# MINERAL SYSTEMATICS
# FROM V.I. VERNADSKY TILL 21 CENTURY

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The article briefly reviews currently most widely accepted systematics of minerals that were developed in the 20th century by V.I. Vernadsky, J.D. Dana, A.G. Betekhtin, I.N. Kostov and G.P. Barsanov. A.A. Godovikov's systematic (Godovikov, 1997) is described in more detail as one reflecting currently acknowledged concepts of relationships between the chemical composition of minerals and their structures and properties. The author considers the structure of a mineral at the level of not upper but middle or even lowermost mineralogical taxons, in close relations with the chemical composition and physicochemical parameters of mineralizing systems. The upper taxons, or mineral types, are distinguished according the type of the dominate chemical bond. The basis for recognizing lower taxons, down to mineral classes, is a classification of the chemical elements. In this context, the classifications of elements suggested by V.I. Vernadsky, A.E. Fersman, A.N. Zavaritsky, A.A. Godovikov are also debated. A.A. Godovikov has more deeply explored the concepts of similarities and differences in the properties of chemical elements to put forth a more detailed mineralogical-crystallochemical systematics of the chemical elements with regard for various properties of elements that are manifested depending on other elements simultaneously occurring in a compound and on physicochemical parameters of the system. A.A. Godovikov applied this classification to distinguish taxons of order lower than type. The criteria suggested for distinguishing taxons in A.A. Godovikov's structural-chemical systematics of minerals are presented.
1 table, 11 figures, 13 references.
Keywords: systematics of minerals, classification of elements, chemical bond type, chemical composition, mineral structure, physicochemical parameters of mineralizing system.

It is often thought to be senseless to elaborate any new systematics of minerals. This opinion is most commonly shared by young researchers, who consider virtual data of minerals to be of much greater importance. However, such distinguished scientists as M.V. Lomonosov, V.M. Severgin, J.J. Berzelius, V.I. Vernadsky, J.D. Dana, A.G. Betekhtin, I.N. Kostov, A.S. Povarennykh, H. Strunz, A.A. Godovikov, J.J. Berzelius, A.R. Hoelzel and A.M. Clark created their own versions of mineral classifications. The reasons why so much importance was attached by these scientists to mineral systematics may be as follows:

1 — there is necessity to systematize different and numerous information on individual minerals. Without this it is not to get slim and scientific description;

2 — there are a lot of mineral properties which are used in their descriptions. We need to know them for mineral diagnostics and for clarification of their searching features, forming conditions of their paragenetic associations, capabilities of mineral utilization by humans;

3 — by belonging of minerals to the complete different chemical compound types; by differences and complexity of their composition;

4 — minerals are formed in completely, even in interexcluded physical-chemical conditions.

Any of mineral systematics appears to be multidementioned, because it should consider all the multitude of different mineral features.

The characteristics taken as a basis for a classification should permit the possibility that the place of a mineral in it may be changed after its composition or structure are determined more accurately and/or in more detail. These characteristics should make it possible to coin new taxons for newly discovered minerals, which are chemical compounds that have not been known before to occur in nature, i.e. the classification should be evolutive system.

Because it is not possible to discuss the whole multitude of currently existing classifications in this article, below I will dwell only on the most widely accepted ones.

**Vladimir Ivanovich Vernadsky** — an academician of the Imperial Academy of Sciences, the Head of the Mineralogical Section of the Geological Museum at the Academy of Sciences (Fig. 1), estimated quite highly efforts to constrict mineral systematics and believed that "*establishing a natural and accurate classification concerned with the deepest comprehension of chemical and mineralogical phenomena*" (Vernadsky, 1927). V.I. Vernadsky's requirements for mineral classification were as follows.

1. The classification should be based on chemical properties of compounds and the chemical elements composing them, similarities and differences in the properties of these elements and other chemical characteristics.

2. The classification should take into account genetic and paragenetic features of min-

erals, what should be expressed in combining minerals into taxons that should comprise as many as possible mineral species similar in genesis (paragenesis) and correspond to understanding physicochemical coherence of the taxons and relations between them.

3. The structural (geometric), often named crystallochemical, traits of minerals are their secondary (follow level after chemical ones) identification features because they are determined by the chemical composition of minerals and the physicochemical parameters of their forms. They surely must be taken into account in the classification, but only at lower levels of its taxons.

V.I. Vernadsky has classified all minerals into **14 series** (Vernadsky, 1927).

**I.** Free elements and their mixtures (native elements).

**II.** Hydrogenous minerals.

**III.** Sulphuric and selenic compounds.

**IV.** Arsine and stibine derivatives.

**V.** Telluric compounds.

**VI.** Bismuthic compounds.

**VII.** Phosphoric, nitrogenous and carbonic metals.

**VIII.** Oxygenic peroxides, bases and anhydrides.

**IX.** Hydrates and fluoranhydrides.

**X.** Oxygenic salts and products of attaching to them.

**XI.** Oxyhaloide compounds.

**XII.** Haloide compounds.

**XIII.** Silicic compounds without clear saline nature (glasses).

**XIV.** YCarbonic compounds containing oxygen, without saline nature.

The series are subdivided into groups according to the character of the chemical elements in the minerals composition. When suggested, the classification comprised more than 200 groups.

Simultaneously with V.I. Vernadsky, **James Dwight Dana**, a mineralogist and geologist at the Yale University (Fig. 2), created an appropriate chemical systematics of minerals based on **Mendeleyev's Periodic Law**. J.D. Dana grouped mineral species into 8 major taxons according to the **types** of their **anions** and resemblance of elements, which followed from their position in the Periodic Table (Dana, 1892).

