (left), and microphotograph of coesite partly replaced by alpha quartz (right), XPL, magnification 200×.

Rapid cooling of melt may support silica (SiO_2) to „skip" over the point of conversion and to occur as high-temperature modification, which temporally should order a crystal lattice and converts into the stable, low-temperature modifications.

14.1.4. QUARTZ (β-QUARTZ)

β-quartz or simply, quartz, as used to be called often, is chemically the silica-dioxide (SiO_2). It is very important petrogenic mineral and the most commonly found in a nature worldwide.

Crystallizes hexagonal and does not have cleavage. Its fracture is uneven. It is commonly found in prismatic crystals, either as individual or in clusters. Granular and massive aggregates are also common.

Lustre is vitreous at faces and resinous on broken surfaces. It is a brittle mineral with hardness of 7 at the Mohs scale and with specific gravity 2.6 to 2.7 g/cm^3. It is very sensitive on pressures.

Gas inclusions, CO_2 and H_2O, are very common, as well as a quartz crystals infiltrated by minerals such as rutile, $CaCO_3$, actinolite or distinct ions and atoms that are distributed in interspaces within the crystal lattice. Twinned crystals are common.

Quartz is igneous, sedimentary, metamorphic and hydrothermally-derived mineral. It is a constituent of numerous rocks.

The most beautiful quartz crystals are found in hydrothermal veins, where it can take a variety of colors: yellow **citrine,** violet **amethyst**, black **morion, c**olorless and transparent **rock crystal** (fig. 345). Quartz pseudomorphs after other minerals are common.

Fig. 345. Quartz varieties: rock crystal (above left), smoky quartz (above in the middle), amethyst (above right), rose quartz (down left) and citrine (down right).

Under the polarizing microscope is quartz grey, with low relief and colorless with parallel nicols (fig. 346). It is the essential mineral of acid igneous rocks: granite, quartzmonzonite, granodiorite (fig. 347) and quartzdiorite. In these rocks it appears in grains approximately a few millimeters in size. Aplite and pegmatite also contains quartz as a chief mineral.

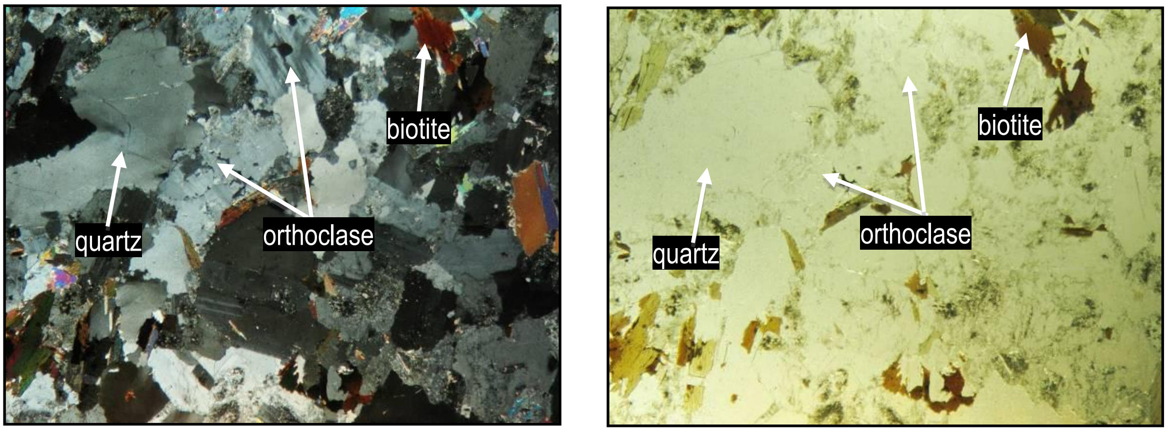

Fig. 346. Microphotograph of quartz grains in granite, grey (left), XPL, the same sample with PPL (right). Magnification 100×.

Fig. 347. Quartz is the essential mineral in granodiorites of Surdulica. Above right is the detail of this rock.

This mineral occurs as the phenocrysts in volcanic rocks of acid chemistry: rhyolite, quartz keratophyre, quartzlatite and dacite (fig. 348 and fig. 349). The morphology of quartz crystals reflects on its derivation whether below or above 573 °C and it could be noted within some volcanic rocks. Quartz, as has been mentioned already, converts into more stable modification temporally. In intrusive igneous rocks is present only the β-quartz.

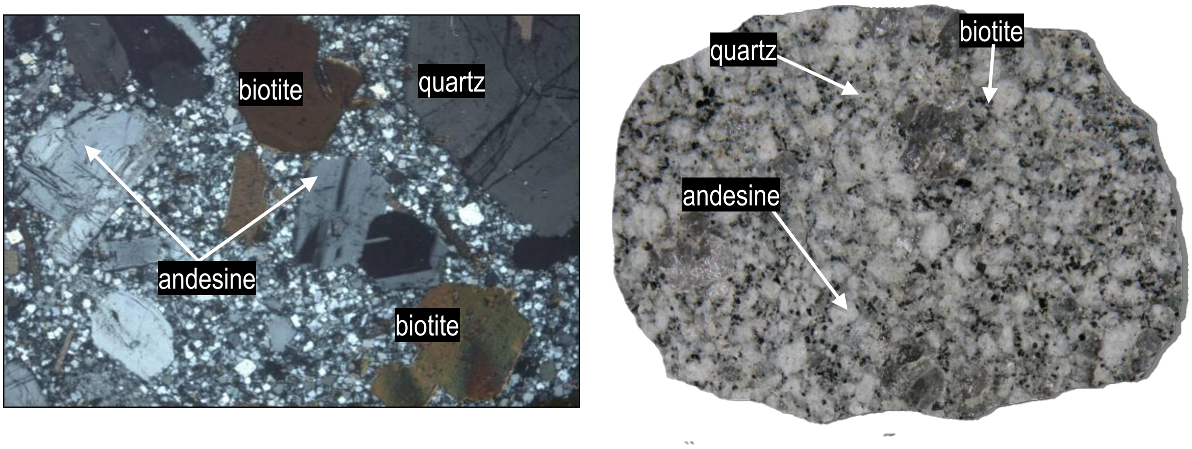

Fig. 348. Phenocrysts of quartz, biotite, and andesine in dacite (left), microphotograph, XPL, magnification 60× , and the sample of dacite (right).

Fig. 349. Dacites of Ljubovija contain phenocrysts of quartz, above right is the detail of a rock.

In metamorphic rocks quartz forms by recrystallization of previously existed SiO_2 minerals or creates quite new minerals. It is one of the essential minerals in micaschist, gneiss and quartzite (rock composed exclusively of quartz). It commonly occurs in granular aggregates. Quartz is very sensitive to pressure when its crystal lattice deforms resembling undulatory extinction in the polarizing microscope (fig. 350 and fig. 351).

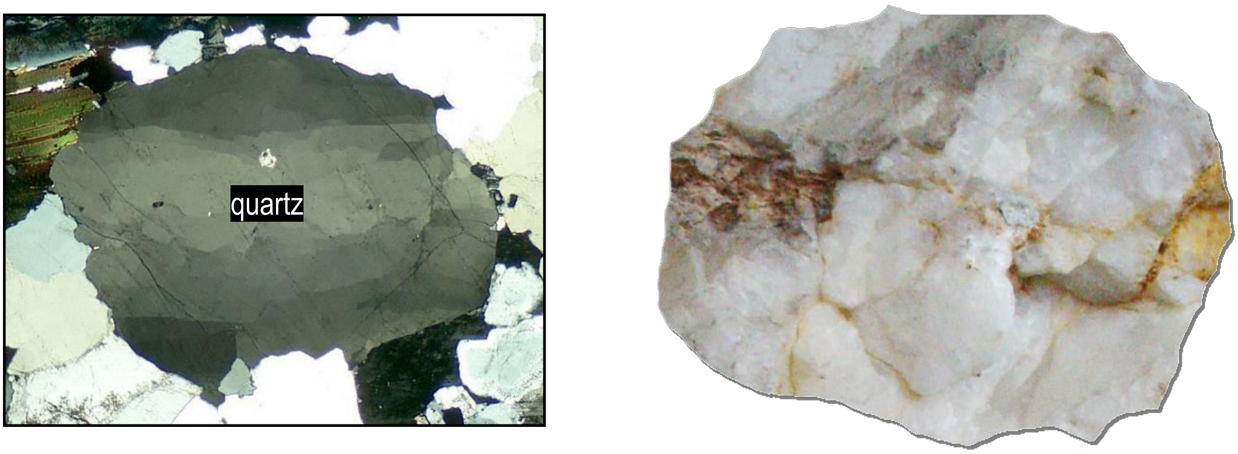

Fig. 350. Microphotograph of quartz in quartzite (left), XPL, magnification 80 x, the sample of quartzite (right).

Fig. 351. Interlayer of quartzite (white) in the Drina Paleozoic near Užice

Quartz is resistant on physical-chemical weathering, hence is very common in sand (fig. 352) and sandstone, usually as the main constituent. It occurs in grains up to 2 mm in size, which depending on the length and way of transport, deserve various roundness grade. The best rounded are those in alluvial and marine environments, the least rounded are in deserts where they have been formed by aeolian erosion (fig. 353).

Fig. 352. Quartz in alluvial sand, above right is the detail of sand.

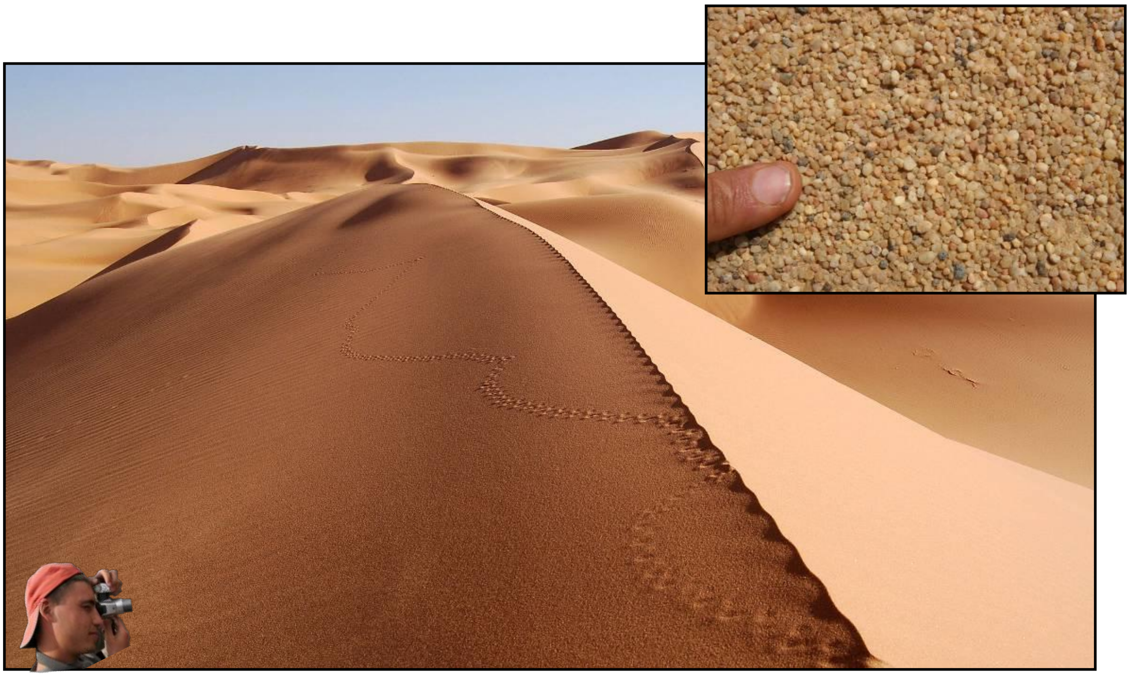

Fig. 353. Sand in Sahara mainly consists of quartz grains.

When quartz in sand exceeds 95 % in abundance it becomes a raw material for glass (fig. 354). Harmful ingredients in quartz sand, assigned for glass, are limonite and minerals of clay.

Fig. 354. Quartz sand in Čučuge close to Ub is a raw material for glass industry. Down left are crystal glasses, made of quartz.

Quartz is commonly the chief constituent of sandstone (fig. 355), a sedimentary rock representing lithified sand. Optical and morphological properties of quartz reflect on conditions during the rock has being formed: angular quartz grains reflect a short transport; undulatory extinction suggests a metamorphic rock as a source; well-sorted and rounded grains were transported on far distances; those bounded by limonite-clayey substance receive red color (fig. 356).

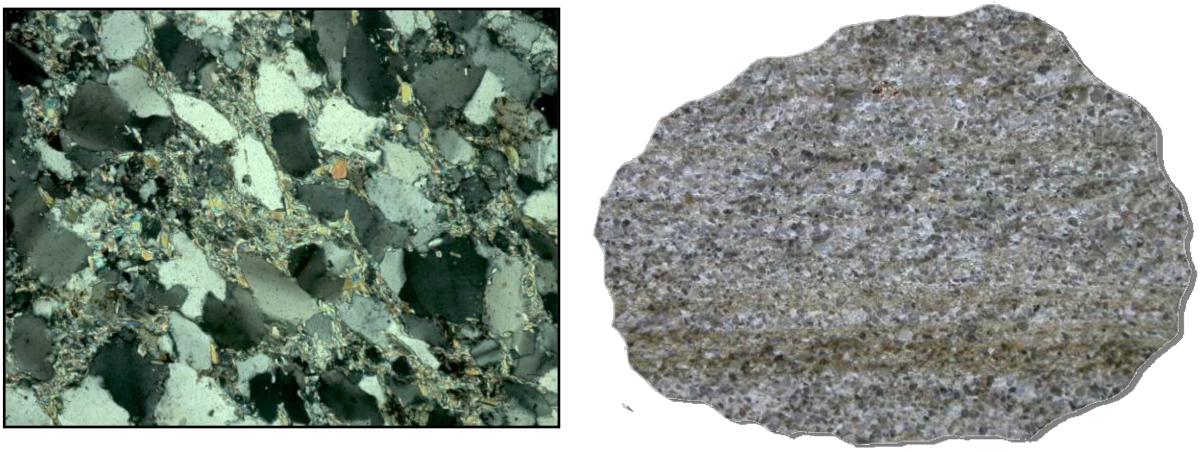

Fig. 355. Microphotograph of quartz in sandstone, grey-colored grains, XPL, magnification 30× (left), quartz in the sample (also grey-colored) of quartz sandstone (right).

Fig. 356. Permian sandstone with quartz and clayey –limonite bounds,Čestobrodica, above right is a detail of rock.

The most beautiful quartz crystals, as has been noted, develop from hydrothermal solution when this mineral accompanies to iron, zinc, lead and copper sulphides as well as to carbonates forming amazing crystal druses (fig. 357). It is worthy to note that quartz crystals originated from hydrothermal solution may exceed 1 m in size.

Fig. 357. Quartz druses (white), rhodochrosite (pink) and pyrite (brown, yellow with metallic lustre) derived from hydrothermal solution.

Chalcedony is cryptocrystalline (fine-grained) aggregate of quartz, which forms at low temperatures, below 150 °C. Radiating aggregates, which compose irregular masses, concretions, lenses or interlayers in rocks, are common (fig. 358).

Fig. 358. Chalcedony species (left), and microphotograph of chalcedony (right). XPL, magnification 100×.

This mineral is a transitional form in recrystallization of amorphous colloid SiO_2 into quartz. Physical properties of chalcedony are like of quartz. It forms from low-temperature hydrothermal solutions. It common appears in differently colored bands and is called **agate** (fig. 359), which is used as a semi-precious stone.

Fig. 359. Agate with recrystallized quartz in mid-parts.

Opal is amorphous and is compositionally $SiO_2 \times nH_2O$. The amount of water varies between 3 and 20 %. Common impurities give rise to a brilliant play of colors: yellow, green, blue, reddish and mottled (fig. 360). Idiochromatic is colorless or milky white. Hardness is from 5.5 to 6.5, specific gravity varies with the content of water and impurities from 2.4 to 2.5 g/cm^3. Fracture is conchoidal, and is brittle. Lustre is glassy, greasy and resinous at broken surfaces. Opal appears commonly in compact masses, kidney-shaped, grape-like, and coatings.

Opal forms by precipitation of hydrothermal solution, mostly at low temperatures of about 100 °C.

Fig. 360. Opal in the sample mass.

Opal may form during disintegration of basic and ultrabasic rocks in the process of serpentinization, i.e. listvenitization (fig. 361). In these processes a mineralization of copper, gold, antimony, and mercury commonly takes part. Opal precipitates around geysers or along edges of hot acid springs. Such variety is named geyserite. Remains of siliceous alga, such as diatoms and radiolarians, as well as some silica sponges, also may produce opal. This kind of opal is common constituent in cherts.

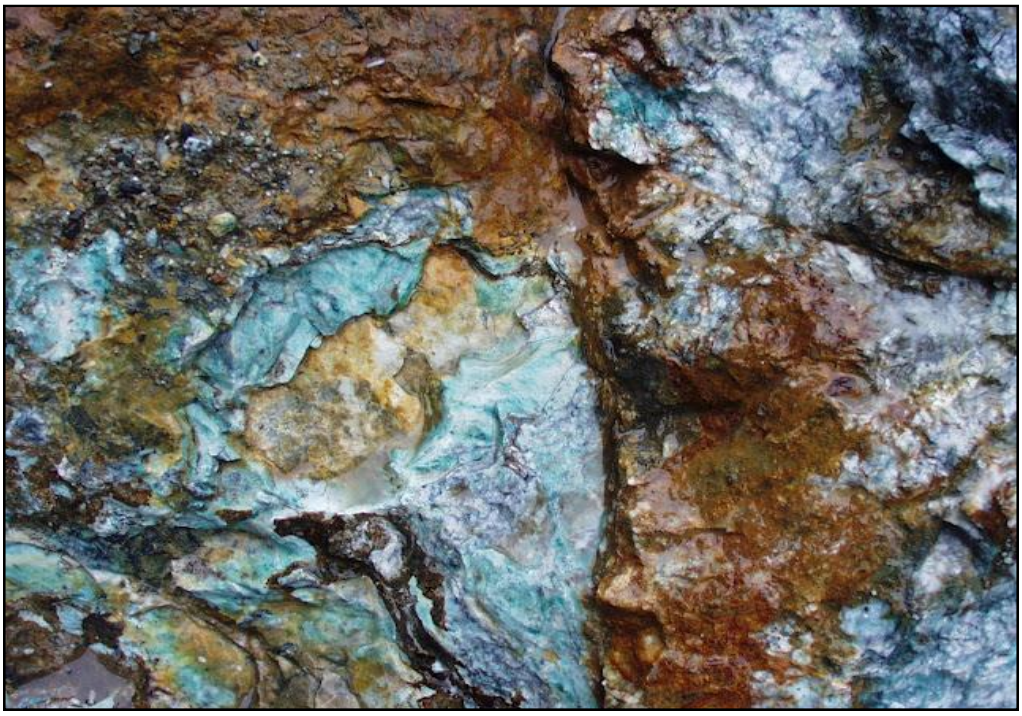

Fig. 361. A part of the listvenite outcrop (Kopaonik), 2 m wide and approximately 1 m in long, with accumulations of opal and antimony and mercury mineralization.

There are few varieties of this mineral: variety of flashing colors and glassy lustre is **precious opal,** which is semi-precious stone, type of **opal,** which is petrified silicified wood, etc. (fig. 362).

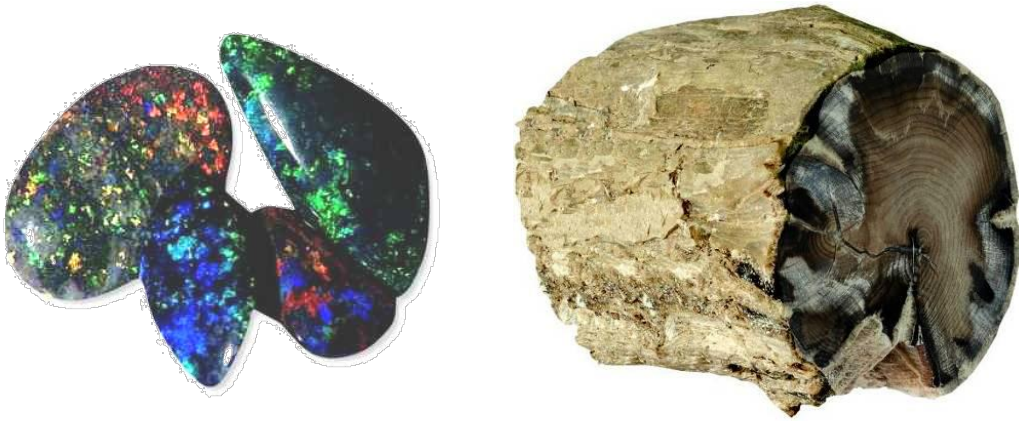

Fig. 362. Agate as a semi-precious stone (left), and silicified wood about 30 cm in diameter (right).

Opal and chalcedony are important minerals of cherts, sedimentary rocks related to deep marine environments (fig. 363).

Fig. 363. An outcrop of chert close to the Monastery Mileševa. Above right is a detail of rock.

The mentioned minerals served for construction of radiolarian`s molds, whose remains appear under the polarizing microscope as white balls (fig. 364).

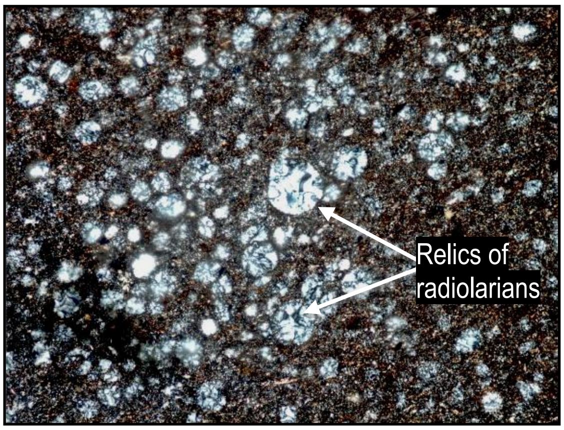

Fig. 364. Microphotograph of chert with remains of radiolarian. XPL, magnification 100×.

Coesite is SiO_2 mineral, which forms when a meteorite impact the Earth. The resulting high pressure and temperature leads to melting of rocks and their rapid cooling (fig. 365).

Fig. 365. Coesite produced in rock impacted by meteorite.

Coesite has been synthesized for the early first time by the chemist Loering Coes Jr. (1915–1973) in 1953. Natural ones have been discovered in 1960. It forms at ultra high pressures (greater then 30 GPa) and temperatures of 700 to 1300 °C.

Crystallizes monoclinic, often is colorless. Cleavage is absent, hardness about 7.5 and specific gravity 2.9 g/cm^3 (fig. 366).

Fig. 366. Crystal of coesite.

Coesite forms additionally, beside the places of meteorite impacts, in subduction zones, during continental collision etc. Thermodynamically obtained data suggests on its origin at depths exceeding 100 km.

Coesite is found in kimberlite and eclogite associated with garnet, kyanite, lawsonite, micas (fig. 367). This mineral is considered as one of the best indicators of ultra metamorphism at high pressures (UHP metamorphism). It is commonly preserved in metamorphic rocks as inclusion, particularly is common in garnet or in other minerals that develop at mentioned conditions (fig. 368).

