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The Current System of Natural Minerals and Prospects for Its Expansion

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Abstract—The principle of an unlimited number of mineral species (NMS) is stated. Its scope includes unique types of rocks and ores with their structurally and compositionally complex minerals, in particular nanometer-sized ones. The unlimited NMS is determined not so much by the vast number of possible combinations of chemical elements as by the infinite multiplicity of structural forms of these combinations, and is associated not so much with the macro- as with the micro-world of minerals, which is still in the early stages of investigation. The number of IMA-approved mineral species is currently about 4300. Predictions for the next few decades suggest that their number will increase to 5000 by 2020 and to 10000–11000 by 2050.

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INTRODUCTION

At the end of XIX and during most of XX mineralogy was absolutely dominated by the idea, which seemed unquestionable, that on Earth there were about two-three thousand minerals in the crystalline state, the majority of which had already been discovered, while prospects of discovering new mineral species were extremely limited [1]. The author of the present article has managed in many respects to break this stereotype and justify the idea of almost unlimited number of mineral species existing in nature which have not been discovered yet [2–8].

The problem of the limited number of mineral species against the background of an astronomical number of possible combinations of chemical elements from Mendeleev's Periodic System, actively debated by A.E. Fersman [9] and his successors has again attracted great attention in connection with the trend of the last decades to significantly accelerated rates in the discovery of new minerals. During the period of 1970–2000 alone there was approximately the same number of mineral species discovered in the world as during the entire previous history of mineralogical discoveries, resulting in an increase in the general system of natural crystalline compounds from two to four thousand minerals; at present the system already includes about 4 300 officially registered mineral species. This more than 2-fold increase in the pool of natural minerals has drastically changed the concept of chemical and structural diversity of the mineral world and distribution characteristics of various elements in rocks and ores, has made it possible to identify fundamentally new types of mineral raw materials, has resulted in full reappraisal of different types of mineral resources deposits, and has acted as a powerful incentive for further development of both mineralogy itself and adjacent sciences. It has also laid the foundation for the principal revision of the existing ideas about the volume of the mineral species system and prospects for its further expansion.

The concept of the limited number of mineral species [1, 9–13], which dominated in mineralogy for almost a century, maintains its significance but only with regard to the most stable part of the mineral world, embracing widespread types of rocks and ores with their minerals of a relatively simple composition and structure, forming comparatively large-size crystals and grains. This idea is gradually replaced with a more universal concept of an unlimited number of mineral species, in addition to ordinary species embracing unique types of rocks and ores with their minerals of a complicated composition and structure, including nanometer-sized ones [2–8, 14–19].

According to our opinion [4–8] shared by other researchers [20, 21], the main source for discovery of new mineral species at the current development stage of science and technology is unique deposits formed under abnormal geotectonic and geochemical conditions. The formation conditions of such deposits in total, on a planetary scale cover almost the whole range of variations in temperature, pressure, and concentrations of various components within reach of experimental equipment, as well as such highly important physical and chemical parameters of the environment as the acid-base and redox potential. This fact breaks many barriers, limiting the multiplicity of natural crystalline compounds, and forms the basis for the concept developed by the author that there are no natural limits to the number of mineral species (within the framework of the definition of the *species* concept, accepted by the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association (CNMNC IMA).

Among mineralogically unique natural objects a special place is taken by solid masses of agpaitic nepheline syenites, which, although accounting for a tiny fraction of igneous rocks, are superior to rocks of any other formation in multiplicity of minerals (more than 1 000 species). Petrologists classify extremely rare types of strongly alkaline magmatic rocks as agpaitic rocks in opposition to less alkaline miaskitic rocks, which are relatively widespread in the earth's crust. There are only 10–15 large-scale masses of the agpaitic type discovered in the world, but it is to them and not to hundreds of smaller intrusions of miaskitic nepheline syenites that commercial deposits of almost half of the elements from Mendeleev's Periodic Table are attributable, including phosphorus, aluminum, niobium, tantalum, zirconium, cerium and yttrium rare earths, strontium, and gallium. Their unique character is determined by a combination of several factors, among which the first priority factor is a very high alkalinity of agpaitic magmatic rocks, which is responsible for the extreme diversity of alkaline minerals crystalline structures.

As the most representative example of such objects, we refer in this work to alkaline masses of Lovozero and Khibiny tundras, significantly outnumbering other solid masses and deposits of the world both in the total number of mineral species (exceeding 600) and the number of mineral species first described in them (about 200). Located in the central part of the Kola Peninsula in close proximity to each other, together they form the giant Khibino-Lovozerskiy complex of agpaitic nepheline syenites about 2 000 km^2 in area. The world largest deposits of rare-metal-phosphate raw materials are attributable to this giant complex. These solid masses, already well-investigated by pre-war expeditions organized by the Academy of Sciences under the leadership of A.E. Fersman [22], still continue to surprise the scientific community with extraordinary discoveries. It is supported by the following statistical data: while during the first 80-year period from the beginning of detailed investigations (1890–1970) 33 minerals, previously unknown to science, were described, for a much shorter period of 1971–2005 approximately 150 such minerals were described [23], and the majority of them (more than 80) were identified by or with participation of the author.