**Type I.** Native elements.

**Type II.** Sulfides, selenides, tellurides, arsenides, stibnides.

**Type III.** Sulfosalts — sulfoarsenides, sulfistibnides, sulfobismuthides.

**Type IV.** Halogenides — chlorides, bromides, iodides, fluorides.

**Type V.** Oxides.

**Type VI.** Oxosalts: 1 — carbonates; 2 — silicates; 3 — titanates; 4 — phosphates, arsenates, vanadates, antimonates, nitrates; 5 — borates, uranates; 6 — sulfates, chromates, tellurates; 7 — tungstenates, molybdates.

**Type VII.** Salts of organic acids: oxalates, mellates etc.

**Type VIII.** Hydrocarbons.

**Anatoly Georgievich Betekhtin** (Fig. 3), the author of "Mineralogy", one of the most comprehensive handbooks on mineralogy (Betekhtin, 1950). A.G. Betekhtin subdivided minerals into 6 sections according to their anions.

**Section I.** Native elements and intermetallic compounds.

**Section II.** Carbides, nitrides and phosphides.

**Section III.** Sulfides, sulfosalts and similar compounds.

**Section IV.** Haloide compounds (halogenides).

**Section V.** Oxides.

**Section VI.** Oxygen salts (oxosalts), consisting of 10 classes: 1 — iodates; 2 — nitrates; 3 — carbonates; 4 — sulfates, selenates, tellurates; 5 — chromates; 6 — molybdates and tungstenates; 7 — phosphates, arsenates and vanadates; 8 — arsenites; 9 — borates; 10 — silicates.

**Ivan Nikolov Kostov** (Fig. 4), a Bulgarian mineralogist and crystallographer, has created a mineral classification based on the chemical composition and paragenetic series of some elements (Kostov, 1965) and subdivided minerals into 12 classes.

**Class I.** Native elements.

**Class II.** Sulfides and sulfosalts.

**Class III.** Halogenides.

**Class IV.** Oxides and hydroxides.

**Class V.** Silicates.

**Class VI.** Borates.

**Class VII.** Phosphates, arsenates, vanadates.

**Class VIII.** Tungstenates, molybdates.

**Class IX.** Sulfates.

**Class X.** Chromates.

**Class XI.** Carbonates.

**Class XII.** Nitrates and iodates.

**Georgii Pavlovich Barsanov** (Fig. 5), a remarkable mineralogist and teacher, Director of the Fersman Mineralogical Museum, Academy of Sciences of the USSR (1952—1976), Vice President of the International Mineralogical Association (1960—1964), Head of the Department for Mineralogy at the Moscow State University (1953—1986). G.P. Barsanov held that the bases for classification of minerals should be:

1) types of chemical bonds in crystals;

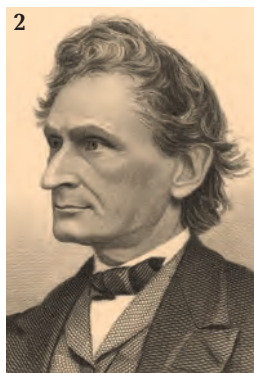*Fig. 1. Vladimir Ivanovich Vernadsky (1863—1945).*
*Fig. 2. James Dwight Dana (1813—1895).*

*Fig. 3. Anatolii Georgievich Betekhtin (1897—1962).*
*Fig. 4. Ivan Nikolov Kostov (1913—2004).*

2) qualitative composition of atoms in the crystal coupled via any type of chemical bond;

3) how and which are the atoms (ions) surrounded by other atoms (or ions) in the three-dimensional crystal structure, i.e. coordination, packing character, structure motif (Barsanov, 1959). G.P. Barsanov divided all minerals into 4 types according to their the chemical bond type. The types are further subdivided into classes according to the qualitative composition of the anions that make up a certain structure. The classes consist of taxons, which are distinguished depending on the presence of additional anions. Finally, a taxon next in the hierarchy is established according to the qualitative composition of the cations. G.P. Barsanov recognized 4 types as highest taxons (Barsanov, 1959).

**Type I.** Atomic (partly ionic) lattices with bonds of metallic or covalent type; which includes 2 classes: 1) free atoms of elements and 2) intermetallic compounds.

**Type II.** Ionic lattices with covalent (rarely ionic) type of bonds, with 5 classes: 1) sulfuric compounds; 2) selenides; 3) tellurides; 4) arsenides; and 5) stibnides.

**Type III.** Typical ionic lattices without complex anion groups in their structures. Herein 3 classes: 1) chlorides, bromides, iodides; 2) fluorides; and 3) oxides.

**Type IV.** Ionic lattices with complex anions. Herein 11 classes: 1) niobotantalates and niobotantalotitanates; 2) silicates; 3) borates; 4) chromates; 5) molybdates; 6) tungstenates; 7) phosphates; 8) vanadates; 9) sulfates; 10) carbonates; and 11) nitrates.