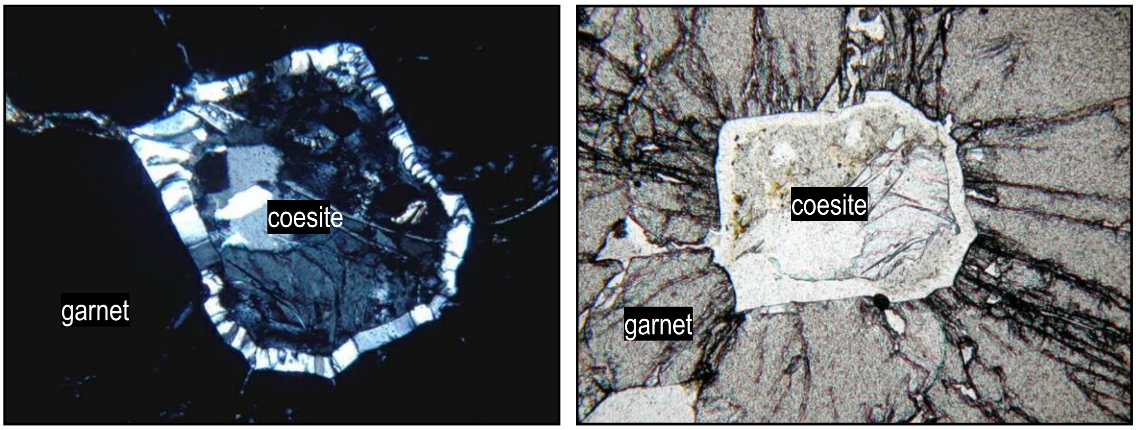

Fig. 367. Microphotograph of coesite as inclusion in garnet from eclogite (left), XPL, and the same mineral with PPL (right). Magnification 300×.

Fig. 368. In eclogite in the North China is coesite enclosed by garnet, above right.

14.2. FELDSPARS

Feldspars are important and widespread petrogenic minerals. They build approximately 60 % of igneous, 30 % of metamorphic and 10 % of sedimentary rocks. This group is also important constituent in weathering crust.

Feldspars have very similar chemical composition, structural, physical and optical characteristics.

Structurally, feldspars are tectosilicates with SiO_4 tetrahedra linked in all directions. Si ion is substituted by Al in every second or fourth tetrahedra and the remained negative charges are compensated with K, Na, and Ca, and Ba, occasionally.

Chemically, feldspars are aluminum silicates of potassium, sodium and calcium, which create their individual minerals:

orthoclase	potassium feldspar,	$KAlSi_3O_8$;
albite	sodium feldspar,	$NaAlSi_3O_8$ and
anorthite	calcium feldspar	$CaAl_2Si_2O_8$

Feldspars are rarely found in a nature as pure forms. They usually build isomorphic series: orthoclase and albite mix partially whereas albite and anorthite continually mix. Individual grains are rare in respect to twins, usually of two or few grains.

Isomorphic series of orthoclase and albite considers to **alkali feldspars**, due to present alkalis, K and Na in their composition.

Isomorphic series of albite and anorthite is known as **plagioclase** or **calc-alkali feldspars**, due to presence of alkalis (Na) and Ca.

The amount of alkali feldspar in plagioclase and opposite, plagioclase in alkali feldspars, depends on the temperature of crystallization (increase with the temperature).

14.2.1. ALKALI FELDSPARS

Alkali feldspars are compositionally isomorphous combinations of potassium and sodium aluminum silicates. They are produced from melts with enough SiO_2. The silica deficient melt favors feldspathoid to form, e.g. leucite instead orthoclase, and nepheline instead albite. From melts enriched with chlorine, sulphur or with sodium and calcium exceeding aluminum sodalite, nosean, and haüyne tend to form. The group of alkali feldspar also includes barium-bearing minerals, celsian and hyalophane.

Isomorphic series of orthoclase and albite may form at high temperatures but tend to separate into sodium or potassium-rich components during slow cooling. This manifestation in alkali feldspars is called perthite.

The most important alkali feldspars in petrology, i.e. as minerals of rocks are: **orthoclase, microcline** and **sanidine.**

14.2.1.1. Orthoclase $KAlSi_3O_8$

Orthoclase is potassium feldspar with partly ordered crystal lattice (fig. 369). Commonly contains from a few, to maximally 30% of sodium component, albite.

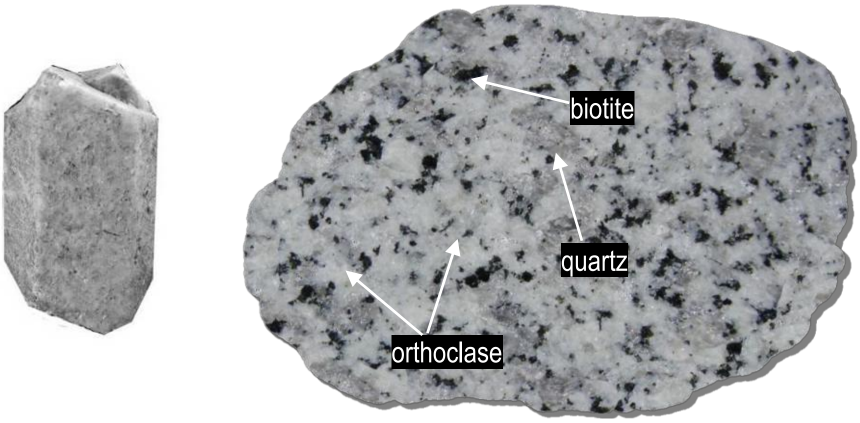

Fig. 369. Crystal of orthoclase (left), and orthoclase in granite (right).

It crystallizes monoclinic; specific gravity is 2.56 g/cm^3, hardness 6. This mineral is primarily colorless, often whitish. The green variety, due to presence of copper (lead by some opinions) is **amazonite,** whereas a red-colored variety, due to presence of iron, is **aventurine** (fig. 370). Amazonite looses a color when heated at 200 to 300 °C. Aventurine displays also allochromatic color, which derived from fine-dispersed hematite.

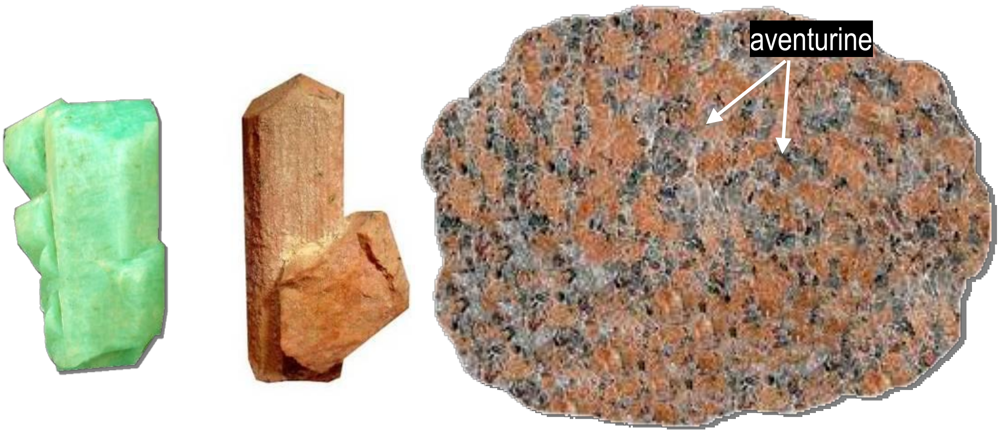

Fig. 370. Crystal of amazonite (left), aventurine in the middle and the same mineral in granite (right).

In the polarizing microscope is orthoclase grey and with low relief with crossed nicols. With parallel nicols is colorless (fig. 371).

It crystallizes from a slow-cooled melt. At higher temperatures occurs almost complete mixing between orthoclase and albite components, but with the temperature drop is less possible. The solid-solutions (mixed crystals) are not stable and the "excess" of albite component in orthoclase, as well as the "excess" of orthoclase component in albite tends to separate. The slower cooling results in larger-sized minerals.

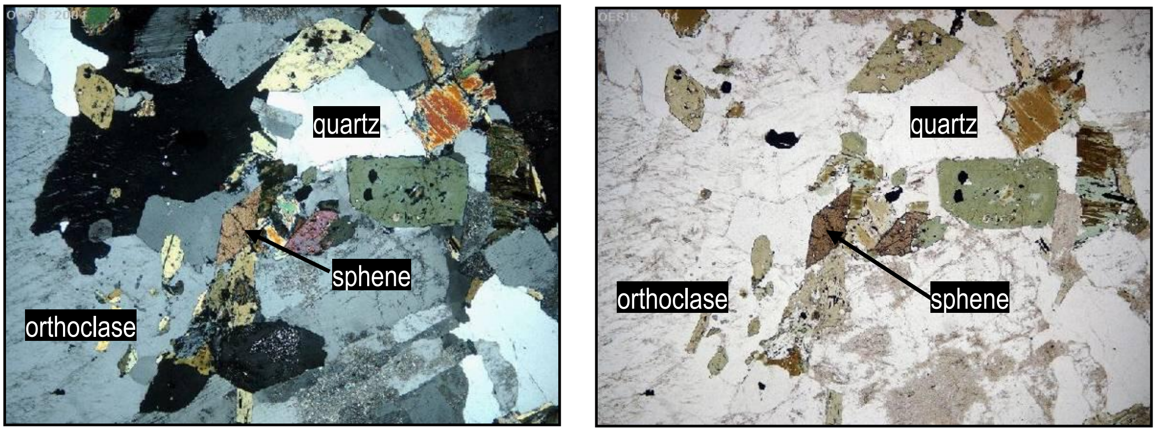

Fig. 371. Microphotograph of orthoclase in granite, XPL (left), and the same mineral with PPL (right). Magnification 100×.

Orthoclase with albite exsolutions is known as **perthite**, and opposite, albite with released orthoclase is **antiperthite** (fig. 372). These feldspars are constituents of intrusive igneous rocks that were cooled very slowly. Orthoclase may contain some calcium, i.e. anorthite component, as well as barium (celsian).

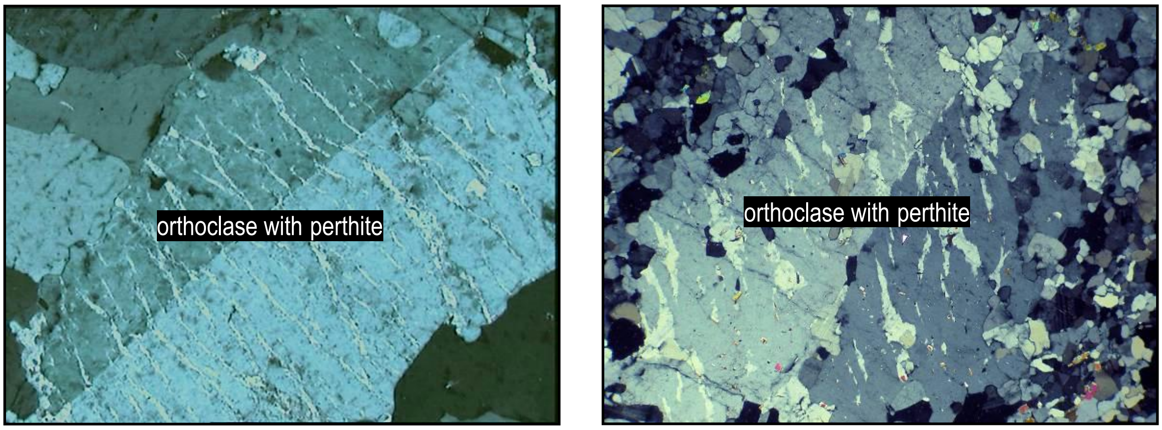

Fig. 372. Two examples of perthite exsolutions from albite in orthoclase, XPL, magnification 100×.

Crystals of orthoclase are usually well-developed and twinned. Two cleavage directions meet at nearly 90º.

It is igneous and metamorphic mineral. Orthoclase is the chief mineral in intrusive acid rocks, such as granite (fig. 373), syenite, quartzmonzonite, granodiorite, aplite and pegmatite. In these rocks it occurs in a few millimeters sized grains, but may occur in huge, euhedral crystals up to a ten cm in size giving rise to porphyroid texture.

In pegmatite is found accompanying muscovite, biotite, tourmaline, and quartz.

Fig. 373. Orthoclase is the essential mineral in granites at Vršači breg. Above left is the detail of rock.

Orthoclase is abundant in metamorphic rock, gneiss (fig. 374), where is also the chief mineral. It forms at high metamorphic grade (pressures exceeding 8 Kb and temperatures greater than 800 °C) from muscovite if the system is opened (allowing water to leave a system) or by recrystallization of previously existed orthoclase in a rock subjected to metamorphism. It commonly associates with muscovite, biotite, garnets, occasionally with staurolite and kyanite. In metamorphic rock is commonly in a form of elongated, lens-shaped grains, so-called "augen", which is much coarser than other constituents representing porphyroblasts.

Fig. 374. Gneiss in Vučje, near Leskovac contains orthoclase as the essential mineral. Above left, a detail of augen gneiss with porphyroblasts of orthoclase.

Orthoclase turns into lath-like muscovite called sericite under the influence of hydrothermal solutions of atmospheric agents. The complete transformations lead to clay minerals.

Orthoclase may form hydrothermally during the potassic metasomatism in metallic, gold, copper, lead and zinc deposits. In such case it has very low content of albite component and is called **adularia** (fig. 375). It crystallizes monoclinic and does not have ordered crystal lattice. Commonly occurs in clear, white, occasionally transparent crystals.

Fig. 375. Crystals of adularia (left), and adularia in a sample mass (right).

Adularia is common in hydrothermally altered intermediate igneous rocks.

In polarizing microscope, with crossed nicols, is adularia grey in color and of low relief. With parallel nicols is colorless (fig. 376).

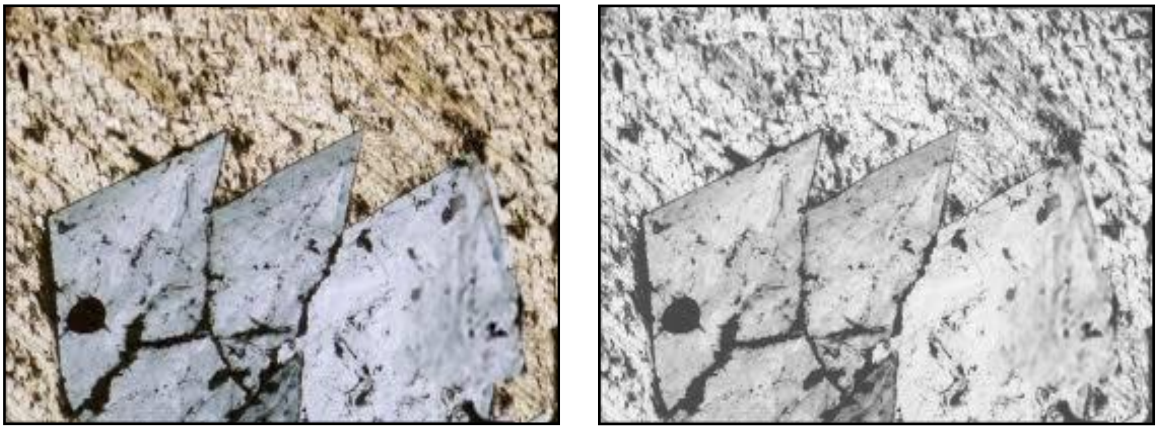

Fig. 376. Microphotograph of adularia, grey, associated with calcite in hydrothermally altered rock (left), XPL, the same sample with PPL (right). Magnification 200×.

Adularia may be related to copper mineralization when serves as the prospecting criterion in searching for new ore bodies of copper, silver, gold, lead and zinc (fig. 377).

Fig. 377. Adularia is found in hydrothermally altered andesite of Veliki Krivelj that bears copper and gold mineralization.

14.2.1.2. Microcline $KAlSi_3O_8$

Microcline is potassium feldspar with the same composition as orthoclase. It crystallizes triclinic. Cleavage directions meet at cross angle, hence the name.

It is white in color and of perfect cleavage (fig. 378). Specific gravity is from 2.54 to 2.57 g/cm^3, and hardness is 6. May contains, such as orthoclase, albite component, (microclinperthite). Such exsolutions derive at low temperatures when isomorphous mixing of albite and microcline is not possible.

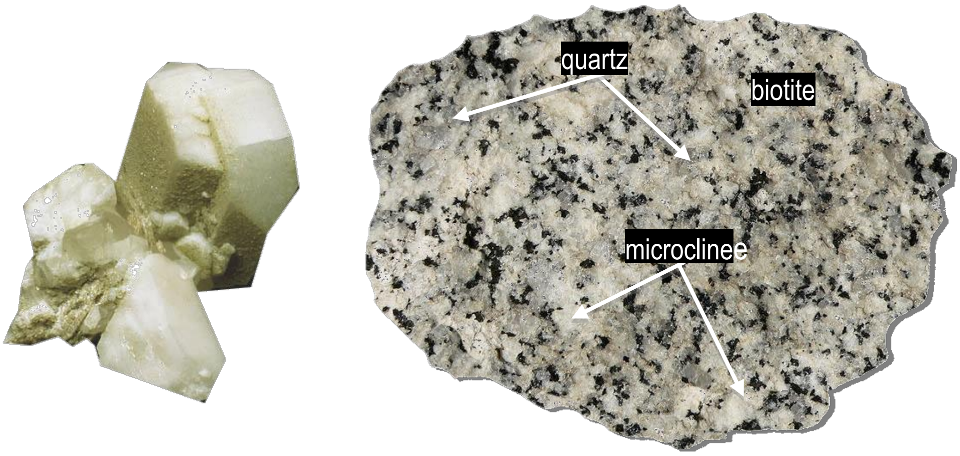

Fig. 378. Crystals of microcline (left), and microcline in granite (right).

In the polarizing microscope microcline displays characteristic grid or quadrille structure (fig. 379), which is a result of complex twinning. Homogenous grains of microcline, hardly distinguishable from orthoclase, are extremely rare.

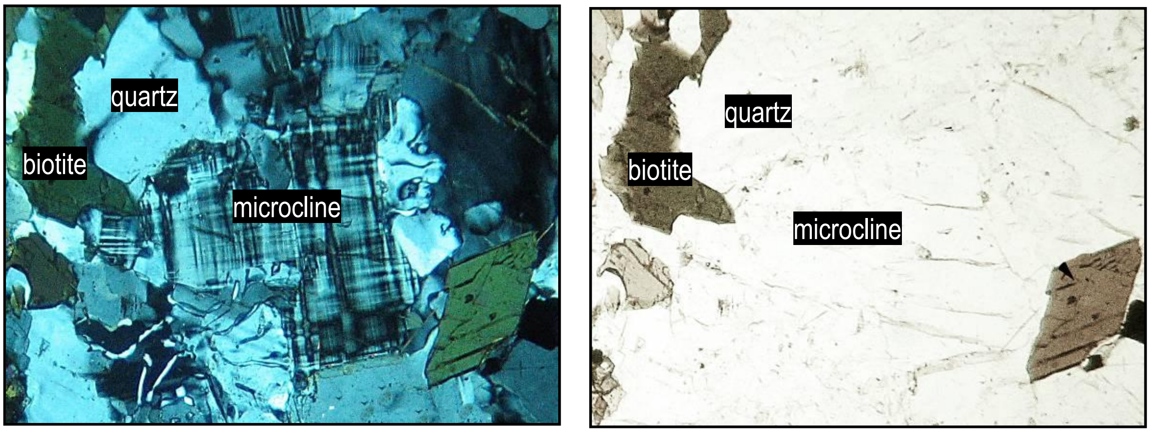

Fig.379. Microphotograph of microcline in granite, XPL (left), and the same mineral with PPL (right). Magnification 100×.

Ordering of the orthoclase crystal lattice gives rise to microcline. It can form by direct crystallization of acid, granitic magma at lower temperatures then orthoclase, usually below 600 ^{0}C. Partial replacement of orthoclase into the more stable modification (microcline) may be seen in some species and recognized by typical grid lamellas that are visible only under the microscope. Microcline is mostly related to rocks formed in great depths where cooling was slowly. It is also common in rocks derived from water-rich melts (pegmatites) that crystallize at low temperatures.

In metamorphic rocks (gneisses) often associates with orthoclase. Subjected to hot solution it alters into sericite, i.e. kaolinite.

14.2.1.3. **Sanidine** (K,Na)$AlSi_3O_8$

Sanidine is potassium-sodium aluminum silicate in composition. Sodium component may approach to 62 %, although is usually about 30 %. Common impurities in sanidine are Ba, Ca and other elements. It crystallizes monoclinic and occurs in tabular, thick platy or granular aggregates, which represents phenocrysts in young volcanic rocks of Cenozoic age.

Sanidine is colorless to white, often transparent. It has glassy lustre and pearly along cleavage directions. Cleavage is perfect, specific gravity 2.57 g/cm^3, hardness 6 (fig. 380).

Fig. 380. Crystal of sanidine (left), and sanidine as phenocryst in quartzlatite (right).

In the polarizing microscope displays very similar optical properties to orthoclase. With crossed nicols is grey, of moderate to low relief and is colorless with parallel nicols (fig. 381).

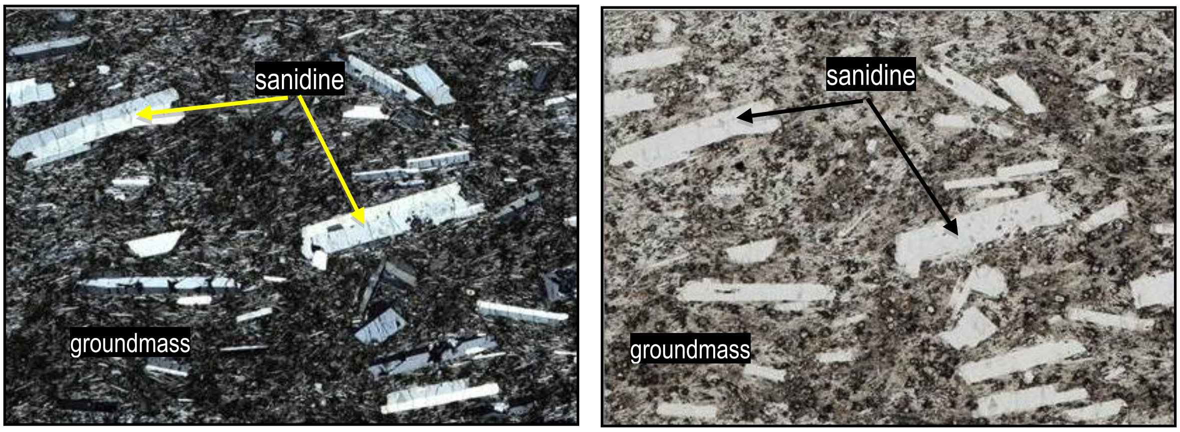

Fig. 381. Phenocrysts of sanidine in trachyte, XPL (left), and the same mineral with PPL(right). Magnification 100×.

Sanidine is igneous mineral and forms at high temperatures. It is mostly related to rapidly crystallizing volcanic rocks of granite and quartzmonzonite, rhyolite and quartzlatite. It is present as phenocrysts, commonly in large, euhedral grains – crystals, up to a few centimeters in size (fig. 382).

