Heirs of the revolution:

X-ray diffraction and the birth of the

Mineralogical Society of America

Dedicated to J Alexander Speer on his retirement as Executive Director of MSA
in thanks for his many years of selfless service

Peter J. Heaney*

Dept. of Geosciences
Penn State University
University Park, PA 16802

*Email: pjheaney@psu.edu

Keywords: Mineralogical Society of America; Mineralogy; Crystallography;
X-ray diffraction; History of Science

ABSTRACT

The founding of the Mineralogical Society of America (MSA) in 1919 followed so closely on the heels of the discovery of X-ray diffraction (XRD) in 1912 that one might hypothesize a causal link. Was MSA born out of this scientific revolution? The formation of our Society conventionally is attributed to the desire for a professional journal and the need to emerge from the shadow of the Geological Society of America, but these issues were not new in 1919. This review argues that MSA's birth can be understood by an exploration of two historical strains: 1) Although modern notions of atomism traditionally are associated with the emergence of the kinetic theory of gases in the late 19th century, mineralogists had invoked ordered atomic spheres as the fundamental metaphor for crystalline structures over a century earlier, leading directly to WL Bragg's discovery of the atomic design in halite; and 2) In contrast to the broader chemistry community, mineralogists were uniquely poised to embrace X-ray diffraction and the revolution in crystallography that attended it. This revelation gave rise to a sense of distinct identity.

An examination of MSA's early records unambiguously reveals that US mineralogists were closely attuned to the crystallographic insurgency as it took place across the Atlantic. In particular, Edgar T. Wherry, one of the organizers of the *American Mineralogist* and of the Society, actively disseminated information about the new discoveries to his colleagues in the United States. Other founders of MSA similarly championed the insurgent character of the new crystallography, and they argued that the discoveries differentiated mineralogy from other styles of geological investigation, thereby warranting the establishment of a specialized professional

society. The continuing force of the revolution is revealed in a counter-reaction a century later, as mineralogists have renewed their focus on phases at the boundary between crystals and glasses, leading to reconsiderations of the meaning of crystallinity.

INTRODUCTION

The six founders of the Mineralogical Society of America were born into a world without atoms (Fig. 1). In December 1919, when MSA held its first meeting, they ranged in age from 34 years (Edgar T. Wherry) to 53 (Alexander H. Phillips). Thus, they all had received their scientific training in the classical 19th-century sub-disciplines of mineralogy: Geometric Crystallography; Physical and Chemical Properties of Minerals; Mineral Classification; and Descriptive Mineralogy. During the 1890s, when most of the founders were working towards their graduate degrees, the ultimate structure of crystalline materials was highly controversial, and most mineralogy textbooks of the time adopted a wait-and-see agnosticism concerning the physical reality of atoms.

Emblematic of the shift of US mineralogy away from European dominance, half the founders received formal instruction in Europe and half learned their mineralogy domestically. Edward H. Kraus, the first president and principal architect of MSA, studied for his Ph.D. with Paul Groth in Munich from 1899 to 1901, eventually assuming a mineralogy professorship at the University of Michigan (Hunt 1955). Frank R. Van Horn pursued a Ph.D. at the University of Heidelberg with Victor Goldschmidt[1] from 1893 to 1897 and then became a professor at the Case School of Applied Science (Kraus 1934). The Canadian Thomas L. Walker received his Ph.D. in 1896 from the mineralogist Ferdinand Zirkel at the University of Leipzig,

---

[1] More specifically, Victor Mordechai Goldschmidt (1853-1933), who specialized in morphological crystallography and is distinguished from Victor Moritz Goldschmidt (1888-1947), who is considered the father of modern geochemistry.

and he then crossed paths with Van Horn as a postdoctoral associate with Goldschmidt in Heidelberg (Parsons 1943).

The three remaining MSA founders were schooled primarily in the United States. Alexander Phillips, born in next-door Lawrenceville, New Jersey, was a Princetonian from his undergraduate A.B. to his graduate Sc.D. degree to his 49 years of college instruction at his alma mater (Buddington 1937). Herbert Whitlock, curator at the American Museum of Natural History, studied with the famed mineralogist Alfred Moses at Columbia University but prided himself on achieving what he did without a doctorate (Pough 1949). The polymath Edgar Wherry received his Ph.D. with Amos Peaslee Brown at the University of Pennsylvania in 1909, but he did spend one summer, in 1910, under the tutorship of Victor Goldschmidt to deepen his knowledge of morphological crystallography (Hooker and Montgomery 1975).

To the degree that six middle-aged, white American men of European descent with a shared love of minerals can be considered eclectic, the founders brought a mix of expertise to the table in 1919. In addition to his duties as mineralogist, Van Horn acted as the athletic director at Case from 1900 to 1926, and he oversaw the development of a high-level football program that toppled Ohio State and Purdue (Grabowski 1992). Alexander Phillips's administrative skills as chair of the organizing committee for MSA in 1919 were enriched by his tenure as mayor of Princeton Township from 1911 to 1916 (Buddington 1937). Before assuming his posts as professor at the University of Toronto and the first director of the Royal Ontario Museum of Mineralogy, TL Walker was the assistant superintendent of the Geological Survey of India from 1897 to 1901. His duties included an arduous scientific expedition through the Himalayan Mountains from India into Tibet. As a youth, ET Wherry collected plants before he discovered minerals, and by the time he helped found MSA, he was working in the US Department of Agriculture, eventually becoming a professor of botany at the University of Pennsylvania in 1930.

Despite their different educational backgrounds and life experiences, as American mineralogists advocating for the establishment of a new professional society in 1919, these men were bound by a transformation within the previous decade that had dramatically redrawn their intellectual landscapes. Whereas nobody knew the fundamental structure of a mineral before 1912, by the end of that decade, researchers across the Atlantic had established the paradigms for crystallinity that still are taught in introductory mineralogy classes today.

To what extent was the founding of the Mineralogical Society of America a response to the X-ray diffraction revolution? How did American mineralogists perceive the relationship between atomic theory and crystallinity before the revolution? Were they aware of the upheaval in European physics as they worked to create MSA in the decade before its birth, and did they anticipate the vast impact those discoveries would exert on the mineral sciences? How has the response of the US mineralogical community to the XRD revolution evolved over the last century? The synchronicity between the establishment of MSA and the transformation of solid-state physics reasonably suggests some kind of linkage. On the other hand, temporal correlation does not necessarily imply causation.

This celebratory article for the centennial anniversary of MSA explores the intellectual framework that guided the six founders and their colleagues in the invention of MSA. For the Society's fiftieth anniversary, George Phair of the United States Geological Survey authored articles on the birth of *The American Mineralogist* in 1916 and the society itself in 1919 (Phair 1969a,b). Whereas Phair skillfully describes *how* MSA came into being, one can question whether he adequately captures *why* the Society and its journal succeeded when prior efforts had failed. Phair repeats the founders' argument that professional mineralogists desired a dedicated periodical amidst a growing incompatibility with the Geological Society of America (GSA), founded in 1888.

As will be argued below, this rationale must represent only a partial explanation. The *American Journal of Science* (*AJS*) had served as an engine for mineralogical research since its inception by Benjamin Silliman in 1818; in 1916 alone, 22 articles of a strictly mineralogical nature appeared in *AJS*. On the other hand, several efforts to jumpstart purely mineralogical journals came to naught in the late 19th and early 20th centuries. Thus, before 1916, mineralogists could not sustain a journal of their own, but they could access a magazine that was prestigious and communal with other branches of geology. From 1916 onwards, *The American Mineralogist* inaugurated a journey that continues today under the auspices of a thriving professional society founded three years later.

Something changed during that decade. Whereas MSA lore paints the founders as reluctant exiles from an insufficiently convivial coalition of geologists, this article asserts that MSA emerged as a separatist movement grounded in a new sense of self-identity. Their feeling of distinctness originated in the redefinition of minerals after the X-ray diffraction revolution. This interpretation will be assessed through two theses: 1) MSA's founders descended from a long lineage in mineralogical philosophy that nurtured notions of atomicity – specifically, of crystals as ordered assemblages of hard spheres. Consequently, mineralogists were primed to accept the implications of X-ray crystallography in the face of persistent skepticism from gas and solution chemists; and 2) The empirical justification of the metaphors that mineralogists used to describe crystalline materials provided the impetus for US mineralogists to distinguish themselves from other kinds of Earth scientists and create a scientific society that has flourished for 100 years.

BEFORE THE REVOLUTION: MINERALOGISTS AND OUR CONCEPTIONS OF ATOMS

Unit Cells and Atomic Spheres

In a retrospective of the X-ray diffraction revolution, Max Perutz, student of William Lawrence Bragg and winner of the Nobel Prize for solving the structures of hemoglobin and myoglobin, reviewed his mentor's accomplishments in the light of Thomas Kuhn's theories of scientific revolutions (Perutz 1990; Kuhn 1996). He asserts that "the perusal of old textbooks of chemistry and mineralogy has convinced me that there was no paradigm for the atomic structure of solid matter before 1912. The results of X-ray analysis opened a new world that had not even been imagined before."

It is a significant overstatement, as Perutz failed to recognize that WL Bragg – for all his undoubted genius – was the direct beneficiary of over a century of mineralogical forays into the ultimate structure of crystals. Intimations of the repetitive unit cells that embody the translational symmetry inherent to all crystals are found in the geometrical crystallography of the French abbé and mineralogist, Renée-Juste Haüy, who argued that mineral cleavage is controlled by *molécules intégrantes* that act as the fundamental building blocks of crystals (Fig. 2). Haüy (1784; 1801) posited an extravagantly large variety of geometric forms for his integrant molecules – including octahedra, tetrahedra, hexagonal prisms, rhombic dodecahedra, and hexagonal bipyramids, but his disciples corrected and refined his speculations (Kubbinga 2012). Over the mid-1800s, Christian Samuel Weiss, Moritz L. Frankenheim and Johann F.C. Hessel in Germany, Auguste Bravais in France, and Alex V. Gadolin in Russia developed our more modern conceptions of space lattices generated by parallelepipeds with constrained morphological symmetries (Weiss 1814; Frankenheim 1826; Hessel 1830; Bravais 1851; Gadolin 1867).

