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Chapter 1

Histories of Crystallography by Shafranovskii and Schuh

Bart Kahr and Alexander G. Shtukenberg

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/46504

1. Introduction

There are at least six book length biographies of Herman Melville (1819-1891) and ten histories of the Russian Revolution currently in print in the English language. On the other hand, if you chase after crystals not whales, or believe that the determination of the structure of matter was a historical pivot, you will be disappointed that there does not exist a single narrative history of crystallography in print in English or any other language to the best of our knowledge. By any measure, crystallography now receives scant attention by historians and scholars.

One admirable attempt to fill this chasm is the wonderfully idiosyncratic *Historical Atlas of Crystallography* published by the International Union of Crystallography (Lima-de-Faria, 1990). It is a treasure of timelines, portraits of crystallographers, and fetishistic reproductions of cover pages of classic monographs, accompanied by revealing essays on various aspects of the history of crystallography by acknowledged experts. But, the *Historical Atlas* is not a narrative history written with one strong voice.

Burke's *The Origin of the Science of Crystals* (Burke, 1966) is such a narrative that runs up to the discovery of X-ray diffraction. It is the best source for those interested in an English language analysis of the history of crystallography. But, this book has been long out-of-print. (We are not oblivious to the ironies of lamenting in an open-access journal about access to print media. Google Books may ultimately obviate such lamentations but to date only a limited preview of *The Origin…* is available on-line).

As a remedy, we set out to produce an English language edition of I. I. Shafranovskii's two volume *History of the Science of Crystals* only available in Russian. The first volume was subtitled *From Ancient Times to the Beginning of the 19h Century* (Shafranovskii, 1978), and the second volume *The 19th Century* (Shafranovskii, 1980, Figure 1). A third volume covering the

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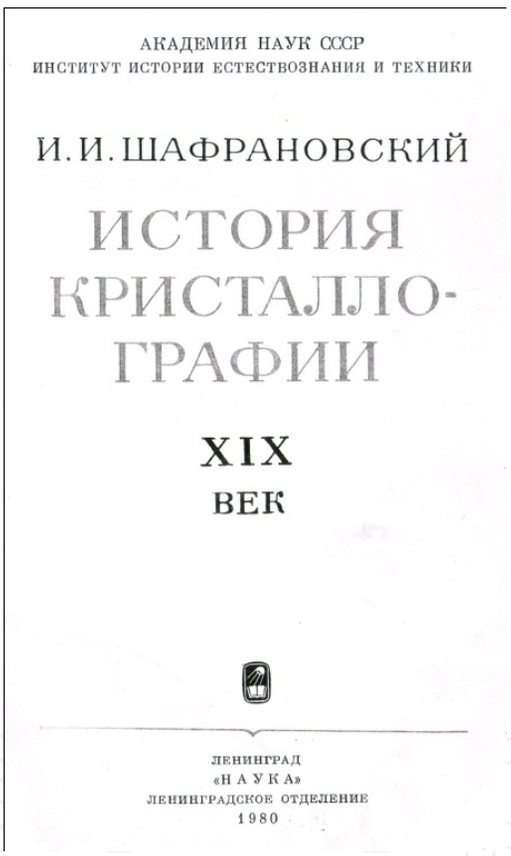
age of X-rays was planned but never materialized. Shafranovskii was a professor at the Leningrad Mining Institute. He had a long-standing interest in the history of crystallography (For a biographical sketch, see next section) and earlier published *The History of Crystallography in Russia* (Shafranovskii, 1962). In many ways, Shafranovskii's later two volume *History of Crystallography* is the best effort to cover a massive subject spanning centuries, countries, and languages. It is a valuable complement to Burke in that it is Russo-centric. Generally speaking, Russian science historians comfortably read English, French, and German while American science historians comfortably read…English, French, and German. This has naturally created a bias against Cyrillic texts that became apparent to us during excursions in some highly circumscribed aspects of the history of crystallography (Shtukenberg & Punin, 2007). Burke, for instance, made scant use of Russian sources. For this reason, Shafranovskii restores some balance to the history of crystallography, even if he sometimes chauvinistically overemphasizes Russian sources.

We began our translation project more than one year ago. We made some progress but the labor ahead is many times over the labor that is behind.

Very recently, we became aware of several remarkable manuscripts in English that are freely downloadable from achives.org. Their author is Curtis P. Schuh, whose surname is linked with Shafranovskii in the title of this article. Though incomplete and unpublished, Schuh's manuscripts obviate our perceived need for an English language translation of Shafranovskii. In light of Schuh, the rewards of fully translating Shafranovskii are diminished. Herein, we aim to introduce readers first to Shafranovskii's book, and then to Schuh's unpublished manuscripts in the final section.

Our translations of Shafranovskii's introduction, table of contents, and a sample chapter, follow. Here, we can see his strategy and style. In preparing an English language edition of Shafranovskii's book we did not aspire to make a one-to-one translation. While Shafranovskii is a formidable historian, he is a tiresome, repetitive writer. He engages the reader with an old-fashioned, didactic, 'Soviet' style. Our intent was to reduce his two volumes to one and in the process produce a readable *History of Crystallography*. Striking out redundancies, directive phrases such as "It is important to remember that…", and so on, nods to Academicians, and irrelevant minutiae, should have accomplished most of our aim. We aspired to preserve Shafranovskii's organization and style when it did not interfere with driving the narrative forward. At the same time we intended to add material that has since come to light, and insert narrative glue in places, even while scraping off irksome residues in other places. We had planned to eviscerate a few of Shafranovskii's chapters that give the impression that the author 'ran out of gas' during his extensive undertaking. In reviewing the birth of physical crystallography, Shafranovskii summarizes the seventeen experiments in Bartholinus' (1625-1698) book on the discovery of double refraction in Iceland spar (Bartholinus, 1669, 1959) in the order given. The numbing chapter reads as follows: "In the first experiment… In the second experiment… In the sixteenth experiment… In the last experiment." We elected to rewrite this chapter from scratch. Even though we planned to take considerable liberties, a small effort would spare readers from author's weakest efforts.

Shafranovskii reviewed the relevant historical literature in his introduction. Here, we introduce major sources upon which he was most reliant, and those he was most critical of. Shafranovskii's naturally acknowledges Burke's text. Both Shafranovskii and Burke were admirers of Metzger (1889-1944?) a crystallographer turned philosopher of science. In her doctoral dissertation, *La génese de la Science des Cristaux* (Metzger, 1918), she emphasized the separation of crystallography from other disciplines during 17th and 18th Centuries with special attention to French texts. "Unfortunately," says Shafranovskii, "the fates of the author and her interesting book were tragic. The first page of the manuscript, kindly sent [to me] from Paris by Dr. K. I. Kurilenko, bears a foreboding inscription: 'Author and her book disappeared during the German occupation 1940-1944'". It is now known that Metzger was deported from Lyon to Auschwitz and was not among the twenty who survived her transport of 1501 persons (Freudenthal, 1990).


АКАДЕМИЯ НАУК СССР
ИНСТИТУТ ИСТОРИИ ЕСТЕСТВОЗНАНИЯ И ТЕХНИКИ

И. И. ШАФРАНОВСКИЙ

ИСТОРИЯ КРИСТАЛЛОГРАФИИ

XIX ВЕК

ЛЕНИНГРАД
«НАУКА»
ЛЕНИНГРАДСКОЕ ОТДЕЛЕНИЕ
1980

Figure 1. I. I. Shafronovski's History of Crystallography, XIXth Century, Volume 2.

German texts dominated the 19th century literature on the history of crystallography, especially those of Marx (1794-1864) and Kobell (1803-1882). Marx's *Geschichte der Kristallkunde* (1825) was valued by Shafranovskii because of its numerous quotations from ancient sources. Kobell's *Geschichte der Mineralogie von 1650-1860,* current at the time of publication (1864, see also Kobell, 1866), contained histories of individual minerals and mineral properties such as magnetism and luminescence. Kobell earned fame as a poet of the upper-Bavarian dialect whose compositions became folk songs. His extended poem *Die Urzeit der Erde* (Kobell, 1856) showcased his knowledge of geoscience in verse.

Groth (1843-1927) published *Entwicklungsgeschichte der mineralogischen Wissenschaften* in 1926. As the founder of the journal *Zeitschrift für Krystallographie*, the author of the collection of crystallographic knowledge *Chemische Kristallographie* (1906-1919), and the source of the crystals that von Laue used for the discovery of X-ray diffraction, his place in the crystallographic firmament is assured. However, according to Shafranovskii, "Despite the prominence of the author, unfortunately the presentation of material [in his history] is sketchy. The review of the second half of the 19th Century is too brief and fragmented for a balanced narrative." Also falling short, according to Shafranovskii, was the Austrian mineralogist Tertsch, whose popular history, *Secrets of the Crystal World. A Romance of Science* (1947), trumpeted hyperbolic language not justified by its contents.



Figure 2. I. I. Shafranovskii age ~ 50.