Fig. 382. Quartzlatite of Kriva Feja (southeastern Serbia) with phenocrysts of sanidine. Above right is a detail of rock with phenocrysts of sanidine.

This feldspar remains preserved only under a rapid cooling of melt (lava) when a crystal lattice does not have enough time to order.

A drop of temperature with a time leads to ordering of crystal lattice and albite component being ex-solved. Therefore, sanidine converts temporally into low temperature modification, orthoclase.

Sanidine is also found in contact-metamorphic rocks derived at low pressures (up to 3 Kb) and high temperatures (above 700 ^{0}C). Such conditions are attained at the immediate contact of clastic sedimentary rocks and magma, commonly of granitic composition. It is also found in xenoliths, pieces of rock that were embedded by magma during its rise and effusion. The previously existed feldspars recrystallized at high temperatures and a new mineral, sanidine that is stable in new-formed conditions being formed on account phyllosilicate minerals (muscovite, sericite) (fig. 383).

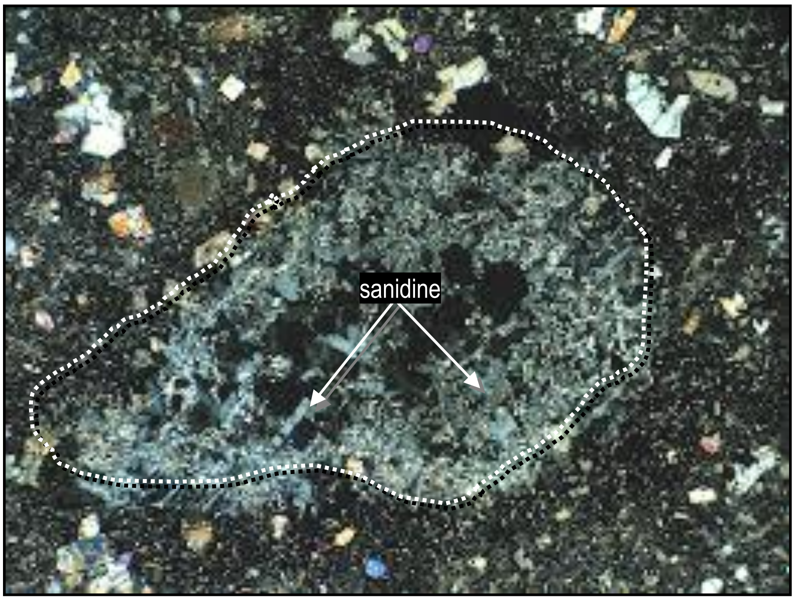

Fig. 383. Xenolith, indicated by white dashed line, with sanidine (grey thin prismatic crystals in basalt). XPL, magnification 40×.

Under the influence of atmospheric agents or hydrothermal solutions sanidine, like orthoclase, alters into sericite and kaolinite.

Rocks with large crystals of sanidine are not suitable as building material, for construction, roads etc. Sanidine reduced physical-mechanical properties of rocks and „drops out" under even weak supergene alterations.

14.2.2. PLAGIOCLASE

Plagioclase is one of the most important mineral in numerous igneous rocks and is also important for their classification. Plagioclase represents isomorphic series of sodium and calcium feldspar **albite** ($NaAlSi_3O_8$) and **anorthite** ($CaAl_2Si_2O_8$) that mix completely. They always contain small amounts of potassium, orthoclase component, which increase with the temperature of crystallization.

The percentage of calcium end-member is used to subdivide the series into a number of individual minerals:

Mineral	% anorthite	
albite	0 - 10	acid plagioclase
oligoclase	10 - 30	intermediate plagioclase
andesine	30 - 50	intermediate plagioclase
labradorite	50 - 70	basic plagioclase
bytownite	70 - 90	basic plagioclase
anorthite	90 – 100	basic plagioclase

Anorthite crystallizes at higher temperature in respect to albite.

14.2.2.1. Albite $NaAlSi_3O_8$

Albite occurs in white, commonly polysynthetic twinned crystals. Cleavage is perfect, lustre glassy. Specific gravity is 2.65 g/cm^3, hardness 6 (fig. 384).

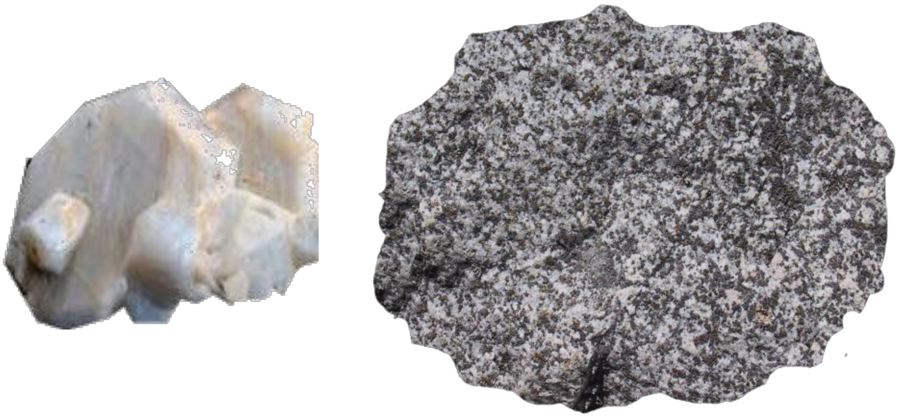

Fig. 384. Crystal of albite (left), and albite in albite granite (right).

Albite is important mineral in acid igneous rocks, granite, syenite, and granodiorite where it associates with orthoclase and microcline.

In albite granites or plagiogranites is it the only feldspar. This is specific kind of rocks related to ophiolites (fig. 385), considered to generate through differentiation of basic (gabbro) magma in the presence of water. These rocks consist, beside albite, of chlorite, epidote, zoisite, and hornblende and quartz occasionally.

Fig. 385. Outcrop of albite granite near Sjenica. Above right a detail of rock.

In the polarizing microscope albite displays, with crossed nicols, grey color and very specific polysynthetic twinning. Twin lamellas are thinner than in basic plagioclase. With parallel nicols is colorless and with low relief (fig. 386).

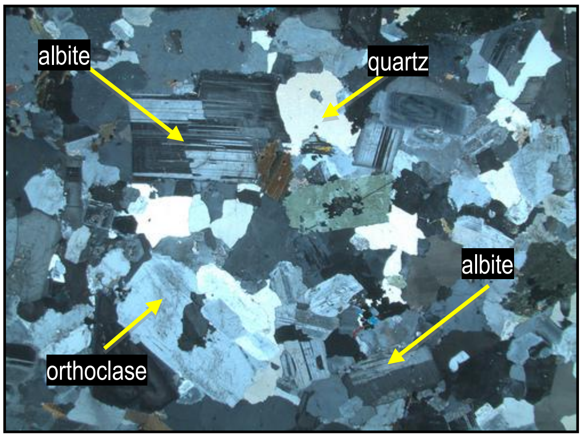

Fig. 386. Microphotograph of albite in granite, XPL, magnification 60 x.

In metamorphic rocks is albite the result of low grade metamorphism of basic rocks (spilite, quartz keratophyre, and keratophyre, less frequent of diabase, basalt and gabbro) and their pyroclastic equivalents and may be the essential mineral (fig. 387).

Fig. 387. Albite in albite-chlorite schists near Vladičin Han. Left, a detail of rock.

It is commonly present in large grains, up to a few millimeters in size, which enclosed inclusions of epidote and zoisite and display the undergone rotation, i.e. syn-kinematic crystallization that reflects on its generation during metamorphism.

Albite usually associates with chlorite, sericite, epidote, zoisite, actinolite, leucoxene and quartz (fig. 388).

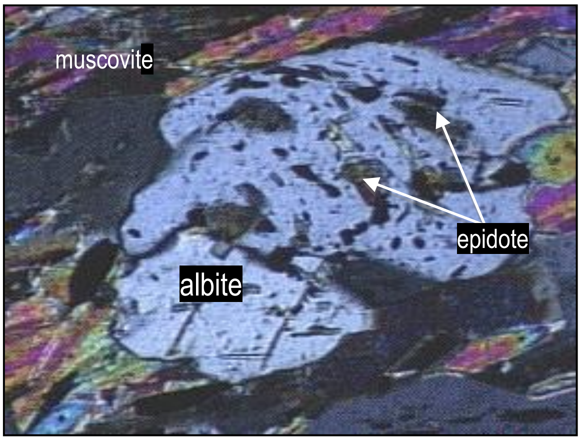

Fig. 388. Porphyroblast of albite with enclosed epidote in albite-chlorite schist. XPL, magnification 100×.

Albite is authigenous mineral of sedimentary rocks. It forms either in alkaline condition by influence of Na-solution on aluminum silicates or by direct precipitation. Allothigenous albite frequently undergoes secondary growth.

14.2.2.2. Oligoclase and andesine

Oligoclase and **andesine** are **transitional** or **intermediate plagioclases** of triclinic symmetry. Oligoclase is with 10-30 % anorthite component, andesine from 30 to 50 %. They take part in making transitional or intermediate igneous rocks (quartz monzonite, monzonite, diorite and quartzdiorite) and their volcanic equivalents (latite, quartzlatite, dacite and andesite).

Andesine was named after Andes, the longest mountain range in South America, where it occurs in volcanic rock andesite, volcanic equivalent of intermediate igneous rock diorite (fig. 389).

Fig. 389. Intermediate plagioclase andesine was named after the Mountain range Andes in South America.

Oligoclase, but more common andesine, is zoned in volcanic rocks. The zoned pattern resulted from reaction of outer part of crystal with magma during crystallization (plagioclase crystallizes continuously), due to viscous melt that under accelerated cooling is not able to attain equilibration with mixed crystals (fig. 390).

Fig. 390. Microphotograph of zoned andesine in andesite, XPL, magnification 80×.

It has been written already that intermediate plagioclase is related to intermediate igneous rocks. In volcanic rocks (quartzlatite, latite, andesite and dacite) is present in a form of white-colored phenocrysts, up to a few mm in size (fig. 391).

Fig. 391. Dacite and andesite at Borač with phenocrysts of intermediate plagioclase and biotite. Above right, a detail of rock.

Intermediate plagioclase is found in metamorphic rocks formed at low to medium metamorphic grade, in conditions of greenschist to amphibolite facies. The most common are in amphibolites (fig. 392) where is rarely zoned. Oligoclase and andesine may be found in contact-metamorphic rocks, too.

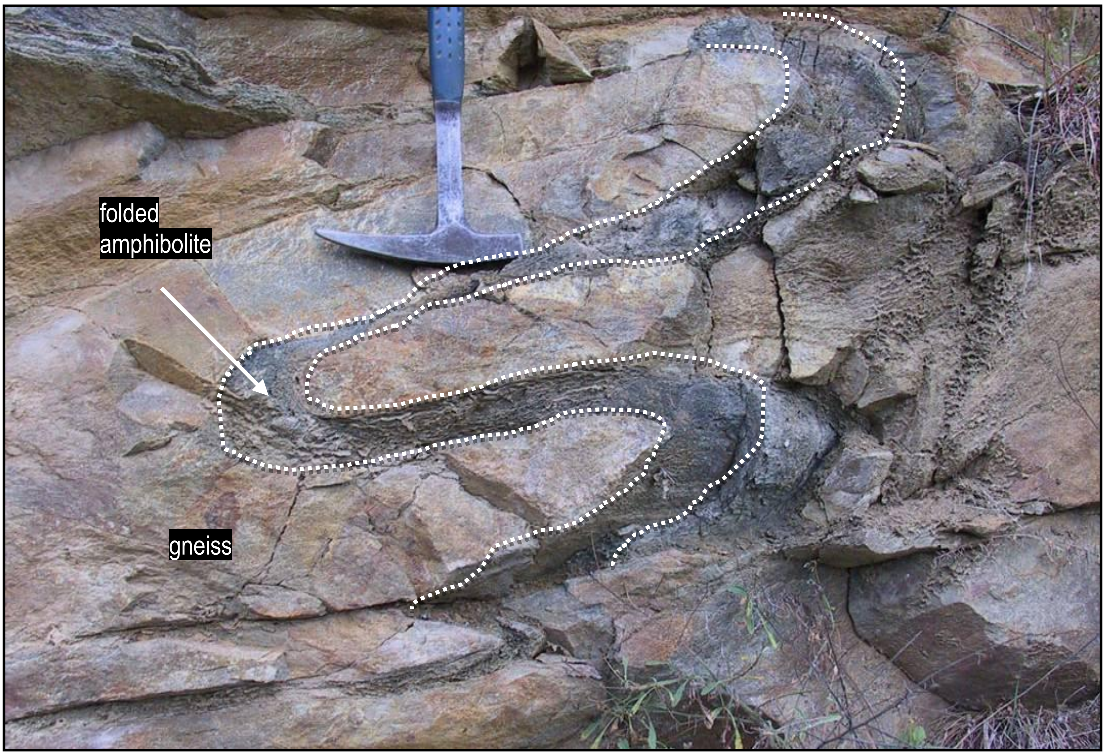

Fig. 392. Folded amphibolite in gneiss from Medveđa consists of andesine and hornblende.

14.2.2.3. **Labradorite**, **bytownite** and **anorthite**

Labradorite, **bytownite** and **anorthite** are **basic plagioclases.** They crystallize triclinic and commonly appear in white, polysynthetic twinned crystals. Cleavage is, like in potassium feldspars, perfect although directions meet at cross angle.

Lustre is glassy, pearly at cleavage planes. Plagioclase has specific gravity 2.8 g/cm^3 and hardness 6 (fig. 393).

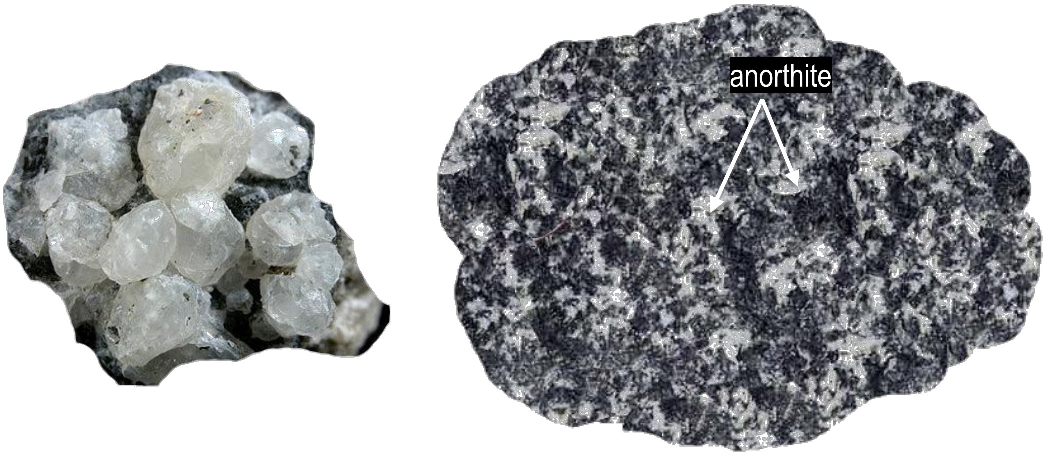

Fig. 393. Crystals of anorthite (left), and anorthite in gabbro, white grains (right).

Their optical properties in the polarizing microscope are similar or quite same as of other plagioclase. They are grey in color and display polysynthetic twinning with crossed nicols, and are colorless, of low relief with parallel nicols (fig. 394). Twin lamellas are wider than in albite.

Identification of basic plagioclase is possible over other minerals they are associated with. Olivine and pyroxene, essential minerals in gabbro, basalt and diabase are their commonest accompanies.

Fig. 394. Microphotograph of basic plagioclase in gabbro (left, and in basalt (right), XPL, magnification 100×.

Basic plagioclase forms, as igneous mineral, by crystallization of basic magma (gabbro) (fig. 395), the same magma that arriving on a surface will produce basalt. These rocks build lower levels in oceanic crust (gabbros) or effuse in mid-ocean ridges, where two plates move apart (basalts).

Fig. 395. Gabbro of Glavica near Paraćin contains basic plagioclase and pyroxene.

They may be found in regional-metamorphic rocks formed at high metamorphic grade (granulite facies), from basic rocks giving rise to granulite, a rock composed of garnet (almandine), pyroxene and basic plagioclase (fig. 396).

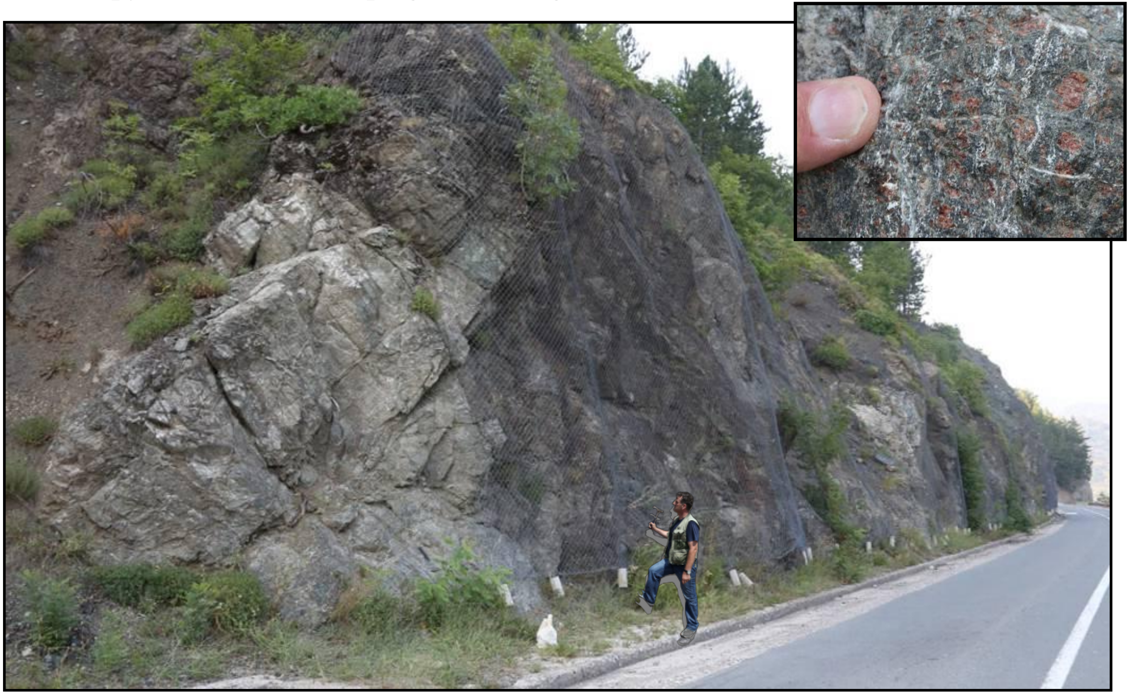

Fig. 396. Outcrop of black granulites with basic plagioclase, garnet and pyroxene close to Bistrica (Prijepolje). Above right, sample of it.

Basic plagioclase is rarely found in contact-metamorphic rocks, commonly at the immediate contact of limestone with acid magma, in silica and aluminum-rich system.

During hydrothermal metamorphism acid plagioclase alters into sericite, zeolite and clay minerals, intermediate plagioclase depending on the kind of alteration, turns into sericite, calcite, epidote, zoisite and minor albite. The basic one will be replaced by zoisite, prehnite and albite.

In basic rocks subjected to autometamorphism plagioclase transforms into the aggregate of epidote, zoisite and remained albite, known as saussirite (fig. 397).

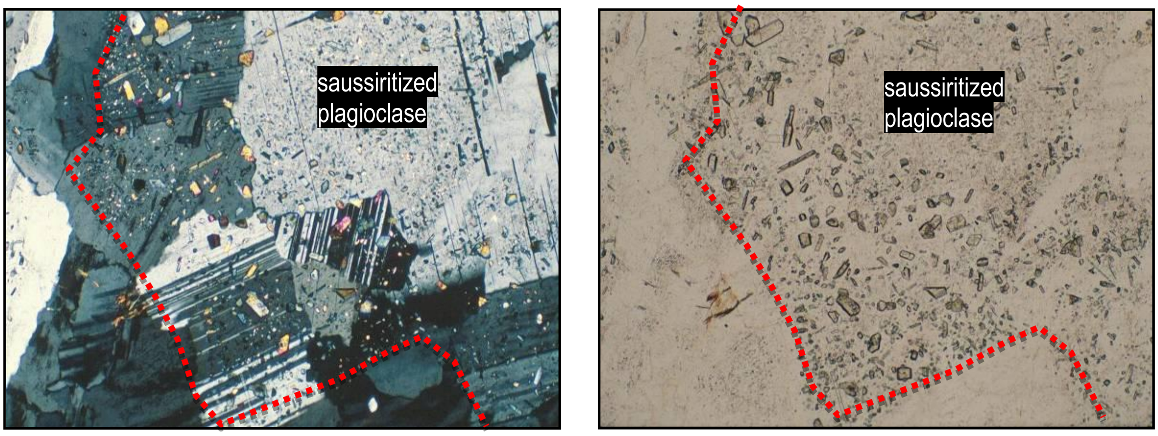

Fig. 397. Saussiritized plagioclase forms most frequently by hydrothermal alteration of primary plagioclase that turns into the fine-grained aggregate of epidote and zoisite. Grey, polysynthetic twinned grains are of plagioclase, XPL (left), the same grains with PPL (right). Magnification 100×. Red line indicates saussiritized plagioclase grains.

14.3. FELDSPATHOIDS

Feldspathoids resemble feldspars in chemistry, but are poorer with silica dioxide (SiO_2). This group of minerals crystallize from alkali (K and Na)-rich magma but with less SiO_2 then is needed for feldspar to being formed. Different contents of SiO_2 in feldspars and feldspathoids could be inferred from their empirical formulas:

orthoclase	$KAlSi_3O_8$	→	LEUCITE	$KAlSi_2O_6$
albite	$NaAlSi_3O_8$	→	NEPHELINE	$(Na,K)AlSiO_4$.

14.3.1. LEUCITE $KAlSi_2O_6$

Leucite is potassium aluminum silicate mineral and is typical igneous mineral. It is isometric above 637 °C. Below this temperature it displays complex mimetic twins (lamellas in tetragonal symmetry). It commonly occurs in ikositetrahedral or granular aggregates. It exhibits white or grey color, indistinct cleavage and glassy lustre (fig. 398).

Specific gravity of leucite is 2.47-2.5 g/cm^3, hardness 5.5–6. It has conchoidal fracture, and is very brittle mineral.