Similarly, the notion that matter ultimately is constructed from the assembly of spherical particles has a deep history in the mineral sciences (Lalena 2006). Johannes Kepler is credited as the first Western natural philosopher to propose that the dense packing of small spherical particles underlies the structure of snowflakes (Fig. 3A; Kepler 1611; Lima-de-Faria 1990); he famously conjectured that the 26% void space within a cubic closest-packed array is the lowest value possible for an assemblage of spheres. (This conjecture was not mathematically verified until the proof by Thomas Hales in 2005.) Robert Hooke (1665) argued in *Micrographia*

Restaurata that quartz crystals are composed of spheroids (Fig. 3B), and in his *Traité de la Lumière* (1690), the wave mechanic Christian Huygens depicted a rhombohedral cleavage fragment from calcite as constructed from packed spheres (Fig. 3C). William Wollaston, the British natural philosopher who refined the reflecting goniometer, revived these ideas in his Bakerian Lecture to the Royal Society in 1813, noting that the tetrahedra, octahedra and cubes that composed Haüy's *molécules intégrantes* in turn could be constructed from the packing of smaller spheres (Fig. 4). To generate the rhombohedral distortions required for carbonate minerals, Wollaston flattened his spheres into ellipsoids (Wollaston 1813).

Contemporaneously, John Dalton – the "Father of Atomic Theory" – adopted a physical model for atoms in which a spherical hard nucleus was enveloped by repelling shells of "caloric" – the term for a hypothetical fluid responsible for heat flow in substances. It was a somatic model earlier promoted by the Irish chemist Bryan Higgins (Grossman 2017), but Dalton (1808) was the first to place atomism on a quantitative footing by weighing common compounds and measuring ratios of elemental masses. Dalton's insights included a recognition that individual elements contain atoms of uniform size and mass, and his analyses revealed that these different elements combine in simple integral ratios to make compounds (Fig. 5).

This work was greatly extended by the Swedish chemist and mineralogist Jöns Jacob Berzelius. Berzelius innovated analytical techniques in chemistry and measured the weights of thousands of compounds in support of Dalton's ideas (Melhado 1981; Melhado and Frdngsmyr 2003). Berzelius developed the system by which we notate elemental symbols, and he created the molecular formula: H_2O, SiO_2, and $CaCO_3$, for example, though he used superscripts (H^2O) rather than subscripts; one finds this superscript notation persisting in late nineteenth-century mineralogy texts (Dana and Brush 1869). Berzelius intuited that compounds are unions of electropositive and electronegative elements, and he was first to propose a mineral classification system that embraced this principle (Berzelius 1814, 1824; Heaney 2016).

The Message in Isomorphs, Polymorphs, and Pseudomorphs

The chemical permutations of similarly shaped minerals provided further support for theories of atomism (Geiger 2016). Wollaston used his state-of-the-art reflecting goniometer to show that the rhombohedral angles for "carbonate of lime" (calcite), "bitter-spar" (magnesite), and "iron-spar" (siderite) are within 2° of each other (Wollaston 1812). Though he is rarely credited with the discovery of isomorphism (Morrow 1969), Wollaston inferred the existence of solid solution based on the mixing of atoms in this system:

> "It is very evident, from the numerous analyses that have been made of iron-spar by other chemists, how extremely variable they are in their composition, and consequently how probable it is, that the greater part of them are to be regarded as mixtures."

And he predicted that the carbonate isomorphs should extend to an as-yet-unknown manganese variety – rhodochrosite, christened by the German mineralogist Johann Hausmann the following year (Hausmann 1813).

Comparisons of synthetic potassium phosphate and arsenate crystals led to a more sophisticated treatment (and naming) of isomorphism by the mineralogical chemist Eilhard Mitscherlich (1819; 1821), who also saw in isomorphism a confirmation of Dalton's notions of atomism (Melhado 1980; Moore 1990). Mitscherlich (1822) further discovered the converse property of polymorphism, and parallel to Wollaston's (1813) thesis, he viewed polymorphism as evidence that discrete particles can assemble in different ways to generate different structures. Importantly, minerals that had the same chemical composition but different crystal structures defied Haüy's conflation of the primary "chemical molecule" of a mineral with its physical integrant molecule.

Another mineral "-morphism" – pseudomorphism – also seemed explicable only through a corpuscular theory of matter. The replacement of one mineral by another with the retention of the original habit was telling testimony that elements were composed of small, discrete particles that could interchange within crystals. In his survey of mineral pseudomorphs, Dana (1845) (who used "atom" and "molecule" interchangeably as was the custom of the time) argues that

> "There appears to be something in the chemical forces excited among the molecules, by the process of solution, when very slow and gradual, which leads the molecules of any body that may be passing at the time from a liquid state, to take the place successively of each molecule that is removed; and thus it is that the original form to the minutest stria, is so exactly assumed by the substituting mineral."

Consequently, pseudomorphism – a phenomenon once viewed as compelling evidence for alchemical transmutation – could now be explained by "the received principles of chemical science" of the mid-nineteenth century (Dana 1845).

From the first (1837) to the fourth edition of the *System* (1854), Dana devoted several pages to a consideration of the particles from which minerals are constructed. In his treatment, he elected to "adopt, in part, Wollaston's theory of spherical and spheroidal molecules…[which] by their aggregations, must produce the same forms as proceed from the aggregation of Abbé Hauy's polyhedral molecules" (Dana 1837, pp. 53). In that first edition of his *System of Mineralogy*, James Dwight Dana (pp. 69) makes clear his expectation that mineralogists would lead the way to an understanding of the ultimate nature of matter:

> "[W]e may be encouraged to hope that ere long this entrance to one of the innermost recesses of the works of nature will be thrown open, and that the qualities of atoms, or molecules, their forms and peculiarities, will soon be fully understood. Its connection with the science of chemistry, and other physical sciences, render it deserving of very minute experimental research."

Dana's intuition regarding the integral role of mineralogy in solving the first crystal structures would be realized through a quirky and largely self-taught genius, William Barlow, an amateur geologist and President of the English Mineralogical Society from 1915 to 1918 (Fig. 6).

A Prototype for Ionic Solids: The Work of Barlow and Pope

William Barlow's income came through an inherited family business, and by his early thirties he had no need of a formal profession, freeing him to muse on problems of three-dimensional crystallography. His long-time collaborator Pope (1935) remarks: "It was never easy to follow his train of thought because he invented his own ways of attaining results; thus, he rarely used the classical methods of spherical trigonometry in crystallographic calculations, but devised special ones of his own for each case which arose." Independent of the techniques employed by mathematicians Arthur Moritz Schönflies and Evgraf Federov, Barlow elucidated space group theory, though he received less credit at the time because he published a few years after they did and his approaches were sometimes inscrutable (Barlow 1894; Pope 1935; Senechal 1990).

While he was working through the 230 space groups, Barlow simultaneously was pondering the question of how spherical atomic particles might arrange themselves to generate crystals. In 1883 he proposed a variety of packing schemes for spherical atoms, including body-centered cubes and cubic- and hexagonal-closest packed arrays, supplementing his sketches with accurate wooden models of his own crafting (Fig. 7; Gibson 1941). He erred in assuming that electropositive and electronegative atoms would have the same radii, leading him to propose, for example, that halite occurs with a cesium chloride structure. Nevertheless, this early work was striking for its attempt to marry the physical behavior of a crystal with its internal atomic structure. Barlow (1883) argues, for example, that quartz "has the property of circular polarisation, from which it has been proved that its molecules must have a *spiral* arrangement" that could be either right- or left-handed. Further, he modeled calcite by considering its chemical composition in conjunction with its uniaxial optical behavior.

Although Barlow's (1883) stacking of like-sized atoms in repetitive unit cells got many details of crystal structures wrong, in 1898 he extended his ideas to consider mixtures of different-sized atoms and produced a visualization (Fig. 8) that would accurately presage WL Bragg's structure solution for NaCl in 1913. The link between Barlow's penetrating insight and Bragg's subsequent "discovery" was William Jackson Pope (Barlow and Pope 1906, 1907). Pope was Professor of Chemistry at the School of Technology in Manchester when their partnership started, and following publication of his work with Barlow, he fortuitously was appointed Professor of Chemistry at Cambridge in 1908, placing Pope in direct contact with WL Bragg, who entered Trinity College, Cambridge in 1909 and was a first-year research student at Cambridge in 1912. Barlow and Pope (1906), borrowing from theories of "atomic dynamism" dating from Boscovich (1758), assumed that crystals represent equilibrium assemblages of balanced forces, with each spherical atom acting as a center of both attraction and repulsion, both governed by an inverse distance law by analogy with gravity.

Barlow and Pope (1907) surmise that the native elements are structured by simple cubic or hexagonal closest packings of equal spheres; the novel powder X-ray diffraction work by the American A.W. Hull would confirm that many (but not all) of their assigned structures were correct (Hull 1922). The closest-packed models for alkali halides are less accurate and would have benefited from a knowledge of Pauling's Rules, whose formulation was still two decades away (Pauling 1929). But in his reminiscences, WL Bragg (1962) nevertheless credited Pope and Barlow for directing his initial X-ray diffraction trials to halite and sylvite:

> "[W]hen my first studies of Laue's diffraction patterns led me to postulate that zinc sulphide was based on a face-centred cubic lattice, Pope saw in it a justification of his theory and urged me to experiment with sodium chloride and potassium chloride crystals which he got for me from Steeg and Reuter [a crystal optics firm] in Germany."

Equally significant, Barlow and Pope (1906, 1907) would provide Bragg with an atomic template for deconstructing his diffraction patterns. Bragg's deference to these early crystal theorists permitted him to eschew the conventional wisdom upheld by virtually every contemporary chemist – that the crystals of alkali halides must reflect diatomic pairings of alkali metals with halogen elements. Instead, Barlow and Pope set the stage for Bragg's bold decision to model the first crystal structure solved – that of halite – as cubic closest packed layers of spherical ions without a hint of molecularity.

ATOMIC DOUBTS BEFORE THE REVOLUTION

A Periodic Table Without Atoms?

Ironically, while wet chemical assays, blowpipe tests, and elemental spectroscopy achieved high levels of rigor in the latter half of the nineteenth century, many chemists retreated from a categorical acceptance of physical atomism (Brock and Knight 1965). Mendeleev's conception of the Periodic Table provides an example. A suite of scientists in the 1860s argued that elements could be tabulated on the basis of atomic weight: John Newlands in England, Julius Lothar Meyer in Germany, and most famously, Dmitri Mendeleev in Russia (Kean 2011). Mendeleev (Fig. 8A) asserted that chemical behavior was modulated as elemental masses increase, and, based on the cyclic reactivity of elemental series, the Periodic Table was born. The regularity was sufficiently remarkable that Mendeleev famously left vacancies where undiscovered elements should reside. Indeed, in his original table, Mendeleev knew that he should leave *two* spaces between zinc and arsenic (van Melsen 1960).

