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Memorial of Nikolai Vasil'evich Belov[1]
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I first became acquainted with the name of N. V. Belov when I was fifteen years old. At that time, I had developed a love of minerals and used to thumb through the "Mineral Chemistry" section in *Chemical Abstracts,* edited by Michael Fleischer. Frequently scattered in that section were abstracts including N. V. Belov's name and the crystal chemistries of most strange and marvelous species. Within two years, I had a certain wish to visit the fabled occurrences of these species—Mt. Karnasurt; the Lovozero, Khibine massifs; in fact, the entire Kola Peninsula.

Academician Nikolai Vasil'evich Belov, dean of Soviet crystallography, was born in Ianov in Lublin Province, Poland, later the Zhitomir Province of the Russian empire and now of the Ukrainian Republic of the Soviet Union. His father was a district doctor, and in 1900 the family moved to Ovruch in the nearby province of Volynia, which N. V. Belov considered his native town.

Belov's upbringing was Russian, and he attended a Russian gymnasium in Warsaw. This distinguished school produced a succession of famous pupils, including V. I. Vernadsky. N. V. Belov was a brilliant student and received the coveted gold medal upon his graduation. His higher education commenced at the Metallurgical Department of the St. Petersburg Polytechnic Institute, where he specialized in electrochemistry, while maintaining an interest in all of the natural sciences as well as the humanities. A. F. Ioffe had great influence on N. V. Belov here, although he was not his thesis supervisor. In addition, the great mineralogist-petrographer, A. E. Fersman, played a key role, and for years portraits of both A. E. Fersman and A. F. Ioffe decorated N. V. Belov's office. While a student, N. V. Belov supplemented his income by giving assistance in thesis projects. In addition, he was an "extra" in the theater; but the main reason for doing this was to hear the famous singer, Feodor Chaliapin. During this period, he met his future wife, Alexandra Grigievna.

After the 1917 Revolution, N. V. Belov moved back to Ovruch with his wife, where he became a designer and builder of bridges and other structures. Since materials were scarce, he also gathered wood for the Red Army, travelling distances of up to 50 km a day. In 1921, he returned to Petrograd (as St. Petersburg was called after 1915), where V. A. Kistiakovskii became his adviser and his thesis "Thermal Coefficients of Galvanic Cells" was completed. Following another hiatus in Ovruch, he settled in Petrograd—now Leningrad—and became Associate of the Central Chemical Laboratory of the Leningrad Leather Foundation, where he was soon in charge of the laboratory. During this period, N. V. Belov expanded his understanding of physics and chemistry largely on his own, and in 1929 became chief of the Institute for the study of the North (Institute of the Arctic and Antarctic). His craving for greater involvement led to his appointment as Associate Editor of the Soviet journal *Priroda* (Nature) where, between 1928–1932, he placed about seventy scientific-popular articles on subjects in physics and chemistry (his mentor, A. E. Fersman, was Editor of this journal).

At the same time, A. E. Fersman introduced N. V. Belov to the Lomonosov Institute of the Academy of Sciences. [It may not be generally appreciated that M. V.

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Lomonosov (1711–1765) was a highly original natural philosopher, in much the same vein as Lavoisier, Berzelius and Dalton.] A. E. Fersman had a passion for nepheline syenites and granitic pegmatites and a great interest in the Khibine, Lovozero and other massifs of the Kola Peninsula. Subsequently, N. V. Belov was commissioned to investigate the chemistry of nepheline and apatite, two major phases in these complexes. In time, V. I. Vernadsky would place special value on N. V. Belov's studies of nepheline. Meanwhile, drawing on his experience in the leather industry Belov suggested the likelihood that nepheline could be used as a tanning agent, and this led to his first patent "On a New Means (Nepheline) of Tanning Leather". In addition, he recommended nepheline for the textile, woodworking, and paper industries. N. V. Belov's first truly scientific articles appeared around 1933, and he was called to the Academy of Sciences as a Senior Scientific Specialist. Expanding on the nepheline syenite theme, his work on apatite led to commercial extraction of rare earths.