These are the most widely accepted mineral classifications suggested before the 1990s. Unfortunately, most of them postulate the formation of various taxons and show their hierarchic arrangement but do not explain the principles and sequence of this recognition , which makes it

hard (if even possible at all) to apply these classifications to the newly discovered species. For this reason, several mineralogical works were recently published that describe minerals in an alphabetic order (Clark, 1993; Robert *et al.*, 1990). However, this practice does not provide the reader with any type of information on a mineral other than its characteristics. The reader remains unaware of the circumstances in which the mineral is formed and its associations and, hence, is not able to predict as to where the mineral may be searched for and how can it be used. As is known, **any hypothesis becomes a theory if it is able to predicted something that turns true in a while.**

**Aleksandr Alekcandrovich Godovikov** (Fig. 6) was a mineralogist of the universal style of thinking, professor, the Director of the Fersman Mineralogical Museum (1984—1996), renowned specialist in theoretic, descriptive, experimental and genetic mineralogy. A.A. Godovikov strove for approaching **mineralogy to the frontier where it would become not a descriptive but precise science.** Thereby he explored theoretical aspects of mineralogy aiming to create a foundation for a uniform classification of minerals based on their chemical features and genetic characteristics, with regard for their structures. These studies conducted by A.A. Godovikov (and described in 6 monogaphs) laid the basis for his *"Structural-chemical classification of minerals"* (Godovikov, 1997), in which he did his best to meet the basic requirements to systematics yet formulated by V.I. Vernadsky. In A.A. Godovikov's opinion, *"it is apparent that mineralogist will be satisfied, if systematic has on its basis chemical features which could enable to understand their connection with mineral structure and properties, mineralforming conditions and paragenesis. Features which are characterizing the structure of minerals should have not the highest*

*Fig. 5. Georgii Pavlovich Barsanov (1907—1991).*

*Fig. 6. Aleksandr Aleksandrovich Godovikov (1927—1996).*

*Fig. 7. Victor Moriz Goldschmidt (1888—1947).*

*taxon positions, but rather middle or even inferior taxon positions, because they are in straight dependence on chemical composition and physical-chemical parameters of mineralforming systems"* (Godovikov, 1997).

A classification should be natural, for "*it must able to account of not only formal features, but also of real mineral associations, their parageneses, differences of those physicochemical parameters at which minerals are formed and exist, giving preferences, in certain instances, to the latter in the classification order of minerals"*.

Naturally occurring mineral associations are genuine criteria of naturality of mineral systematic. It is necessary that there were gradual transitions from one taxon to another showing their multiple interrelations.

In effort to make mineralogy closer to exact science, A.A. Godovikov introduced the concept of power characteristics (PC).

Power characteristics of atoms and ions are a measure of Coulomb's interaction between an electron (mostly a valence one) torn off the nucleus ($\gamma$). The possible power characteristics of atoms and ions in the free state and cations in ionic crystals are:

a) $\gamma_{orb.} = F/r_{orb.}$, where F is the affinity of the atom to electron and $r_{orb.}$ is the orbital radius of the atom;

b) $\gamma_{orb.}^{n+} = I_n/r_{orb.}^{n+}$, where $I_n$ is the $n^{th}$ ionization potential and $r_{orb.}^{n+}$ is the orbital radius of the ion with valence number $n+$;

c) $\gamma_i = I_n/r_i$, where $r_i$ is the effective ionic radius of the cation with valence number $n+$ in the ionic crystal.

Power characteristics serve as a measure of donor-acceptor (acid-alkaline) properties of atoms and ions.

As a basis for a mineral classification within chalcogenic, oxygenous and halogenic compounds, i.e. **within upper taxons of the classification (types), the dominant type of chemical bond is used.**

In the range metallides → semimetallides → chalcogenic compounds → oxygenic compounds → halogen compounds, the chemical bond changes consistently: metallic → metallic-covalent → ionic-covalent → covalent-ionic → ionic bond. The type of the chemical bond also changes according to the affiliation of compounds with elementary substances, binary compounds, or salts and is controlled by the fundamental properties of atoms composing a given mineral, namely their power characteristics (PC), atomic number Z in the Periodic System and their interrelations. The general trend manifests itself in the fact that the transition elementary compound → binary compound → salt proceeds so far as the difference $\Delta$PC of power characteristics of consisting cations increases, i.e. according to increasing ionicity of the bond.

According to A.A. Godovikov, a **classification of chemical elements must be utilized as a basis for distinguishing taxons of order lower than type and higher than classes inclusive**. A number of geochemical classifications of elements were created in the 20$^{th}$ century. The most widely known classifications of elements are described below.

**Victor Moritz Goldschmidt** (Fig. 7), a crystallographer, the director of the Geological Museum in Oslo. On the basis of crystal chemistry, he analyzed the distribution conditions of elements in various minerals and conditions of their concentration and migration. Using the dependence of the atomic volume (V) on the atomic number of the corresponding elements (Z), V.M. Goldschmidt was the first to suggest a classification of elements (Fig. 8) and devided them into 4 groups (Goldschmidt, 1937).

*Siderophylic* elements are located around the minima on the curves of atomic volumes as functions of atomic numbers. These elements were C, P, Fe, Co, Ni, Tc, Mo, Ru, Rh, Re, Os, Ir and Pt.
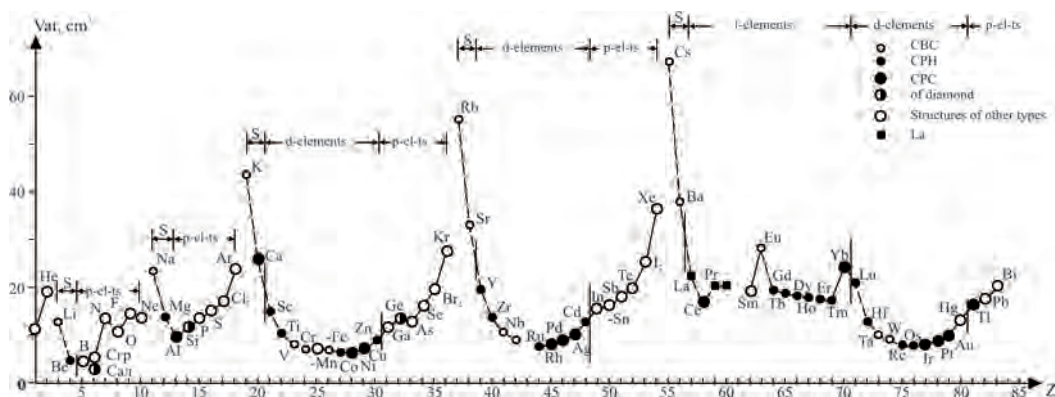
*Fig. 8. Atomic volume (V) dependency on atomic number of corresponding elements (Z). Structures: space-centered cubic − CBC, hexagonal close packing CPH, cubic close packing − CPC, of diamond, structures of other types, La − structures of La type.*