The Periodic Table did not prove atomism, but it was highly suggestive that the elemental series was composed by sequential additions of discrete particles. Nevertheless, unlike Julius Meyer (Kaji 2002), Mendeleev's views of atomism were complex and equivocal (Niaz et al. 2004; Gordin 2019). On the one hand, Mendeleev (1879) writes, "By replacing the expression of *atomic weight* by that of *elementary weight*, I think we should, in the case of elements, avoid the conception of atoms." Conversely, Mendeleev (1891) argues that "The law of combining weights is formulated with great ease, and is an immediate consequence of the atomic theory. Without it, it is even difficult to understand." Nevertheless, Mendeleev persistently rejected the notion that atoms themselves could be divisible, and he was a vocal antagonist to JJ Thomson in his identification of electrons as sub-atomic particles (Kargon 1965).

Mendeleev's ambivalence was steeped in a Positivist philosophy that demanded a strictly empirical approach towards the apprehension of natural processes and prevailed for much of the nineteenth century (Niaz et al. 2004). The German acoustical physicist Ernst Mach (Fig. 8B) famously expressed his skepticism of atomic theory in the context of logical positivism by averring that scientists must differentiate between reality and those metaphors that fruitfully predict what our senses perceive (Mach 1883, translated in Mach 1919; Brush 1968):

> "The atomic theory plays a part in physics similar to that of certain auxiliary concepts in mathematics; it is a mathematical *model* for facilitating the mental reproduction of facts. Although we represent vibrations by the

> harmonic formula, … no one will fancy that vibrations *in themselves* have anything to do with the circular functions."

Mach conceded that atomic theory had a provisional usefulness, but only as a heuristic idea that would be discarded as soon as a better theory appeared (Blackmore 1972), and Mach's opposition to the atomic theory became a hallmark of his epistemological purity (Pojman 2011): "If belief in the reality of atoms is so important to you, I cut myself off from the physicist's mode of thinking, I do not wish to be a true physicist, I renounce all scientific respect – in short: I decline with thanks the communion of the faithful."

Mach was not alone in his skepticism at the turn from the 19th to the 20th century. Whereas some thermodynamicists like Ludwig Boltzmann rooted their interpretations of energy flow in statistical models that demanded the existence of moving atomic particles (Lindley 2015), prominent contemporaries were skeptical, including Lord Kelvin, Wilhelm Ostwald, Josiah Willard Gibbs, and Pierre Duhem (Fleck 1963; Chalmers 2014). Beyond the absence of direct sensory confirmation for the reality of atoms, these thermodynamicists perceived a continuity in energetic processes that seemed incongruent with the actions of discrete corpuscles. They also were challenged in developing mathematical formulations for energy fluxes in systems of atoms separated by vacuum. Ostwald, as co-editor of the influential *Zeitschrift für Physikalische Chemie* and author of a widely admired textbook on physical chemistry, strongly influenced this anti-atomic school. In his 1904 Faraday lecture to the Chemical Society of London, he argued (Ostwald 1904):

> "It is possible to deduce from the principles of chemical dynamics all the stoichiometrical laws: the law of constant proportions, the law of multiple

> proportions and the law of combining weights... Chemical dynamics has, therefore, made the atomic hypothesis unnecessary…"

Josiah Gibbs concurred in his introduction to *Statistical Mechanics* (Gibbs 1902): "Certainly, one is building on an insecure foundation, who rests his work on hypotheses concerning the constitution of matter," citing the lack of agreement between theory and experiment for the number of degrees of freedom exhibited by a diatomic gas molecule.

The Structure of Matter in Mineralogy Texts

Mineralogists of the time mirrored this unsettled state. Dana's *System* retreated from its earlier progressive role in championing atomic theory and skirted the subject in later editions. Whereas Dana's *System* promoted atomism from the first (1837) to the fourth edition (1854), JD Dana omitted all discussion of the ultimate constituency of matter in the fifth edition of the *System* (1869) and beyond. Ironically, the fifth edition is considerably more explicit than the fourth in its appropriation of atomic theory to describe mineral chemistry. It includes a table of atomic weights in alphabetical order, and it discusses mineral formulas with respect to atomic ratios and masses much more comprehensively than did prior editions.

As inorganic chemistry became rigorously quantitative in the second half of the nineteenth century, JD Dana may have decided that conjectures concerning the shapes and arrangements of atomic particles were too speculative and unscientific. Richard Harrison Solly, the demonstrator in mineralogy at Cambridge, explicitly expresses this sentiment in his manual (Solly 1894):

> "There is still complete ignorance as to which of the possible geometrical structures suggested by Bravais, Groth, Sohncke and Liveing, can and does really exist. We can say that a system of atoms grouped in a certain manner, will have certain symmetry but we do not know whether they can remain in equilibrium and subsist. To solve this problem we must possess an increased knowledge of molecular forces."

In his influential mineralogy textbook, the German mineralogist Paul Groth (1906) treats atoms as objects of theoretical utility. He approvingly cites Sohncke's (1888) interpretation of a crystal as "a finite number of interpenetrating regular point systems, which all possess like and like-directed coincidence movements," such that each point "may equally well be supposed to be occupied by similar *atoms*, as by *molecules*."

Groth anticipates the lack of molecularity in ionic solids: "It is evident, however, that in such a structure 'molecules,' in the sense in which we speak of gaseous molecules, are altogether wanting, and it is a matter of choice what is to be called the unit of crystal structure or the crystal molecule." In parallel, many mineralogy textbook writers wrestled with the question of whether chemical formulas are imprinted somehow within a crystal structure. MSA founder Alexander Phillips of Princeton, for example, asserts (Phillips 1912): "There is no method of demonstrating whether the solid or crystalline molecule and the chemical molecule are identical. Since a number of atoms combine to form a chemical unit, it is also probable that a number of chemical units combine to form a crystalline unit or molecule."

In his mineralogy textbook, Henry Miers, mineralogy professor at Oxford and Fellow of the Royal Society, described the same state of confusion. Interestingly, Miers offers the following pragmatic assessment of crystals that escaped many of the thermodynamicists of the time (Miers 1902):

> "It is reasonable to suppose that the particles of which a crystal consists are placed side by side in some regular arrangement, like the men in a battalion of soldiers; whereas in an amorphous substance they have no regular order. Without some such hypothesis it is impossible to understand how the properties of a crystal vary regularly with the direction."

It is important to note that Miers uses the term "particles" rather than "atoms" in this context, because he liberally employs the word "atom" elsewhere when he is dealing with chemical rather than physical units. Similar efforts to adopt atomic theory but to elide any speculations regarding the physical nature of atoms also are apparent in the pre-revolutionary mineralogy texts of Moses and Parsons (1900), WS Bayley (1910), and ES Dana (1912).

1909-1919: THE CRYSTAL REVOLUTION

The Atom as a Physical Entity

The existence of atoms was resolved rapidly and decisively in the decade before the birth of MSA. At the beginning of this decade, an image of the physical structure of atoms was taking form through the cathode ray tube studies of JJ Thomson, who developed a "plum pudding" model for the atom, in which negatively charged electrons are embedded within a positively charged matrix, like raisins within dough (Thomson 1904). In 1911, Ernst Rutherford dispensed with this metaphor on the basis of his high-angle scattering experiments, arguing persuasively that backscattering of α- and β-particles by gold foil could be explained only by a concentration of positive charge in a small, central nucleus (Rutherford 1911).

The next year, 1912, the momentous X-ray diffraction experiments of Max von Laue resulted in the integration of crystallinity with atomic theory. Max Laue (Fig. 10), a Privatdozent in physics at the Ludwig Maximilian University of Munich, was stimulated by a discussion of Paul Ewald's doctoral dissertation to consider the scattering of X-ray radiation by an ordered lattice of polarizable atoms (Laue 1962). With Arnold Sommerfeld's half-hearted permission, two assistants – Walther Friedrich, who had finished a doctoral thesis with Röntgen and was serving as an assistant to Sommerfeld, and Paul Knipping, a doctoral student with Sommerfeld – were set to the task of demonstrating X-ray diffraction by a crystal of copper sulfate (Friedrich et al. 1912; 1913). The revelations that we associate with this discovery today were not instantly evident (Fig. 11). Laue originally hypothesized that secondary fluorescent X-rays generated from *within* a crystal would diffract from the crystalline lattice, so Friedrich initially placed photographic plates to the *sides* of the copper sulfate crystal, and even *between* the incident X-ray beam and the crystal, before actually observing scattered X-rays when a plate was placed *behind* the crystal (Forman 1969; Eckert 2011). Equally misguided, William Henry Bragg initially interpreted Laue's diffractions as a focusing of X-ray corpuscles along "avenues" between the crystal's atoms (Bragg WH 1912).

WH Bragg's perspicacious son, William Lawrence Bragg, bested his father by inferring a wave-like nature for X-rays from von Laue's data (Fig. 12A), and he outdid von Laue by recognizing that white X-radiation was selectively reflected from "sets of parallel planes on which the atom centres may be arranged" (Bragg WL 1912). He followed with a presentation to the Cambridge Philosophical Society (November 1912) and paper (January 1913) that accounted for Laue's diffraction of zincblende (sphalerite) according to his famous law: $n\lambda = 2d \cos \theta$ (when θ is measured from the normal to the plane, by analogy to Snell's law) (Fig. 12B; Bragg WL 1913a; Perutz 1990). Only 22 years old at the time, WL Bragg thereupon published the first crystal structure, of the halite crystal loaned to him by Pope (Bragg WL 1913b), and père et fils followed with the structure of diamond (Bragg WH and Bragg WL 1913). Within another year, WL Bragg single-authored solutions to the structures of fluorite, sphalerite, pyrite, calcite and dolomite (Bragg WL 1914).