This significant contribution of the Khibino-Lovozerskiy complex into the general system of mineral species within the latest 35-year period is largely due to the results of many years of the author's mineralogical investigations at deep levels of these solid masses, unaffected by weathering processes, where we have been able to detect a widespread occurrence of ultra-agpaitic silicate-salt rocks, supersaturated with alkaline, volatile, and rare elements [3, 5, 24, 25]. The specific feature of these rocks, confined to the contact zones of the rare-metal-phosphate deposits, is the presence of a number of quite uncommon minerals, such as natrosilite ($Na_2Si_2O_5$) and natrite (Na_2CO_3), which are the most alkaline of all the silicates and sodium carbonates found in nature. It was impossible to predict the existence of such water-soluble compounds of the salts group in form of rocks crystalline phases on the basis of the traditional views; therefore, the detection of their plentiful accumulations at deep levels of the masses basically meant a discovery of a new phenomenon – the ultra-alkaline state of natural matter. In this state all positive elements of the Periodic System, less basic than sodium, exhibit amphoteric properties stimulating their transition from the cation part of the magmatic melts structure to the anion part of a much more capacity, the melts obtaining properties of universal solvents, which makes it possible for agpaitic magmatic rocks to accumulate great amounts of various valuable components. This fact determines supergiant sizes of the deposits associated with agpaitic magmatism and their distinct complex character, as well as the

occurrences of a large number of minerals, unique in composition, structure, and properties in ultra-agpaitic rocks.

In alkaline solid masses of the agpaitic formation there are petrogenic elements: O, Si, Al, Na, K, Ca, Fe, Mg, Mn, and Ti, and about 30 more elements forming their own minerals: Li, Cs, Be, Sr, Ba, B, La, Ce, Y, Zr, Nb, P, Th, U, Ag, Au, Tl, Cu, Zn, Sn, Pb, As, Sb, Mo, W, Co, and Ni, as well as F, S, Cl, C, and H. A significant number of these minerals are of a rather complicated composition and many of them contain up to 10 elements, holding independent positions in the crystalline structure. The author [3–5, 18] has calculated a number of combinations on the basis of a conditionally given number of chemical elements in the system (n) and a number of species-forming elements in each individual mineral (m). In these calculations according to the factorial formula, two argument selection options have been applied, one of them accounting for approximately 1/3 of Mendeleev's Table elements (n = 30), forming relatively simple compounds ($m \leq 5$), and the other accounting for a limited number of the most typomorphic elements of alkaline rocks (n = 17), forming more complicated compounds ($m \leq 8$). The calculation results have demonstrated that at n = 30 and m varying from 2 to 5, the number of combinations is equal to 174 406; and at n = 17 and m varying from 2 to 8, the number of combinations is equal to 65 518. Despite the conditionality of the applied approach, it has allowed us to roughly estimate a number of possible minerals of alkaline rocks at the level of $n\times10^4$–$n\times10^5$ species.

In compliance with the concept developed by the author [2–8, 14–19], the diversity of natural minerals is determined not so much by the great number of possible combinations of chemical elements as by the infinite multiplicity of structural forms of these combinations, and is associated not so much with the macro- as with the micro-world of minerals, which is just starting to become an object of systematic investigation.

The significance of minerals structural characteristics as a factor of species diversity in the mineral world can be illustrated with an example of zeolite-like titanosilicates and their analogues which are typomorphic for agpaitic rocks, classified as "amphoterosilicates" [3, 5, 26]. In the structures of such minerals, described by the general formula $A_xM_ySi_pO_q$ (A is Na and other strongly alkaline cations, M is Ti, Nb, Zr, Be and other amphoteric elements), Ti and its analogues together with silicon form framework, sheet, double-chain, and other mixed-type radicals, their negative charge compensated by A-cations. Presence of Na among the latter has a great species-forming significance in connection with the unique set of coordination numbers (from 4 to 12) and forms of the corresponding polyhedra characteristic for its atoms. The polyhedra are capable of joining together with their vertices, edges, and faces, forming various structural motifs, including one-dimensional and two-dimensional. Apart from that, sodium as a large cation in compliance with the provisions of the Second Chapter of silicates crystallochemistry [27] plays the role of the template or "hard fragment" in these structures, determining the architecture of more flexible MSiO-radicals.

In the structures under examination an even wider variety is found in M–O and Si–O fragments. Thus, for Ti-polyhedra it is characteristic to form rings, chains, ribbons, single-stage and n-stage layers, and skeletal frameworks of various geometry, alongside with single and coupled octahedra. Great polymorphism of Si–O fragments in silicate structures is well-known: for instance, the same metasilicate formula $[SiO_3]_n$ can correspond to Si_2O_6 pyroxene chain or to one of more than ten ribbons of various topology; the dimetasilicate formula $[Si_2O_5]_n$ corresponds to ring groupings, various ribbons, layers, and frameworks. Alongside with homogeneous silicon-oxygen motifs, some structures are characterized with combinations of heterogeneous Si–O fragments, such as noncuple and triple rings in minerals of the eudialyte group, as well as ribbons and chains in vinogradovite.