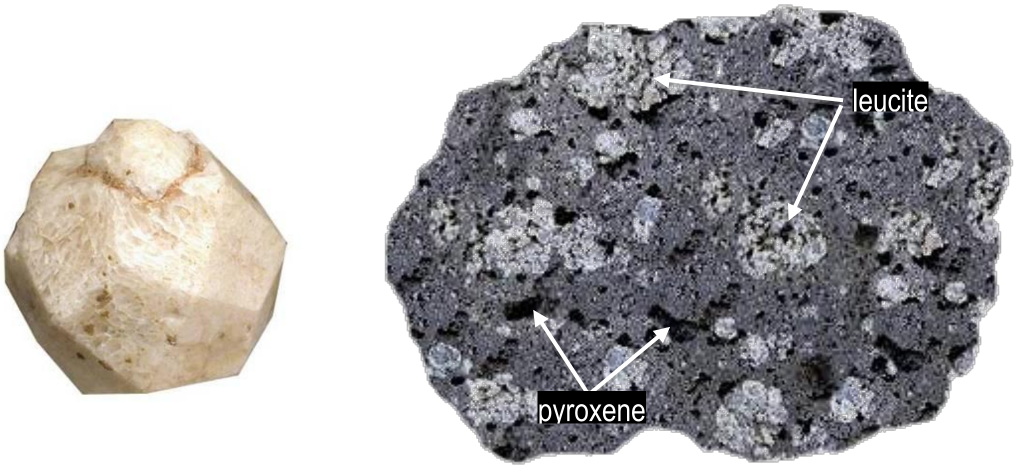

Fig. 398. Crystal of leucite (left), and leucite in basalt (right).

Leucite crystallizes from potassium, sodium and aluminum enriched, and silica deficient melt. It is important petrogenic mineral in alkali basic volcanic rocks, leucite-basanite and leucite-tephrite, in which occurs as phenocrysts commonly associated with sanidine. It is found in groundmass of lamprophyre (minette) as a fine-grained.

In the polarizing microscope, with crossed nicols and low magnification is isotropic whereas is lamellar at high magnification. It is colorless and of low to moderate relief with parallel nicols (fig. 399).

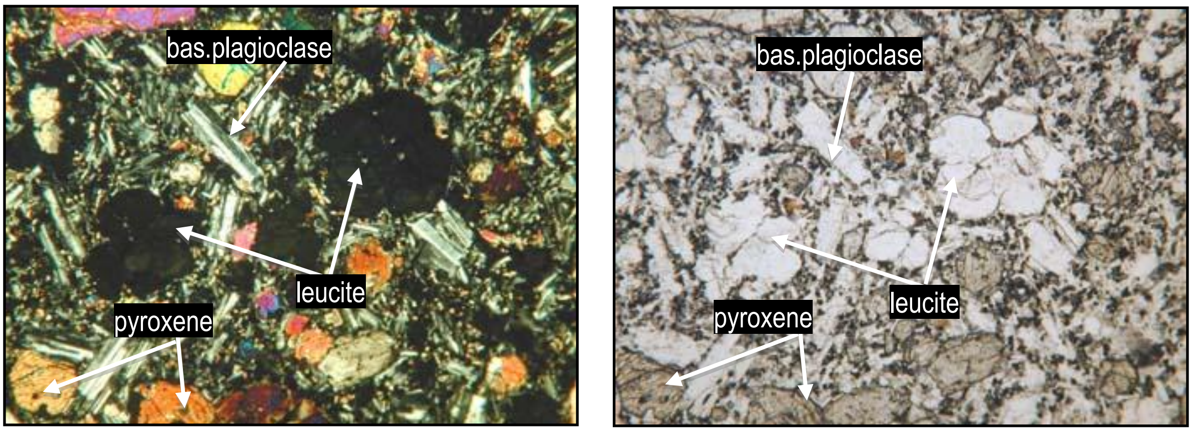

Fig. 399. Microphotograph of leucite in basalt, XPL (left), and the same image with PPL (right). Magnification 100×.

Subjected to hot solution or atmospheric agents, leucite alters like orthoclase, into sericite (lathy muscovite) and clay minerals. Leucite found application in production of artificial fertilizers.

14.3.2. NEPHELINE $NaAlSiO_4$

Nepheline is sodium aluminum silicate. May contains variable amounts of K, Ca, Mg and Ba. It is present, like leucite in rocks with less SiO_2 than is needed for feldspar formation. Nepheline, as leucite, is never found in rocks with free quartz. It crystallizes hexagonal and rarely occurs in tabular to prismatic crystals. Usually appears in granular to massive aggregates (fig. 400).

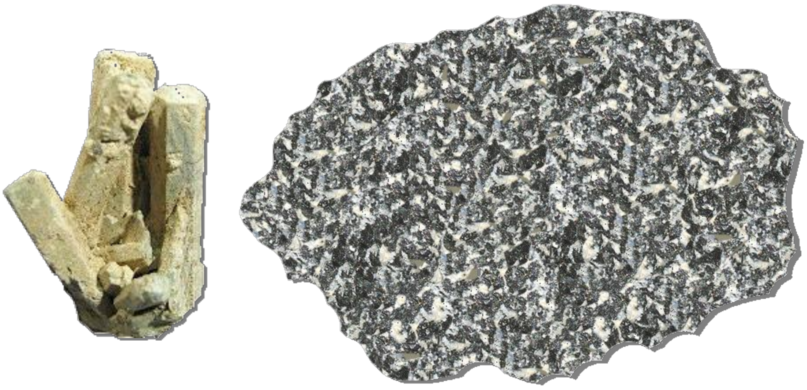

Fig. 400. Crystals of nepheline (left), and nepheline in nepheline-syenite (right), white grains accompanying orthoclase.

Fracture is uneven or conchoidal, specific gravity 2.50 to 2.65 g/cm^3, hardness 5.5 to 6. Crystal faces display glassy lustre, whereas broken surfaces are greasy. It is colorless; white to light grey, although may be variously colored. In polarizing microscope resembles orthoclase. With crossed nicols is grey and anisotropic. In parallel nicols is colorless, with low relief (fig. 401).

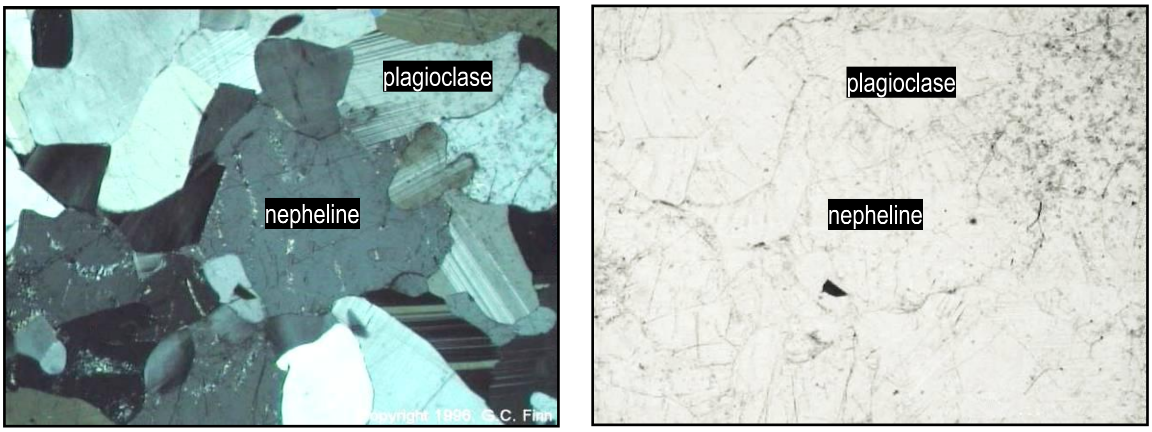

Fig. 401.Microphotograph of nepheline in nepheline-syenite, XPL (left), same image with PPL (right). Magnification 60×.

It is igneous mineral and occurs in intrusive igneous rocks without quartz, nepheline-syenite and alaskite, as well as in alkali volcanic rocks silica-deficient, such as nepheline-basalt and phonolite (fig. 402). Commonly associates with alkali pyroxenes and alkali amphiboles. Alters like albite, into sericite, kaolinite or converts into minerals of the zeolite group.

Fig. 402. Phonolite of Banjica, in Belgrade. Above right is a microphotograph of rock consisting alkali, zoned, amphiboles and nepheline. XPL, magnification 100×.

14.4. SCAPOLITE

Scapolite forms isomorphic series of Na-Ca aluminum silicates (like plagioclase), with additional anions, Cl, CO_2, and SO_3. End members are:

MARIALITE $Na_4(Al_3Si_9O_{24})Cl$ and
MEIONITE $Ca_4(Al_6Si_6O_{24})CO_3$

Common impurities are cations Fe^{2+}, Mg^{2+}, and K. Crystallizes tetragonal and produced crystals, which are elongated along vertical axis and ends with bypyramids. Commonly occurs in prismatic, or radiating and fan-shaped aggregates as well as in granular to massive accumulations. All members of a series will be present together.

They are white or grey, sometimes red or blue, transparent to translucent, with glassy lustre and perfect to apparent cleavage (fig. 403). Specific gravity, depending on composition, is 2.6 to 2.75 g/cm^3, hardness varies from 5 to 6.

Fig.403.Crystals of scapolite (left), and scapolite in pegmatite (right).

In the polarizing microscope is recognizable by interference colors, commonly first-order and by crystal habit. With parallel nicols are colorless and of moderate relief (fig. 404).

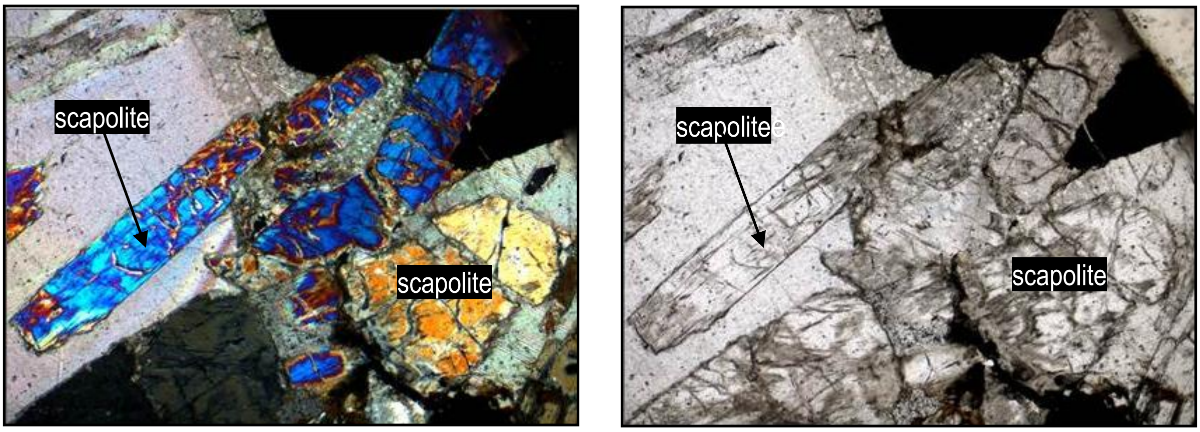

Fig. 404. Microphotograph of scapolite in skarn, XPL (left), and the same minerals with PPL (right). Magnification 100×.

Scapolite derives in contact-metasomatic rocks, at contact of granite with carbonate rocks, within skarn associating with wollastonite, Ca-pyroxene, and Ca-garnets (fig. 405). Based on conditions of their origin, they refer to immediate contact or just to it, in so-called medium zone and temperatures about 500 °C.

Figl. 405. Skarns at Jaram (Kopaonik), above right is a sample of rock with scapolite.

Scapolite is in skarn found in characteristic radiating, fan-shaped aggregates colored in white, grey or yellowish what enables its identification.

Scapolite may be found in regional-metamorphic rocks when it forms in wide temperature range, since greenschist to granulite facies.

They are also secondary minerals, formed by action of pneumatolytic or hydrothermal solutions bearing chlorine and carbon acid on basic plagioclase.

Scapolite alters at superficial conditions into zeolite, epidote and clay minerals.

14.5. ZEOLITES

Zeolites are hydrated aluminum silicates of sodium, calcium, barium and potassium. Crystal structure of zeolites actually represents "skeletons" of SiO_4 and AlO_4 networks of different morphology and with wide-opened holes in which are cations Ca and Na, rarely K or Ba, Mg and water molecules, accommodated.

Water disappears from zeolites under heating without disturbing a crystal lattice. Subsequent cooling allows water as well as to other liquid or vapor substances to return into preserved structural voids of different morphology. This property enables the application of zeolites as molecular sieve, for purification of various liquid and vapor substances.

Zeolites include the group of minerals with similar morphology and physical-chemical properties:

analcime	$Na(AlSi_2O_6)\times H_2O$
natrolite,	$Na_{16}(Al_{16}Si_{24}O_{80})\times 16H_2O$
heulandite,	$(Ca,Na_2,K_2)_4(Al_8Si_{28}O_{72})\times 24H_2O$.
chabazite,	$Ca(Al_4Si_8O_{24})\times 12\ H_2O$
phillipsite,	$K_2Ca_{0.5}Na)_4(Al_6Si_{10}O_{32})\times 12H_2O$
laumontite,	$Ca_4(Al_8Si_{16}O_{48})\times 6H_2O$

Zeolites crystallize tetragonal, rhombohedral and monoclinic. Twins are common. Specific gravity varies from 2.1 to 2.5 g/cm^3, and hardness from 3 to 5. They are colorless or white, but with impurities become yellow, pinkish or green. They are easy soluble in chlorine acid. Lustre is glassy, pearly (fig. 406), sometimes are earthy, too.

Fig. 406. Radial and fan-shaped aggregates of natrolite (left) and “balls“ of thomsonite (right).

Zeolites appear in fibrous, radiating, pseudo-micaceous or granular aggregates, depending on type of bonds between Si and Al tetrahedra.

They form as post-volcanic phases within cavities and amygdales in volcanic rocks or by hydrothermal alteration of volcanic and pyroclastic rocks.

Devitrification of volcanic glass also leads to zeolite development. They may form at room-temperature and could be additionally found in deep-water sediments at sea- or ocean bottoms (phillipsite).

Zeolites are common in Neogene sediments deposited in saline lakes.

The most important petrogenic minerals from the zeolite group are analcime and laumontite.

14.5.1. ANALCIME

Analcime is hydrated sodium aluminum silicate. Common impurities are K and Ca. It crystallizes isometric, commonly deserves ikositetrahedral and hexahedral habit. It appears in individual crystals, druses or granular aggregates, as well as pseudomorphs after leucite, nepheline, and sodalite. May be found in amygdales in basalt (fig. 401).

Fig. 407. Coarse crystal of analcime (left), and analcime in geode (cavity) in basalt (right).

Specific gravity is 2.2 to 2.5 g/cm^3, hardness 5 do 5.5, lustre glassy. This mineral displays uneven fracture and indistinct cleavage. Analcime is usually white, but may appear as yellow, red, and even transparent. In optical properties is similar to leucite, from whose transformation forms (fig. 408).

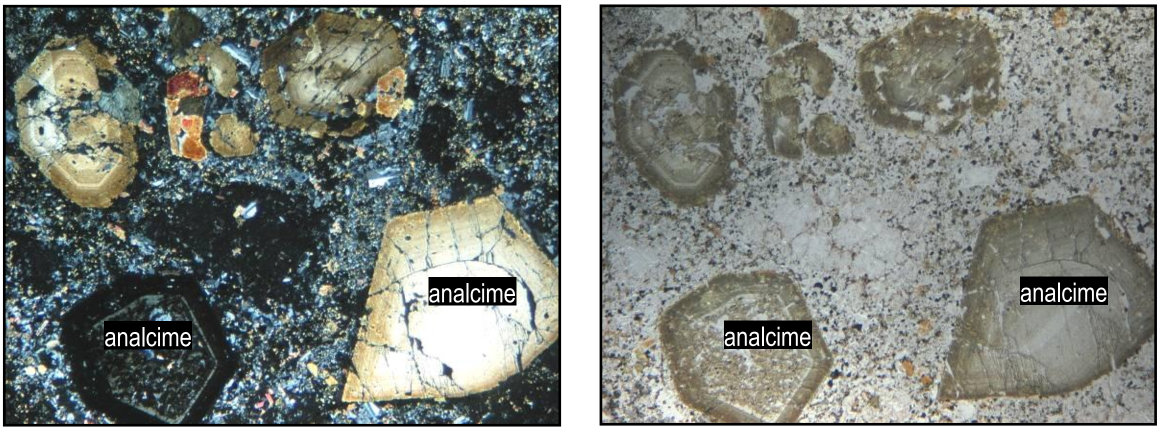

Fig. 408. Microphotograph of leucite crystal in basalt replaced with analcime. XPL (left), and the same image with PPL (right). Magnification 50×.

Analcime occurs in cavities, voids and amygdales in basic volcanic rocks, or as has been noted already, by alteration of nepheline and leucite. Very rare may form as igneous mineral, if being the last crystallized phase in alkali volcanic rocks.

14.5.2. LAUMONTITE

Laumontite is zeolite colored in white, grey, sometimes even pink. It crystallizes monoclinic, has hardness 3 to 3.5, and specific gravity 2.3 to 2.4 g/cm^3. Crystals are acicular to prismatic, of glassy lustre and perfect cleavage (fig. 409).

Fig. 409. Crystals of laumontite (left), and vein of laumontite in rock (right).

In polarizing microscope, with crossed nicols, is grey and is colorless of low relief with parallel nicols (fig. 410).

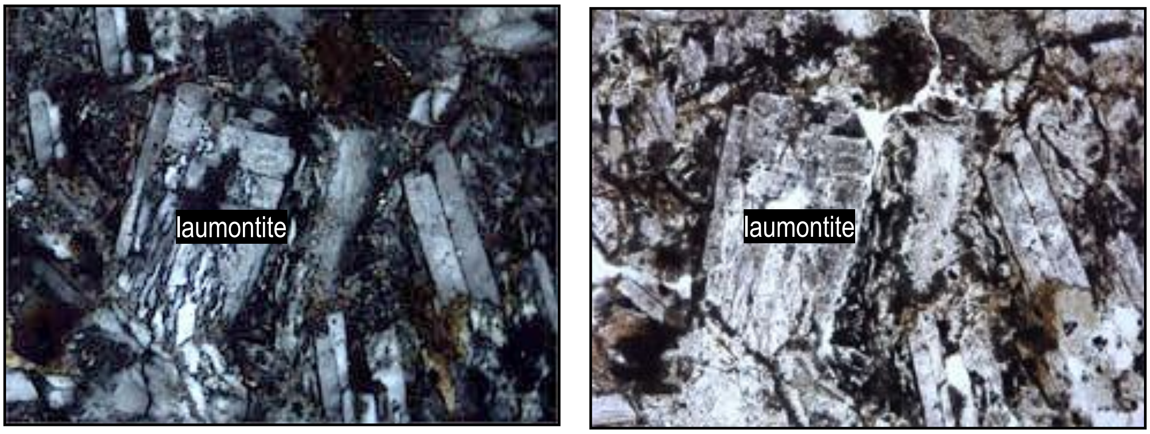

Fig. 410. Microphotograph of laumontite crystals, XPL (left), the same mineral with PPL (right). Magnification 60×.

Laumontite forms hydrothermally, at low temperatures, in cavities or in veins, commonly together with calcite in intermediate and basic rocks and their pyroclastites (fig. 411). “The source” for it is feldspars.

Fig. 411. Andesites and andesite-basalts, along with their pyroclastic equivalents in the Timok eruptive area (east Serbia), contain veins of laumontite and calcite. Above righ, a detail of the outcrop.

This mineral, together with epidote, chlorite and calcite, are found in sulphide deposits, commonly of copper, gold, lead and zinc, thus may serve as the criterion in their prospection.

Lomontite or laumontite, as called is also, is a mineral related to late stage of diagenesis (lithification) of sediments and records, by opinion of a certain authors, the end of sedimentary processes and the beginning of metamorphism, at temperatures about 200 °C and maximal pressure of 2 Kb.

Zeolites have useful applications as molecule sieve, in agriculture for fertilizers and in medicine. The largest masses of it are forming throughout zeolitization of tuffs, particularly of intermediate composition, andesite, dacite and quartzlatite subjected to action of low-temperature hydrothermal fluids (fig. 412).

Fig. 412. Outcrop of zeolitized tuff on Fruška gora. Above right, a rock sample.

15. CARBONATES

Apart from silicates, carbonates also exist among minerals of rocks. They represent salts of carbon acid. They belong to a very important group of sedimentary, organic and chemical rocks. According to structural characteristics we can differentiate orthorhombic and trigonal carbonates.

15.1. CALCITE $CaCO_3$

Calcite is a carbonate of calcium according to its chemistry. Ni, Mn, Co, Fe and Mg are the impurities that can be found in it. It appears in the crystals of various forms (fig. 413) usually twinned. In the rocks, we find it in platy crystals or granular aggregates.

It crystallizes trigonal. It has no color, so it is as transparent as the glass in thin crystals. It can also be pinkish, green, red, and when contains organic matter can be dark gray to almost black.

Fig. 413. Different colors and forms of calcite.

Calcite has specific density from 2.7 to 2.9 g/cm^3, hardness 3. It is shiny as glass and of perfect cleavage along two directions, and of uneven fracture.

It dissolves with effervescence in cold dilute HCl; hence we distinguish it from dolomite in the field, although they are macroscopically similar.

It displays a distinct effect of double refraction of light, and in polarizing microscope, under the crossed nicols, its color is grey, brown, yellowish brown, with extreme birefringence.

Under the parallel nicols, it has no color and displays low to high relief.

In the sedimentary rocks, it can often be found in very fine-grained, microcrystalline to cryptocrystalline aggregates (fig. 414).

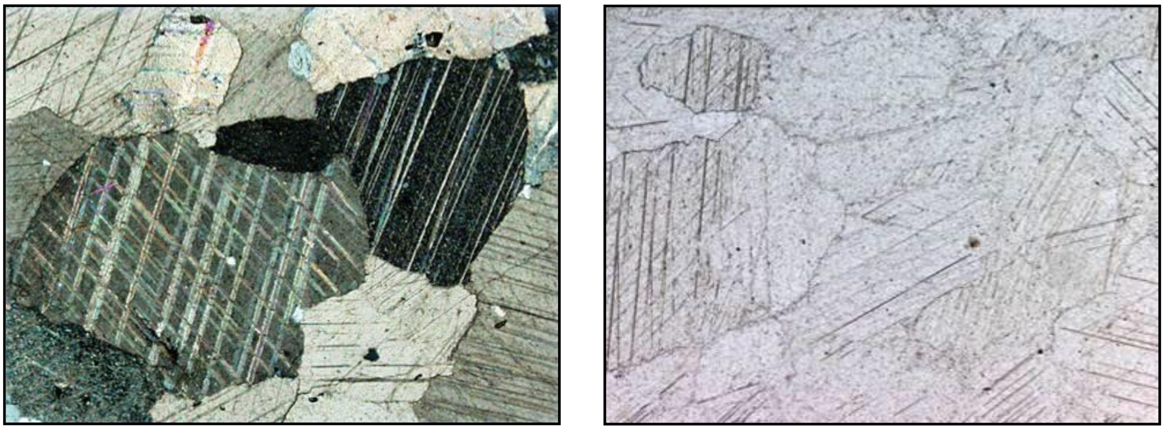

Fig. 414. Microphotograph of coarse-grained calcite crystals; XPL (left), and the same sample, under PPL (right). Magnification 100x.

Calcite is easily dissolved at the surface, and it transforms into calcium-hydrocarbonate, which is being transported and precipitated when the conditions are favorable.

Calcite forms:

- Biogenic, when it is a part of the composition of animals‘ shells or plants. The most of limestone, sedimentary rock, made only of calcite find their origin in the leftovers of these shells, especially of corals, after their extinction (fig. 415).