At this same time, the nature of those atomic scatterers came into sharper focus thanks to a lifelong friend of WL Bragg and a student of Rutherford, Niels Böhr (Fig. 13). Rutherford was puzzled by his own model for the atom, because classical mechanics predicted that negatively charged electrons orbiting a positively charged nucleus would degenerate as the electrons lose energy and spin into the core. Niels Böhr solved this paradox by unifying the quantum theory of Max Planck with elemental emission spectra collected over the previous half century. He proposed that electrons encircle the positively charged nucleus of the atom in inherently stable, energetically quantized orbitals (Böhr 1913; Rhodes 1986). He mailed his landmark paper to Rutherford in March 1913, and later that year received additional experimental vindication from the X-ray scattering work of Henry Moseley. Killed in World War I only 2 years later at the battle of Gallipoli, Moseley systematically explored the relationship between the frequency of an element's characteristic K_α X-ray and the nuclear charge of the element. His observation that the frequency varies as the square of the charge provided a rigorous method for identifying elements, and it quantitatively distinguished between atomic number and atomic mass (Moseley 1913; Assmus 1995; Authier 2013).

The mathematical forms for describing diffraction came next (reviewed in James et al. 1948). WL Bragg was more physicist than mineralogist, and to his later chagrin he developed his own notation for the X-ray "reflecting planes" that betrayed his ignorance of the Miller indices devised in 1825 by Cambridge mineralogy professor William Whewell (Hunter 2004). The reciprocal nature inherent in the Miller plane notation fortuitously presaged the inverse relationship between real space and diffraction space. In 1912, Laue offered a "geometrical theory" of the diffraction process that mathematically captured the scattering of X-rays by a three-dimensional grating (Laue 1912). Paul Ewald (Fig. 14A), who studied the scattering of visible light by periodic arrays of oscillating dipoles for his Ph.D., quickly absorbed its implications and unified Laue's physics with X-ray diffraction phenomena to develop a new mathematical formalism: the reciprocal lattice, such that $\vec{a} \bullet \overrightarrow{a^*} = 1$ where $\overrightarrow{a^*}$ is normal to $\vec{b}$ and $\vec{c}$, etc. Using this new reciprocal space basis, he further expressed the conditions for diffraction through the construction of the "Ausbreitungskugel", literally, the "scattering sphere", but what we now call the "Ewald sphere" (Fig. 14B; Ewald 1913; Authier 2004).

Additional contributions to the interpretation of X-ray diffraction patterns were immediately forthcoming (Buerger 1990). Laue was surprised that left- and right-handed quartz crystals apparently gave rise to the same diffraction pattern, and Georges Friedel explained this observation by noting that the diffraction process inherently adds a center of symmetry, which today we know as Friedel's law (Friedel 1913). Peter Debye, another Sommerfeld student, deduced a correction for the decrease in X-ray diffraction intensity caused by thermal agitation of atoms (Debye 1913), and CG Darwin, grandson of the famed evolutionary biologist, developed additional correction factors for the effects of polarization and for increasing diffraction order *n*, later to be known as the Lorentz correction factor (Darwin 1914).

Two years later, in 1916, Peter Debye and Paul Scherrer developed a camera specifically for diffraction from powders, a technique that would flourish among Earth scientists for mineral identification (Debye and Scherrer 1916). Albert Wallace Hull, the US physicist employed with General Electric, heard a guest lecture by WH Bragg in 1915 and invented a different powder diffraction geometry that has found renewed importance in the modern age of digital imaging plates (Hull 1917a). Hull used it to determine the crystal structure of α-iron (Hull 1917b), which had eluded the Braggs, and eventually published the structures of over 25 native elements (Hull, 1922, 1946; Authier 2013).

Ionic and covalent chemical bonding models appear

The modern metaphors we use to understand the bonding of atoms in crystals also emerged in the decade before MSA's founding. The chemical duality implicit in our picture of crystals as marriages of electropositive and electronegative elements appeared in the work of Berzelius and Faraday in the early 1800s (Berzelius 1814; Melhado 1981). A century after Berzelius's ground-breaking work, Erwin Madelung (1909) examined the energetic implications of crystals as arrays of positively charged metal ions electrostatically attracted to negatively charged non-metallic ions.[2] He intuited that attraction was limited by repulsions arising from electronic shells surrounding atomic nuclei, and this model did remarkably well in predicting the energies of formation for alkali halides (Wooster 1990).

In contrast to this model for an ionic solid, Gilbert Lewis – a professor of chemistry at UC-Berkeley – realized that in nonpolar molecules the electrons between atoms are shared rather than exchanged, and in 1916 he wrote the template for covalent bonding (Lewis 1916), complete with the dot notation that we still employ to describe valence electrons (Fig. 15). Lewis published major works in many areas, coining the terms "fugacity" (Lewis 1908) and "photon" (Lewis 1926), and he perhaps is most famous for his theory of acids and bases. In his prescient 1916 paper, Lewis interpreted covalent bonding as a mechanism to complete the outer electron shell. Building on Lewis's work (and winning a Nobel prize instead of Lewis), Irving Langmuir introduced the term "covalence" to describe the sharing of electrons between atoms in the year of MSA's birth (Langmuir 1919).

---

[2] The word "ion" derives from the Greek for ιω, meaning "I go", based on Faraday's observations of their migration toward electrically charged poles (Van Melsen 1960).

VIEWING THE X-RAY REVOLUTION FROM THE OTHER SIDE OF THE ATLANTIC

Edgar Wherry: America's Evangelist for the XRD Revolution

Thus, in the space of a single decade our modern understanding of crystal chemistry was born. By 1919, minerals could be visualized as ordered arrays of atoms with positively charged cores enveloped by quantized electron orbitals that swap or share electrons to fill valence shells and lower the energy state of the atomic collective. To assess whether the impact of this sweeping transformation ignited the origin of MSA, one must answer two questions: What did American mineralogists know about the XRD revolution, and when did they know it? If the work of von Laue and the Braggs eluded the founding members, then demonstrating a connection between the birth of MSA and the XRD revolution is short-circuited at the outset.

But the evidence is clear that the founding members *did* know about the exciting developments in Britain and Germany, and they recognized their relevance to mineralogy, thanks largely to the efforts of founding member Edgar T. Wherry, who served as an assistant professor of mineralogy at Lehigh University from 1908 to 1913 and then as an assistant curator of mineralogy at the Smithsonian Institution until 1917 (Hooker and Montgomery 1975). Over his career, Wherry was a prolific author of papers at the intersection of mineralogy and botany, and arguably his most significant scientific contribution was the recognition that bentonite clays are of an igneous rather than sedimentary origin (Wherry 1917a); this insight kick-started the application of bentonite beds for precise stratigraphic correlation, and it also has marked bentonites as records of global volcanic events (Kolata et al. 1996; Christidis and Huff 2009).

In 1916, Wherry was recruited by 19-year-old Samuel Gordon, assistant curator of the Academy of Natural Sciences in Philadelphia, and H.W. Trudell, a member of the Philadelphia Mineralogical Society, to launch the *American Mineralogist* (Fig. 16; Phair 1969a). W.G. Levison, secretary to the New York Mineralogical Club, for a short time served as the inaugural Editor-in-Chief, but he withdrew at the close of 1918 when it became clear that Wherry was running the show. The first six issues that year (July through December) were devoted largely to descriptive mineralogy. Wherry warned in a letter to Gordon that "Perhaps the greater part of our readership will be amateurs…, and if we put in too much unintelligible high-brow dope they will not renew their subscriptions." (Quoted in Phair 1969a)

Nevertheless, Wherry and his co-editors found ways to highlight discoveries in X-ray diffraction. The first mention of the Braggs appears in the March 1917 edition of *American Mineralogist* through a review of Irving Langmuir's paper on the fundamental properties of solids (Wherry 1917b):

> "The work of the Braggs and others on the study of crystal structure with the X-ray is reviewed, and the structures are described which have been found to exist in the minerals halite, sylvite, diamond, sphalerite, fluorite, pyrite, hauerite, calcite, dolomite, rhodochrosite, siderite, magnetite, spinel, copper, silver, gold, lead, sulfur, quartz, zircon, rutile, and cassiterite. The inevitable conclusion is admitted – that in… these substances, which belong to the class of 'polar compounds,' the whole crystal must be regarded as a single molecule."

The June 1918 volume was dedicated to the 175th anniversary of the birth of René Juste Haüy, and with this issue "*The American Mineralogist* came of age," in the estimation of Phair (1969a), earning the journal international esteem and attracting a spike in subscriptions and advertisements. The multi-lingual Wherry (1918) summarized articles from German and even Japanese journals that otherwise were inaccessible to the readership for his "Abstracts of the Crystallographic Literature," a section that highlighted 33 recent articles of mineralogical relevance. Twenty-one of these explicitly dealt with the X-ray diffraction of crystals, and Wherry continued abstracting XRD-based articles in multiple issues in 1919.

Moreover, Wherry proselytized for the new crystallography through lectures to the major mineral clubs. In the "Notes and News" section of the May 1917 issue of the *American Mineralogist*, Levison conveys the sophistication of Wherry's presentation to the New York Mineralogical Society (Levison 1917):

> "Dr. Wherry's paper consisted of a historical sketch and detailed review of the revelations resulting originally from the suggestion by Dr. Laue of Zurich, of employing a crystal as a "space diffraction grating" for X-rays, the successful realization of the idea by Messrs. Friedrich and Knipping in 1912, and its subsequent more elaborate and effective development by Messrs. W.H. and W.L. Bragg, whereby great progress has been attained on the one hand in our knowledge of the nature of X-rays, and on the other of the architecture of crystals, or the disposition within them of the various elementary atoms of which they are constructed.
>
> "Dr. Wherry's review was illustrated with blackboard formulas, adjustable models of the atomic structure of crystals, and a series of lantern slides showing the X-Ray Spectrometer and the evidence it has afforded of crystal structure by both the photographic and ionization methods, taken largely from the recent treatise on the subject by W.H. and W.L. Bragg."

In a following note, Samuel Gordon records that Wherry gave the same talk for the Philadelphia Mineralogical Society (Gordon 1917); likely, he did so for other East Coast mineralogy clubs as well.

First Depictions of Crystal Structures in *The American Mineralogist*

Wherry's (1918) "Abstracts" include the first atomic drawings of mineral structures published in *The American Mineralogist*. In a preface intended so that "space-lattices may be intelligible" to the reader, Wherry himself illustrates five structure types: 1) Double face-centered cubic or diamond; 2) Simple cubic; 3) Body-centered cubic; 4) Face-centered cubic; and 5) Combinations of different lattices (Fig. 17). To our modern eyes, these depictions err in basic ways. For example, halite and galena are classified as simple cubes rather than as face-centered cubes, and hexagonal symmetries have no representation.