Naturally, Shafranovskii gave special attention to the Russian literature. Terniaev's (1767-1827) history of mineralogy predated (1819) Marx's comparable work, with a stronger focus on recent events, especially emphasizing the contributions of Haüy (1743-1822). Vernadsky's (1863-1945) *Foundations of Crystallography* (1904) contains a splendid introduction to the history of crystallograpy. He gives affectionate portraits of giants such as Kepler (1571-1630), Steno (1638-1686), Romé de l'Lisle, Haüy (1736-1790), and Bravias (1811-1863), but also acknowledges lesser heroes such as Bernhardi (1770-1850), who helped to conceive the crystallographic systems, and Grassmann Sr. (1779-1852) who developed the stereographic projection, among others. Lemmlein (1901-1962), a specialist in mineral genesis, treated crystallography's past with great respect, especially the work of Lomonosov (Lemmlein, 1940). His brilliant comments to *On Precious Stones* (1989) by the 11th Century Persian scholar Al-Biruni, frame gemology. Shubnikov (1887-1979) posthumously published his brief "Origins of Crystallography" (1972), a popular introduction to the history of crystallography that, like Vernadsky's text, provides biographical information about pioneers.

Memoirs by Ewald (1888-1985) and Bragg (1890-1971), describe the first steps and subsequent developments in X-ray crystallography (Ewald, 1962; Bragg, 1975). Shafranovskii's history ends as X-rays are discovered. A full history of X-ray crystallography, a story of the 20th century, has yet to be written.

Here follows a biographical sketch of Shafranovskii, his table of contents, as well as a translation of the introduction to his two-volume opus, and a late chapter on Pierre Curie's Universal Principle of Symmetry.

2. Ilarion Ilarionovich Shafranovskii (1907-1994)

Ilarion Ilarionovich Shafranovskii (Anonymous, 1957, 1967, 1977, 1987, Figure 2), the son of a mathematician, was born in St. Petersberg. He first studied crystallography with Ansheles (1885 - 1957) at Leningrad University, graduating in 1931. In 1934, Shafranovskii began a professorship at the Leningrad Mining Institute, founded in 1907 by Fedorov (1853-1919), Ansheles' teacher. Shafranovskii received his doctoral degree in 1942 for studying diamond crystals with unusual morphologies. In 1946, he assumed the E. S. Fedorov Chair of Crystallography. Shafranovskii's name is frequently linked that of Federov. Shafranovskii wrote a biography of Fedorov (Shafranovskii, 1963), and in 1970 was awarded the E. S. Fedorov prize of the Academy of Sciences of the USSR for his work on the morphology of crystals and contributions to the history and popularization of crystallography.

Shafranovskii wrote some 500 articles and books. Among his major works are a textbook on crystallography with Popov, *Mineral Crystals* (1957), *Lectures on Crystallomorphology,* translated into English (1973), and *Outlines of Mineralogical Crystallography* (1974). In addition to the histories mentioned in the previous section, Shafranovskii published monographs on Koksharov (1818-1892) (Shafranovskii, 1964), Werner (Shafranovskii, 1968a), and Steno (Shafranovskii, 1972), among others, in addition to Fedorov, already mentioned. He wrote popular accounts of crystallography including *Diamonds* (1964) and *Symmetry in Nature* (1968b) that won the All-Union Knowledge Competition prize for the best popular science book.

In 1982, a mineral was named in Shafranovskii's honor, Shafranovskite, found the mountains of the Kola Peninsula, the eastward-jutting, thumb-shaped landmass atop Finland.

3. History of crystallography table of contents

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4. A translation of the "Introduction" to *History of Crystallography*[1]

Goethe said, "The history of science is science itself" (Fink, 1991). Crystallography well illustrates his aphorism, at least as judged from its development in textbooks. Indeed, turning the pages of an elementary treatise in crystallography takes us from the simple to the complex following the chronological development of the science of crystals. For instance, the chronology of discoveries in geometrical crystallography mimics the order in which the associated concepts are presented in most textbooks. Pliny the Elder (AD 23 – 79) marveled at the extraordinarily flat faces of quartz crystals: "not even the most skillful lapidary could achieve such a finish" (Healy, 1999). A long time passed before the law of the constancy of interfacial angles was articulated in 17th and 18th centuries by Steno (1638-1686), Henkel (1678-1744), Lomonosov (1711-1765), and Romé de l'Lisle (1736-1790). Häuy (1743-1834) went further with law of rational indices, and the relationship between external shapes and internal structure. Weiss and Mohs deduced the zone law at the start of the 19th Century. Hessel, Bravais, and Gadolin (1828-1892) derived the finite symmetry classes, the 32 crystallographic point groups. Frankenheim (1801-1869), Bravias (1811-1863), and Sohncke (1842-1898) introduced the infinite symmetries of lattices. Fedorov and Schoenflies (1853-1928) carry us into the 20th Century and modern structural crystallography with derivations of the 230 space groups.

We could reconstruct the development of crystal physics likewise by tracing a path through discovery of double refraction in Iceland spar by Bartholinus (1669), to the correlation of optical and morphological symmetry by Brewster (1781-1868), to the correlation of all physical properties of crystals with symmetry by Neumann (1798-1895), and to the general symmetry principle of Curie (1859-1906) and modern solid state physics.

We thus might conclude that organizing a history of crystallography is a simple task. We need only enumerate in chronological order, and then elaborate on, all the achievements of crystallography. Of course, the situation is more complicated than it appears at first blush. The skeletal historical outlines above are idealized and purged of detours. Bewilderment, the lifeblood of the scientific enterprise, is nowhere in evidence. Such an accounting prejudicially selects only those developments that are organically incorporated into modern crystallography without disturbing the harmony of the imposing edifice. A faithful history of crystallography -- in all its fullness -- muddles the implicit history of the textbooks.

Foremost among the characteristics of crystals that have guided the development of crystallography is the problem presented by the stridently polyhedral shapes of crystals. "Crystals flash forth their symmetry"[2] according to Fedorov on the first page of his *Course in Crystallography* (1901). This fact had practical consequences: Agricola (1494-1555) instructed miners to identify minerals through their external "angular figures" (Agricola, 1556, 1950). Yet, Nature's well-facetted crystals presented a clearly defined problem to natural

[1] In order to provide more complete citations, we have added some sources that postdate Shafranovskii.

[2] The English rendering of this phrase was taken from Archard's translation of Shubnikov and Kopstik (1974).

philosophers that could not be solved without comprehensive geometrical analyses. Cardano (1501-1576) first proposed (1562) that the hexagonality of the rock crystal might arise from an internal structure consisting of densely packed spheres, anticipating Harriot (1560-1621) and Kepler, in part (Shafranovskii, 1975; Kahr, 2011). Ever since, the theoretical and empirical sciences of crystals developed in parallel. Albeit theory outpaced experiment until the 20th Century.

On the slight basis that crystals have geometrical shapes, are homogeneous, and anisotropic, theorists created a breathtaking mathematical crystallography. First articulated were laws that controlled the appearance of crystals of finite point symmetry. Like other mathematical disciplines, the development of theoretical crystallography was strictly logical, led to prediction, and guided subsequent experimental studies. The deduction of crystal classes (Hessel, 1830; Gadolin, 1867) was carried out before many of were illustrated by minerals; of the 32 crystal point groups, Gadolin found only 20 examples in nature. The laws governing crystal point symmetries were then extended to cover the symmetries of infinite crystal lattices. Indeed, at the end of the 19th Century, achievements in mathematical crystallography were so impressive that Fedorov proclaimed that its mathematical character rendered it "one of the most exact sciences" (Fedorov, 1901). Only now have advances in analysis matched those of theory, restoring balance to the science of crystals.

In the middle of 19th Century Frankenheim and Bravais developed the concept of the crystal lattice enumerating the 14 frameworks that form the basis of the modern structural crystallography. "Nature knelt before the hard theory, and the crystals positioned themselves in those classes where they should be according to the geometrical systems of points (space lattices)," expressively wrote Fedorov (1891). The 14 Bravais lattices and the 32 point groups were the constraints between which Fedorov, and independently Schoenflies (1853-1928), deduced in 1890-1891 the 230 possible space groups that restrict the mutual arrangement of building units (atoms, ions, molecules) inside crystals (1891). These far-seeing predictions were fully supported by experimental data subsequent to the discovery of X-ray diffraction by von Laue (1912), an achievement that is no less impressive than Mendeleev's expectations of undiscovered chemical elements on the basis of the periodic system. The derivation of the 230 space groups of Fedorov caps our history; it is the pinnacle in development of the classical science of crystallography.

Along the way, sharp conflicts between scientists were provoked. Romé de l'Lisle clashed with Häuy on the relationship between morphology and internal structure. The German physiographical school of Weiss (1780-1856), Mohs (1773-1839), and Naumann (1797-1873), conflicted with theoretical studies by Hessel (1796-1872) and Bravias. Mineralogists Koksharov and Eremeev (1830-1899) fiercely resisted the mathematical generalizations of the Fedorov.