*Chalcophylic* elements correspond to ascending parts of the curves: S, Cu, Zn, Ga, Ge, As, Se, Pd (which seems to be more appropriate for the siderophile elements), Ag, Cd, In, Sn, Sb, Te, Au, Hg, Tl, Pb, Bi and Po.

*Lithophylic* elements cluster on descending parts: Li, Be, B, Na, Al, Si, K, Ca, Sc, Ti, V, Cr, Mn, Rb, Sr, Y, Zr, Nb, Cs, Ba, Ln, Hf, Ta, W and Fr (it was not shown in the V. M. Goldschmidt's diagram), Ra, Ac, Th, Pa, U. Taking into account the common presence of O, F, Cl, Br and I in minerals of rocks and deviating from the logically formal classification of elements in favor of natural one, V. M. Goldschmidt attributed them to the same group, although they are located on ascending segments of the curves.

*Atmophylic* elements located on the upper parts of curves. These are He, N, Ne, Ar, Kr, Xe, Rn (Em); hereto he also referred H.

Dissatisfied with V.M. Goldschmidt's classification, A.E. Fersman and A.N. Zavaritsky have elaborated their own geochemical classifications.

**Aleksandr Evgenyevich Fersman** (Fig. 9), an academician and the Director of the Mineralogical Museum of the USSR's Academy of Science (starting in 1919). The sphere of his interest was extremely wide: mineralogy, crystallography, geochemistry, studying mineral resources and the processing technologies of minerals. In his systematics, A.E. Fersman segregated typical elements (i.e. elements with kainosymmetric outer and pre-outer electrons) by means of separating them from the others (in the Periodic System) with a doubled horizontal line (Fersman, 1933). The upper part of the System includes all typical elements of the first three periods and elements from K through Ni. This was done to emphasize the unusual properties of most refered ascribed to the first series of d-elements, that are kainosymmetric too, as it was discovered later.

**Aleksandr Nikolaevich Zavaritsky** (Fig. 10), an academician, great geologist, petrographer, specialist in ore deposits and volcanology, elaborated his geochemical classification of elements (Zavaritsky, 1950) based on the properties of elements reflected in an extended version of the Periodic System . Within the framework of the Periodic System, he distinguished 11 fields of elements:

1 − hydrogen − H;

2 − noble gases − He, Ne, Ar, Kr, Xe, Rn;

3 − rock-forming elements − Li, Na, K, Rb, Cs, Be, Mg, Ca, Al, Si;

4 − elements of magmatic emanations − B, C, N, O, P, S, F, Cl;

5 − elements of the iron group − Ti, V, Cr, Mn, Fe, Co, Ni;

6 − rare elements − Sc, Y, Ln, Zr, Hf, Nb, Ta;

7 − radioactive elements − Fr, Ra, Ac, Th, Pa, U;

8 − elements of the platinum group − Ru, Rh, Pd, Os, Ir, Pt;

9 − metallic elements (nonferrous metals) − Cu, Ag, Au, Zn, Cd, Hg, Ga, In, Tl, Ge, Sn, Pb;

10 − metalloid metallogenic elements (elements of sulphoacids) − As, Sb, Bi, Se, Te, Po;

11 − heavy haloids − I, Br, At.

The elements Mo, W, Tc, Re were not ascribed to any particular fields.

As was mentioned above, classifications of elements were suggested by several mineralogists but mostly satisfy neither their authors nor their colleagues because the mineral systematics based on these classifications were not natural. These systematics did not take into account the actual associations of minerals, their parageneses and variations in the physicochemical parameters under which minerals

Fig. 9. Aleksandr Evgenyevich Fersman (1883–1945).



Fig. 10. Aleksandr Nikolaevich Zavaritsky (1884–1952).

can be formed and exist, as well as the fact that natural associations of minerals are not generated randomly but result from the grouping of elements according to all of their properties into natural associations.

Aleksandr Nikolaevich Zavaritsky's classification proved most acceptable. Unfortunately, it inherited certain disadvantates from earlier classifications.

A significantly more detailed classification of elements was put forth by V.I. Vernadsky. His classification was based on characteristics of isomorphism of elements, genesis of minerals and and parageneses. The core idea of this classification was expressed in the form of the widely known isomorphous series (Vernadsky, 1923; 1927). Vernadsky not only grouped elements similar in chemical properties but also showed how these series dependend on the genesis.