In 1934, the headquarters of the Academy of Sciences moved from Leningrad to Moscow, and Belov moved from the Geochemical Division of the Lomonosov Institute to the Crystallographic Institute at the invitation of Alexei V. Shubnikov. This was a crucial move, indeed! A. V. Shubnikov was a brilliant crystallographer and group theoretician, a favorite maxim of whose was "There are no bad people; there are only bad relationships". For N. V. Belov, the switch was easy, because the field of geochemistry was already crowded with geochemists due to the influence of V. I. Vernadsky, while crystallography was relatively sparsely populated. He immediately fell in love with crystal structures, with all their elegance and mystery. While A. V. Shubnikov developed an independent laboratory in crystallography, N. V. Belov became preoccupied with building up his crystallographic brain, at this stage only in its infancy. But growth was rapid, accelerated by deliberate translations of major Western treatises. First was Odd Hassel's "Kristallchemie," translated in 1936 with many supplements and additions so that it became almost a two-author work! In addition, he translated crucial papers and pamphlets in the realm of geochemistry-crystallography-crystal chemistry by such authors as F. Machatschki, W. H. and W. L. Bragg, E. Schiebold and W. H. Taylor. For recently determined crystal structures and earlier ones, he built models.

N. V. Belov had planted his crystallographic roots at the Leningrad Mining Institute, and the plant later nourished at the Institute of Crystallography of the Academy of Sciences. He presented structural genealogies of fundamental units for inorganic compounds. Through detailed and elaborate explication of densest sphere packing theory, he showed that any homogeneous sphere packing belonged to one of eight admissible Fedorov (space) groups. In the 1890s, it might be remembered E. S. Fedorov and H. Schönflies designed the well-known planar trellisses in three-dimensions, and these were expected to occur in real structures. In the early twentieth century, L. Pauling demonstrated that there exist infinitely many dense packings. N. V. Belov characteristically explained his finding in these words: "Look here, this is not complicated at all. It explains itself." His observations, constructions and conclusions on dense-packed structures were compiled in his "Blue Book," and became the subject of his doctoral dissertation of 1943. The problem was then extended to spheres of *different* radii and dense-packed spherical clusters. These were to become the key to the more complex structures and constituted his platform on all future studies.

In N. V. Belov's "Blue Book," polyhedra were used to describe structures based on dense-packing of spheres and the polyhedral representation of structure was his principal means of displaying crystal structures. In 1947, the book was published as "The Structure of Ionic Crystals and of the Metallic Phases". During World War II, when the crystallography laboratory was moved to a Moscow suburb, N. V. Belov rigorously pursued silicate structures, in collaboration with graduate students, as well as his investigations of space groups, which combined the results of H. Schönflies and E. S. Fedorov. He devised an ingenious way of deriving them by group-subgroup relationships, which he called the "class method". He also further developed Fourier methods and Beevers-Lipson strips, a combination that he imparted to his students. N. V. Belov insisted that "The crystal is always found in the condition of a trellis" and he used tapestries and wallpapers as visual means of illustration.

Symmetry became a greater concern for N. V. Belov. A. V. Shubnikov and E. G. Pinsker had trained many crystallographers at Gorky State University, where N. V. Belov was appointed to a Chair, making Gorky a center for crystallography. N. V. Belov inculcated a love of the science in his students, and not only were many more structures derived but also the 1651 black–white symmetry groups—which he named Shubnikov groups—and the polychromatic as well as four-dimensional space groups. His presentations were characterized by clarity of thought, and he always sought simple solutions to complex problems. Many of his more prominent students contributed to the systematic programs of structure elucidation. With I. M. Rumanova, Patterson methods were explored, including the famous problem of unique structure solutions from maps in the hexagonal system. With N. I. Golovastikov, he pursued direct methods through structure semi-variants developed by H. Hauptmann and J. Karle (U.S.A.), but traced back to D. Sayre and F. W. H. Zachariasen (also U.S.A.). In fact, outstanding students of N. V. Belov are to be noted in a continuous stream of independent structure studies in the literature (in the U.S.A., published mainly in the translated journals *Soviet Physics-Doklady* and *Soviet Physics-Crystallography*). The names include, apart from I. M. Rumanova and N. I. Golovastikov, V. V. Ilyukhin, A. A. Voronkov, Z.

V. Pudovkina, Yu. A. Piatenko, Kh. S. Mamedov, V. I. Simonov, E. A. Pobedimskaia, V. V. Bakakin and B. M. Shchedrin. Always supportive of his students, never interested in methodologies as ends in themselves, N. V. Belov forever searched for the grail of structure unity. In 1961, the search culminated in "Crystal Chemistry of Large Cation Silicates".