In this history, chapters devoted to the development of important crystallography concepts alternate with chapters devoted to the lives, creative work, and struggles of the greatest crystallographers. Biographical details that inform certain advances are vital in that they color the local character or "microclimate" out of which those advances arose. Accounts of

the fate of a discovery, involving the collective acceptance or negation of an idea by many scientists working in disparate countries over centuries, illustrate the global character of the history of crystallography. Experiment and theory drive one another while great currents sweep up individuals whose works and words broaden the stream.

The use of crystalline materials by various professionals, further confounds the author of a history of crystallography. Since ancient times minerals guided miners in search of raw materials. Subsequently, the growth of crystals became a part of problem solving in metallurgy, physics, chemistry, and pharmacology, connecting crystallography with many branches of pure and applied science. This prevented crystallography from coalescing as an independent science for a long time. Crystallography was variously considered as a part physics, chemistry, mathematics, or especially mineralogy. In the 19th Century, crystallography was "preparatory mineralogy". Young Fedorov called crystallography "geometrical mineralogy". Even after having placed the capstone on the science of classical crystallography with the derivation of the space groups, Fedorov wrote at the end of his life: "[Crystallography] plays an essential role at the heart of mineralogy and as part of mining science whose primary purpose is utilization of natural resources" (Fedorov, 1955). Only recently has the characterization of crystallography as a "servant of mineralogy" faded. Today even cell biologists, and biomedical researchers embrace crystallography although this aspect of the history of crystallography is not covered herein.

Metzger, it her doctoral dissertation *Genèse de la Science d'Cristaux* (1918), previously considered crystallography's emergence from other sciences. Nevertheless, there is backflow; advances in the aforementioned disciplines draw crystallography back in. For instance, according to Vernadsky, "Crystallography has not been separated from mineralogy. It embraced mineralogy in a new way, entered its foundations and changed it radically…Mineralogy does not need to free itself from the physical sciences. Rather we must build new relationships between crystallography and mineralogy so as to transform the latter" (Vernadsky, 1928). Similar things have been said about the relationship of crystallography to chemistry (Engels, 1954) and to pharmacy (Fabian, 1967).

The changing interrelations among the sciences and their sub-disciplines complicates a reconstruction of the history of crystallography. Important threads must be picked from the vast literature on mineralogy, mathematics, physics, chemistry, metallurgy, medicine, and biology among others disciplines. This extraction requires an enormous amount of time and effort. Obviously, the history of crystallography can be only conditionally likened to a continuous, smooth line. In reality, we face something like a dotted line diving in and out of the general tableaux of the development of science.

So, how shall we write a history of crystallography? We can follow Metzger and little by little separate crystallography from historically related sciences, stressing the increasing independence from other disciplines. Alternatively, we can consider the development of crystallography as a natural structure constrained by the symmetries of regular crystal packing that started with minerals and gradually subsumed a wider spectrum of objects from synthetic molecular crystals to semi-conductors to drugs to proteins. The development

of crystallography validates both approaches. This happens due to dialectic process of the differentiation and synthesis of the sciences (Figurovsky, 1969). Indeed, specialization of the science of crystals results in great progress; narrow disciplines can probe ever more deeply. On the other hand, increasing contacts among a rising number of allied disciplines obscures the main themes that specifically delineate the development of crystallography.

These ideas fully correspond to the new conceptions of the development of sciences. It is interesting to note that Fedorov stands at the beginning of such a systems approach. In his philosophical treatise "Perfectionism" he wrote: "The scientist is perpetually faced with the generalization of proven laws. The higher the philosophical development of a scientist, the clearer he understands the need to generalize even further because the logic of philosophy requires complete reduction" (Fedorov, 1906). The same ideas expressed more emphatically can be found in his later papers: "Are there true boundaries between sciences? Maybe all the sciences constitute something united and indivisible. Maybe the boundaries of a science, as they are established, represent only artificial constructions adapted to current understanding" (Fedorov, 1917). Thus, we must follow the historically conditioned development of the science of crystals without becoming isolated behind "artificial partitions" established by other disciplines.

Crystallographic phenomenology is emblematic to scientific generalization. Now, scientists often invoke "isomorphic laws" in different fields of science. It is gratifying to witness symmetry laws, firstly discovered in crystals, transferred to other fields of science. The beautiful examples of "isomorphism" underscore the relationship of geometrical crystallography to chemistry; the Steno-Lomonosov-Romé de l'Lisle law of the constancy of crystal angles is "isomorphic" to the law of Proust (1754-1826) on the constancy of composition of "true chemical compounds". Lomonsov's mentor, Henkel, formulated the law of the constancy of crystal angles as follows: "Nature in the confusion of her varied combinations has chosen the structure and external appearance of substances according to their properties and corresponding to external conditions and circumstances. She does not deviate from this rule; she sets a compass and measures the angles establishing one substance for all time." (Marx, 1825). Of his eponymous law, Proust said: "A compound is a privileged product, that Nature has given a constant composition. Nature, even with the intercession of people, never produces a compound without balance in hand; everything is in accord with weight and measure" (Menshutkin, 1937). The similarity in the formulation of this statement with that of Henkel is startling.

The law of the constancy of angles combined with the observation of cleavage phenomena led Häuy to formulate the unique "polyhedral molecules" (crystal structures in modern parlance) for a given crystalline compound. In the 20th Century, Goldschmidt (1888-1947) interpreted this statement as "the primary basis of crystal chemistry" (Goldschmidt, 1937). The thesis of Häuy combined with Steno's law is the crystallographic analogue of the Proust's generalization in chemistry. The law of rational indices in crystals by Häuy is "isomorphous" to the basic law of chemistry, Dalton's (1766-1844) law of multiple proportions. Obviously, the older crystallographic laws played some role in establishing of

latter ones. Thus, once again we see the impossible task of the historian keen to separate unadulterated crystallography from closely related disciplines of physics, chemistry, and mineralogy.

Periodization, the subdivision of a long history into stages of development, provides further practical problems for the historian. Lenin (1870-1924) provides a general guide: "From living contemplation to abstract thinking *and then to practice* – this is a dialectic way in perception of *truth*, perception of objective reality" (Lenin, 1967). These words agree well with a statement by Fedorov: "When the nearest practical consequences of a given theory become known, we acquire the power to control Nature…the task of any science is to obtain such a power. Therefore, everything that gives this power is scientifically true" (Fedorov, 1904).

According to Kedrov (1903-1985), there are three main stages in the development of any science: (1) empirical fact gathering, (2) theory and explanation, and (3) prognostication (Kedrov, 1971). In the history of crystallography, we can see all three periods. For example, previously, with Grigoriev, we divided the history of Russian mineralogy and crystallography into four stages: narrative-descriptive, exact-descriptive, theoretical, and synthetic (Grigoriev, Shafranovskii, 1949). To a certain extent this division agrees with Kedrov if the two descriptive stages are aligned with his empirical stage. While mindful of the dual theoretical and practical development of crystallography, we recognize that a strict division into stages is impossible. In fact, Kedrov admits the conditional character of his divisions. In Russian crystallography, these periods are intertwined, overlapped, and sometimes inverted. Sometimes all three Kedrov stages can be identified in the activity of one and the same scientist. Nevertheless, stages are evident when we take a course-grained, centuries-wise perspective of the most significant achievements that carried the science forward: rules of morphology by Steno (1669), formulation of descriptive and theoretical crystallography by Romé de l'Lisle and Häuy (1783-1784), the mathematical inventions of Fedorov (1881-1919). In the 20th Century we have to acknowledge two "great revolutions in crystallography" as they were called by academician Belov (1891-1982): the epochal discovery of X-ray diffraction by von Laue (1912) and revolutionary developments in the growth of technically important single crystals in the 1950s and1960s (Belov, 1972).

In this work, for operational purposes, we distinguish four periods in the history of crystallography:

1. Prehistory, from ancient times to Steno;
2. Emergence of crystallography as an independent science, from Steno to Romé de l'Lisle and Häuy;
3. Development of classical, geometrical, crystallography, from Häuy to Fedorov;
4. The modern period, from Fedorov and von Laue to the present day, with its powerful synergy of crystal physics, crystal chemistry, structural biology, and crystal growth technologies.

A finer grained division into stages requires accounting of the related scientific disciplines: geology (Tikhomirov & Khain, 1956; Gordeev, 1967; Batyushkova, 1973), mineralogy

(Povarennyh, 1962), physics (Dorfman, 1974), and chemistry (Figurovsky, 1969) among others.

5. Translation of "Universal Symmetry Principle – Curie"[3]

Pierre Curie (1859-1906, Figure 3) was crushed under the wheels of a horse drawn carriage on a Paris street, a great misfortune for the world science. One of the most splendid French scientists of all time died at the peak of his power. Curie's deep insights survive in just a few, unusually concise articles. For this reason, the impact of his ideas, especially those related to crystallography and the symmetry principle, were not fully realized for some time.