In addition, the concept of a spherical atom had not survived the Atlantic crossing intact. In Wherry's diagrams, "the heavy dots represent the *positions of centers of gravity of atoms* [italics added]." The "shape of each atom," as drawn by Wherry, belonged to one of several polyhedra, "which may perhaps be regarded as the 'integral molecules' sought by Haüy." Indeed, whether the point scatterers described by the Braggs represented individual atoms or molecular clusters was a point of heated debate through the 1920s (Miers 1918; Rogers 1921; Armstrong 1927). In addition to perceptions that the Bragg structures violated contemporary valence theory (Pfeiffer 1917; Smits and Scheffer 1917), scientists subscribed to Newton's dictum that nature abhors a vacuum. Unlike spheres, polyhedra can fill all available space when closest packed. Moreover, chemical reactions of the common elements proceeded in such a way as to fill the outermost shells with 8 electrons. A cube has 8 corners. Could that be coincidence? And so one finds that the US chemists Gilbert Lewis (1916) and Irving Langmuir (1919) promote atoms with "cubical" rather than spherical symmetry (Fig. 18). It is evident that Wherry likewise had not yet absorbed Bragg's reconciliation of Barlow and Pope's closest-packed atomic spheres with the translational symmetry of the Bravais lattices.

Although he was arguably its most ardent advocate, Wherry was not the only American mineralogist who recognized the impact of the X-ray diffraction revolution. In the fifth edition to their *Elements of Mineralogy, Crystallography, and Blow-Pipe Analysis*, Moses and Parsons (1916) already were referencing the 1915 text by the Braggs on *X-rays and Crystal Structure*. E.H. Kraus, the first president of MSA, saluted their achievements in the preface to his textbook *Mineralogy: An Introduction to the Study of Minerals and Crystals* (Kraus and Hunt 1920):

> "Many of the important laws in physics, especially those relating to the properties of light, have been studied principally on crystallized minerals. The Nobel prizes in physics for 1914 and 1915 were awarded to Laue and the Braggs (father and son) for epoch-making investigations upon the structure of crystallized minerals by means of the x-ray."

Similarly, on the West Coast, Austin Flint Rogers, professor of mineralogy at Stanford, concludes in his *Introduction to the Study of Minerals and Rocks* (1921) that

> "The X-ray analysis of crystals combined with a mathematical study of the possible arrangements of points in space has furnished us with a means of determining the stereochemistry of the solid or crystalline state and has thus thrown new light on the structure of matter. This work also promises to be of

> value in settling many doubtful questions concerning crystals. It has truly opened up one of the most interesting fields in the whole realm of science."

Rogers also offers the most sophisticated discussion of space groups and X-ray diffraction in a mineralogy text to that date, devoting 13 pages (pp. 133-146) to the topic.

DID MSA NEED THE XRD REVOLUTION TO INVENT ITSELF?

The historical record reveals without ambiguity that the founding members of MSA were aware of the import of X-ray diffraction to the mineral sciences before the society was founded. Would they have created MSA in 1919 had von Laue and the Braggs conducted their experiments a decade later? The evidence for a cause-and-effect relationship between the XRD revolution and the birth of MSA is real but indirect. Naysayers might cite two arguments to dissociate these events: 1) Contemporary accounts of the motivation for forming MSA placed strongest emphasis on the need for a specialized journal; and 2) MSA was following rather than leading international trends in the professionalization of mineralogy. Of greater significance, however, are two supporting arguments: 1) As illustrated in the preceding discussion, mineralogists were even better prepared than many chemists to accept the lack of molecularity inherent in the Bragg model for ionic crystals; and 2) As will be explored in the next sections, the XRD revolution offered a redefinition of mineralogy that encouraged a new sense of separateness from geologists.

A Need to Detach from GSA

At the end of his term as the inaugural president of MSA in 1920, University of Michigan mineralogist Edward Kraus offered a review of the long- and short-range factors that led to MSA's formation. Of the latter, he points to a recent specialization in US mineralogy that could no longer be accommodated by the Geological Society of America. The first two decades of the twentieth century was a time of enormous investment in domestic science and in higher education, and mineralogy was a major beneficiary (Kraus 1921):

> "During this period, the development of science was indeed marvelous. This statement applies to no science more than it does to mineralogy, by which term we obviously include what may be readily interpreted as the broader field, namely crystallography. Moreover, it was during the war that the prominent position of the United States in the production of minerals and mineral products, and the vastness of our mineral resources, were brought most forcibly to the attention of the general public."

As increasing numbers of scientists self-identified as mineralogists, they found GSA conferences less congenial and editors of GSA journals less receptive to their articles. Kraus (1921) notes that mineralogists "soon felt that aside from the social aspect of the meetings, the society offered them but little in their own field."

An attempt to form MSA was essayed in 1913. Alexander Winchell[3], professor of mineralogy at the University of Wisconsin, circulated a letter in January of that year among ~20 mineralogists to address the possibility of organizing the "National Association of Mineralogists and Petrologists." The response to the

---

[3] Alexander Newton Winchell (1874-1958) is not to be confused with Alexander Winchell (1824-1891), a co-founder of GSA and a controversial professor of geology and paleontology at the University of Michigan for his racist attitudes towards evolution

proposed separation from GSA was lukewarm, telling evidence that the mineralogy community at this late date still was unprepared to stand on its own. Instead, the community decided to explore an alternative to divorce. In an effort at accommodation, GSA offered to provide sectional mineralogy-based meetings, but over the next three years they never materialized (Phair 1969b).

The true seeds of change began with a meeting of the six founders in December 1916 at the annual GSA conference in Albany, New York to discuss the establishment of a new mineralogical society. Winchell eventually would serve as president of MSA in 1932, but he was not a part of this renewed effort. Instead, Messrs. Kraus, Phillips, Van Horn, Walker, Wherry, and Whitlock circulated a letter (Fig. 19) in 1917 to 51 mineralogists in the US and Canada to argue that "the founding of a Mineralogical Society would do much to stimulate greater interest in the subject and also give wider recognition to the work being done in this field in America." Consequently, "the time has come when an organization which might be called 'The Mineralogical Society of America' should be formed at as early a date as possible."

This exploratory letter emphasizes the need for a specialized journal as the primary driving force for establishing MSA (Phair 1969b):

> "[P]erhaps the greatest benefit to be derived would be the founding by the society of a journal to be devoted exclusively to the publishing of mineralogical papers. As is well known, there is great need for a dignified medium of publication for the increasing volume of mineralogical investigations which are being carried on in America."

It was not a new complaint. Mineralogy journals had come and gone in the United States for over a century. In fact, *The American Mineralogical Journal*, started by New York City physician Archibald Bruce (who identified the eponymous Mg hydroxide mineral), was "the first specialized American scientific periodical", running from 1810 to 1814 (Bruce 1968; Greene and Burke, 1978).

In his presidential address, Kraus (1921) provides a detailed overview of the rise and fall of American mineral societies and the often transient journals that attended their limited existence. Typically, these magazines were published by mineral enthusiasts with careers outside the field, and their journalistic experiments ended when the individuals fell ill, passed away, or found themselves in financial embarrassment. In this regard, the long-lived success of Benjamin Silliman's *American Journal of Science* was truly an aberration (Brown 2014). The Yale mineralogist founded *AJS* in 1818, and *AJS* is the oldest continually published scientific journal in the US. Even in 1916, *AJS* was receptive to articles that were narrowly mineralogical. One finds papers on the variable compositions and optical behaviors of natural melanochalcite (Hunt and Kraus 1916), bornite (Allen 1916), and hydro-zincite (Ford and Bradley 1916b), as well as reports of new minerals and crystal growth processes (Phillips 1916; Ford and Bradley 1916a; Taber 1916). Indeed, some of the first X-ray crystallography papers on minerals published by an American scientist appeared in *AJS* rather than the *American Mineralogist* (e.g., Wyckoff 1920; 1921; 1925). On the other hand, entire monthly issues sometimes were bereft of mineralogy, devoting space instead to articles on paleontology, sedimentology, volcanology, atmospheric sciences, and experimental chemistry.

Of pressing concern to the founders, efforts to establish strictly mineralogical magazines repeatedly sputtered. *The Young Mineralogist and Antiquarian* (1994-1885) yielded to the *Mineralogists' Monthly* (1885-1892), which joined forces with *Goldthwaite's Minerals* (1892-1894) to be reborn as *The Mineral Collector*, which ceased publication in March 1909. The *Collector* had successfully straddled the amateur and professional communities for 15 years, but its publisher, Arthur Chamberlain, a printer, discontinued it for health reasons. The very first article in the first issue of *American Mineralogist* pays tribute to Chamberlain's efforts (Bates 1916). Moreover, with the onset of World War I, German outlets such as *Zeitschrift für Kristallographie, Mineralogie und Petrographie* interrupted publication for many years and were anyway unreceptive to American contributors.

It was the death of *The Mineral Collector* that drove Samuel Gordon, assistant curator at the Academy of Natural Sciences in Philadelphia, to initiate a new journal with support from the Philadelphia Mineralogical Society, the New York Mineralogical Club, and the now-defunct Mineral Collector's Association (Phair 1969a). Gordon had no academic degrees in mineralogy but received training through Edgar Wherry, and Phair (1969a) identifies Gordon rather than Wherry as the guiding force in putting together a staff and, against considerable financial and logistical odds, creating the *American Mineralogist* (or more precisely, <u>*The*</u> *American Mineralogist* since the definite article was dropped from the masthead only in 1988). Wherry was trusted and respected by both the academic and amateur communities, and Gordon enlisted Wherry to bridge these not always compatible populations.

As Kraus and colleagues looked to build a professional society, their respect for the fledgling journal suggested that, given the costs and the challenges in recruiting a subscriber base, adopting *The American Mineralogist* made more sense than developing a competing journal. The staff of the magazine were receptive, and Whitlock (1920) announced in a message to *Science* the intent to "enlarge the *American Mineralogist* to include research papers and abstracts, but at the same time to retain the valuable features of this publication which has become recognized as of permanent interest to such collectors and amateurs who are eligible for membership but not fellowship." "Fellows," in this prospectus for MSA, were differentiated from "members" by "having produced some published results of research in mineralogy, crystallography, or the allied sciences."

This early alliance with the amateur community was a necessary concession for the staff of the *American Mineralogist*, but the efforts to appeal to the collecting community faded quickly as articles became more technical and the content more arcane. In 1926, sensing that the professional community had usurped their publication and a new journal was needed, Peter Zodak – an engineering inspector for the Westchester County (NY) Park Commission – founded *Rocks and Minerals* to service the collectors (Montgomery 1951). *Rocks and Minerals* has been joined by *Lapidary Journal* (1947), the *Mineralogical Record* (1970), and other bulletins targeted for amateur mineralogists (Neumeier, undated). MSA's takeover of the *American Mineralogist* was a statement of professional self-determination, allowing US mineralogists to control the content of their publications, and in that fashion, to define the boundaries of their science. But it also estranged MSA from those enthusiasts who had sustained mineralogy over the previous century.