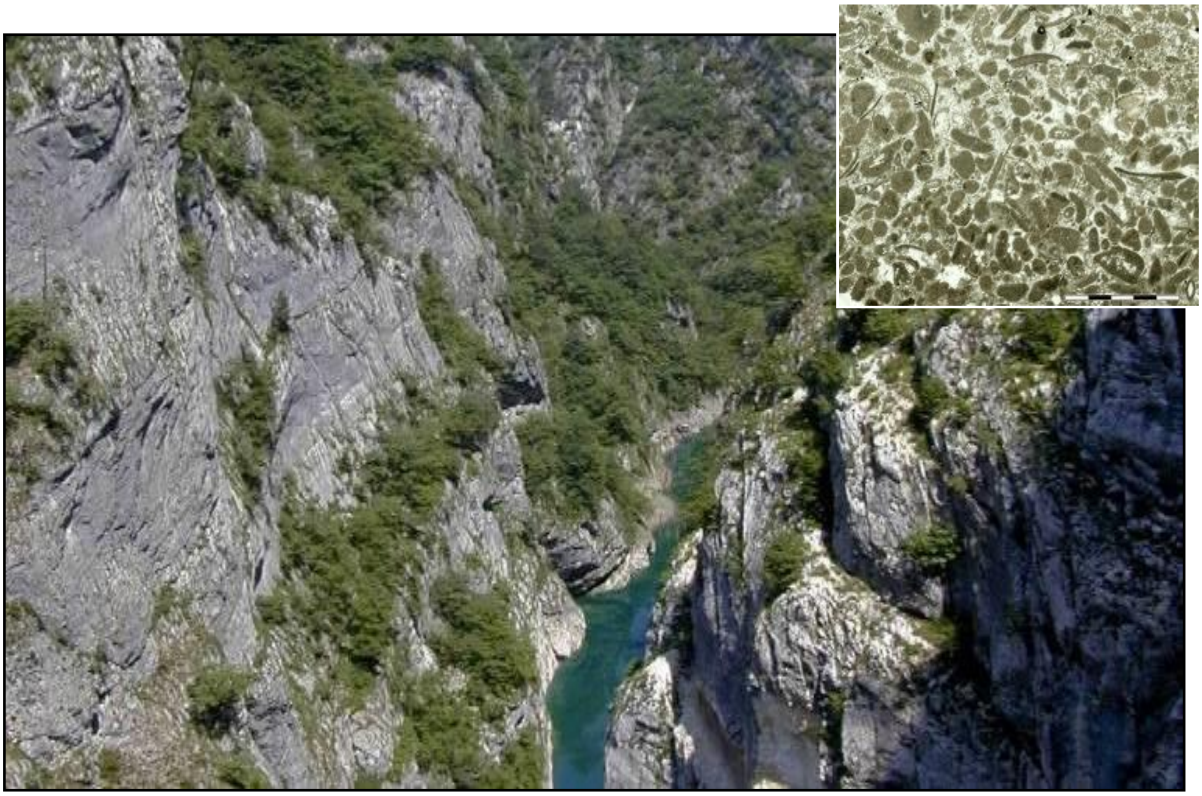

Fig. 415. Mass of limestone, originating in the leftovers of animals and plants. In the upper right corner, microphotograph of the same rock with fossils, XPL, magnification 100x.

- Precipitates around hot springs, when water with dissolved calcium-bicarbonate from great depths pours out to the surface. As a consequence of decreased pressure, carbon dioxide is being released and insoluble calcium-carbonate precipitates. This is how a rock, travertine appears. It is of banded structure, and delightful, pastel colors (fig. 416).

Fig. 416. Calcite precipitates from hot springs, when travertine appears.

- By excretion of calcium-carbonate from the solution, with pH values higher than 7. The most commonly it is brought down as aragonite, which transforms into calcite rapidly. This way, cave 'draperies' appear, when the caves are in the limestone (fig. 417).

Fig. 417. Cave draperies made of calcite.

- Around cascades and waterfalls where the amount of water, rich in dissolved calcium-bicarbonate $Ca(HCO_3)_2$, increases due to scattering. It enables the release of CO_2 in the air and piling insoluble calcite up, creating rock tufa (fig. 418).

Fig. 418. „Precipitation“of calcite and the creation of tufa. The sample of this rock is in the upper left corner.

- Hydrothermally, when associates with Fe, Pb and Zn sulphides and Cu, Mn and Fe carbonates. The most beautiful crystals of calcite are made in these conditions (fig. 419).

Fig. 419. Crystals of calcite derived from hydrothermal solutions.

- Small amounts of calcite can appear by evaporation of the sea salt (arid areas), when this mineral is depositing as a chemical sediment, along with gypsum and anhydrite. It is not very significant.
- Calcite is also a secondary mineral among silicates, plagioclase, hornblende and micas. It appears by addition calcium and carbon-dioxide to hydrothermal solutions or atmospheric waters.
- In metamorphic conditions, calcite is stable up to high temperatures in the closed system (unless there are other components as well), when marble is being created, under recrystallization of the existing carbonate rocks (fig. 420).

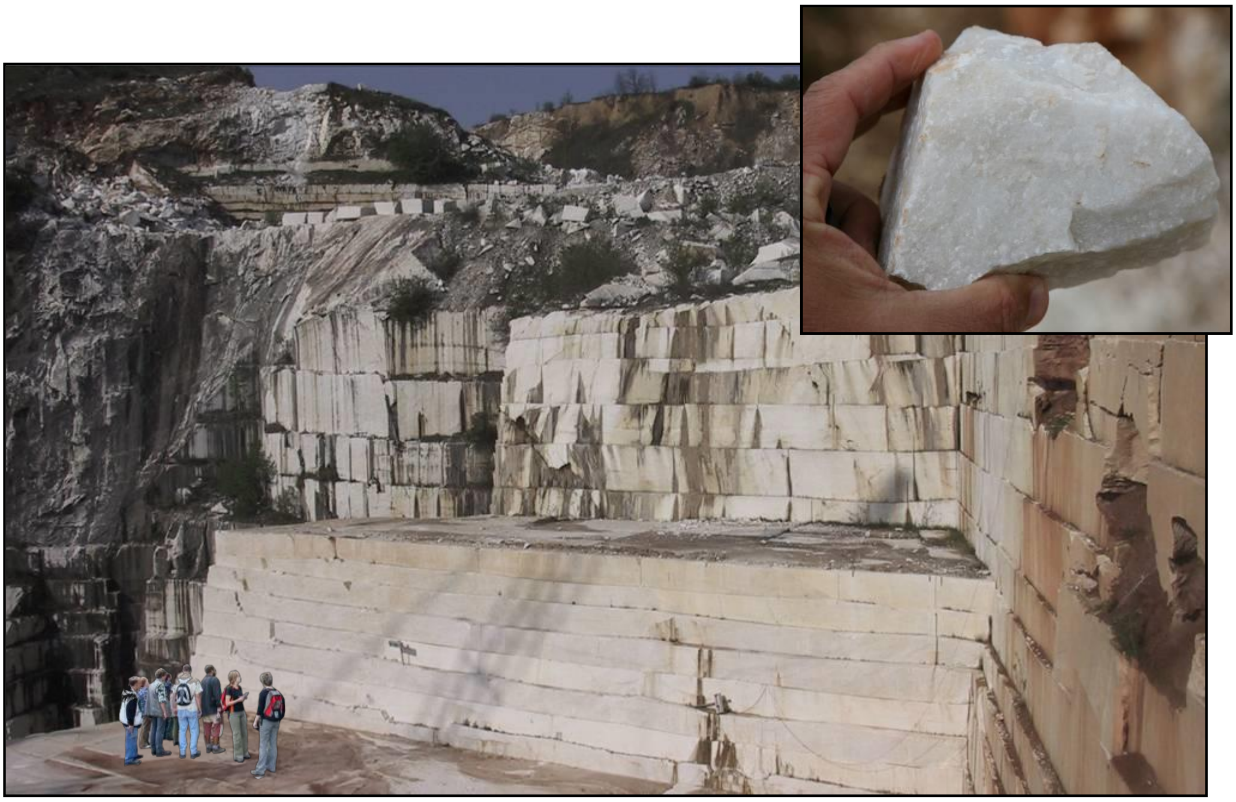

Fig. 420. Marble mine in Venčac. A detail of the rock is in the upper right corner.

In the presence of silica, calcite transforms into wollastonite, in metamorphic conditions (contact metasomatism). If there are some other minerals in the rock: clay, chlorite or limonite, calcium garnet is being created (grossular, andradite), pyroxene, diopside, salite, vesuvianite, epidote and zoisite. The system has to be open so CO_2 could be released.

15.2. ARAGONITE $CaCO_3$

In its chemical composition, aragonite is also calcium-carbonate, but unlike calcite, it crystallizes orthorhombic. It also contains Mg, Fe and Sc.

The most commonly, it appears in needle-shaped or laminar aggregates, or as oolite. Very often, it is of zoned pattern, creating pearls with organic matter (fig. 421).

Aragonite is white, but it also can be colorless. It is sometimes translucent to transparent, vitreous. It has perfect cleavage, uneven to conchoidal fracture. Its specific density is 3 g/cm^3, hardness also 3. It appears hydrothermally, usually. It is common mineral of hot springs, geysers, but it also appears in caves. It forms pearls, and is found as a mineral of salt deposits.

Fig. 421. Aragonite crystals (left) and aragonite "pearls" (right).

Aragonite transforms into calcite under the regulation of crystal lattice. This process is very often in caves, where aragonite crystallizes first, and afterwards recrystallizes into calcite (fig. 422).

Fig. 422. Cave draperies with aragonite crystallizing as first, and then turning into calcite.

15.3. **DOLOMITE** Ca,Mg $(CO_3)_2$

Dolomite is Ca, Mg $(CO_3)_2$ in its structure, and the amount of calcium and magnesium varies. This mineral often contains Fe and Mn. It was named after French geologist Dolomieu (fig. 423).

Fig. 423. Deodat Grated de Dolomieu (1750–1801).

Dolomite appears in crystals in the shape of primitive rhombohedra, rarely scalenohedral or grainshaped, massive to laminar aggregates. It crystallises orthorhombic, has perfect cleavage and is vitreous.

It is white, rarely colorless. Due to impurities, it can be light yellow, grey, and purple. In thin sections, it is translucent to semi-transparent (fig. 424).

Fig. 424. Dolomite crystals (left) and dolomite rock (right).

Dolomite's specific density is 2.85 g/cm^3, and its hardness 3.5 to 4. It is dissolved in heated hydrogen chloride acid, which is how it differs from calcite. Its optical properties are similar to calcite, but what is different is the shape of its grains – rhombohedrons, when appears in crystals (fig. 425).

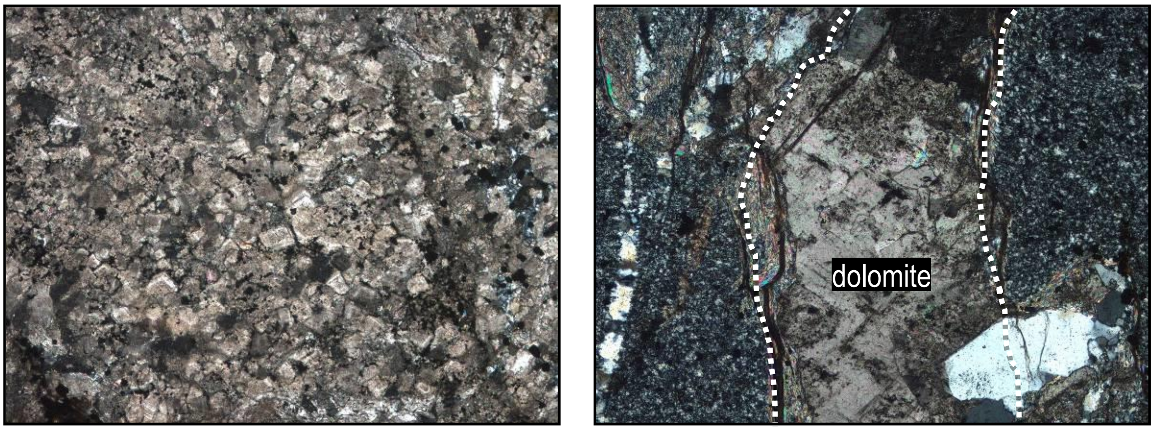

Fig. 425. Microphotograph of dolomite. Left in the mass of the rock; right in the vein (marked with white dots). XPL, magnification 100×.

Dolomite appears in different ways. It is created metasomatically with diagenetic processes, with the effect of solution of Mg on limestones. Its origin can be organic, hydrothermal or it can be found in metamorphic rocks. It is often associated with calcite. It is a very important mineral of dolomite sedimentary rocks, because they create huge massifs, just like limestones (fig. 426).

Fig. 426. Mountain range Dolomiti in Italy, made of dolomite rocks, which is made of dolomite mineral.

Dolomite is similar to limestone in the field. It differs from limestone in characteristic decomposition, when this rock breaks into small pieces, from a few centimeters in size to sand-size under the influence of weathering. Gruss becomes in these circumstances (fig. 427).

Fig. 427. Dolomite gruss.

Dolomite transforms into dolomite marble with metamorphism. Dolomite as a mineral is less stable then calcite under the metamorphic processes. In the presence of silica and water, in regional metamorphism, dolomite transforms into talc; and in contact metamorphism it transforms into tremolite, pyroxene, and garnet.

15.4. MAGNESITE $MgCO_3$

Magnesite is a carbonate of magnesium, $MgCO_3$. It contains SiO_2, as impurity, nicely dispersed quartz. It is more important as an ore mineral then as petrogenic one. It crystallizes trigonal.

It is white in color and can be found in fine-grained, compact aggregates with characteristic conchoidal fracture.

Magnesite is as shiny as glass, but when it appears in fine-grained aggregates, it becomes opaque. The specific density of this mineral is 3 to 3.5 g/cm^3, and hardness 4 to 4.5.

Magnesium excretes in alkaline environment, when pH is 9, in the presence of CO_2 and with pH 10 if there is this gas lacking.

The size of the magnesite grains depends on the ability and speed of solution to become oversaturated. In the nature we can find it in compact, fine-grained mass (fig. 428).

Fig. 428. Crystals of magnesite (left), and fine-grained microcrystalline magnesite with conchoidal fracture (right).

Magnesite becomes as a transformation of ultrabasic rocks, i.e. olivine in the presence of CO_2 or sedimentary.

It often builds veins, up to a few tens of centimeters in thickness in peridotites (so called veined magnesite) (fig. 429) or layers, together with other carbonates and minerals of clay (so called sedimentary magnesite).

It can also be created metasomatically, suppressing calcite with magnesite (so called crystalline magnesite).

Fig. 429. Magnesite veins in peridotites near Čajetina (Zlatibor), a small detail in the upper left corner.

In the sea water magnesite precipitates due to organisms that use it to build shells. In the marine environment, this mineral becomes by evaporation, when associate with haloids, halite, silvine and Ca sulphates.

Magnesite is used for making flame-resistant bricks.

15.5. **SIDERITE** $FeCO_3$

Siderite is iron carbonate, $FeCO_3$. Its color is pale yellow to reddish-brown and is transparent to translucent on thin pieces. Common impurities are Mn, Ca, and Mg, rare is Mg.

It crystallizes trigonal. Crystals are commonly scalenohedral or rhombohedral, although granular, platy and compact aggregates are more frequent. It may be found in botryoidal and ball-shaped masses, when is called spherulite (fig. 430).

Siderite has perfect or distinct cleavage, and glassy to semi-adamantine lustre. Specific gravity is 3.5 to 4 g/cm^3, and hardness 4 to 4.5. Fracture is conchoidal to splintery. It is within the group of brittle minerals.

Fig.430. Siderite crystals (left), and siderite in the rock mass (right).

Siderite appears hydrothermally in a wide temperature range. It usually comes with sulphides of Pb, Zn and Cu.

It can also appear sedimentary in reduction conditions, when it is earthy, usually associated with minerals of clay or organic substance, coal. In reduction conditions, in the presence of CO_2, Fe precipitates as siderite. Favorable conditions for creation of siderite are under the level of underground waters and in poorly ventilated parts of the sea. In a very reduction environment, in the presence of sulphur, pyrite is being created. We find these conditions in deeper parts of the closed seas where organic leftovers decompose without the presence of oxygen, but with the presence of anaerobic bacteria. This is how barite becomes.

Siderite can appear as secondary mineral, when it needs the influence of cold waters rich in CO_2 on minerals with high contents of Fe.

At the surface (weathering crust), it is transformed into limonite.

16. OXIDES AND HYDROXIDES

Oxides and hydroxides are compounds of metals and nonmetals with oxygen and water. Therefore, they are very important ingredients of rocks and soil. As petrogenic minerals, opal and chalcedony, oxides and hydroxides of iron, aluminum, chromium and titanium are especially important. Many oxides transform into hydroxides under the influence of weathering (compounds of metals and nonmetals with the OH group), thus forming more stable compounds.

16.1. IRON OXIDES AND HYDROXIDES

The most important ones among the iron oxides are **magnetite**, **hematite** and **limonite**.

16.1.1. MAGNETITE Fe_3O_4

Magnetite is an iron oxide, $FeO \times Fe_2O_3$. It contains its impurities, such as Mg, Mn, Ni, Ti which substitutes Fe^{2+} and Al, V, Ti and Cr which substitutes Fe^{3+}, and Al partly.

It crystallizes cubic. It appears in nice, regular octahedral crystals. In the rocks, it is more often in granular to firm, massive aggregates.

It is black, with metallic lustre, opaque, of conchoidal fracture, black when scratched, and without cleavage. It is extremely magnetic mineral. Its hardness is 5 to 6, with specific density 5.2 g/cm^3 (fig. 431).

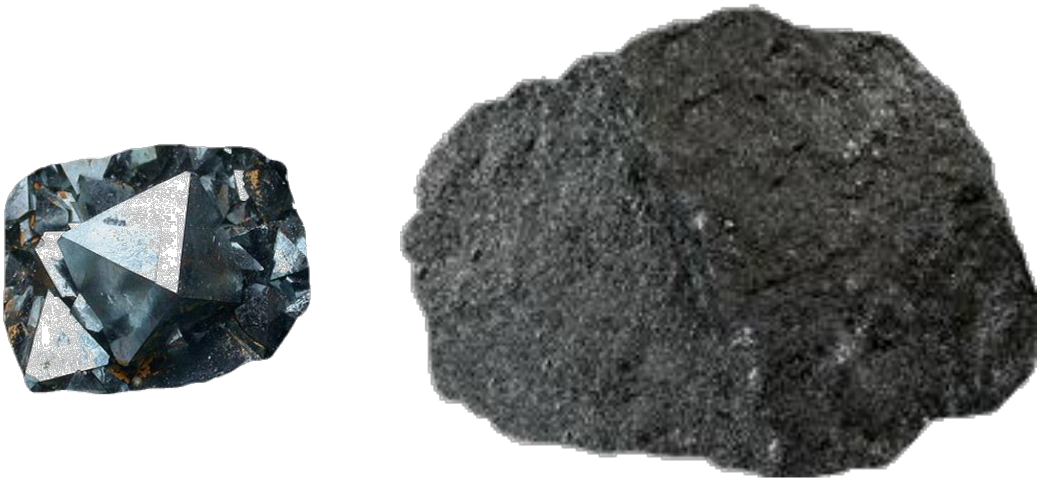

Fig. 431. Crystal of magnetite (left), and magnetite in ore (right).

It can become in a few ways: magmatic, contact-metamorphic and hydrothermally.

In the magmatic cycle, it appears in ultrabasic rocks (fig. 432), where it can form significant economic bearings. In basic rocks, it is associated with ilmenite, when it appears as accessory, minor constituent. It is opaque in the polarizing microscope.

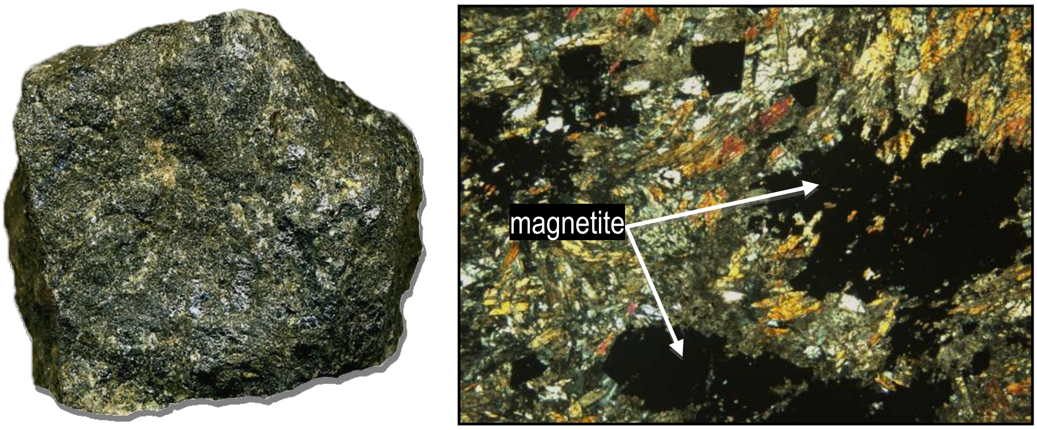

Fig. 432. Magnetite in peridotite (left), and in polarizing microscope for transmitted light (right). XPL, magnification 60×.

In contact metamorphic rocks, it appears where limestone and acid magmatic rocks meets each other, forming ore bearing skarns (fig. 433).

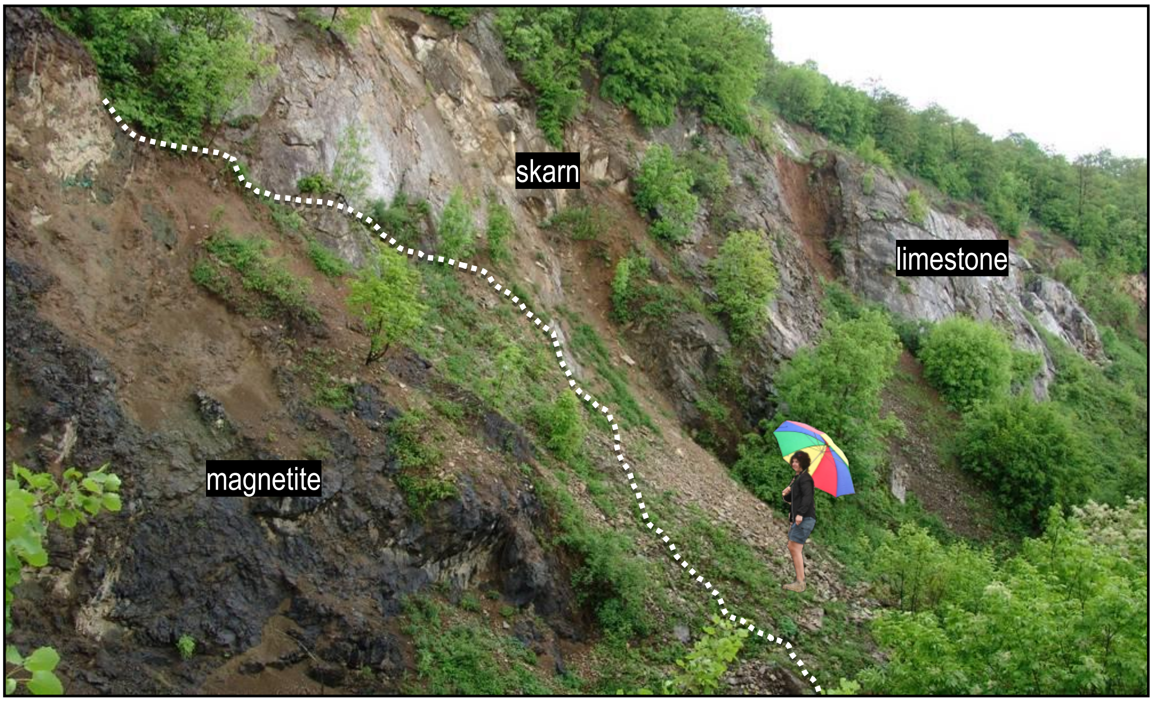

Fig. 433. Magnetite in skarn Rudna Glava, east Serbia.