The life and scientific work of Curie is described in a modest book by his wife Marie Curie (1867-1934) (Curie, 1963). Her brief biography of her husband succeeded in fleshing-out some of Pierre's ideas on symmetry that were not found in his publications. Marie also conveyed a sense of her husband's simple character and his devotion to the abstract life of the mind. Marie wrote, "He could never accustom himself to a system of work which involved hasty publications, and was always happier in a domain in which but a few investigators were quietly working" (Curie, 1963).

Pierre Curie was born in Paris, the son and grandson of physicians. He was schooled at home, but began attending lectures at the Sorbonne at a comparatively early age. At 18 he obtained a licentiate in physics after which he worked as a laboratory assistant in charge of the practical operations of the *École municipale de physique et de chimie industrielles*. He served as an instructor in physics until his appointment as Professor at the Sorbonne in 1903.

Curie's first papers describing the discovery of piezoelectricity in tourmaline, quartz, and other crystals (1880-1882), were written with his brother Jacques. His doctoral dissertation (1895) was an investigation of magnetism and the distinctions among diamagnetic, paramagnetic, and ferromagnetic substances, especially their temperature dependences. Pierre was a collaborator in the studies of radioactivity initiated by his wife Marie Skłodowska Curie. This work led to their joint discovery of polonium and radium in 1898. In 1903 they were awarded the third Nobel Prize in physics, together with Henri Becquerel (1852-1908). However, less well known than Pierre's highly publicized and well recognized work on radioactivity, but arguably as important, were theoretical papers devoted to crystallography and symmetry.

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[3] In his scientific work, Shafranovskii was driven to understand the well know fact that crystals frequently have lower morphological symmetry than that expressed by physical properties or by X-ray diffraction. He recognized that the dissymmetry of the medium was often responsible for "false" crystal morphologies. This relationship between dissymmetric cause and effect was understandable in terms of Pierre Curie's Universal Symmetry Principle. For this reason, the work of Curie was of special interest to Shafranovskii. And for this reason, we provide a translation of one of the last chapters of the second volume of the *History*: "University Symmetry Principle – Curie".

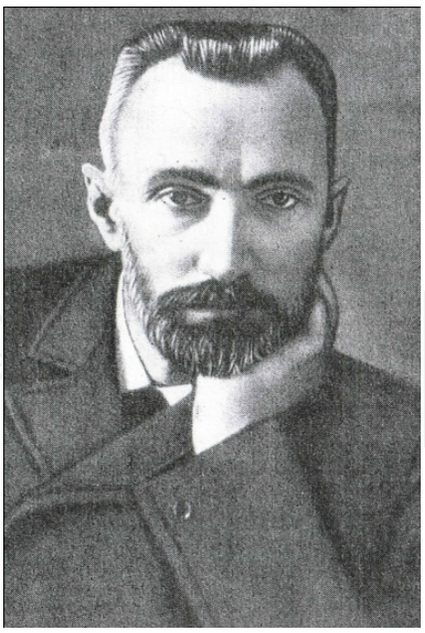


Figure 3. Pierre Curie.

Physics and crystallography, explained Marie in the foreword to Pierre's collected works, were "two sciences equally close to him and mutually complementary in spirit. For him, the symmetry of phenomena were intuitive." (Curie, 1908). Thus, he was perfectly positioned to fully apply symmetry to physical laws. Still, distractions of work on radioactivity, adverse health effects associated with handling radium, and the burdens of fame left him wanting of more time to devote to his first loves, symmetry and crystallography. In her biography, Marie wrote, "Pierre always wanted to resume his works on the symmetry of crystalline media…After he was named professor at the Sorbonne. Pierre Curie had to prepare a new course…He was left great freedom in the choice of the matter he would present. Taking advantage of this freedom he returned to a subject that was dear to him, and devoted part of his lectures to the laws of symmetry, the study of fields of vectors and tensors, and to the application of these ideas to the physics of crystals."

The crystallographic legacy of Pierre Curie consists of only 14 extremely brief articles, each a classic. Curie's earliest contributions to crystallography are devoted piezoelectricity. Then follow the papers on the Universal Symmetry Principle. Finally, there is a small article on the relationship of crystal form to surface energy (Curie, 1885). This is now known as the Gibbs-Curie-Wulff rule.

It is commonly stated that piezoelectricity of crystals was discovered by the Curie brothers in 1880. This assertion must be qualified. In 1817, Häuy published a communication "On the electricity obtained in minerals by pressure" (Haüy, 1817). Pierre and Jacques Curie rediscovered this lost and incompletely described phenomenon. For sphalerites, boracites, calamine, tourmaline, quartz, Rochelle salt and other compounds, the Curie brothers showed that piezoelectricity can be present only in hemihedral crystals with inclined faces – in other words in acentric crystals – and that electric dipole moments can arise only along polar directions. Thus, knowing the crystal symmetry it became possible to predict the

orientation of electrical axes. "This was by no means a chance discovery. It was the result of much reflection on the symmetry of crystalline matter that enabled the brothers to foresee the possibilities of such polarization", wrote Marie (Curie, 1963).

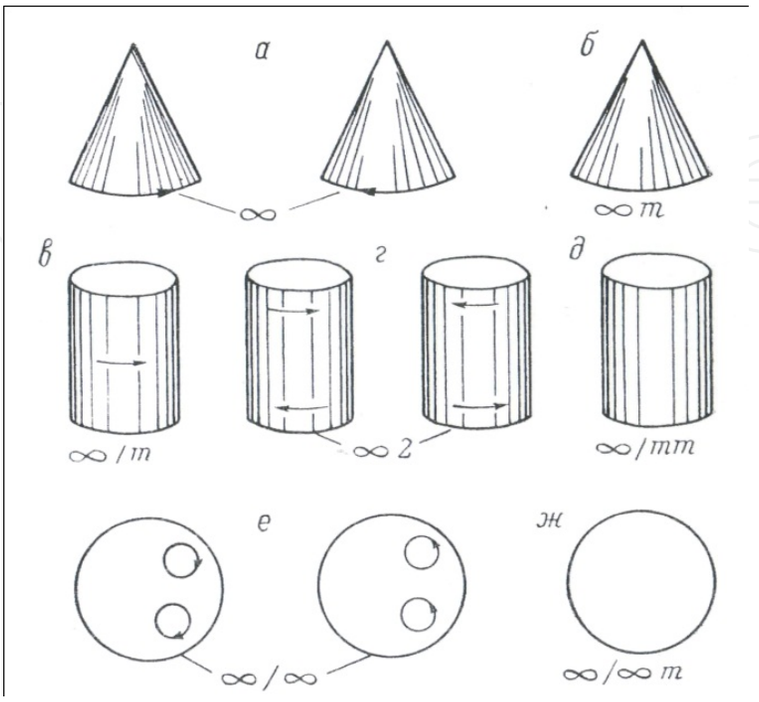


Figure 4. Seven infinite point groups of symmetry: rotating cone, cone at rest, rotating cylinder, twisted cylinder, cylinder at rest, rotating or chiral sphere, and sphere at rest.

Quartz crystals were studied in the most detail. The brothers Curie carried out a series of careful experiments that enabled them to establish general principles of piezoelectricity and define the magnitude of the quartz piezoelectric coefficient. The most complicated part of experimental work concerned the measurement of electrostriction, the deformation of piezoelectric crystals by applying an electric field (Curie, 1889). They proved the existence of this phenomenon, known as the inverse piezoelectric effect, first theoretically predicted by Lippmann (1845-1921). Finally, they invented and developed a series of devices for the study of piezoelectricy including a press with a manometer, a tool combining a lever and microscope for the measurement of electrostriction, and an extremely accurate electrometer in which metallized quartz surfaces were used to collect charges generated when pressure was applied to the quartz (Mouline & Boudia, 2009). Curies' works on piezoelectricity were inspirational to giants such as Röntgen (1845-1923), Kundt (1839-1894), Voigt (1850-1919), and Ioffe (1880-1960), among others. Langevin (1872-1946) utilized the piezoelectricity of quartz to produce ultrasound that is now used for measuring sea depth and detecting underwater objects.

At this same time, Curie worked out his theory of symmetry in a pair of papers (Curie, 1884, 1885b). Unlike Hessel, Bravais, and Fedorov, Curie's approach to symmetry fully integrated physics with mathematics. His lattices were made from physical objects, not geometrical points. The vectoral and tensorial physical properties of which he was so well aware

through experimental work on magnetism and piezoelectricity were poorly accounted for by point lattices. “Significant difficulties arise”, he said, “when points have associated properties related to direction in space. Such points should be represented by geometric figures embodying both magnitude and direction”(Curie, 1885). In searching for the proper figures, Curie was the first to establish the seven so-called “infinite point groups of symmetry” (Figure 4) with an infinite order axes (L_∞). Hessel identified only three: $L_\infty\infty P$ (∞m) (symmetry of the cone), $L_\infty\infty L_2\infty PC$ (∞/mm) (symmetry of the bi-cone or cylinder), and $\infty L_\infty\infty PC$ ($\infty/\infty m$) (symmetry of the sphere). Curie completed this set by adding four additional infinite groups: L_∞ (∞) (symmetry of rotating cone), $L_\infty\infty PC$ (∞/m) (symmetry of rotating the cylinder), $L_\infty\infty L_2$ ($\infty 2$) (symmetry of the twisted cylinder), and ∞L_∞ (∞/∞) (symmetry of the sphere lacking mirror planes; all diameters of such a sphere are twisted to the right or left).