The crystal chemical relationship between diorthosilicates [= oligosilicates] and orthoborates [= oxyborates] serves his point well. It seems N.V. Belov sought a general "hypothesis of granular accretion" among inorganic salts. Here, the kernel of the argument is a postulated array or a fragment—let us call it a cluster—which recurs over and over again in combinatorial modulations. Such thinking may be considered fanciful by many, but it takes on a special meaning if predictable recurrence and repetition in Nature come into play. Seen in this light, N. V. Belov's thrusts in mineralogic crystal chemistry were of an unusually robust nature. Some tasty broths include structure systematology of the rosenbuschite–låvenite mineral group, the long-standing murmanite–lomonosovite problem, and titano- and zirconosilicates in general. With emphasis on the Lovozero Massif in the Kola Peninsula, N. V. Belov perhaps as much as any other person achieved the task of unravelling the crystal chemistry of a complex and unusually diversified group of minerals within one broad rock type: the nepheline syenites. No doubt, this was the result of his early imprinting at the Vernadsky Institute and of his early recognition that nepheline itself would play an important role in the leather tanning industry.

Perhaps N. V. Belov's finest hour was his study with Kh. S. Mamedov of the crystal-chemical relationship between diorthosilicates [= oligosilicates involving two tetrahedra sharing a common vertex] and orthoborates [= oxyborates, with oxide anions and BO_3^{3-} triangles]. In one simple assertion, a whole family of crystal structures fell into place. The oligosilicates under discussion are largely accessory phases from nepheline syenites, while the oxyborates are phases usually found in crystalline marbles of granulite facies. Certain near-isostructural pairs can be written out, based on $[Si_2O_7]^{6-}$–$[2BO_3]^{6-}$ = $[B_2O_6\square]^{6-}$, where □ is a vacancy.

Oligosilicates
$Ca_4[Si_2O_7]F_2$, cuspidine
$Ca_6[Si_2O_7](OH)_6$, TSH (synthetic)

Oxyborates
$Mg_3Ti[B_2O_6\square]O_2$, warwickite
$Mg_6[B_2O_6\square]F_6$, fluoborite

The last pair deviates somewhat because the linking topology between pairs is a bit different, but the point is clearly made. Other paired relationships include such phases as pinakiolite, $Mg_4Mn_2^{3+}[B_2O_6]O_4$ and seidozerite $Na_4MnTiZr_2[Si_2O_7]_2O_2F_2$; fluoborite, $Mg_3F_3(BO_3)$ and jeremejevite, $Al_6(OH)_3(BO_3)_5$. Rewriting these two formulae demonstrates the relationship:

jeremejevite	Al_6	$B_2\square$	B_3	O_{15}	$(OH)_3$
fluoborite	Mg_6	Mg_3	B_3	O_9F_6	F_3

Here, the essence of the structures is the common type of anion packing, followed by appropriate partitionings of the cations.

Many remarkable structure types have thus appeared, exciting for the mineralogist because they focused on accessory phases in nepheline syenites which formerly were regarded as exotica or curiosity pieces. Lovozerite, $Na_2Zr[Si_6O_{15}] \cdot 3H_2O$, proved to possess a novel six-ring with only 2-fold symmetry. In addition, the free termini of the ring were hydroxyl groups, and the formula was in effect $Na_2Zr[Si_6O_{12}(OH)_6]$. Narsarsukite, $Na_2(TiO)[Si_4O_{10}]$ proved to be a tubular structure, a result published by N. V. Belov's group about the same time (1960) as the work of the D. R. Peacor-M. J. Buerger American team became known.

N. V. Belov was also deeply involved with the "second chapter" silicate structures. The idea, largely his own, was conceptually simple. A spanning unit between the free vertices of a linear edge-sharing octahedral chain would be the $[SiO_4]$ tetrahedral edge if the octahedral cations were small, e.g., Mg^{2+}, Fe^{2+}, Fe^{3+}, Al^{3+}, Ti^{4+}. Since the gap between free successive octahedral vertices would be ca. 2.6Å, this would be commensurate with the tetrahedral edge of $[SiO_4]$. Such arrangements could be traced back to the early classical investigations of W. L. Bragg and constituted the "first chapter". However, a new class of structures appeared for silicates when the cations in octahedral coordination by oxygens were large, such as Na^+, Ca^{2+}, Sc^{3+} and the gap between free successive octahedral vertices was about 3.8Å. Here, the spanner between octahedral vertices was not $[SiO_4]$ which was too small, but the termini of $[Si_2O_7]$. In fact, this fundamental idea paved the way to a huge list of mineral species peculiar to nepheline syenites—the niobo-, titano- and zirconosilicates of Na^+, K^+, Mn^{2+}, Ca^{2+}, Sr^{2+}, Ba^{2+}, Sc^{3+}, Y^{3+}, RE^{3+}, Th^{4+}. Especially fruitful were the systematic studies of a paragenetic collection wöhlerite, rosenbuschite, låvenite, bafertisite, extending into vinogradovite, labuntsovite, lawsonite, seidozerite.