We can find magnetite in regional metamorphic rocks, when it occurs as interlayers or lenses. It is considered that it became by recrystallization of iron hydroxides under metamorphic processes.

Magnetite can also be a secondary mineral made by transformation of minerals containing Fe: olivine, pyroxene, amphibole, mica (biotite). That's when it appears in fine-grained, dusty accumulations concentrated along cleavage planes and cracks (fig. 434).

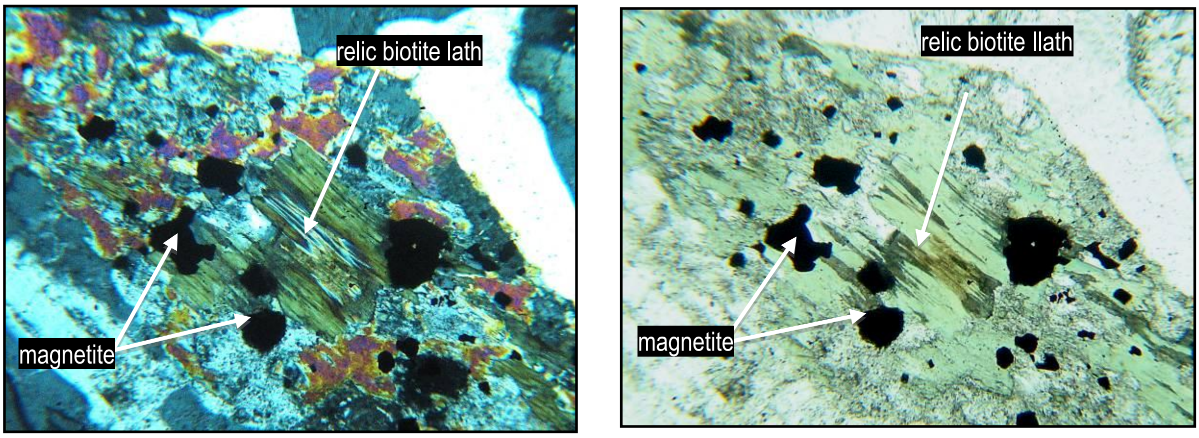

Fig. 434. Magnetite, became by alteration of biotite, XPL (left), and the same mineral with PPL, (right). Magnification 100×.

It often concentrates in the sand as being resistant to surface disintegration.

16.1.2. HEMATITE Fe_2O_3

Hematite is Fe_2O_3 in its composition. It contains Al and Ti as impurities. It is one of the most important iron ores. It crystallizes in trigonal system and appears in columnar, lath-like, leaved, and rarely granular to earthy aggregates, when it builds compact masses.

It is red, hence the name (Greek – blood) (fig. 435). It can be metallic grey or black, and is transparent in thin sheets. It is of metallic lustre, hardness 5 to 6, with specific density 5.0 to 5.2 g/cm^3. It has no cleavage, with conchoidal to uneven fracture. It belongs to fragile, weakly magnetic minerals.

Fig. 435. Crystals of hematite (left), and hematite in mass (right).

Grey hematite with steel-grey to black color and of brilliant metallic lustre is called **specularite,** which usually appears in regionally metamorphic rocks. Its streak is always red or dark red (fig. 436).

Fig. 436. Dark red streak of hematite.

Hematite is very rare in igneous rocks. It usually appears in granite or pegmatite. It becomes pneumatolytic, rarely hydrothermally.

The greatest masses of hematite are created by submarine eruptions of basic lava, often accompanied with silica, opal, i.e. jasper, which deposit as the rock, chert (fig. 437).

Fig. 437. The outcrop of hematite (3 × 1 m) with cherts, rich in iron.

It is also created sedimentary, in shallow environments, like oolite, excretion from iron colloids and combined with limonite. If there are significant masses, it creates mineral deposits. Hematite also appears as cement in sandstone (fig. 438).

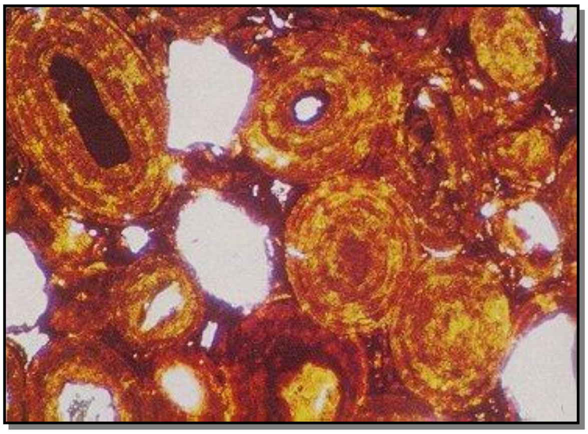

Fig. 438. Oolites of hematite and limonite in sandstone. PPL, magnification 200 x.

Hematite is also a secondary mineral, which occurs by oxidation of minerals rich in Fe, when the rock gains distinctive red color.

Hematite also becomes metamorphic, due to transformation of magnetite, siderite or iron oxides with water (limonite). We often find hematite pseudomorph after siderite, magnetite. Due to disintegration, this mineral transforms into limonite.

16.1.3. **LIMONITE** $Fe_2O_3 \times nH_2O$

Limonite is $Fe_2O_3 \times H_2O$ in its composition, and it belongs to the group of amorphous iron minerals. The amount of water varies in it. It occurs in grapy, kidney-shaped to earthy aggregates, masses, oolites, coatings, or as pseudomorph over pyrite and other iron-containing minerals (fig. 439).

Fig. 439. Kidney-shaped, botryoidal (left) and earthy mass of limonite (right).

Limonite's specific density is 3.0 to 3.4 g/cm^3, and its hardness is 1 to 3.

Limonite is yellow to dark yellow, rarely black. In thin sections, it is semi-translucent. It has semi metallic lustre, sometimes even silky. Earthy, yellow representatives, that can color your fingers are called ocher. Its scratch is yellow to dark yellow. It is present in the superficially altered rocks that contain minerals with iron. Under the influence of weathering, ultrabasic rocks underwent serpentinization and depending on the composition, limonitization in further phase of disintegration, creating in most parts weathering crust (fig. 440) with characteristic oolites of this iron hydroxide and clay minerals.

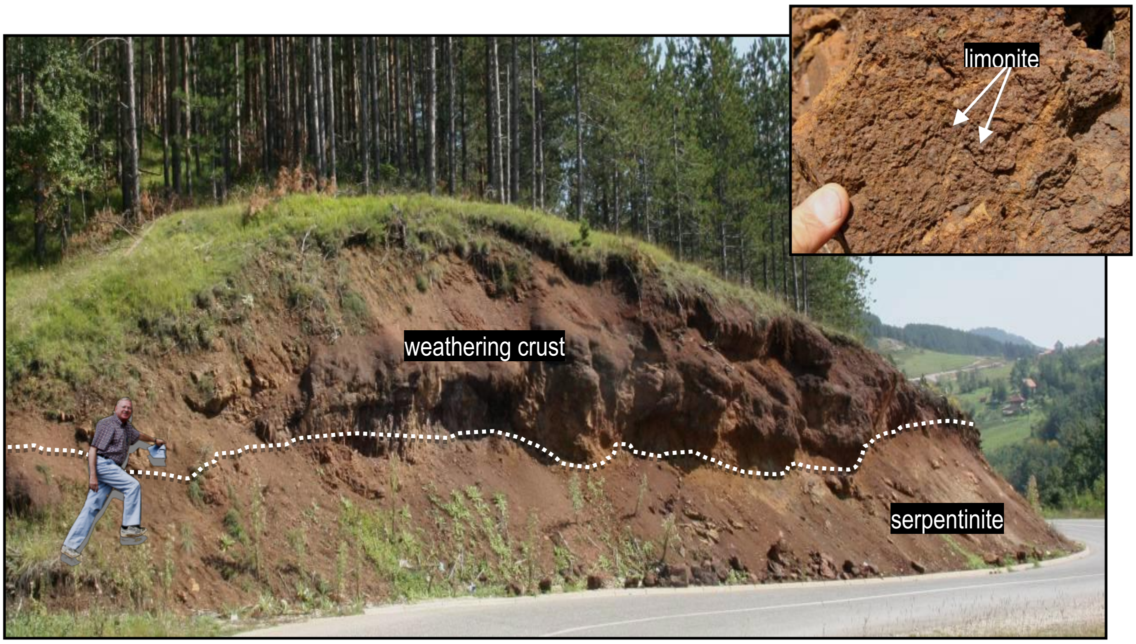

Fig. 440. Weathering crust at Zlatibor (near Kokin Brod). In the upper right corner we can see oolites of limonite.

Limonite appears in oxidizing zone of sulphide deposits, when it creates ‘iron hats’.

It also appears in sedimentary processes when it can be cement (fig. 441), or it creates sedimentary iron ores. Limonite is used as pigment in the production of colors.

Fig. 441. The outcrop of red Permian sandstone with limonite bonds, Pesača on Danube. In the upper left corner we can see microphotograph of the rock, XPL, magnification 40×.

16.2. THE CHROMITE SERIES

16.2.1. CHROMITE $FeCr_2O_4$

Chromite is $FeCr_2O_4$ in its chemical composition. It contains Mg, Al i Fe^{3+} as impurities.

It crystallizes cubic, rarely in crystals, surrounded by octahedrons. They are usually granular, massive aggregates. It is dark brown to black in color (fig. 442), metallic, sometimes of resinous lustre, and gives dark yellow to dark brown streak. Its specific density is 4.0 to 4.8 g/cm^3, and its hardness is 5.5 to 6. Chromite doesn't have cleavage.

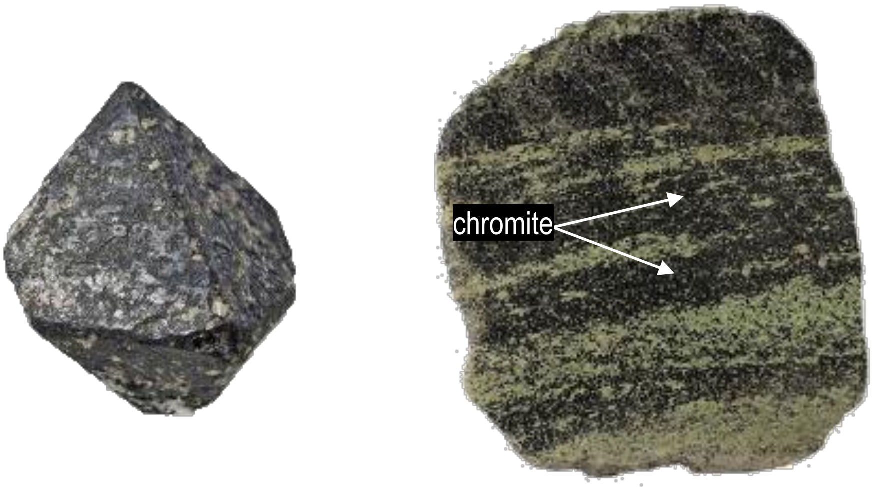

Fig. 442. Chromite crystal (left), and chromite in the mass of peridotite, dunite (right).

In polarizing microscope, chromite is black when nicols are crossed, and red to yellowish brown when nicols are parallel (fig. 443) which is a distinctive color for mineral. It has high relief and it belongs to stable minerals.

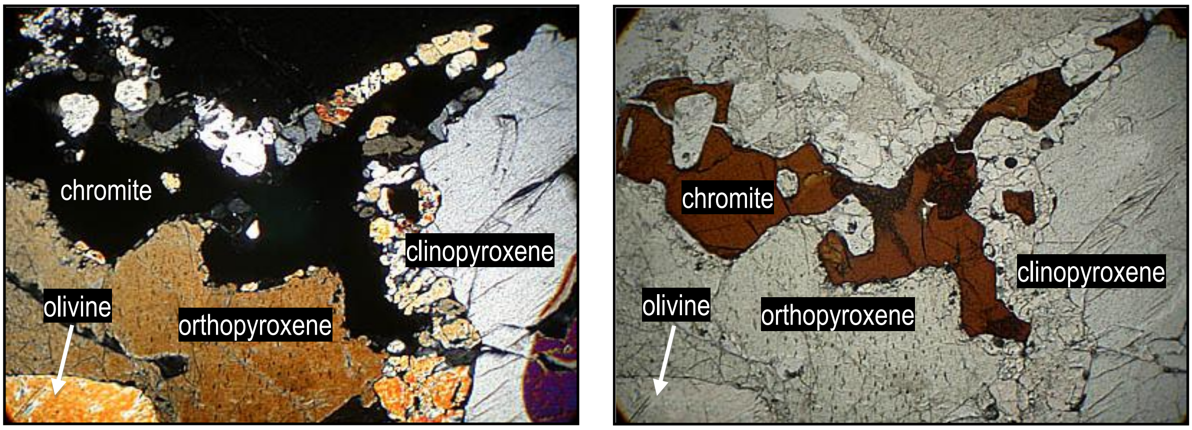

Fig. 443. Microphotograph of chromite in peridotite, XPL (left), and chromite in the same rock, PPL (right). Magnification 100×.

Chromite is igneous and it related to ultrabasic rocks, peridotites, where it usually crystallizes first (fig. 444). In these rocks, it appears as an accessory mineral. There is significant concentration of it, when it forms ore bearings.

Fig. 444. Abandoned chromite mine in Brezovica, Šar mountain.
In the upper right corner, sample of chromite.

16.3. GROUP OF SPINELS

Spinels are very complex in their composition. They are compounds of aluminum with Mg, Fe, Mn and Zn. Chromite and magnetite also belong to this group of minerals. Most commonly, spinels appear as accessory minerals in ultrabasic and basic rocks. We'll only mention the most important ones: **spinel** which is $MgAl_2O_4$ in its composition and **hercynite** which is $Fe2^{+}Al_2O_4$ in its composition.

They crystallize cubic; they have different colors, from red, brown, and black to green, yellow and grey. They don't have cleavage. They appear in octahedral and rhombododecahedral crystals, often twin. But they can also be found in granular to massive aggregates.

They have vitreous shine and conchoidal fracture. Their specific density varies from 3.6 to 3.7 g/cm^3, and hardness from 7 to 8. In rock mass it appears as black grains, up to few mm in size (fig. 445). However, these minerals can be very pretty when we refer them as gemstones (fig. 446).

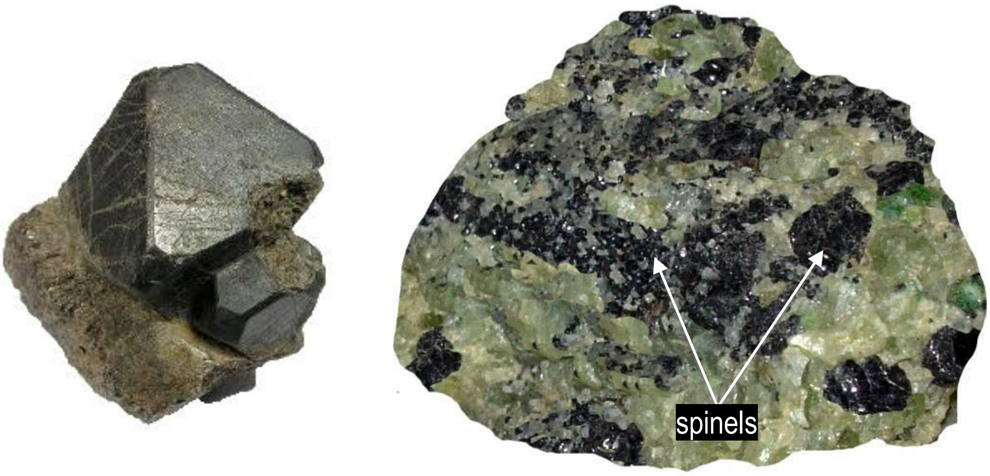

Fig. 445. Crystal of spinel (left), and spinel in the rock mass (right).

Fig. 446. Spinels as gemstones.

In polarizing microscope, when nicols are crossed, spinels are black, and when the nicols are parallel, they are green (when they contain chromium) (fig. 447).

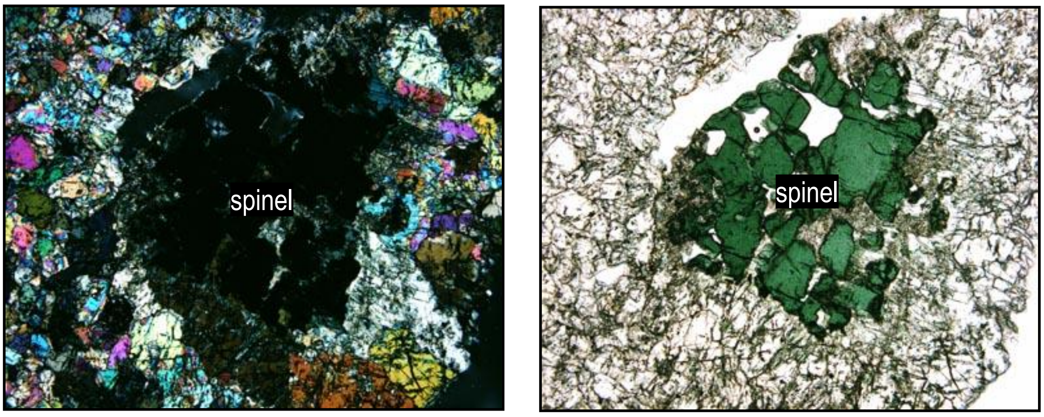

Fig. 447. Microphotograph of spinel rich in chromium in peridotite, XPL (left), the same mineral, PPL (right). Magnification 60×.

Spinels can be igneous when they appear as accessory minerals, the most commonly in ultrabasic and basic rocks (fig. 448). We find them also in regional metamorphic rocks, created under medium to high metamorphic grade (granulites). They can also appear in contact metamorphic processes.

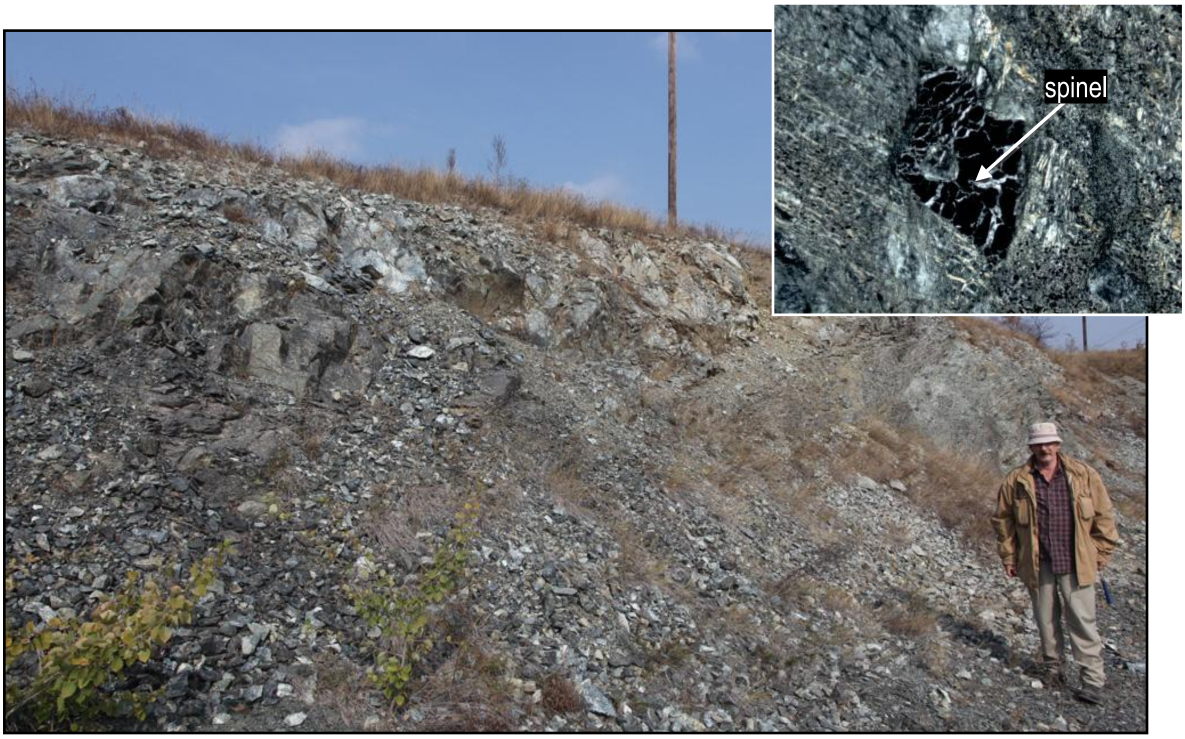

Fig. 448. Serpentized peridotites in Petrovo selo (East Serbia) containing spinel as accessory mineral. In the upper right corner, we can see microphotograph of the spinel from this rock. XPL, magnification 100×.

16.4. TITANIUM OXIDES

Titanium oxides can be of simple and complex chemical composition. Simple oxides are: ilmenite, which is Ti and Fe oxide in its composition, and rutile which is Ti oxide. Among complex minerals we distinguish: perovskite, a titanate of calcium. They are mainly connected to basic rocks.

16.4.1. ILMENITE $FeTiO_3$

Ilmenite is a titanate of ferrous iron, $FeTiO_3$. It contains Mg, Al, Mn and Ca as impurities, which isomorphous combine with Fe.

It crystallizes trigonal. It appears in crystals or prismatic to granular aggregates. It is very common included as lamellar in other minerals (magnetite).

Ilmenite is dark brown to black in color, metallic to semi metallic lustre, with reddish brown fracture. It can be partly translucent in thin sections.

Ilmenite doesn't have cleavage, and streak is black. This mineral is very fragile. Its specific density is 4.8 g/cm^3, and its hardness from 5 to 6 (fig. 449).

Fig. 449. Ilmenite crystal (left), and ilmenite in pegmatite (right).

In polarizing microscope, with nicols crossed and parallel, it is black, because it belongs to opaque minerals according to optical characteristics (fig. 450).