An illustration of seven infinite point groups after Shubnikov is given in Figure 4 (enantiomorphs are not shown). Curie illustrated these groups by examples from physics. The chiral sphere was associated with an optically active liquid. The $L_\infty\infty L_2$ case corresponded to two identical cylinders placed one onto another, filled with a liquid, and rotating with the same speed in opposite directions around their common axis L_∞. The symmetry of a cone ($L_\infty\infty P$) was compared with the symmetry of electric field, and the symmetry of a rotating cylinder ($L_\infty PC$) with the symmetry of the magnetic field (Curie, 1894). Infinite point groups are important because all other point groups are subgroups thereof.

Curie was the first to distinguish electric and magnetic dipoles. (Curie, 1894) Therefore, for example, in cubic crystals $m3m$ and 432 Curie considers the double number of axes compared to conventional notion: $6L_4$, $8L_3$, $12L_2$. Obviously, this approach was initiated by his studies of piezoelectricity in which it is essential to distinguish reversible and irreversible (polar) directions.

This profound approach to symmetry enabled Curie to discover a new symmetry element, the “periodically acting plane of symmetry.” This symmetry element now corresponds to the improper rotation axis. Bravais, in his paper, *Note sur les polyèdres symétriques de la géométrie* (1849) "studied the symmetric polyhedra, but accounted only for proper rotation axes, centers of inversion, and mirror planes. He did not take into account periodically acting planes of symmetry,” said Curie (1966). However, Curie did not know that this concept already had been proposed by Hessel in a different form, and by Gadolin in 1867 during his deduction of the 32 symmetry classes.

Almost simultaneously with Curie, Fedorov introduced mirror-rotation axes in his first book *Introduction to the Doctrine of Figures* (1855). Federov simultaneously discovered the mirror-rotation axes. In a letter to Schoenflies (1853-1926), Fedorov protested against calling the 32 crystal classes “Minnigerode groups”. “In my opinion,” he wrote, “this name is especially wrong, because in a paper by Curie as well as in my “Principles of doctrine on figures” (which, as I mentioned in my previous letter, was submitted for publication before Curie’s paper) there were some new ideas, whereas the paper by Minnigerode (1837-1896)

did not contain anything new" (Bokii & Shafranovskii, 1951). This question of priority lost its meaning when Sohncke (1842-1897) discovered that Hessel was in fact the first.

In 1885, Curie published a small but very important paper *Sur la formation des cristaux et sur les constants capillaires de leurs differrentes faces* (Curie, 1885a) in which he established that a crystal or an assemblage of crystals in equilibrium with a solution adopts a form that minimizes the surface energy. This result was obtained by Gibbs (1839-1903) in 1878, however, his work languished in the literature, unappreciated for a long time. In his classic paper "On the problem of growth and dissolution rates of crystal faces", Wulff (1863-1925) expressed this idea in terms that were easily applied (Wulff, 1952). The Wulff theorem states that "The minimum of the surface energy for a crystalline polyhedron of fixed volume is achieved, when the faces are spaced from the same point on distances that are proportional to the surface free energies" (Wulff, 1952). This theorem results in the important consequence that the growth rates of crystal faces are proportional to the specific surface energies of the faces. Wulff gave only an approximate proof of this theorem.

The theorem of Gibbs-Curie-Wulff was intensively debated. In 1915, Ehrenfest (1880-1933) emphasized that vicinal faces of real crystals have higher surface energies. This fact formed the basis of the objections to Curie's idea by the Dutch inorganic chemist, Van Arkel (1893-1976). But, this principle can be unconditionally applied only to the equilibrium shapes of the crystal.

In 1894, Curie published an especially important paper on symmetry: *Sur la symétrie dans les phénomènes physiques. Symétrie d'un champ électrique et d'un champ magnétique*. This paper begins with a following sentence: "I believe that it would be very interesting to introduce into the study of physical phenomena the property of symmetry, which is well known to crystallographers" (1894). This paper contains the most important ideas on the universal significance of symmetry. Reflections on these ideas can be found in the biographical sketch by Marie, *Pierre Curie, with the Autobiographical Notes of Marie Curie*: "It was in reflecting upon the relations between cause and effect that govern these phenomena that Pierre Curie was led to complete and extend the idea of symmetry, by considering it as a condition of space characteristic of the medium in which a given phenomenon occurs. To define this condition it is necessary to consider not only the constitution of the medium but also its condition of movement and the physical agents to which it is subordinated." And, "For this it is convenient to define the particular symmetry of each phenomenon and to introduce a classification which makes clear the principal groups of symmetry. Mass, electric charge, temperature, have the same symmetry, of a type called scalar, that of the sphere. A current of water and a rectilineal electric current have the symmetry of an arrow, of the type polar vector. The symmetry of an upright circular cylinder is of the type tensor" (Curie, 1963).

General statements found in the above paper are of great significance. "The characteristic symmetry of a given phenomenon is a maximal symmetry compatible with this phenomenon. The phenomenon can exist in the medium, which has a characteristic symmetry of this phenomenon or a symmetry of a subgroup of the characteristic symmetry. In the other words, some symmetry elements can coexist with some phenomena but they are

not requisite. Some symmetry elements should be absent. That is, dissymmetry creates the phenomenon" (Curie, 1894).

Curie gave much broader interpretations to the concept "dissymmetry" than did Pasteur. He ascribed dissymmetry to the absence of symmetry elements that actuate some physical properties. For example, in the tourmaline crystal ($L_3 3P$ – $3m$) the absence of the perpendicular symmetry plane gives the polar character to the L_3 axis. This polarity makes pyroelectricity in tourmaline possible. For Curie, dissymmetry, the absence of symmetry, was as palpable as symmetry itself. He believed that the dissymmetric elements (e.g. a dissymmetry plane is any plane that is *not* a symmetry plane, a dissymmetry axis is any axis that is *not* a symmetry axis) could give a deeper insight into the physical meaning of phenomena. However, the infinite number of dissymmetry elements, unlike the very restricted number of symmetry elements, forces us to operate with the latter.

Shubnikov best characterized Curie's emphasis on dissymmetry: "symmetry must not be considered without its antipode – dissymmetry. Symmetry treats those phenomena at equilibrium, dissymmetry characterizes motion. The common conception of symmetry-dissymmetry is inexhaustible" (Shubnikov, 1946).

Curie formulated several important consequences to what is now called Curie's Universal Principle of Symmetry-Dissymmetry. "Superimposition of several phenomena in one and the same system results in addition of their dissymmetries. The remaining symmetry elements are only those that are characteristic of both phenomena considered separately. If some causes produce some effects, the symmetry elements of these causes should be present in the effects. If some effects reveal dissymmetry, this dissymmetry should be found in the causes" (Curie, 1894).

The statements cited above were illustrated by Curie with the infinite symmetry classes. He emphasized the special importance of class $L_\infty\infty P$: "Such a symmetry is associated with the axis of the circular cone. This is the symmetry of force, velocity, and the gravitational field, as well the symmetry of electric field. With respect to symmetry, all these phenomena may be depicted with an arrow" (Curie, 1894).

In fact, consequences of the association of symmetry $L_\infty\infty P$ with gravity are inexhaustible. For example, it explains evolution of the symmetry in organic life. The simplest organisms evolved in a medium of spherical symmetry ($\infty L_\infty\infty PC$ ($\infty/\infty m$)) such as the protozoan suspended in a homogeneous fluid. Then the cone symmetry ($L_\infty\infty P$ (∞m)), that describes gravity begins to exert its influence pinning life to the ground. The plane symmetry $P(m)$ is actualized for moving organisms. Thus, the evolution of the organic life is controlled by the following sequence of desymmetrization of the medium: $\infty/\infty m > \infty m > m$ (Shafranovskii, 1968; Spaskii & Kravtsov, 1971).

Likewise, in mineralogy (Shafranovskii, 1974) detailed investigations of real, naturally occurring crystals requires a thorough knowledge on the medium in which the crystals were formed. Curie's principle does not allow us to consider the resulting crystal in the absence of its growth medium because the symmetry of the growth medium is superimposed on the

symmetry of the growing crystal. The resulting form of the crystal can preserve only those symmetry elements that coincide with the symmetry elements of the growth medium. Of course, the internal symmetry, the crystal structure, does not change. The observed crystal morphology is a compromise resulting from the superimposition of two symmetries: internal symmetry of the crystal and the external symmetry of the medium. Thus, distorted crystal shapes, frequent in nature, are indicators of growth medium dissymmetry.