The examples above are but a few of the families of compounds studied by N. V. Belov's group from the late 1940s on. He was at his best when describing crystal structures. It is a difficult and subtle art. From inadequate description, the structure rarely rises out of its grey two-dimensional gloom and usually dies on the printed page, an abandoned orphan of science. But a proper description evokes a three-dimensional edifice which can be stored in the brain. The brain—that magnificent "meat machine" as Nikola Tesla called it—can then process and integrate it with other structures. And here N. V. Belov acted like a humanist, poet and painter. His choices of words are ingenious, exotic, florid but certainly descriptive. In English translation they come out like this: ultramarines (sodalite) contain "Chinese lanterns," innelite's structure has corrugated strips called "landing fields"; while other structures have "armored walls" or "chain mail"; and tetrahedral vacancies are often called "pits". N. V. Belov, indeed, was one of the few people who made science an art and art a science (e.g., his analysis of mosaics). He was present in 1970 at the Royal Institution in London for the celebration of the eightieth birthday of Sir William Lawrence Bragg, where I, an awed junior faculty member, first met him. He referred to the Lecture Hall as the "Lion's Den," for here once the most notable of scientists held forth, including Sir Humphrey Davy, Michael Faraday, and more recently Sir Lawrence himself.

Julian Goldsmith relates an event which portrays N. V. Belov's humor. Back in the early sixties and in the midst of a Chicago winter (usually much like a Muscovite winter), N. V. Belov visited The University of Chicago, and Julian was walking him home from the Quadrangles. The sidewalks were heavily sprinkled with salt and footsteps were greeted with inconveniences. Julian apologized for the nasty weather and the messy sidewalks. N. V. Belov said: "Is nothing. In Moskva, I fall on my head at least twelve times each year [pause]. Why do you think Russians wear big fur hats?" I suspect there is a good evolutionary explanation for this. Russians have had a very long time to ponder their climatic harshness and adapt to it. Chicagoans have had only 150 years!

As an Academician and the leading world thinker in crystallography, crystal chemistry and mineral chemistry, N. V. Belov received many honors, prizes and awards. From 1966 to 1969, he was President of the International Union of Crystallography. Over the years, he became an Honorary Member of the mineralogical societies of the USSR, USA, England, and France and of the Geological Society of East Germany and a Foreign Member of the Polish Academy of Sciences. He received an Honorary Doctorate from Wrocaw University in Poland. At home, he received, among many awards, the first Fedorov Prize (1947), the State Prize First Class (1952), the Order of the Banner of Red Labor, the Order of the October Revolution, the title Hero of Socialist Labor (1969), the Lomonosov Gold Medal from the Academy of Sciences (1969), and three Orders of Lenin for his essays on structural mineralogy. In 1946, N. V. Belov was elected a Corresponding Member of the Soviet Academy of Sciences and in 1953 he became a full Academician. Few Westerners realize the significance of the title Academician in the USSR. The Soviet physicist Vladimir Kresin, writing in *The Soviet Union Today* (ed. J. Cracraft, 1983, University of Chicago Press) states that "From being a Corresponding Member of the Academy of Sciences [about 480 in 1981] one advances to the rank of full Member [about 260 in 1981]. . . ." Does V. Kresin refer to N. V. Belov when he states that "By the end of his life [one] Academician had published more than 1200 papers. . . ."?

And so it came to pass that Academician Nikolai Vasil'evich Belov—Doyen of Soviet and world crystallography; Nestor of a whole Pleiad of brilliant and capable young disciples, in his homeland, died on March 6, 1982, aged ninety-one. A model of dedication, decency, explication and imagination, he now sits at the High Table of our science together with the other immortals.