Following Well-Trodden Paths to a New Mineral Society

The emergence of the *American Mineralogist* was different from the genesis of journals that originate in response to a paradigmatic discovery that inspires proponents of the new vision to split from traditionalists. In our lifetimes, innovations involving fractal geometry, nanoscience, astrobiology, and microbial geochemistry offer examples of this latter pathway, and a host of new journals dedicated to these subjects have appeared since 1990.

In contrast, the creation of the *American Mineralogist* – and the society that supported it – was not disciplinarily groundbreaking. At least five countries can boast continuously functioning mineralogical societies that are older than MSA: The Russian Mineralogical Society (1817), which recently celebrated its *bi*centennial; the Mineralogical Society of Great Britain and Ireland (1876); the French Society of Mineralogy and Crystallography (1878); the Austrian Mineralogical Society (1901); and the German Mineralogical Society (1908). Moreover, many of these associations sponsored the publication of journals: *Zapiski RMO* (*Proceedings of the Russian Mineralogical Society* since 1830); the Mineralogical Society's *Mineralogical Magazine* (1876); and one can include the *European Journal of Mineralogy*, which in 1989 merged long-running mineralogical bulletins from France, Germany, Spain, and Italy.

Even within the US, many specialized mineralogical societies had formed and disappeared in the century before the formation of MSA. The history of these evanescent groups is explored in Kraus (1921) and Greene and Burke (1978)[4], but three mineral collecting clubs that predate MSA are with us still: the New York Mineralogical Club (1886); the Philadelphia Mineralogical Society (1892); and the Newark (New Jersey) Mineralogical Society (1915). At the turn of the 19th century, these three clubs served the needs of both professors and amateur collectors. They held regular meetings with invited lecturers, and they published newsletters and booklets to which professionals contributed.

The Connection between the XRD Revolution and the MSA

What convinced US mineralogists that the time had come to establish a society organized and administered not by enthusiastic amateurs but by professors of major universities? In his first presidential address, Kraus (1921) explicitly acknowledges the X-ray diffraction revolution as sharing credit for the explosive growth of the field, noting that mineralogy

> "is no longer merely a descriptive science but by virtue of the development of many quantitative methods and especially as the result of the epoch-making

---

[4] The first mineralogical society in the US was founded in 1797 by Samuel Latham Mitchell, a professor at the College of Physicians and Surgeons in New York City. Named "The American Mineralogical Society" to promote "the investigation of the mineral and fossil bodies which compose the fabric of the Globe; and, more especially, for the natural and chemical history of the minerals and fossils of the United States," its aim was "to arm every hand with a hammer, and every eye with a microscope" (Greene and Burke 1978). The AMS vanished in 1801.

> discoveries in the field of crystal structure *it is now an exact science of fundamental importance.*" [Italics added]

Although American mineralogists were not yet actively engaged in X-ray diffraction experiments, they recognized in the work of European physicists a seed that now distinguished them from the more qualitative "geologists".

In this regard, the proposal for a new society did not go far enough for Frederick E. Wright of the Carnegie Geophysical Laboratory and for Prof. A.C. Gill of Cornell University. As detailed in Phair (1969b), Wright and Gill believed that crystallography was the *only* trait that differentiated MSA from GSA, and Wright insisted on an organizational name change to "The Crystallographic Society of America." Gill concurred that "the crystallographic part was highly desirable" and argued that "we need a *mineralogical* society as much as a cat needs three tails." Wright was a highly accomplished optical mineralogist, and he argued in a letter to Kraus (Phair 1969b): "Crystallography is a much broader subject than mineralogy and if we look upon crystallography as the science which has to deal with matter in the crystal state then crystallography is on a par with physics and chemistry."

The need to mollify Wright and Gill induced Kraus and Wherry to propose a compromise title: The Crystallographical and Mineralogical Society of America. This name appeared in the preliminary constitution and in a November 1919 announcement of the new society in *Science* (Fig. 20; Kraus et al. 1919). Wright's efforts did not survive the organizational meeting in December 1919 because, Phair

(1969b) speculates, the name was too cumbersome. But they elected Wright as Councilor in an act of appeasement, and he eventually served as President in 1941.[5]

The emergence of the new crystallography from the realm of physics rather than mineralogy was a double-edged sword for MSA's founders. On the one hand, the idea that mineralogy is more closely affiliated with physics than geology offered a quantitative rigor that justified a separation from GSA and the creation of a new society. Indeed, one can argue that history repeated itself in the 1970s with the emergence of "mineral physics" and the inauguration in 1977 of *Physics and Chemistry of Minerals* to accommodate articles in high-pressure crystallography that were not being accepted by the *American Mineralogist* (Charles Prewitt, pers. comm.) On the other hand, the instrumental techniques to produce and detect X-rays needed to be learned, and Ewald's invention of reciprocal space demanded a sophisticated training in the mathematics of the scattering process.

Consequently, the first mineral structures to be solved in the US were the work of physical chemists rather than mineralogists. Charles L. Burdick was a graduate student at the Massachusetts Institute of Technology with Arthur A. Noyes, soon afterward one of the founding fathers of Caltech. In 1914, Burdick snared a compartment on the last German ocean liner to leave from New York for Hamburg to pursue his Ph.D. research in Basel and Berlin. In early 1916, Burdick received a letter from Noyes urging him to spend his final months in Europe with WH Bragg in

---

[5] A Crystallographic Society of America with MSA representation was organized in 1939, suspended during the Second World War, and reinstated in 1946 (Notes and News, 1946). It merged with the American Society for X-Ray and Electron Diffraction in 1949 to create the American Crystallographic Association, which continues to thrive.

London because of Noyes's "strong belief in the importance of x-ray atomic structure analysis for the future of theoretical chemistry, and his wish to get something of the kind started at MIT (Burdick 1958)." Burdick returned to MIT, built a Bragg X-ray spectrometer, then followed Noyes to Caltech and built another spectrometer that was "probably the best of its day" (Burdick 1958). This instrument enabled Burdick to collect high-quality data on a natural chalcopyrite crystal from French Creek, PA, and he therewith published the first structure determination of a mineral originating in the US (Burdick and Ellis 1917a,b).

Ralph Wyckoff received his doctorate in physics at Cornell under the tutelage of Shoji Nishikawa, who himself had been trained in space group theory by Torahiko Terada, "one of the few to work in Germany during the 1890s when the theory was being created" (Wyckoff 1962). After Wyckoff received his degree in 1919, he moved to the Carnegie Geophysical Laboratory "to begin there an application of X-ray diffraction to minerals (Wyckoff 1962)," though he also studied artificial crystals as well. Wyckoff revisited the structure of calcite and published XRD analyses of rhodochrosite, magnesite, and siderite (Wyckoff 1920). Soon after, he published the first structure for alabandite (MnS; Wyckoff 1921) and re-examined structures for dolomite (Wyckoff and Merwin 1924) and cristobalite (Wyckoff 1925). Wyckoff also collaborated with Herbert Merwin and Henry Washington of the Geophysical Lab to standardize pyroxene terminology. Using a suite of minerals loaned by William F. Foshag at the Smithsonian, they were first to observe that "all of the different kinds of minerals usually grouped amongst the pyroxenes have the structure of either diopside, enstatite, wollastonite, or rhodonite. (Wyckoff et al. 1925)."

Wyckoff's eight years at the Geophysical Laboratory saw a prolific output of natural and artificial crystal structure refinements as well as several treatises on space group theory and general structure analysis. In 1927, however, he moved away from geology to apply X-ray diffraction techniques to biological systems at the Rockefeller Institute in New York. In a speech given to the Institute of Physics in London nearly 30 years later, Wyckoff (1954) reflected that "[f]or the first 25 years following the discovery of X-ray diffraction, there were very few in the United States carrying out research in the subject." He attributes the lag to several factors, of which one was the recalcitrance of mineralogists:

> "Our subject [i.e., crystallography] in America suffered severely from not finding general acceptance as part of one branch of university science. With us, crystallography has never been more than an occasional course given to students of mineralogy, and our mineralogists were singularly slow in realizing the value of X-ray methods."

That is not a very generous characterization of the mineralogical community, nor is it very accurate.

The record clearly shows that MSA members were highly attuned to the wall of separation between physicists and mineralogists, and they were unhappy about it. The Canadian MSA founder TL Walker (1923) laments, "Owing possibly to their familiarity with the necessary technique and the possession of the laboratory equipment, most of the work in this field [X-ray diffraction] up to the present time has been carried on by physicists rather than by mineralogists." In an assessment of modern analytical techniques, Wyckoff's collaborator, H.S. Washington, explicitly lauds his achievements (Washington 1925):

> "Study of minerals along such lines is still in its infancy, but such examples as have come under my notice lead to the conviction that X-ray methods, especially when employed in conjunction with some of those longer known, are not only the most recent but among the most powerful methods of arriving at an understanding of what minerals, as well as artificial crystals, really are, how they are constituted, and how they are related."

Arthur S. Eakle (1926), professor of mineralogy at the University of California-Berkeley and MSA president in 1925, argued that mineralogical education needed to be updated to include the new approaches in X-ray crystallography:

> "The physicist with his superior electrical and instrumental knowledge has devised instruments for important x-ray investigation of crystal structure and mineral composition, and has substantiated the "space-lattice" theory of internal molecular, or atomic, structure of crystals, and has been enabled to make important additions to our knowledge of crystal symmetry. *We must look to our crystallographers and mineralogists to carry on in this work since it manifestly comes within their province; but there must be more of them to keep pace with our modern methods of investigation.*" [Italics added]

These are not the musings of a community that was "singularly slow" in appreciating the value of X-ray diffraction.

Instead, they reflect the reality that X-ray crystallography is a skill attained through apprenticeship with expert practitioners. Burdick trained with the Braggs, and Wyckoff was mentored by Nishikawa. And if mineralogists were ignorant of physics, it is equally true that physicists were ignorant of mineralogy. The founders of X-ray diffraction, von Laue and WL Bragg, admitted as much. In a posthumously translated autobiographical remembrance, von Laue (1962) stated:

> "Now, I had never studied mineralogy. During my first stay in Gottingen I had made a halfhearted attempt to attend a mineralogy course but had given up very soon. From books I then learned the rudiments of crystallography, that is to say, crystal classes, that was all. The exam was administered by the geologist, Prof. Konen, and I still remember how his amusement grew and grew in the face of my entirely obvious ignorance until he finally broke off the interview."