Curie's thoughts on symmetry have been only recently duly appreciated. Vernadsky was an advocate in his declining years. He wrote posthumously, "More than 40 year ago, in unfinished works interrupted first by the distraction of radium and then by death, Pierre Curie for the first time showed that the symmetry principle underlies all physical phenomena. Symmetry is as basic to physical phenomena as is the dimensionality of geometrical space because symmetry defines the physical state of the space – *état de l'éspace*. I have to stop here and emphasize the often forgotten importance of the force of personality. The premature depth of Curie at the peak of his powers stopped progress in this field for decades. Curie understood the significance of symmetry in physical phenomena before the causal relationship between symmetry and physical phenomena was not realized. He found the significance of this relationship previously overlooked" (Vernadsky, 1975).

Vernadsky writes: "The physically faithful definition [of symmetry], that we encounter throughout this book, was given by Curie…This is representation of a symmetry as a state of the earth, i.e. geological, natural space, or, more accurately as states of the space of natural bodies and phenomena of our planet Earth. Considering the symmetry as a state of the earth space it is necessary to emphasize the fact was expressed by Curie and recently stressed by A.V. Shubnikov, that the symmetry manifests itself not only in a structure but also in motions of natural bodies and phenomena" (Vernadsky, 1957).

Vernadsky knew Curie, whom he describes as "charming but lonely" (Vernadsky, 1965).

Detailed and very clear analyses of crystallographic ideas by Curie is presented in Shubnikov's paper "On the works of Pierre Curie in the field of symmetry" (Shubnikov, 1988): "P. Curie is known to broad audience of scientists as an author of influential works in the field of radioactivity. But he is almost unknown as the author of profound studies in the field of symmetry and its applications to physics. However, these studies, if they were continued by P. Curie, could have hardly less significance for development of natural science than his works on radioactivity for development of chemistry and physics."

Shubnikov noted that Curie's papers were "extremely concise", a style that did not lend itself to the general the acceptance of ideas that were before their time. He forecast that future generations would need to finalize Curie's ideas" (Shubnikov, 1988). At the same time, Shubnikov, with Koptsik argued that the Curie principle is part of a tradition, in that it is a generalization of the principles of his predecessors, Neumann and Minnegerode. This is true only in part. In fact, there is a vast difference between the scope of Curie's vision that expanded the significance of symmetry to all natural phenomena and the observations of Neumann and Minnegerode that were restricted to crystals. While, Curie is today rightly

recognized as the forefather of the modern crystal physics, which is based entirely on symmetry laws, his ideas on symmetry in nature have penetrated into all branches of modern science.

5. Curtis Schuh, his *Biobibliography,* and Companion *History*

5.1. Curtis P. Schuh (1959-2007)

As we were working on the Shafranovskii translation, we became aware of three unfinished and unpublished documents on the website archives.org by Curtis P. Schuh (Figure 5): *Mineralogy & Crystallography: An Annotated Biobibliography of Books Published 1469 Through 1919, Volumes I & II* (Schuh, 2007a,b), as well as *Mineralogy & Crystallography: On the History of These Sciences From Beginnings Through 1919* (Schuh, 2007c). The *Biobibliography* has been incorporated into the Biographical Archive of the Mineralogical Record (2012). Schuh was an independent scholar working in Tucson, Arizona. He describes his 561 history based on the most complete bibliography of sources ever assembled (1562 pages) as a "derivative" study that no "true" historian would write. This is false. Though incomplete, it will have a lasting impact on future research in the history of crystallography for generations to come.

Curtis Schuh died prematurely in 2007. A sketch of his life was recorded in *The Mineralogical Record* by its editor and Schuh's friend, Wendell E. Wislon (2007, 2012). The following facts of Schuh's life were taken from Wilson's obituary, and also from an entry on the website Find a Grave by Bill Carr (2008).

Curtis Paul Schuh was born in Boulder, Colorado in 1959 and raised in the Denver area. After he graduated from high school, his father, a newly retired IRS agent, moved the family to Tucson. Schuh studied engineering and mathematics at the University of Arizona, earning three Bachelor of Science degrees. Subsequently, he worked in the field of computer support for a number of organizations in the Tucson area.

In both Colorado and Arizona, Schuh was fortunate to have found concerned and dedicated mentors in the mineralogy community who shared their love of minerals and books about minerals. The library of rare crystallography volumes belonging to Richard Bideaux, the owner of a local mineralogy shop in Tucson, inspired the preparation of a comprehensive bibliography of mineralogy and crystallography. The *Biobibliography* is dedicated to Bideaux who encouraged this decades-long undertaking. Schuh did not anticipate at the outset that he was embarking upon a lifelong project.

Schuh lived a quiet, solitary life of scholarship. Ill at age 48, Curtis Schuh ended his life in the Arizona desert. His abandoned car was found. He left a note claiming that "my body will never be found." It has not been.

We are grateful that before his death Schuh left behind electronic copies of his masterworks, freely available to anyone wishing to benefit from his labors (Schuh, 2007a,b,c).

There is no better way to appreciate the detail of Schuh than to download his documents (617 megabytes) and explore for one's self. Short of direct inspection, what can we say here?



Figure 5. Curtis P. Schuh (2005). Photograph courtesy of Wendell E. Wilson (2012).

5.2. Biobibliography

The *Biobibliography* has too many entries to count accurately. Figure 8 shows the first and last scientists illustrated, **A**bildgaard and **Z**ittel. If an image of a significant survives, chances are very good that it can be found here.

Schuh's *Biobibliography* and *History* enable translation of Shafranovskii more than any other resource. For instance, Shafranovskii relies heavily the history of crystallography by C. M. Marx. What was this book? What can we learn about it short of locating a copy and reading it? Here is what Schuh says about this volume, the 3255rd entry of some 5170 likewise described:

> 3255. German, 1825. Geschichte Der Crystallkunde von Dr. C.M. Marx, Professor der Physik und Chemie in Braunschweig. [rule] Mit neun schwarzen Kupfertafeln und einer colorirten. [rule] Carlsruhe und Baden. D.R. Marx'sche Buchhandlung. [rule] 1825. Gedruckt bei Friedrich Bieweg und Sohn in Braunschweig. 8◦: p7 1-198 206; 165?.; [i]-xiv, [2], [1]-313, [3] p., 10 plates (one folding and colored). Page size: 185 x 115 mm.
>
> Contents: [i-ii], Title page, verso blank.; [iii], Dedication to Count von Schmidt–Phiseldeck.; [iv], Blank.; [v-xii], Preface—signed Carl Michael Marx, 16 May 1825.; [xiii]-

xiv, “Uebersicht des Inhalts.”; 1, “Geschichte der Crystallkunde.”; [2], Quotation from Goethe concerning colors.; [3]-297, Text.; [298]-301, “Rückblick.”; [302]- 309, “Zusätze.”; [310]-313, “Namen–Verzeichniß.”; [1 pg], “Berichtigungen.”; [1 pg], “Abbildungen.”; [1 pg], Blank.; [At end], 10 plates (one folding and hand-colored).



Figure 6. *Biobibliography* from **A**bildgaard to **Z**ittel. Left: Peder Christian Abildgaard (1740-1801) founded the Veterinary School of Copenhagen but earns his place in Schuh for describing Cryolite from Greenland. Right: Karl Alfred von Zittel (1839-1904) served on the Geological Survey of Austria and rose to the Presidency of the Royal Bavarian Academy of Sciences.

Very rare. A highly respected work that develops an understanding of concepts in what was then modern crystallography through historical perspective. As a result, the book covers the history of crystallography from ancient times to 1824. The development is told by describing the contributions of the individuals in chronological order. The text is divided into six sections, each representing a specific time period. The first covers the ancient Greek and Roman researches. The others span (2) Albertus Magnus to Robert Boyle, (3) Nicolaus Steno to Johann Henckel, (4) Carl Linneaus to Jean Baptiste Louis Romé de l’Isle, (5) René Just Haüy to Henry James Brooke, and (6) Abraham Gotthelf Kästner to Friedrich Mohs. The name index lists about 300 researches [sic], whose contributions are described in the text. The plates illustrate various concepts brought forth in the discussion by reproducing recognizable figures from important crystallographic works.

> Facsimile reprint, 1970: Geschichte...Wiesbaden Dr. Martin Sändig oHG. 8◦: [i]-xiv, [2], [1]-313, [2], [1] blank p., 10 plates (one folding and colored). Photographic reprint of the original edition with a modified title page. ISBN 3500220002. References: BL: [726.c.34.].
>
> Of direct relevance are the passages from Shafranovskii that Schuh has already translated. On Lomonsov's doctoral dissertation Shafranovskii worte, "His conceptions of the structure of crystals formulated in this dissertation are so significant that the year this dissertation was written might well be considered the origin of Russian scientific crystallography" (Grigorev & Shafranovskii, 1949). Regarding the doctoral dissertation of Vernadsky on crystallographic gliding, Shafronovkii says: "Here we find the richest synthesis of data relating to unique deformations of crystals, created as a result of gliding, that is the shifting of separate parts of a crystal along straight lines while preserving the volume, weight, and homogeneity of matter. Vernadsky revealed the connection between the planes of gliding, the crystalline facets and elements of symmetry. Here for the first time, he underlined the need to make several qualifications in our conceptions about the complete homogeneity of crystalline polyhedra in connection with changes in their physical features in their surface state. According to this idea, crystals are viewed not as abstract geometrical systems, but as real physical bodies (Shafranovskii, 1980)."