V.I. Vernadsky's isomorphous series:

**1** − **Al, Fe, Cr, Mn**│**Ti, B, (Y), (Ce), V, In?**, where ***Al, Fe, Cr, Al, Fe, Cr, Mn***, Al, Fe, Cr, Mn│Ti, B, (Y);

**2** − **Ba, Ca, Sr, Pb**, where ***Ba, Ca, Sr, Pb, Ba, Ca, Sr***, Ba, Ca, Sr;

**3** − **Br, I, Cl, F**, where ***Br, I, Cl, F, Cl, F***, Cl, F;

**4** − ***V, P, As, Sb?***;

**5** − **Bi, Sb, As**, where ***Bi, Sb, As***, Bi, Sb, As;

**6** − **K, Na, Cs, Rb**│**Tl, Li, H**, where ***K, Na, Cs, Rb, K, Na, Cs, Rb***│***Tl, Li, H***, K, Na, Cs, Rb│Tl, Li, H;

**7** − ***W, Mo***;

**8** − ***Ge, Sn***;

**9** − **Mg, Mn, Fe, Zn, Cd, Cu, Ni, Co, In?**, where ***Mn, Fe, Zn, Mg, Mn, Fe, Zn, Cd, Cu, Ni, Co***, Mg, Mn, Fe, Zn, Cd, Cu, Ni, Co;

**10** − **Au, Ag, Hg, Cu, Pb, Tl**, where ***Pb, Tl (?)***, ***Au, Ag, Hg, Cu, Pb, Tl***, Au, Ag, Hg, Cu, Pb, Tl;

**11** − Pt, Fe, Pd, Ir, Rh, Cu;

**12** − Os, Ru, Rd, Ir;

**13** − **Ca, Mg, Mn, Fe**, where ***Ca, Mg (?)***, ***Ca, Mg, Mn, Fe***, Ca, Mg, Mn, Fe;

**14** − O, F (?);

**15** − **Co, Fe, Ni**, where ***Co, Fe, Co, Fe, Ni***;

**16** − **Si, Ti, Zr, Mn**, where ***Si, Ti, Zr, Mn***, Si, Ti, Zr, Mn;

**17** − Th, U;

**18** − Zr, Hf;

**19** − Nb, Ta;

**20** − **S, Se, Te?**, where ***S, Se, Te?***, S, Se, Te?

**Symbols print in bold** denote the whole isomorphous series and other prints select elements of various "thermodynamic shells": ***bold italic*** − material of weathered mantles (so-called weathering crusts), ***underlined bold italic*** − metamorphic, regular − magmatic shells (Vernadsky, 1927).

These isomorphous series show that similarities between elements may appear in different ways depending not only on the formation conditions (thermodynamic shells) but also on other elements constituting a given isomorphous series. At the same time, certain elements can be found in more than one of such series. For example, Fe occurs in 5 series − 1, 9, 11, 13, 15; Mn is in 4 series − 1, 9, 13, 16; and Ca is in 2 series − 2, 13, etc.

Therefore, isomorphous series attract attention to the versatility (plurality) of the chemical properties of some chemical elements, because of which such elements may simultaneously fall into a few isomorphous series. At the same time, the series cannot (for the same reason) be directly applied in a mineral classification.

This led A.A. Godovikov to alaboration more fundamental concepts of similarities and differences in properties of elements, which allowed to create a more detailed mineralogical-crystallochemical classification of elements, with regard for the variability of properties of elements that is manifested depending on other elements involved in a given compound and on the physicochemical parameters of the system. A.A. Godovikov divided all elements into 8 groups.

**1. Hydrogen** $-$ H. Separating H into an individual group complies with systematics of A.N. Zavaritsky.

**2. Lithophylic elements with low PC:** 2.1. alkaline and alkaline-earth elements $-$ Li, Na, K, Rb, Cs, Fr; Mg, Ca, Sr, Ba; 2.2. rare-earth and radioactive elements $-$ Sc, Y, Ln (La $-$ Yb), Th, U; 2.3. amphoteric elements $-$ Be, Al, (Ga); 2.4. kainosymmetric d'-elements $-$ Ti, V, Cr, Mn, Fe, Co, Ni. This group of elements is entirely analogous with A.N. Zavaritsky's group of iron;

**3. Lithophylic elements with intermediate PC:** 3.1. non-kainosymmetric d'-complex formers $-$ Zr, Hf, Nb, Ta; 3.2. Mo and W.

**4. Noble-metallic (Siderophylic) elements** $-$ Ru, Rh, Pd, Ag, Os, Ir, Pt, Au. Among them, Ag and Au are often contained in chalcophylic minerals and associations.

**5. Chalcophylic elements:** 5.1. chalcophylic elements with low PC $-$ Cu, Zn, Cd, Hg, (Ga), In, Tl, Pb; 5.2. chalcophylic elements with middle PC $-$ Ge, Sn, As, Sb, Bi, Se, Te. Groups 5.1. and 5.2. are very closely similar to, respectively, groups 9 $-$ metallic (colored) elements and 10 $-$ A.N. Zavaritsky's metalloid metallogenic elements (elements of "sulphoacids"), except Ge and Sn, which were referred by A.N. Zavaritsky to the group 9.

**6. Light anion-forming elements** $-$ B, C, Si, N, P, O, S, F, Cl. This group of elements is completely analogous to A.N. Zavaritsky's group of elements of magmatic emanations that compose lithophile minerals as anion-forming elements (B, C, Si, N, P, S) or anions (O, F, Cl); with only S able to additionally act as an anion in chalcophylic minerals.