In accepting the Roebling Medal from MSA in 1948, WL Bragg likewise expressed his surprise in receiving the recognition (Bragg 1949):

> "I am glad that you do not expect the recipient of the medal to pass a simple examination in mineralogy before he can accept his prize, for I am sure I would fail in that test. It is not merely a matter of knowing the subject, it is a deeper and more fundamental difference in outlook which divides the physicist from the mineralogist…
>
> "An exact scientist endeavours to simplify and generalize problems so that comparatively unequivocal decisions can be made. Followers of descriptive sciences such as mineralogy and petrology can never approach their problem from a one-sided standpoint, but must consider how products of nature came to be…"

To a much greater degree than is true today, in the early decades of the twentieth century, the separate branches of the physical sciences were isolated, and crossing boundaries would take time.

But not too much time. C.H. Stockwell, of the University of Wisconsin and then the Canadian Geological Survey, published the first XRD article in *The American Mineralogist* in 1927, on unit-cell parameters obtained from powder diffraction patterns of the garnet group (Stockwell 1927). The next year, John W. Gruner of the University of Minnesota published a technical article on the oscillation method for X-ray diffraction of crystals (Gruner 1928). Significant contributions to crystallography were developed by US scientists who made minerals a major part of their research: Linus Pauling, who won Nobel prizes in chemistry and peace; Martin Buerger, inventor of the precession camera; and JDH Donnay, who revealed relations between crystal form and atomic structure, among others. By the late 1930s, *The American Mineralogist* offered about a half-dozen articles on X-ray crystallography of minerals each year. By the late 1940s, that increased to two dozen per year, and a decade later there are too many to count. These trends also are documented in Barton's (2019) data analysis of the ascension of X-ray diffraction in the discovery of new minerals from the 1930s to the 1970s.

IMPLICATIONS

Reverberations of the XRD Revolution Today

The force with which mineralogists applied X-ray diffraction to extract the crystal structures of materials inspired an equal and opposite response as new techniques challenged our concepts of atomic order. Not surprisingly, incongruities between the classical model of crystallinity as conceived by the Braggs and the structural shortcomings exhibited by natural materials were recognized early. MSA founder Edgar T. Wherry, who first realized that bentonite is altered volcanic ash, was stymied by its classification. Are clays with intensive stacking disorder to be described as crystalline? Wherry (1925) argued that bentonite could be regarded as a "one-dimensional colloid." The semi-random intergrowths characteristic of illite-smectite mixtures continues to inspire new formalisms for the taxonomy of intermediate order (Moore and Reynolds 1997).

The advent of high-resolution transmission electron microscopy shifted the focus from averaged atomic structures as deduced using X-rays to particular atomic configurations as resolved in micrographs. With this curtain drawn, the universality of nanoscale defects in natural materials became evident (Wenk 1976; Nieto and Livi 2013), and they came in myriad styles: layer-, chain- and tunnel-width disorder (Veblen and Buseck 1979; Turner and Buseck 1979; Veblen 1983); commensurate and incommensurate layer modulations (Drits 1987; Guggenheim and Eggleton 1988); temperature- and strain-induced microtwins (Van Tendeloo et al. 1976; Goltrant et al. 1991); assorted line dislocations and ordered point defects (McLaren 1991); fine-scale exsolution lamellae (Brown and Parsons 1984), and more. The observations of these microstructures posed a profound question regarding crystallinity: After how many unit-cells of repetitive stacking disorder, or superperiodic tunnel structures, or exsolution intergrowths, does the defect itself constitute a new mineral (Fig. 21)?

These issues have grown even more pertinent in light of the most recent explorations of nanomaterials. As reviewed in the *American Mineralogist* Centennial article by Caraballo et al. (2015), in the last 25 years we have grown increasingly aware that the geochemistry of near-surface environments is controlled largely by nanophases (Fig. 22). The small dimensions of these particles yield high surface areas that can change their thermodynamic stabilities relative to the bulk (Navrotsky 2004), and the increased reactivity of the surfaces dramatically enhances their abilities to sorb and transport dissolved species or to promote redox or other chemical reactions (Hochella et al. 2008). These particles can grow through epitaxial attachment to form larger particles, requiring the introduction of states of intermediate crystallinity, sometimes termed mesocrystals (Cölfen and Antonietti 2005). Characterizing the formation and evolution of these nanoparticles is at the heart of some of the most exciting science today, and it requires techniques that are themselves at the boundary between diffraction and spectroscopy, such as pair distribution function (PDF) analysis and synchrotron-based extended X-ray absorption spectroscopy (EXAFS) (O'Day et al. 1994; Michel et al. 2007).

One hundred years ago, MSA materialized from a revolution that seemed finally to have resolved a most fundamental problem for Earth scientists: What do we mean when we say that a mineral is "crystalline"? A cutting edge of mineralogy today and for the foreseeable future is the exploration of the hypnagogic state for minerals: crystals that fall within that twilight zone between rigid order and atomic turmoil. Ironically, then, as MSA celebrates its centennial, we find ourselves revisiting the very problem whose solution inspired the Society's birth.

ACKNOWLEDGMENTS

The author acknowledges support from National Science Foundation Grant EAR1552211. Early drafts of this paper were greatly improved by stimulating discussions with and helpful comments by Charlie Burnham and Jeffrey Post. I also thank journal reviewers Charles Geiger and Keith Putirka, whose criticisms tightened the focus of the manuscript, and associate editor Warren Huff for handling this unusually long contribution.

References

Allen, E.T. (1916) The composition of natural bornite. American Journal of Science, 245, 409-413.

Armstrong, H.E. (1927) Poor common salt! Nature, 120, 478.

Assmus, A. (1995) Early history of X-rays. Beam Line, 25, 10-24.

Authier, A. (2004) Dynamical theory of X-ray diffraction. Oxford University Press, Oxford.

Authier, A. (2013) Early Days of X-ray Crystallography. Oxford University Press, Oxford.

Barlow, W. (1883) Probable nature of the internal symmetry of crystals. Nature, 29, 186-188 and 205-207.

Barlow, W. (1894) Über die Geometrischen Eigenschaften homogener starrer Strukturen und ihre Anwendung auf Krystalle. Zeitschrift für Krystallographie und Minerologie, 23, 1–63.

Barlow, W. and Pope, W.J. (1906) A development of the atomic theory which correlates chemical and crystalline structure and leads to a demonstration of the nature of valency. Journal of the Chemical Society, Transactions, 89, 1675-1744.

Barlow, W. and Pope, W.J. (1907) The relation between the crystalline form and the chemical constitution of simple inorganic substances. Journal of the Chemical Society, Transactions, 91, 1150-1177.

Barton, I. (2019) Trends in the discovery of new minerals over the last century. American Mineralogist, 104, 641-651.

Bates, A.C. (1916) Arthur Chamberlain and his magazines. American Mineralogist, 1, 1-2.

Bayley, W.S. (1910) Elementary Crystallography. McGraw-Hill Book Company, New York.

Berzelius, J.J. (1814) Attempt to Establish a Pure Scientific System of Mineralogy by the Application of the Electro-Chemical Theory and the Chemical Proportions. Translated by John Black. C. Baldwin, London.

Berzelius, J.J. (1824) Om de förändringar i det chemiska Mineralsystemet, som blifva en nödvändig följd af isomorpha kroppars egenskap att ersätta hvarandra i obestämda förhållanden. Konglig Vetenskaps-Academiens Handlingar, 112-142

Blackmore, J.T. (1972) Ernst Mach: His Work, Life, and Influence. University of California Press, Berkeley.

Bohr, N. (1913) I. On the constitution of atoms and molecules. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 26, 1-25.

Boscovich, R.G. (1758) Philosophiae naturalis theoria redacta ad unicam legem virium in natura existentium. Prostat Viennae Austriae, Officina Libraria Kaliwodiana.

Bragg, W. H. (1912) X-rays and crystals. Nature, 90, 219.

Bragg, W.H. and Bragg, W.L. (1913) The structure of the diamond. Proceedings of the Royal Society of London. Series A, 89, 277-291.

Bragg, W.H. and Bragg, W.L. (1915) X-rays and Crystal Structure. G. Bell and Sons, London.

Bragg, W. L. (1912) The specular reflection of X-rays. Nature, 90, 410.

Bragg, W.L. (1913a) The diffraction of short electromagnetic waves by a crystal. Proceedings of the Cambridge Philosophical Society. 17, 43-57.

Bragg, W.L. (1913b) The structure of some crystals as indicated by their diffraction of X-rays. Proceedings of the Royal Society of London Series A, 89, 248-277.

Bragg, W.L. (1914) The analysis of crystals by the X-ray spectrometer. Proceedings of the Royal Society of London Series A, 90, 468-489.

Bragg, W.L. (1949) Acceptance of the Roebling Medal of the Mineralogical Society of America. American Mineralogist, 34, 238-241.

Bragg, W.L. (1962) Personal reminiscences. In Ewald, P.P., Ed. Fifty Years of X-ray Diffraction. International Union of Crystallography, Glasgow. pp. 531-539.

Bravais, A. (1851) Etudes cristallographiques. Journal de l'Ecole Polytechnique, 20, 101-276.

Brock, W.H. and Knight, D.M. (1965) The atomic debates: “Memorable and interesting evenings in the life of the Chemical Society. Isis, 56, 5-25.

Brown, C. M. (2014). Benjamin Silliman: A life in the young republic. Princeton University Press, Princeton, N.J.

Brown, W. L. and Parsons, I. (1984) The nature of potassium feldspar, exsolution microtextures and development of dislocations as a function of composition in perthitic alkali feldspars. Contributions to Mineralogy and Petrology, 86, 335-341.

Bruce, A. (1968) The American Mineralogical Journal. Contributions to the History of Geology, vol. 1. Hafner Publishing, New York.

Brush, S.G. (1968) Mach and atomism. Synthese, 18, 192-215.

Buddington, A.F. (1937) Memorial of Alexander Hamilton Phillips. American Mineralogist, 22, 1094-1098.

Buerger, M.J. (1990) Brief history of structure determination. In Lima-de-Faria, Ed., Historical Atlas of Crystallography, Kluwer Academic Publishers, Dordrecht, pp. 109-123.