Perhaps you have wondered how many volumes comprised the *Materialy dlia Mineralogii Rossii* (1852) of Koksharov, another Shafranovskii favorite? Here is the answer which corrects a Shafranovskii pecadillo:

> 6 vols. plus atlas. [vol 1: 1852] 8◦: [6], I-III, [1] blank, [1]-412, [4] p., illus. [vol 2: 1855] 8◦: [4], [1]- 339, [1] blank, [4] p., illus. (Page numbers of the first signiature are reversed). [vol 3: 1858] 8◦: [6], [1]-426, [4] p., illus. [vol 4: 1862] 8◦: [4], 515, [5] p. [vol 5: 1866] 8◦: [2], 373, [3] p., plates LXXV-LXXVII. [Atlas] 4◦: 1-4 p., 74 plates (numbered I-LXXIV).

The bibliography of this Russian edition is difficult because of the rarity of the work. Contrary to what Sinkankas (1993) states this Russian edition did not exceed volume five as a separate publication, and contrary to what Grigoriev & Shafranovskii (1949) state volume six did not appear as a separate volume. Instead it made an appearance as an article in the *Gornoi Zhurnal*. In addition the plates are numbered I- LXXVII. In the copy examined, plates LXXV-LXXVII were bound in at the end of volume five and not included in the Atlas proper. Page size: 225 x 148 mm.

Schuh displays such an obsessive commitment getting the facts right that it is hard not to cheer him on in his solitary and unrewarded work.

Care to evaluate early editions of Giorgio Agricola's *De Re Metallica*, one of the most influential works of metallurgy? Now you can (Figure 7). And, is there a Polish edition, should you prefer it? Yes there is.



Figure 7. *De Re Metallica* by Giorgio Agricola. From upper left to lower right: Latin, 1530; Italian, 1550; German, 1557; German, 1580; Italian, 1563; Latin, 1657. See Schuh for many others editions and citations.

5.3. History

The *History* is labeled "(Rough Notes)". We would be grateful for the ability to produce "rough notes" mostly complete and so remarkably refined. Nevertheless, the *History* is incomplete. This is manifest as sections marked for insertion, sections taken verbatim from other sources, but always set-off with "**REWORK**" as a warning, and sections that were delivered directly from machine translators without refinement (In fact, Schuh was engaged in writing machine translating software, presumably to assist him in this work (Wilson, 2004, 2012)).

Schuh's *History* begins in pre-history, 25,000 years ago when humans first learned to distinguish quartz-rich flint rock from softer stones. He then discusses the ancients. Treatment of Islamic scholars is especially comprehensive. While Shafranovskii writes of the importance of al-Biruni's gemology, we learn from Schuh that this Persian Shiite scholar

loathed Arabs, mined the emerald riches of the now lost Mount Muqattam, and made remarkably accurate measurements of specific gravity in the 11th century. He reviews the contributions and biographies of some three-dozen other Muslim mineralogists, emphasizing the curative properties of minerals purported in medieval texts as well as the use of minerals as poisons.

Chapter 5 covers physical crystallography. We read carefully the passages associated with Malus, Arago, Brewster, and Biot, pioneers in crystal optics whose work we have previously studied in detail (Kahr & McBride, 1991; Kahr & Claborn, 2008; Shtukenberg & Punin, 2007, Kahr & Arteaga, 2012). From these circumscribed aspects of the history of crystallography that we know best, we can declare that Schuh's understanding is accurate and deep, his comments nuanced and sophisticated. If we multiply this judgment by the thousands of episodes in the history of crystallography that he knows better than we do, it is hard to imagine how half a lifetime was enough for Schuh.

Certain subjects receive short shrift. For instance, section **8.5 Liquid Crystals**, says precisely this and no more. "Liquid crystals were discovered and studied in the 19th century and were studied primarily by Lehmann, Schenk and Vorlander. By 1908 a theoretical framework for liquid crystals was established and other theoretical studies by E. Bose, Max Born, F. Rhimpf, O. Lehmann, and G. Friedel were made. It was not until after World War II that practical applications for this class of substances were created. Today, every laptop computer, not to mention virtually every digital display utilizes liquid crystals as a display." We cannot know if he intended more for later – or whether this was enough for a subject somewhat tangential to Schuh's main love, mineralogy. We are fortunate to now have excellent liquid crystal histories including *Crystals that Flow* (Sluckin, Dunmur, & Stegemeyer, 2004) containing translations and reproductions of important papers with commentary, Schuh's principle resource for his brief remarks. See also the more accessible general history (Dunmur, Sluckin, 2010).

Section 11.0, "Regional Topographies", has "short histories outlining the development of mineralogy and crystallography in the countries of the world." He means, *all* the countries. He didn't make it through the >200 or so countries and territories, but there are 110 entries including those for Tasmania, the Faroe Islands, and Macedonia (Schuh is the Alexander of crystallography historians – he aspired to conquer the world).

In the chapter on "Mineral Representations", we learn of the first book illustration of a mineral crystal, gypsum from Meydenbach in 1491 (Figure 8, Pober, 1988,) and the fact that some minerals illustrated themselves – *Naturselbstdruckes* – by the direct transfer of mineral texture to paper with ink. Figure 9 shows striations printed from a meteor section (Schreibers, 1820).

Schuh includes chapters on nomenclature, journals, collectors and dealers, instruction, and instrumentation. The latter naturally contains a detailed discussion of the development of the goniometer, from the simplest protractors to the most artfully machined, multi-circle,

reflecting instruments. More interesting, however, his discussion of how the goniometer was turned "inside-out", not for the purpose of indexing crystals but rather for constructing accurate plaster or wood models of crystal polyhedra. At first, apparatuses constructed by Fuess (Figure 10) for cutting precise sections from crystals were adopted to cut crystal models. Goldschmidt (Figure 10) published the first description of a device specifically designed to prepare models. His device was refined by Stöber (Figure 10).

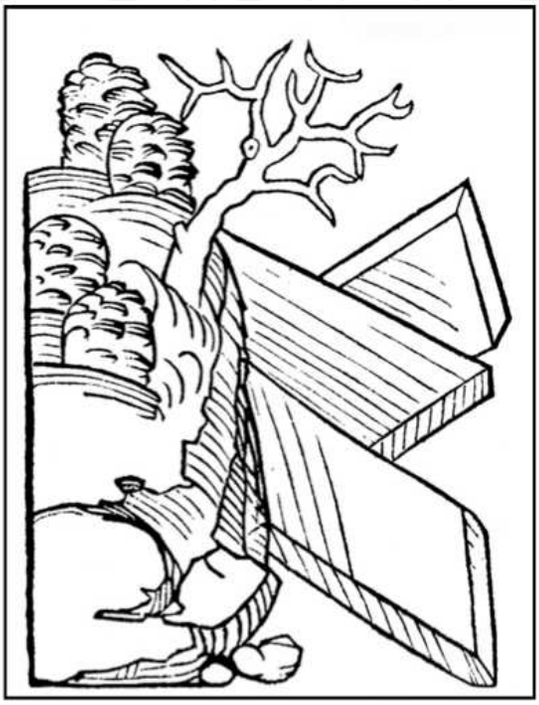


Figure 8. Left: Gypsum, Meydenbach, (1491).



Figure 9. *Naturselbstdruck*. Meteroite slice. Schreibers (1820).

Crystal drawing is surely a lost art. While it is unlikely to be recovered given crystal drawing software, Schuh allows us to appreciate it better than anyone else. Early representations of crystals from nature aimed at capturing the true symmetries, first appeared in the sixteenth century. See Bodt and Linnaeus, Figure 11a,b. Shading was used to capture three-dimensionality. It 1801, Haüy first introduced dashed lines to represent

hidden faces (Figure 11c). This became standard. Twinning and concavities appeared in later plates, especially those of Dana in his *System of Mineralogy* (1877) (Figure 11i).

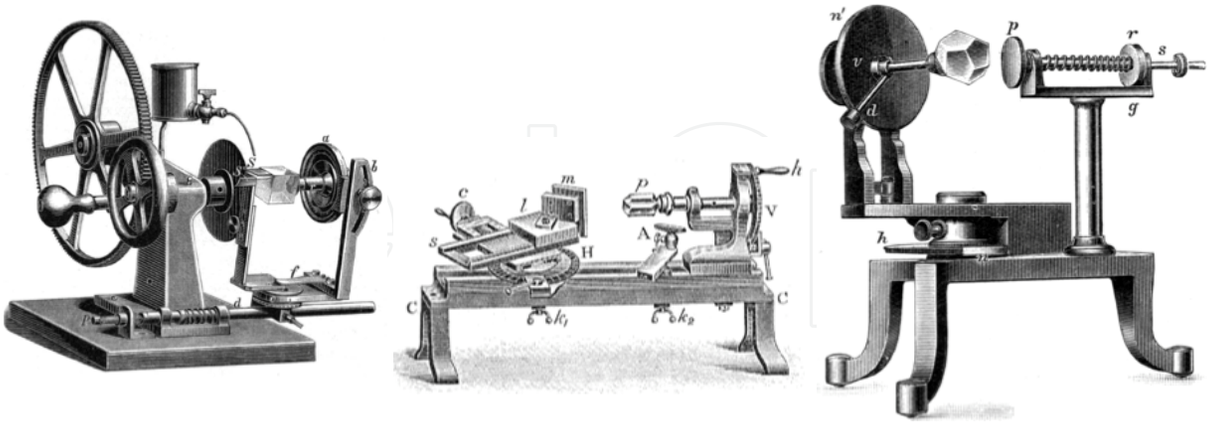


Figure 10. Crystal model making devices. From left to right: Fuess, 1889; Goldschmidt, 1908; Stöber, 1914.