**7. Heavy anion-forming elements** $-$ Br and I.

**8. Noble gases elements** $-$ He, Ne, Ar, Kr, Xe, Rn.

This classification was later proved to also need refining, because most elements turned out to be amphoteric, with their acid-base properties defined by the properties of other elements of composition, the proportions of these elements, the physicochemical parameters of the systems in which the minerals exist or were generated. Thus, depending on its CN in a compound, a typical siderophylic or even chalcophylic element can become a crystalochemical analogue of typical lithophylic elements. This classification cannot thus form a basis for selecting taxons of order lower than **type**, because the same cations can play a cation role in different mineral types e.g. lithophylic and chalcophylic and be cations in certain minerals manifesting their alkaline properties, or anion-forming elements in other miner-als and manifest acid properties. It was demonstrated to be convenient to express differences in the acid-base properties of cations with various CN by the produced PC values i.e. their PC/CN ratio, which enables one, together with the cation electronic type (*s-, f-, d-, p-*) and its order number, to present a classification of major mineral-forming ions in a tabular form (Fig. 1).

At the same time, A.A. Godovikov has demonstrated that the PC/CN ratio determines the role of cations in compositions but cannot be used as a strict formalized criterion, because cation properties also depend on some minute features of the atomic structure, in particular, their Z value and affiliation with kaino- or nonkainosymmetricals. However, in several instances, it elucidates not only the role of a cation in a compound but also the possibility of isomorphism between it and other cations, especially when they are similar in terms of other features. On the basis of this cation classification (Godovikov, 1997), A.A. Godovikov has worked out a more detailed grouping scheme for structural-chemical groups of elements (cations) depending on their chemical and crystallochemical properties (Godovikov, 2001).

1. $H^+$
2. $Li^+$
3. $Na^+$, $K^+$, $Rb^+$, $Cs^+$, $Fr^+$; $Ba^{2+}(CN = 12)$; $Pb^{2+}(CN = 12)$; $Tl^+(CN = 12)$
4. $Mg^{2+}$, $Fe^{2+}$, $Mn^{2+}$, $Co^{2+}$, $Ni^{2+}$
5. Ca, Sr, Ba; $Cu^{2+}(CN = 12)$; $Pb^{2+}(CN = 12)$
6. Sc, Y, Ln; Th, U
7. Be
8. $Al^{3+}$, $Fe^{3+}$, $Mn^{3+}$, $Cr^{3+}$, $V^{3+}$, $Ti^{3+}$
9. $Ti^{4+}$
10. $V^{4+}$, $Mn^{4+}$
11. $V^{5+}$
12. $Cr^{6+}$
13. $Zr^{4+}$, $Hf^{4+}$
14. $Nb^{5+}$, $Ta^{5+}$
15. $Mo^{4+}$, $W^{4+}$
16. $Mo^{6+}$, $W^{6+}$
17. Ru, Rh, Pd; Os, Ir, Pt
18. Au
19. $Cu^+$, $Ag^+$, $Tl^+(CN = 2-4)$
20. Zn, Cd
21. Hg
22. Ga, In, $Tl^{3+}$
23. $Pd^{2+}(CN \leq 12)$
24. Ge, Sn
25. $As^{3+}$, $Sb^{3+}$, $Bi^{3+}$, $Te^{4+}$

Comparison of these series of cations (elements) with V.I. Vernadsky's isomorphic series show that they are mostly similar, but they is able to more completely take into account the
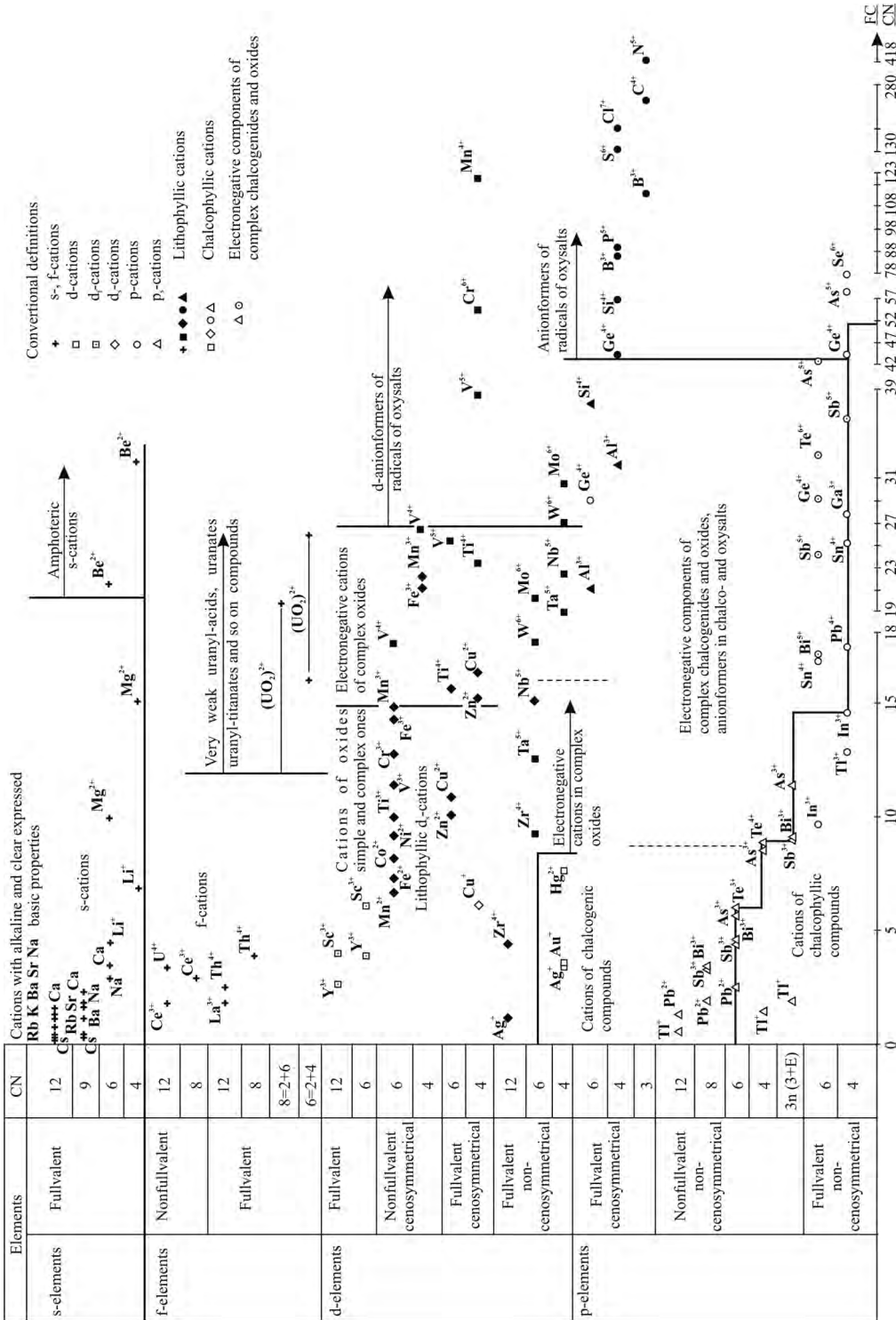
Fig. 11. Tabulated classification of main ions containing in minerals.