Turning to mutual combinations of A-, M- and Si–O motifs in structures of $A_xM_ySi_pO_q$ minerals, we should note that the variety of these combinations is no less than the diversity of the motifs themselves, and the variety of MSiO-combinations increases drastically at higher degrees of condensation. Thus, among mixed-type anion radicals we know about a dozen of ribbon radicals and half a hundred of sheet radicals, while the number of framework radicals reaches several hundred [28]. The diversity of cation and anion motifs and their combinations explains the abundance of independent structural types of alkaline amphoterosilicates and the existence of large families of their Ti-, Nb-, Zr-, and Be-representatives. Many of them are close or identical in composition of elements, but different in stoichiometry and/or structural characteristics. Among other representatives of the mineral world a wide range

of structural types has been identified in aluminum silicates, as well as in alkaline titanoniobates, phosphates, carbonates, halides, and sulphides.

A number of individual structural types discovered so far in structures of natural compounds belonging to different chemical classes exceeds the number of chemical elements in Mendeleev's Table more than 10-fold [17]; moreover, this number is steadily increasing due to the growing pool of newly discovered minerals [29, 30]. Taking into account various geochemical and physical-chemical conditions of natural processes on a planetary scale and a geological time scale, this fact brings us close to proposing the principle of an unlimited number of mineral species as the central principle of mineralogy [31]. The main ideas of this principle were first formulated by the author in his work at the 14th General Meeting of the International Mineralogical Association [2] and in his monograph [3], afterwards they have been elaborated in a number of later works. These ideas, first met with incredulity and skepticism, have become widely recognized quite quickly, and at present according to N.P. Yushkin [32] "the majority of researchers on the basis of different empirical and theoretical assumptions are inclined to the opinion that the number of minerals is almost unlimited."

It is evident that the idea of the absence of natural limits to the number of mineral species, arising from the specified principle cannot be treated as a literal or absolutely concept, due to at least two reasons. Firstly, the whole *mineral species* concept is characterized with a significant uncertainty, and from time to time it is reviewed by the international mineralogical community. Thus, although the current *mineral species* definition accepted by CNMNC IMA [33] limits the frameworks of this concept as referring only to natural substances, possessing three-dimensional periodicity of the crystalline structure, it is quite possible that later the concept will also embrace such natural objects as ultra-thin layers with two-dimensional periodicity of the atom grid, covering crystalline faces of ordinary minerals. However, such drastic changes in the framework of the *mineral species* concept, recommended by some researchers [34], will hardly change the essence of the ideas we are developing, although it will certainly significantly enhance the prospects for the discovery of new minerals in future. Secondly, a number of minerals that actually exist but have not been discovered yet cannot exceed any prescribed limit, for instance, a number of individual minerals in the earth's crust, estimated by Yushkin [32] as $n\times10^{31}$.

At the same time, according to a figurative expression of B.S. Gorobets [35], a well-known mathematician and an expert in crystallophysics, with whom the author has discussed the problem of an unlimited number of mineral species many times, "physical, geological, and anthropogenic evolution, including its historical and cultural aspect, is always moving away the imaginary "limit." And over millennia, the natural, nonmathematical, and culturelogical limit for the discovery of new minerals can only be the destruction of the noosphere." In other words, it is possible to say with high probability that in the culturological space of the coming millennia the discovery of each n mineral will be followed by the discovery of $(n + 1)$ mineral. Turning to the near future, according to more or less realistic forecasts it is expected that the total number of mineral species discovered in the world will have increased from the current 4 300 to 5 000 by 2020 [20] and by 2050 this figures will have reached 10–11 thousand species [14].

Discussing the concept of an almost unlimited number of potentially possible mineral species, we have already emphasized that the majority of these species belong not so much to the macro-, as to the micro-world of minerals, as it is evident that minerals, forming large-size crystals and grains (1–10 cm and more) have been already discovered to a great extent. In this connection, we should note that according to their size the majority of minerals, which have not been discovered yet, can be tentatively divided into four classes, corresponding to object of the visual (1–10 mm), "binocular" (0.1–1 mm), micro- (0.001–0.1 mm), and nano-level (<0.001 mm). Moreover, according to our estimates [14], a number of the "binocular" level minerals alone is at least 10-fold higher that the number of minerals discovered so far. It is possible to assume that in the coming decades an increase in the general system of mineral species will still largely result from discoveries of new minerals of the first and second classes. And although in the vast majority of cases these minerals will be referred to as mineralogical rarities, investigation of new minerals will still be of great interest both from the scientific and economic points of view. Among these species there will certainly be representatives of various types of commercial mineralization, as well as objects of the unique structure, possessing technically important properties. Acquaintance with the still undiscovered

part of the mineral diversity of the Earth and other celestial bodies will lead to fundamental changes in the current system of minerals and, as the historical experience shows, will significantly enrich various branches of both theoretical and applied sciences with new mineralogical data.

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