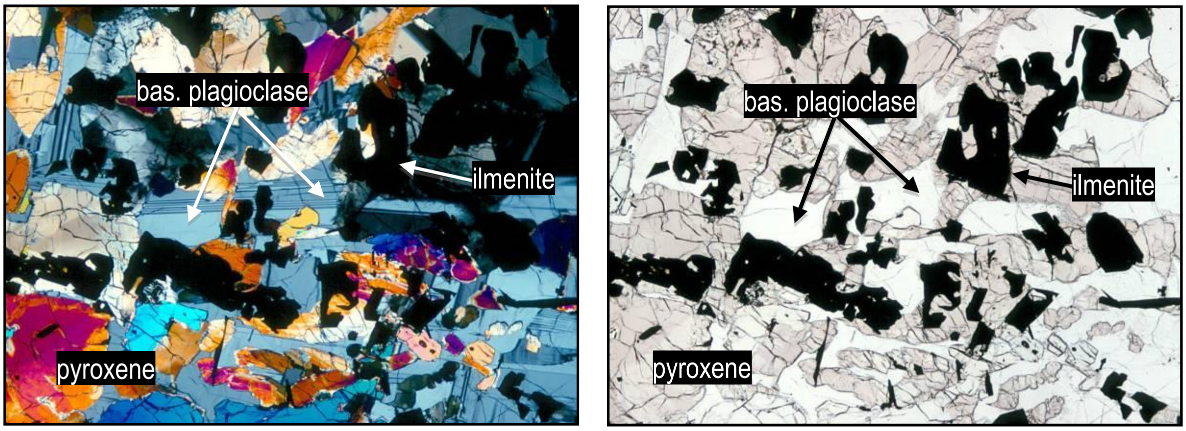

Fig. 450. Microphotograph of ilmenite in gabbro, XPL (left), and PPL (right), magnification 100×.

The presence of this mineral in microscope can be determined according to the shape of crystal, when they are euhedral.

It is often joined with titanomagnetite or magnetite.

Ilmenite is common as an accessory mineral in igneous, and is particularly often in basic igneous rocks, gabbros and their pegmatites, where we can find significant accumulations, forming ore deposits (fig. 451). Under the influence of hydrothermal solutions and processes of alteration, ilmenite, as well as titanite, transforms into leucoxene.

Fig. 451. In gabbro from Glavica near Donji Milanovac ilmenite is accessory mineral. In the upper right corner, there's a sample of the rock with ilmenite.

16.4.2. **Rutile** TiO_2

Rutile is TiO_2 in its composition. As impurities in it, often occurs Fe, Nb, Ta, W, Sn and other elements. It crystallizes tetragonal.

It appears in prismatic crystals (fig. 452). It can be lathy to acicular. Twin forms of this mineral are quite common.

In thin sections, rutile is transparent to translucent. Due to impurities, it is usually light yellow, yellowish brown to brown, dark red to black.

It has adamantine to metallic lustre, perfect cleavage and conchoidal to uneven fracture.

Fig. 452. Crystal of rutile (left), and rutile in the rock mass (right).

Rutile's streak is yellowish brown to brown; hardness is 6 to 6.5, with specific gravity from 4.2 to 4.5 g/cm^3. Rutile appears also as an inclusion in quartz (fig. 453).

Fig. 453. Needles of rutile in quartz crystal.

It is igneous in its origin, but it is often accessory mineral in acid intrusive igneous rocks or in basic rocks, when is associated with ilmenite and magnetite. It appears in pegmatite, sometimes even forms as contact metamorphic, pneumatolytic and hydrothermal mineral.

We often find it in metamorphic rocks, as accessory mineral.

In polarizing microscope, rutile has strong pleochroism in yellowish brown to brown color and high relief (fig. 454).

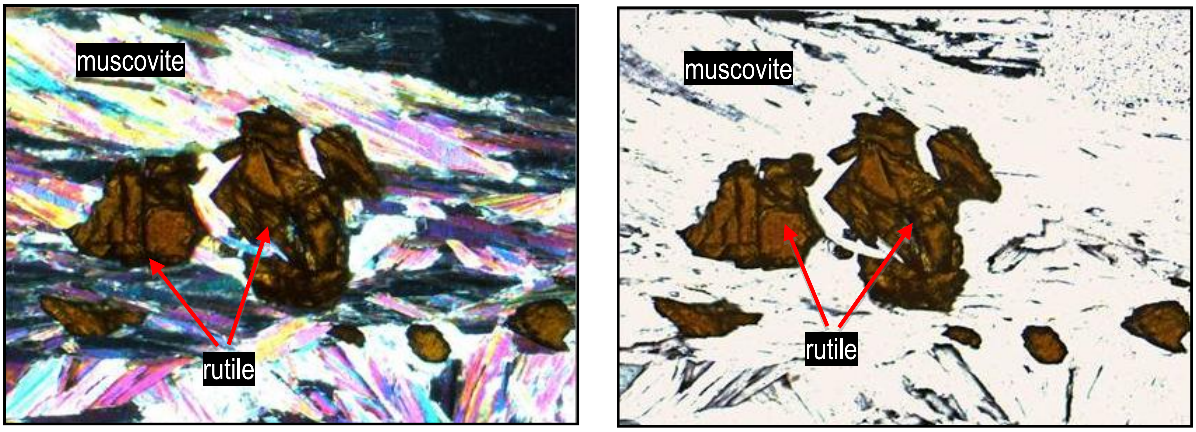

Fig.454. Microphotograph of rutile, XPL (left), and rutile with PPL (right). Magnification 100×.

Rutile also forms by hydrothermal transformation of other titanium minerals: ilmenite, biotite, hornblende etc. There is it usually in needle shaped aggregates.

When it is found at the surface, rutile is chemically stable, so we find it in sea and river deposits.

16.4.3. PEROVSKITE $CaTiO_3$

Perovskite is a titanate of calcium. As impurities, it contains: Na, Fe^{2+}, Ce, Sr, Nb and Ta.

It crystallizes orthorhombic; its colors are brown, yellow and black (fig. 455). When it appears in crystals, it is in the shape of cube, octahedral or a combination. It is usually present in firm, kidney-shaped aggregates. Complex mimetic twinning gives teseral habitus to a crystal.

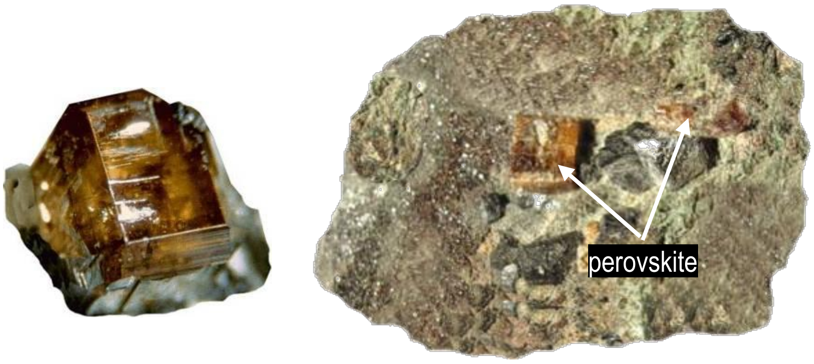

Fig. 455. Crystal of perovskite (left), and perovskite in rock (right).

It has imperfect cleavage, and specific density 4 to 4.8 g/cm^3, hardness 5 to 5.5. Its shine is metallic, with uneven fracture. The structure of perovskite is very dense, so it is considered to being present in the mantle at depths of 400 to 1000 km. According to experimental and theoretical examinations, most of the minerals at these depths have the structure of perovskite, including CaSiO3, $FeSiO_3$, $MgSiO_3$. In polarizing microscope, its relief is high with strong brown pleochroism (fig. 456).

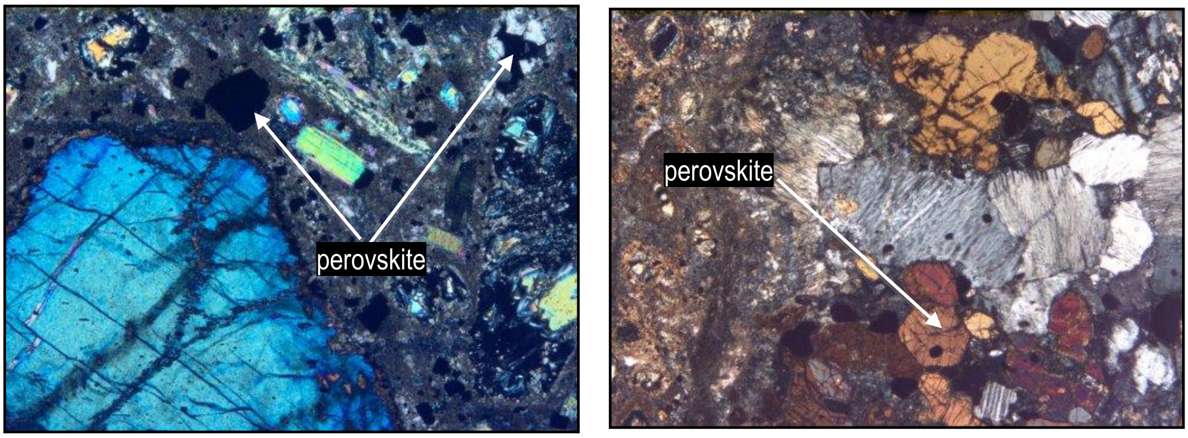

Fig. 456. Microphotograph of perovskite, XPL, left and PPL, right. Magnification 80×.

Perovskite is very often accessory mineral in igneous rocks of acid to basic composition. And it is commonly associated with melilite, leucite and nepheline. It can appear in metamorphic or contact metamorphosed rocks.

16.5. ALUMINUM OXIDES AND HYDROXIDES

We'll show corundum and bauxite from this group of minerals.

16.5.1. CORUNDUM Al_2O_3

Corundum is an aluminum oxide, Al_2O_3. As impurities, it contains Fe, Cr, Ti, V and Ni. It crystallizes trigonal, sometimes even in nice shapes (fig. 457). Corundum doesn't have cleavage, and has vitreous lustre. Its specific density is 4.0 g/cm^3. Originally is it colorless, but it can have various colors, depending on the impurities: blue **sapphire** and red **ruby** that are gemstones (fig. 458). Previously mentioned minerals are very hard - 9, with uneven fracture.

Fig. 457. Corundum crystals (left), and corundum grains in micaschists (right).

Corundum, ruby and sapphire can be made artificially. Alumina is used as raw material, and appropriate color is achieved by adding titanium, vanadium, iron or chromium.

Fig. 458. Ruby crystal, left, and sapphire (middle); the same minerals as gemstones (right).

In polarizing microscope, when nicols are crossed, corundum is grey, yellow and yellowish red, and when nicols are parallel, it is transparent and with high relief (fig. 459).

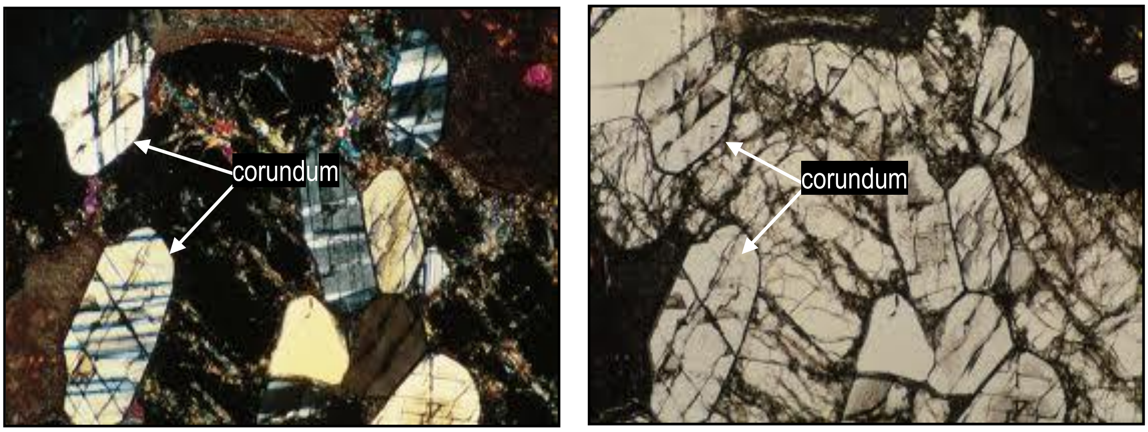

Fig. 459. Microphotograph of corundum in schist, XPL (left), the same mineral with PPL (right). Magnification 100×.

Corundum appears in regionally metamorphosed clay sediments rich in aluminum and poor in alkalis, earth-alkalis, iron and magnesium, under conditions of intermediate and high metamorphic grade (fig. 460). We also find it in pegmatite of acid igneous rocks and in wall-rock altered rocks, allied to ores of copper, gold, lead and zinc. It is very resistant when falling apart, it concentrates in deposits.

Fig. 460. In Bistrica amphibolite (Prijepolje) occurs corundum. In the upper right corner is corundum.

16.5.2. BAUXITES

Bauxites are specific kind of sedimentary rocks, in its composition aluminum hydroxides. There is a variable quantity of clay minerals, quartz and opal, as well as Fe hydroxide. Rutile, ilmenite, etc. can appear as accessory minerals. With these minerals, oolites, Fe and Ti often appear.

The most important bauxite minerals are gibbsite, boehmite and diaspore. We will discuss gibbsite and diaspore.

Gibbsite is very rare present in small, laminar, pseudo hexagonal crystals (fig. 461). It usually makes earthy to clayish aggregates.

It is white and grey, often colored in yellow and red, but it can be light green, due to presence of iron hydroxides. It's vitreous, pearly along the cleavage planes. It crystallizes trigonal.

Fig. 461. Gibbsite crystals (red).

It has perfect cleavage, tough. Its hardness is 2.5 to 3, and its specific gravity varies from 2.5 to 3.5 g/cm^3.

It results from the weathering of igneous and metamorphic rocks (granite, gneiss under wet and hot conditions of tropical climate) when aluminum and iron are kept as insoluble remains, creating laterites, in characteristic red color, because of iron hydroxide (fig. 462). Apart from the mentioned minerals, there are ferruginous clays, silica (amorphous) and titanium oxides. When these minerals dissolve, they can be further transported by atmospheric agents (usually water) and deposited again. This is happened mainly in limestone areas, as favorable collectors for the deposits. Succeeding chemical processes (hydrolysis), aluminum is being even more released and it concentrates, producing bauxites. A lot of these limestone laterites and bauxites, we find in Zlatibor area.

Fig. 462. Laterites on Zlatibor. The sample of bauxite in the upper left corner.

Diaspore is rarely found in prismatic and bypyramidal crystals. It usually makes earthy to clayey masses.

It is vitreous in crystals, and pearly at the cleavage planes. It is often yellowish brown, due to presence of Fe hydroxides. It has conchoidal fracture, hardness 6.5 to 7, specific density 3.3 to 3.5 g/cm^3. It crystallizes orthorhombic.

It becomes in the same way as other bauxites: weathering of aluminous silicate rocks in tropical conditions (high humidity and temperature).

Bauxites differ from clays, because they aren’t plastic in contact with water. Diaspore transforms into corundum when heated on high temperatures.

Bauxites are essential raw material for aluminum manufacture.

17. SULPHATES

Sulphates are salts of sulphuric acid. In rocks are less abundant than carbonates, but are frequent in weathering crust. Two sulphate minerals, gypsum and anhydrite, will be present in the text ahead.

17.1. GYPSUM $CaSO_4 \times 2H_2O$

Gypsum is hydrated calcium-sulphate, $CaSO_4 \times 2H_2O$. Common impurities are Si, Al, Fe etc.

It crystallizes monoclinic and under suitable conditions forms amazing crystals or twins known as swallow tail twins. Fine-grained, white aggregate is alabaster. Gypsum occurs in granular, platy to earthy aggregates (fig. 463).

Gypsum is almost usually white to whitish-grey, with glassy lustre or pearly along the cleavage directions. May be translucent or transparent. Cleavage is distinct to perfect in three directions. When heated lost water, but easily absorbs it again. Specific gravity is 2.3 g/cm^3, and hardness is 2.

Fig. 463. Crystal of gypsum (left), and gypsum in a rock mass (right).

It forms on few ways:

- hydrothermally, when associates with copper, lead and zinc sulphides, with carbonates, quartz;
- precipitates from oversaturated ionic solution in sea, commonly by evaporation;
- in desert regions, also in evaporates, when beautiful rosette shaped crystals known as desert rose form (fig. 464);
- crystallize from cold water solutions in salt deposits;
- through hydration of anhydrite.

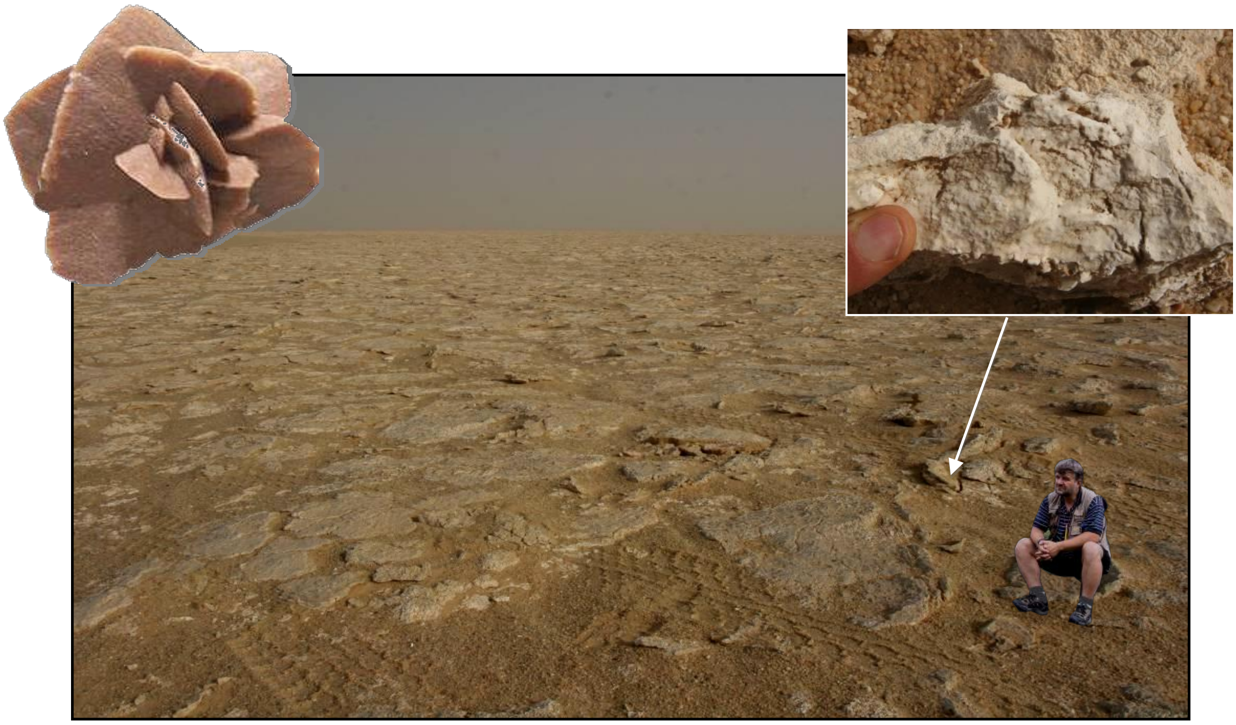

Fig. 464. Gypsum masses formed in desert area (Sahara). Above right, a detail. The same conditions lead to formation of the desert rose, above left.

In polarizing microscope gypsum displays grey interference colors with crossed nicols and is colorless, of low relief with parallel nicols (fig. 465). It is very important mineral, together with other alteration minerals, in exploration of copper, lead and zinc mineralizations and may indicate on new ore bodies.

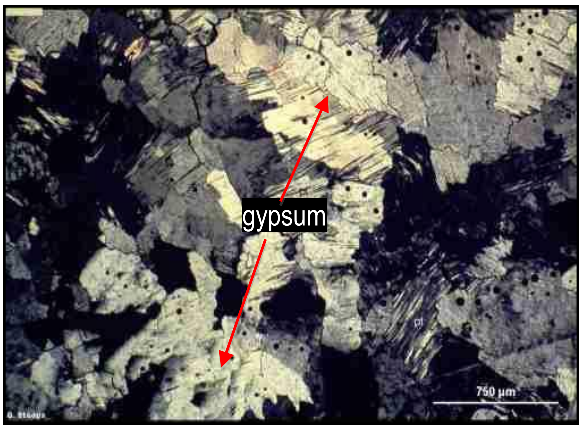

Fig. 465. Microphotograph of gypsum, XPL, magnification 80×.

17.2. **ANHYDRITE** $CaSO_4$

Anhydrite is sulphate, $CaSO_4$. As impurities occur Ba and Sr. It is orthorhombic and appears in granular or compact masses. Crystals are rare.

Cleavage is perfect, color white and lustre pearly. It is transparent to translucent, with specific gravity 3 g/cm^3, and hardness, also 3 to 3.5 (fig. 466).

Fig. 466. Crystals of anhydrite (left), and anhydrite in a rock mass (right).

It is found in salt deposits as evaporate mineral that used to be precipitated as the first. Absorbing water anhydrite converts into gypsum.

Anhydrite is also found in marls and claystones in a form of concretions that derived by sulphuric acid action on existed carbonate minerals. It forms also hydrothermally within the alteration products related to Cu, Zn and Pb mineralizations. In polarizing microscope exhibits yellow interference colors, with crossed nicols, and is colorless with low relief, at parallel nicols (fig. 467).

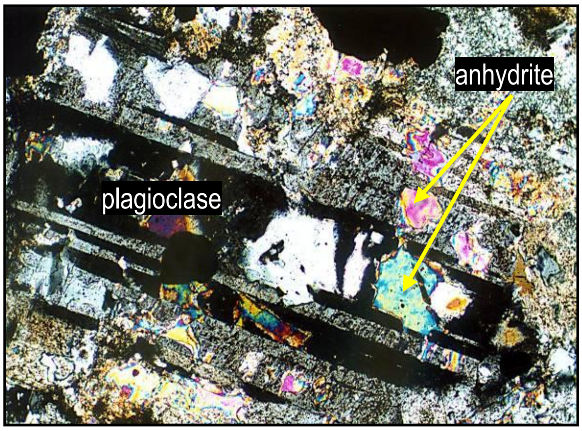

Fig. 467. Microphotograph of anhydrite partly replacing plagioclase. XPL, magnification 60×.

Vast masses of gypsum and anhydrite develop in oxidation zones in metalliferous sulphide deposits of Fe, Pb, Zn and Cu (pyrite, galena, sphalerite, chalcopyrite), when SO_4^{2-} ion adsorbs water from the air and generates sulphuric acid. Acid „attacks“primary minerals in a host rock, including calcium-bearing intermediate plagioclase, resulting in their partial to complete replacement by newly-formed anhydrite and gypsum.

This is a common process, may be very intensive at copper mineralizations. Anhydrite, gypsum and other alteration minerals, sericite, kaolinite, alunite, neobiotite, chlorite, epidote, zunite, diaspore and andalusite are prospection criterions in discovering new ore bodies of mentioned metal, copper (fig. 468).

Fig. 468. Andesites-bearing mineralizations in the copper mine Majdanpek are hydrothermally altered and contain anhydrite and gypsum. Above right is a sample of altered andesite.

18. HALIDES

Potassium and sodium are easily soluble elements. Both precipitates from solutions only after it evaporate. Potassium is, due to large ion radius, mostly „captured” in clay minerals (illite) and significantly less abundant than sodium in the sea-water. However, in igneous rocks, which are the source of the both elements, their content is nearly equal.