*Table 1.* **General enumeration of the taxons of structural-chemical classification of minerals**

| Taxon | Feature | Examples |
|---|---|---|
| 1 | 2 | 3 |
| Type | It is principle type of chemical bond (but not a single type of chemical bond) | The five types are uniting all minerals species: 1. Type: Minerals with principal metallic and metallic-covalent bond − native metals and semimetals, metallides and semimetallides. 2. Type: Minerals with principal metallic-covalent and ionic-covalent bond, rare van der Waals forces − chalcogen compounds and native VIa nonmetals. 3. Type: Minerals with principal ionic-covalent and covalent-ionic bond − nonmetallides of light (typical, noncenosymmetrical) VIa element (O) − oxygen compounds. 4. Type: Minerals with principle covalent-ionic and ionic bond − halogen compounds. 5. Type: Carbon, its compounds (without carbonates) and related substances. |
| Quasitype* | Type of chemical bond (this taxon is divided when more higher taxon unites the minerals with three or more types of chemical bond) | There are two quasitypes at the second type of minerals with principal metallic-covalent and ionic-covalent bond, rare van der Waals forces − chalcogen compound and native VIa nonmetals: 2a. Native VIa nonmetals (van der Waals forces); 2b. Chalcogenic compounds (metallic-covalent and ionic-covalent bond rare van der Waals forces) − simple (isodesmical) → complex → chalcosalts (anisodesmical). |
| Subtype | 1. Type of chemical bond, (only single type of chemical bond) | There are two subtypes at the 1. taxon of minerals with principal metallic and metallic-covalent bond − native metals and semimetals, metallides and semimetallides: 1.1. Metals and metallides; 1.2. Semimetals and semimetallides. |
|  | 2. Type of cation (siderophyllic, chalco-phyllic or lithophyllic) | There are two subtypes at the 2b. quasitype of the second type: 2b.1. Chalcogenic compounds of sidero − and chalcophyllic cations (metallic-covalent bond); 2b.2. Chalcogenic compounds of lithophyllic cations (ionic-covalent bond). |
|  | 3. Belonging of mineral to isodesmical and ani-sodesmical compounds | There are two subtypes at the 3 type of minerals with principal ionic-covalent and covalent-ionic bond -nonmetallides of light (typical, noncenosymmetrical) VIa-element (O) − oxygen compounds: 3.1. Oxides and hydroxides (isodesmical); 3.2. Oxysalts (anisodesmical). There are two subtypes at the 4 type of minerals with principle covalent-ionic and ionic bond − halogen compounds: 4.1. Halogenides (isodesmical); 4.2. Halogenosalts (anisodesmical) (with hexacyanoferrates and hexatiocyanates, rhodonides). |
| Quasi-subtype* | 1. Anion | There are two quasitypes at the 2b.1. subtype chalcogen compounds of sidero- and chalco phyllic cations (metallic-covalent bond): 2b.1a. Sulfides and sulfosalts of sidero- and chalcophyllic cations; 2b.1b. Selenides and selenosalts of sidero- and chalcophyllic cations. |
|  | 2. Type of cation and FC of cation | There are six consequently changing quasitypes at the 3.1 Subtype oxides and hydroxides (isodesmical), that are corresponding for transferal from the cations with low FC to the cations with high FC, from lithophyllic cations to chalcophyllic and to nonmetallic cations of the elements with mostly high FC: 3.1a. Oxides and hydroxides of lithophyllic cations with low FC; 3.1b. Oxides and hydroxides of lithophyllic cations with middle FC; 3.1c. Oxides and hydroxides of chalcophyllic cations (without Va- and VIa- cations); 3.1d. Oxides and hydroxides Va- cations (As, Sb, Bi); 3.1e. Oxides and hydroxides VIa- cation (Te); 3.1f. Oxides and hydroxides of nonmetals (lithophyllic) elements. |
| Overclass* | Cation | There are seven overclasses at the 3.1b. taxon − oxides and hydroxides of lithophyllic cations with middle FC: 3.1b.1. Oxides Zr; 3.1b.2. Oxides Ti ($Ti^{4+}$); 3.1b.3. Oxides and hydroxides $Nb^{5+}$ and $Ta^{5+}$; 3.1b.4. Oxides and hydroxides Mo and W; 3.1b.5. Oxides and hydroxides $Mn^{4+}$; 3.1b.6. Oxides and hydroxides $V^{4+}$; 3.1b.7. Oxides and hydroxides $V^{5+}$. |