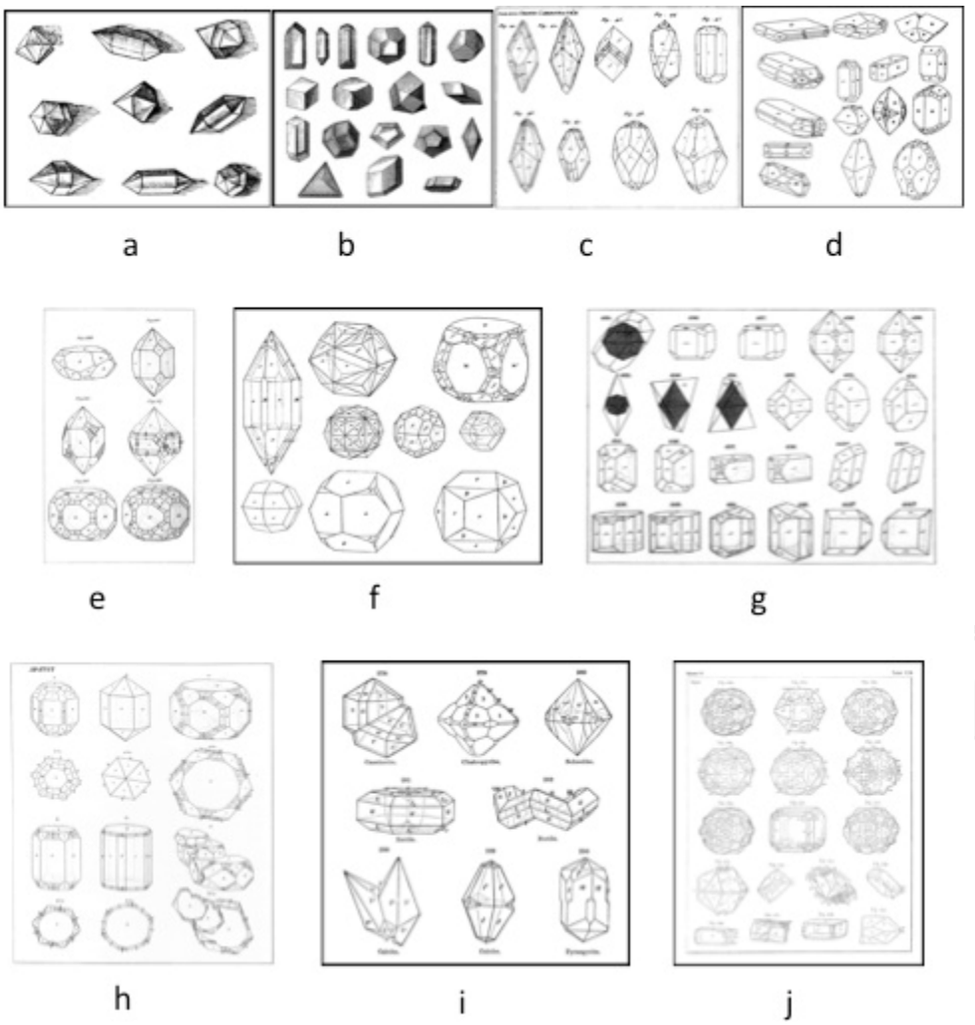


Figure 11. Crystal drawing from Schuh, 2007c. (a) Boodt, 1647; (b) Linneaus, 1768; (c) Haüy, 1801; (d) Dana, 1837; (e) Mohs, 1825; (f) Naumann, 1830; (g) Kopp, 1849; (h) Koksharov, 1853; (i) Dana, 1877; (j) Goldschmidt, 1913.

Section 15.3, "Minerals Illuminated in Colors", is the most luscious. We will indulge in a page of representations of in Figure 12 because we can in an on-line journal without consuming ink.

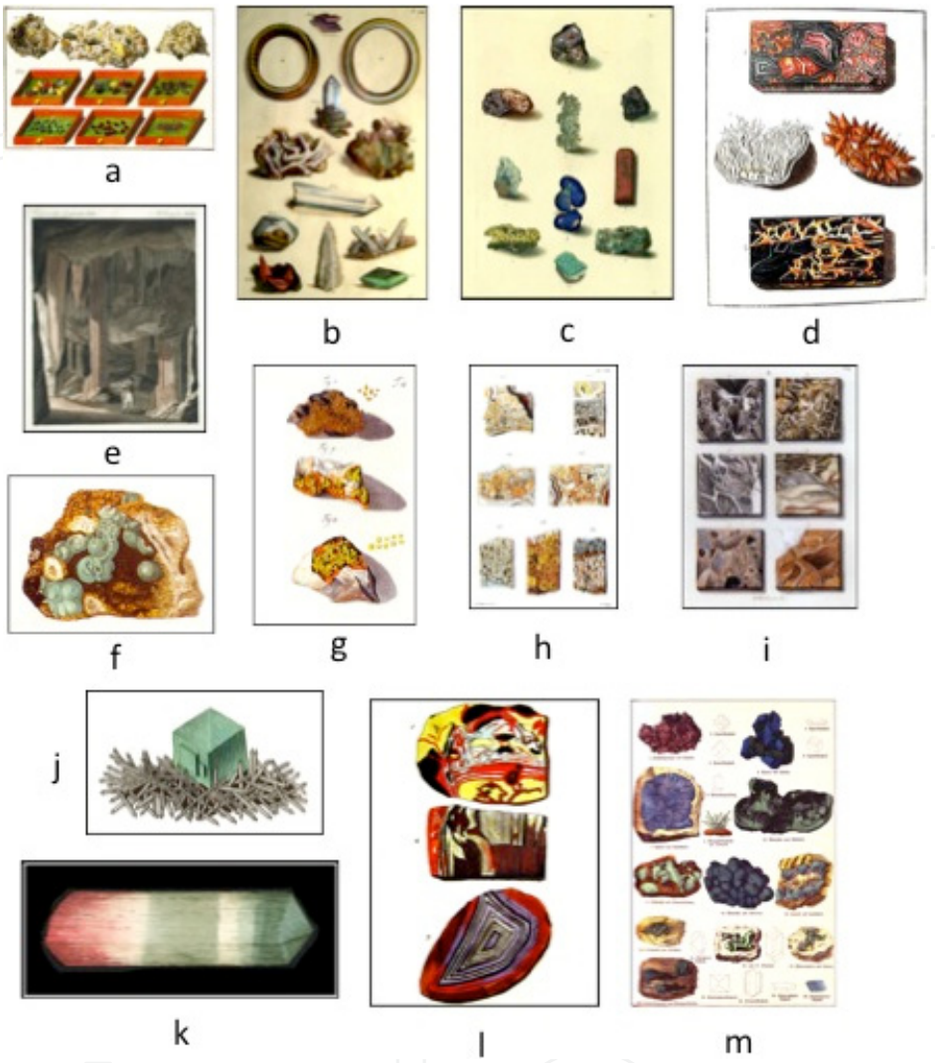


Figure 12. Color mineral illustrations from Schuh, 2007c. (a) Seba, 1734; (b) Knorr, 1754; (c). Rumphius, 1705; (d) Baumesiter, 1791; (e) Bertuch, 1798; (f) Wulfen, 1785; (g) Uibelaker, 1781; (h) Wirsing, 1775; (i) Sowerby, 1804; (j) Patrin, 1801; (k) Wilhelm, 1834; (l) Kurr, 1858; (m) Hamlin, 1873.

The *History* ends with a planned eighteenth chapter. Nothing was written but the chapter title: "18: STUDY OF CAVES". This is a foreboding final phrase. It represents all that remained unsaid by the author's premature death, and all that will remain hidden.

6. Conclusion

The range and detail of Schuh's *History*, supported by the *Biobibliography*, is unlikely to be surpassed for a very long time. It is an extraordinary achievement that deserves wider notice. It is the single narrative in English that we felt was lacking when we began the translation of Shafranovskii. The chasm is filled. The considerable effort of a full translation

of Shafranovskii is not longer as urgent (if it ever was). We now terminate our translation project, having introduced English readers to the flavor of Shafranovskii's history, the most complete work of its kind until that of Curtis P. Schuh.

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