Sodium and rest of potassium, along with some calcium and magnesium, precipitate in closed seas through evaporation, i.e. from drying up. When the sea-water (without tributaries bringing fresh-water) evaporates the calcium-sulphate (gypsum) precipitates as the first (due to relatively low solubility) and anhydrite afterwards. Ongoing evaporation leads to precipitation of halite rather than potassium-magnesium salts, although is more soluble. The reason is its higher abundance in the sea-water.

In desert, arid-climate areas evaporate minerals (potassium-sodium carbonates, borates, nitrates) form under disappearing of water from desert lakes. Under evaporation the capillary water rise up towards the surface and precipitate dissolved substances. Such occurrence is known as „efflorescence”.

Salts do not have importance as building material, but are, at least some of them, important for human beings. Here will be mention the halite, inevitable flavor in cooking.

18.1. HALITE NaCl

Halite is rock-salt, sodium chloride (NaCl) in composition. Pure halite is not common; it often contains smaller amounts of magnesium and potassium chlorides, sulphates, clays, and organic matter, which impact its physical and physiological properties.

Specific gravity is 2.2 g/cm^3, and hardness 2 to 2.5. It is brittle and water soluble mineral. It is white, or colorless and transparent, but may be bluish or violet-blue if lattice is deformed (fig. 469).

Fig. 469. Crystals of halite (left), and halite as a salt-mass (right).

Halite crystallizes cubic, predominantly in cubic crystals or octahedral, but also occurs in granular masses known as a rock-salt. Cleavage is perfect, lustre vitreous, colorless or white, or pinkish and green with impurities.

Halite testes salty, or bitter-salty when contains some magnesium.

It forms, as has been said already, in salt deposits by evaporation (disappearing) from sea-water that contains dissolved sodium chloride (fig. 470). Commonly associates with gypsum, anhydrite and borates.

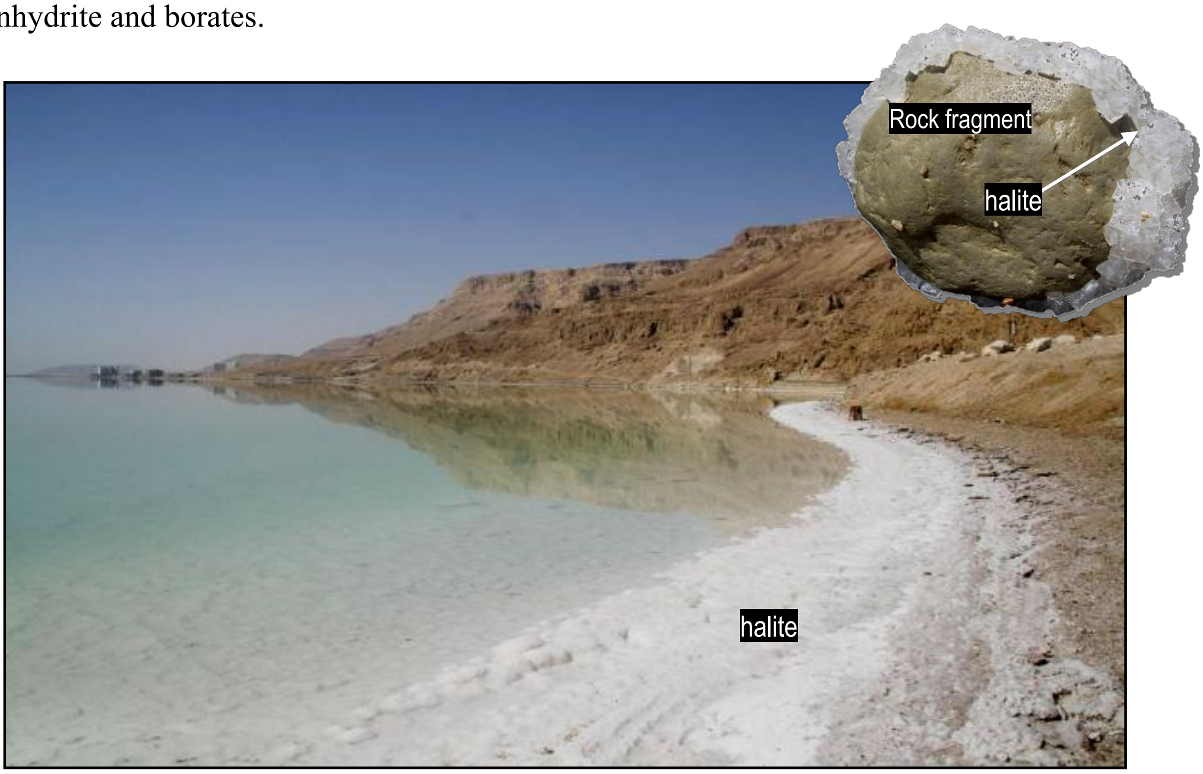

Fig. 470. Deposited halite, white, at the Dead Sea coast. Above right is a rock fragment coated with halite.

Halite forms as a product of „efflorescence“from the soil containing it, after sudden and rapid drying up. It also may be a sublimation product in volcanic regions when synchronously deposit or crystallize with potassium chloride.

19. PHOSPHATES

Phosphates are salts of phosphoric acid. They are common accessory minerals in rocks. Apatite is by far, the most important for petrology.

19.1. APATITE $Ca_3(PO_4)_3(F,OH,Cl)_2$

Apatite is calcium-phosphate with appreciable chlorine and fluorine content. Crystallizes hexagonal and occurs as a very common accessory constituent in almost all igneous rocks, from acid to basic.

Apatite occurs rarely in crystal forms; generally it appears in oval, rounded grains (fig. 471). Apatite is often included in silicate minerals, such as biotite, amphibole and pyroxene.

Fig. 471. Crystal of apatite (left), and apatite in a rock-mass (right).

Apatite is generally colorless, but may be yellowish-green, bluish-green, violet or pinkish. Transparent to translucent grains of vitreous lustre are quite common. Occurring in granular or massive aggregates exhibits resinous lustre. The absence of a good cleavage and its specific gravity from 3.2 to 3.4 g/cm^3, and the hardness 5 are its additional distinguishing features. In polarizing microscope, apatite displays grey to bluish-grey color under crossed nicols, and the high relief in colorless crystals under parallel nicols (fig. 472).

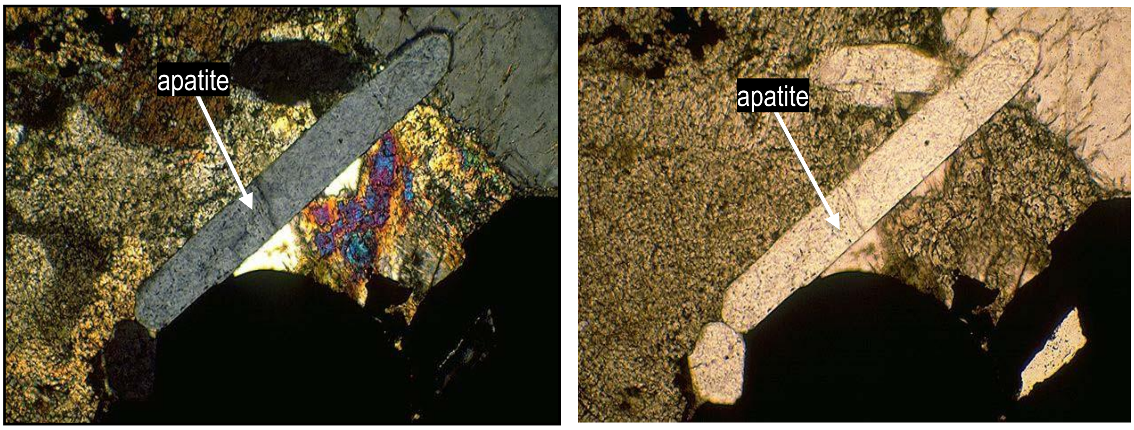

Fig. 472. Microphotograph of a large apatite crystal in granite, XPL (left); same image with PPL (right). Magnification 60×.

Apatite is igneous mineral. It is mostly related to acid (fig. 473) and to alkali igneous rocks where occurs as an **accessory mineral**. Apatite is not uncommon in pegmatitic-pneumatolytic phase, as well as in metamorphic rocks. As being highly resistant to weathering, apatite concentrates in detrital deposits.

Fig. 473. Syenite at Tanda (East Serbia) contains apatite as an accessory mineral. Above right, the rock sample.

This mineral forms sedimentary, too. Such formed apatite occurs in cryptocrystalline accumulations, concretions or earthy masses and is named **phosphorite** (fig. 474). Cryptocrystalline phosphorite is rarely pure, commonly contains impurities of clay and occurs as crusts, botryoidal and earthy masses.

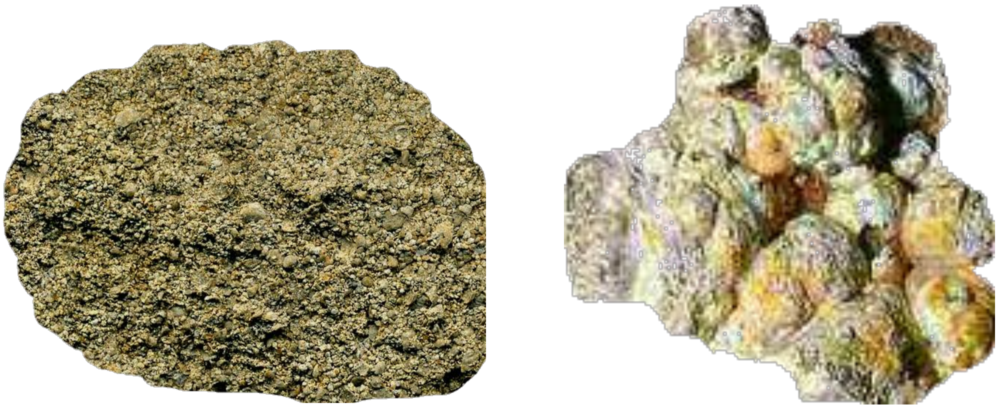

Fig. 474. Phosphorite (left), and nodular phosphorite (right).

Phosphorite forms throughout biochemical processes in shallow-sea environments or from seabird excrements in so-called guano deposits (fig. 475).

Fig. 475. Formation of phosphorite in guano deposits. Above right – a detail.

20. SULPHIDES

Sulphides are important group especially within the metalliferous minerals. They rarely appear as petrogenic minerals. Pyrite, the iron sulphide is the commonest in rocks.

20.1. PYRITE FeS_2

Pyrite is iron sulphide with variable amounts of Cu, Ni, Au, Ag, Cu, Sb, Tl and As.

In the nature occur beside pyrite other modifications of FeS_2 composition: **marcasite,** of same composition, and orthorhombic **melnicovite**, which is amorphous to cryptocrystalline.

Pyrite crystallizes in cubic system and appears in cubes (fig. 476) or pentagonal dodecahedron crystals habit with "striated" faces. It is often large-sized; up to a few cm. Druses are common. Pyrite occurs in granular, botryoidal, ball-shaped and compact masses or aggregates. Color is brass-yellow, lustre metallic, opaque with indistinct cleavage. Streak is greenish-black to brownish-black; specific gravity is 4.92 to 5.01 g/cm^3, and hardness 6. Pyrite twinkles when hammered and smells like sulphur dioxide.

It is not resistant mineral. In the presence of atmospheric agents decomposes into limonite, with producing sulphuric acid that is very aggressively affecting rocks.

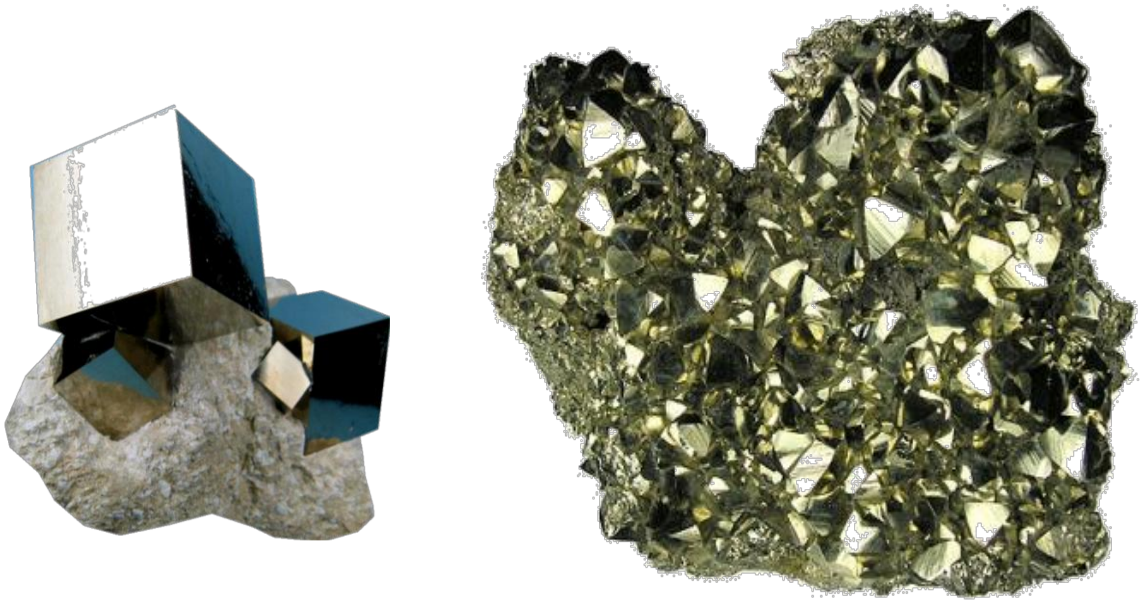

Fig. 476. Crystals of pyrite (left), and pyrite in a mass (right).

Pyrite is the most widespread sulphide. It is igneous, sedimentary and metamorphic mineral and may form within a wide range of pressures and temperatures, including superficial, reduction conditions. The commonest form of pyrite is in hydrothermal veins (fig. 477). It appears in wide variety of forms, but the most beautiful crystals are of hydrothermal origin (fig. 478).

Fig. 477. Pyrite vein, 5 cm thick in ore-bearing rock in the mine Rudnik.

Fig. 478. Twinned crystals of pyrite (left), rosette (middle) and as fossil replacement pseudomorphs (right).

21. ELEMENTS

A small number of elements occur as a native one building their own minerals. A small number of minerals - elements take part in rock-forming processes. The commonest and not less important are carbon and sulphur.

21.1. DIAMOND C

Diamond is cubic crystallized carbon, which appears in amazing octahedral, less frequent hexahedral and rhombododecahedral forms.

Sub-microscopic sized garnet (pyrope) grains, olivine and pyroxene are possible to being impurities in diamond. Diamond may be variously colored. It is often colorless but due to impurities resembles yellow, red, violet, blue and green colors. It is the hardest natural mineral (10). Cleavage is perfect, fracture conchoidal. Specific gravity is 3.5 g/cm^3 (fig. 479).

Diamond is very important as a precious stone. High hardness enables its application in diamond drilling as diamond-studded bits. It is very resistant mineral and tends to concentrate in placer deposits.

Fig. 479. Diamond crystal (left), and cut diamond (right).

Primarily forms as igneous mineral at very high pressures and temperatures. Genetically is mostly related to specific kind of igneous rock, kimberlite (fig. 480), volcanic breccias that occur in channels (pipes). Kimberlite is named after Kimberley, the city of diamond in South Africa. Kimberlite being considered as formed the upper mantle at depths exceeding 150 km. They were erupted rapidly with significant presence of CO_2 and other volatiles.

Fig. 480. Underground exploitation of diamonds from kimberlites, South Africa.

Kimberlites are ultrabasic alkali rocks consisting of olivine (forsterite), ilmenite, chromium-bearing garnet, pyrope, chromium diopside, phlogopite, and enstatite. These rocks also carry xenoliths of peridotite with pyrope (fig. 481). Mentioned minerals occur as large crystals embedded in fine-grained groundmass revealing brecciated texture to a rock. Diamond may be found in alkali volcanic rocks, too.

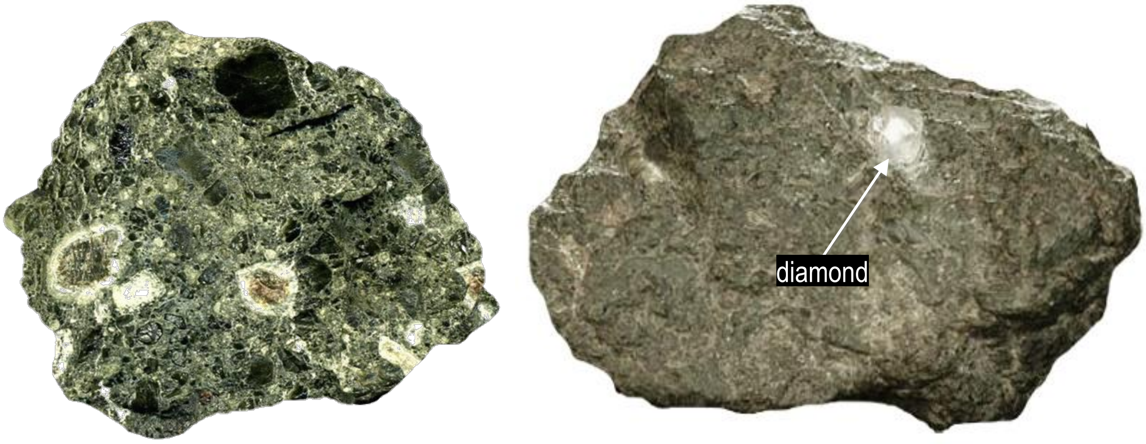

Fig. 481. Kimberlite (left), and kimberlite with diamond (right).

21.2. GRAPHITE C

Graphite is, like a diamond, native carbon mineral. Common impurities are Si, Al, Mg, Ca and Fe. It crystallizes hexagonal in platy crystals, micaceous aggregates or compact masses. Its color is grayish black to almost black, cleavage perfect, and streak black or dark grey. Specific gravity is 2.2 g/cm^3, hardness 1 to 2. Lustre is metallic and leaves mark on fingers when touched (fig. 483).

It is good conductor of electricity and heat. It is used for writing tools (pencils), as fill in tire-production and in electro industry.

Fig. 483. Crystals of graphite (left), and graphite in a rock mass (right).

It forms regionally-metamorphic from organic matter-enriched sediments (fig. 484), contact-metamorphic, rarely igneous in pegmatitic phase.

Fig. 484. Graphite schist near Bosilegrad.

21.3. SULPHUR S

Native sulphur, as being called often, is very abundant in nature. Elemental sulphur may contain Se, As and Te as impurities, whereas the biogenic sulphur contains organic matter. It crystallizes orthorhombic with a monoclinic polymorph modification. It appears in crystals, although coatings and earthy masses are more common. It is typically lemon-yellow in color (fig. 484), but becomes red with presence of Se. It is brittle, soft (hardness 1 to 2), with specific gravity 2 g/cm^3.

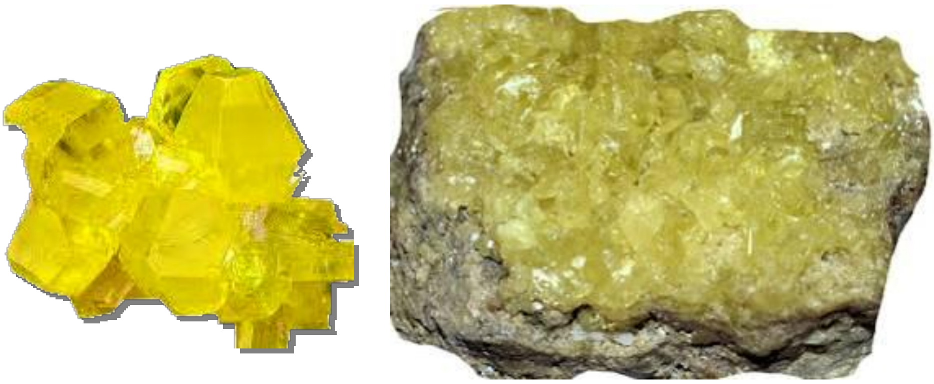

Fig. 484. Crystals of sulphur (left), and sulphur in a rock mass (right).

It is transparent to translucent, of adamantine to semi-adamantine, even resinous lustre. Elemental sulphur is commonly found near hot springs or solfatare in volcanic regions (fig. 485). Vast masses of sulphur are synthesized by sulphur bacteria. It is found in greater depths in oxidized zone of copper, lead and zinc sulphide deposits.

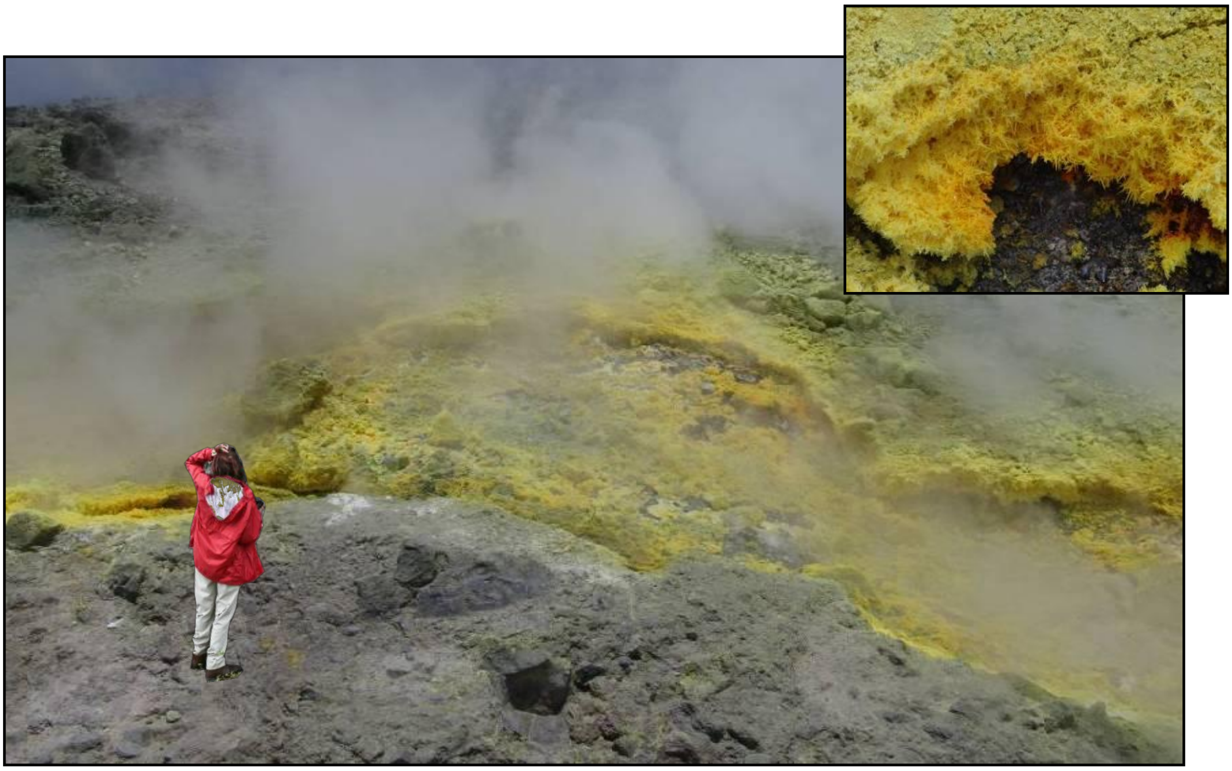

Fig. 485. Sulphur may be found in fumaroles, above right is a detail.

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