*Table 1.* **Continue.**

| | | |
|---|---|---|
| Class | 1. Type of anion (simple, complex) or compound (simple, complex) | There are two classes at the 2b.1a. quasitype − sulfides and sulfosalts of sidero- and chalcophyllic cations:<br>2b.1a.1. Class: Sulfides of sidero- and chalcophyllic cations;<br>2b.1a.2. Class: Sulfosalts of sidero- and chalcophyllic cations. |
| | 2. Anionforming, when minerals are anisodesmical compounds | There are two classes at the 3b.1b.1. overclass − oxides Zr:<br>3.1b.1a. Class: Simple oxides of Zr;<br>3.1b.1b. Class: Complex oxides of Zr $\rightarrow$ titanates of Zr $\rightarrow$ zirconotitanates.<br>There are eleven classes at the 3.2. subtype - Oxosalts (anisodesmical):<br>3.2.1. Class: Silicates;<br>3.2.2. Class: Borates;<br>3.2.3. Class: Carbonates;<br>3.2.4. Class: Phosphates;<br>3.2.4a. Class: Arsenates;<br>3.2.5. Class: Sulfates;<br>3.2.6. Class: Sulfites;<br>3.2.6a. Class: Selenites;<br>3.2.7. Class: Nitrates;<br>3.2.7a. Class: Iodates;<br>3.2.7b. Class: Rhodonates (tiocyanates). |
| Quasiclass | Coordination number of the anionforming | There are three quasiclasses at the 3.1b.7b. class - complex oxides and hydroxides of $V^{5+}$:<br>((6)-vanadates $\rightarrow$ (5)-vanadates $\rightarrow$ (4)-vanadates);<br>3.1b.7b.1. Qusiclass: (6)-vanadates;<br>3.1b.7b.2 Qusiclass: (5)-vanadates;<br>3.1b.7b.3 Qusiclass: (4)-vanadates.<br>There are tree quasiclasses at the borates class: 1) (4)-borates; 2) (3)-borates; 3) (4)-(3)-borates:<br>3.2.2.1. Quasiclass: (4)-Borates;<br>3.2.2.2. Quasiclass: (3)-Borates;<br>3.2.2.3. Quasiclass: (4)-(3)-Borates. |
| Subclass | The size of FC | There are three subclasses at the class of silicates:<br>1) silicates with low FC;<br>2) silicates with middle FC;<br>3) silicates of chalcophyllic elements. |
| Family | The minerals of one family have similar of equal compound, single genesis or paragenesis | The family of zeolites unite the subfamilies: thomsonite, scolecite-natrolite, garronite, wairakite, gmelinite, stilbite, stellerite, mordenite.<br>The micas family unite dioctahedral and trioctahedral micas and all polytypes. |
| Subfamily | Similar or equal compound and same type of structure | There are five subfamilies at the chalcopyrite family: talnakhite, actually chalcopyrite, germanite, briartite, morozeviczite.<br>There are three subfamilies at the stannite family: stannoidite, actually stannite, rodostannite. |
| Series (genus) | Uninterrupted solid solutions between two or greater number of the extreme members | The forsterite genus and garnet genus among of the middle tetrasilicates. |
| Group | The same type of the compound or structure | The dolomite group include dolomite, ankerite, kutnohorite, benstonite, eitelite. All its minerals have one type structure, but they have not the uninterrupted solid solutions between ones. |
| Mineral species | There is an individual chemical compound, extreme member of the solid solutions, middle member of the uninterrupted solid solutions | a) There are three mineral species at the genus monticellite: monticellite, glaucochroite, kirnschsteinite.<br>b) There are five mineral species at the forsterite genus: forsterite, fayalite, tephroite, liebenbergite, laihunite. |

*Notes: asterisks after taxon names dente taxon introduced but not named by A.A. Godovikov. Their names were suggested by S.N. Nenasheva, for exaple, quasitype\*, quasisubtype\*, ore overclass\*.*

mineralogical and crystallochemical similarity of cations (elements).

These series of cations (elements) are taken as a basis of a further classification of minerals within classes distinguished according to anions features.

Thus, **higher taxons up to classes are selected according to the prevailing type of the chemical bonds**. All minerals are grouped into **five types** (see Table 2).

In conclusion, it is pertinent to quote A.A. Godovikov: "*the fundamentals of the mineral classification elaborated by V.I. Vernadsky and their further development made it possible to construct a natural classification of minerals so much needed during his lifetime, with a firm foundation laid for this classification by V.I. Vernadsky himself*" (Godovikov, 2001).

As became evident over years that has passed since the publication of the structural-chemical classification of minerals, it enables accurate arranging newly discovered species. During this time, cells in the systematic table were found for 1457 species, most of which are newly discovered minerals and lesser part are minerals known earlier but not fit into the systematic tables proposed by A.A. Godovikov. The features assumed as the basis the of classification allow one to change the position of a mineral in this classification after more accurate and/or precise data are obtained on the composition or structure of this mineral. The classification makes it possible to distinguish new taxons for newly discovered minerals that present chemical compounds not known in the early 1990s. Thus, **this is not a frozen concept but a developing system.**

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