Burdick, C.L. (1958) The genesis and beginnings of X-ray crystallography at Caltech. Physics Today, 11, 20.

Burdick, C.L. and Ellis, J.H. (1917a) The crystal structure of chalcopyrite determined by X-rays. Journal of the American Chemical Society, 39, 2518-2525.

Burdick, C.L. and Ellis, J.H. (1917b) The crystal structure of chalcopyrite determined by X-rays. Proceedings of the National Academy of Sciences, 3, 644-649.

Caraballo, M.A., Michel, F.M. and Hochella Jr, M.F. (2015). The rapid expansion of environmental mineralogy in unconventional ways: Beyond the accepted definition of a mineral, the latest technology, and using nature as our guide. American Mineralogist, 100, 14-25.

Chalmers, A. (2014) Atomism from the 17th to the 20th Century. In Zalta, E.N., Ed., The Stanford Encyclopedia of Philosophy, URL <https://plato.stanford.edu/archives/win2014/entries/atomism-modern/>.

Christidis, G.E., and Huff, W.D. (2009). Geological aspects and genesis of bentonites. Elements, 5, 93-98.

Cölfen, H. and Antonietti, M. (2005) Mesocrystals: inorganic superstructures made by highly parallel crystallization and controlled alignment. Angewandte Chemie International Edition, 44, 5576-5591.

Dalton, J. (1808) A New System of Chemical Philosophy. S. Russell, Manchester.

Dana, E.S. (1912) A Textbook of Mineralogy. John Wiley and Sons, New York.

Dana, J.D. (1837) A System of Mineralogy. Durrie & Peck and Herrick & Noyes, New Haven.

Dana, J.D. (1845) Observations on pseudomorphism. American Journal of Science and Arts, 48, 81-92.

Dana, J.D. (1854) A System of Mineralogy, 4th Ed. George. P. Putnman, New York.

Dana, J.D. and Brush, G.J. (1869) A System of Mineralogy, 5th Ed. John Wiley and Son, New York.

Darwin, C.G. (1914) The theory of X-ray reflexion. Philosophical Magazine, 27, 315-333 and 675-690.

Debye, P. (1913) Über den Einfluss der Wärmebewegung auf die Interferenzerscheinungen bei Röntgenstrahlen, Verhandlungen der Deutschen Physikalischen Gesellschaft, 15, 678-689.

Debye, P. and Scherrer, P. (1916) Interferenz an regellos orientierten Teilchen im Röntgenlicht. I. Physikalische Zeitschrift, 17, 277-283.

Drits V.A. (1987) SAED and HREM Study of Order/Disorder and Structural Heterogeneity in Layer Minerals. In Drits, Ed. Electron Diffraction and High-Resolution Electron Microscopy of Mineral Structures. Springer, Berlin, Heidelberg, pp. 217-238.

Eakle, A.S. (1926) Needed extension in mineralogic instruction. American Mineralogist, 11, 45-52.

Eckert, M. (2012). Disputed discovery: the beginnings of X-ray diffraction in crystals in 1912 and its repercussions. Acta Crystallographica Section A: Foundations of Crystallography, 68(1), 30-39.

Ewald, P.P. (1913) Zur Theorie der Interferenzen der Röntgenstrahlen in Kristallen. Physikalische Zeitschrift, 14, 465-472.

Fleck, G.M. (1963) Atomism in late nineteenth-century physical chemistry. Journal of the History of Ideas, 24, 106-114.

Ford, W.E. and Bradley, W.M. (1916a). Margarosanite, a new lead-calcium silicate from Franklin, New Jersey. American Journal of Science, 248, 159-162.

Ford, W.E. and Bradley, W.M. (1916b) On hydro-zincite. American Journal of Science, 247, 59-62.

Forman, P. (1969). The discovery of the diffraction of X-rays by crystals; a critique of the myths. Archive for History of Exact Sciences, 6, 38-71.

Frankenheim, M. L. (1826). Crystallonomische Aufsätze. ISI Enzyklopadische Zeitung Oken, 5, 497-515 and 542-565.

Friedel, G. (1913) Sur les symmetries cristallines que peut reveler la diffraction des rayons Röntgen. Comptes Rendus de l'Académie des Sciences, 157, 1533-1536.

Friedrich, W., Knipping, P. and von Laue, M.T. F. (1912) interferenz-Erscheinungen bei Röntgenstrahlen. Sitzungsberichte der Mathematischen-Physikalischen

Klasse der Königlich Bayerischen Akademie der Wissenschaften zu München, 303-322.

Friedrich, W., Knipping, P., and Laue, M. (1913) Interferenzerscheinungen bei roentgenstrahlen. Annalen der Physik, 346, 971-988.

Gadolin, A.V. (1867) Deduction of all crystallographic systems and their subdivisions by means of a single general principle. (In Russian) Annals of the Imperial St Petersburg Mineralogical Society Series 2, 4, 112-200.

Geiger, C.A. (2016) A tale of two garnets: The role of solid solution in the development toward a modern mineralogy. American Mineralogist, 101, 1735-1749.

Gibbs, J.W. (1902) Elementary Principles in Statistical Mechanics Developed with Especial Reference to the Rational Foundation of Thermodynamics. Scribner's Sons, New York.

Gibson, C.S. (1941) Sir William Jackson Pope 1870-1939. Obituary Notices of Fellows of the Royal Society, 3, 291-324.

von Gliszczynski, S. and Stoicovici, E. (1938) Beitrag zum Melanophlogitproblem. Zeitschrift für Kristallographie-Crystalline Materials, 99, 238-250.

Goltrant, O., Cordier, P. and Doukhan, J.C. (1991) Planar deformation features in shocked quartz; a transmission electron microscopy investigation. Earth and Planetary Science Letters, 106, 103-115.

Gordin, M.D. (2019) A Well-Ordered Thing: Dmitrii Mendeleev and the Shadow of the Periodic Table. Princeton University Press, Princeton, NJ.

Gordon, S.G. (1917) Proceedings of Societies. American Mineralogist, 2, 68.

Grabowski, J.J. (1992) Sports in Cleveland: an illustrated history. Case Western Reserve University, Cleveland.

Greene, J.C. and Burke, J. G. (1978). The science of minerals in the age of Jefferson. Transactions of the American Philosophical Society, 68, 1-113.

Grossman, M.I. (2017) John Dalton and the origin of the atomic theory: reassessing the influence of Bryan Higgins. The British Journal for the History of Science, 50, 657–676.

Groth, P. (1906) An Introduction to Chemical Crystallography. John Wiley and Sons, New York.

Gruner, J.W. (1928) The oscillation method of X-ray analysis of crystals. American Mineralogist, 3, 123-141.

Guggenheim, S. and Eggleton, R.A. (1988) Crystal chemistry, classification, and identification of modulated layer silicates. Reviews in Mineralogy and Geochemistry, 19, 675-725.

Hales, T. C. (2005). A proof of the Kepler conjecture. Annals of Mathematics, 1065-1185.

Hausmann, J.F.L. (1813) Handbuch der Mineralogie. 3 volumes, Göttingen. Second edition. pp. 302.

Haüy-R.-J. (1784) Essai d'une Théorie sur la structure des Crystaux. Gogué and Née de la Rochelle, Paris.

Haüy, R.J. (1801) Traité de Minéralogie. Council of Mines, Paris.

Heaney, P. J. (2016). Time's arrow in the trees of life and minerals. *American Mineralogist*, *101*(5), 1027-1035.

Hessel, J.F.C. (1830) Krystall. In Gehler's Physikalisches Wörterbuch, 5, 1023-1360. Schwickert, Leipzig. Reprinted in W.F. Ostwald (1897). Klassiker der exacten Wissenschaften, 89, 41-124.

Hochella, M.F., Lower, S.K., Maurice, P.A., Penn, R.L., Sahai, N., Sparks, D.L. and Twining, B.S. (2008) Nanominerals, mineral nanoparticles, and earth systems. Science, 319, 1631-1635.

Hooke, R. (1665) Micrographia: or some physiological descriptions of minute bodies made by magnifying glasses with observations and inquiries made thereupon. Jo. Martyn and Ja. Allestry, Royal Society, London.

Hooker, M. and Montgomery, A. (1975) Edgar Theodore Wherry. American Mineralogist, 60, 533-539.

Hull, A. W. (1917a). A new method of X-ray crystal analysis. Physical Review, 10, 661-697.

Hull, A.W. (1917b) The crystal structure of iron. Physical Review, 9, 84-87.

Hull, A.W. (1922) The crystal structures of the common elements. Journal of the Franklin Institute, 189-216.

Hull, A.W. (1946) Thirty years of X-ray research at the General Electric Research Laboratory. American Journal of Physics, 14, 71-79.

Hunt, W.F. (1955) Edward Henry Kraus. American Mineralogist, 40, 945-951.

Hunt, W.F. and Kraus, E.H. (1916). Note on the variable composition of melanochalcite. American Journal of Science, 242, 211-214.

Hunter, G.K. (2004). Light is a messenger: the life and science of William Lawrence Bragg. Oxford University Press.

Huygens, C. (1690) Traité de la lumière. Pieter van der Aa, Leiden.

Jackson, J. (2005) A World on Fire. Viking Press, New York.

James, R.W. (1948). The Optical Principles of the Diffraction of X-rays. G. Bell and Sons, London.

Johnson, S. (2008) The Invention of Air. Riverhead Books, New York.

Kaji, M. (2002) D.I. Mendeleev's concept of the chemical elements and *The Principles of Chemistry*. Bulletin for the History of Chemistry, 27, 4-16.

Kargon, R. (1965). Mendeleev's chemical ether, electrons, and the atomic theory. Journal of Chemical Education, 42, 388-389.

Kean, S. (2011) The Disappearing Spoon. Little, Brown, and Company, New York.

Kepler, J. (1611) Strena seu de nive sexangula. Gottfried Tampach, Franfurt.

Kolata, D.R., Huff, W.D., and Bergstrom, S.M. (1996). Ordovician K-bentonites of eastern North America (Vol. 313). Geological Society of America.

Kraus, E.H. (1919) Crystallographical and Mineralogical Society of America. Science, 50, 497.

Kraus, E.H. (1921) The future of mineralogy in America. American Mineralogist, 6, 23-34.

Kraus, E.H., and Hunt, W.F. (1920). Mineralogy: An Introduction to the Study of Minerals and Crystals. McGraw-Hill book Company, Inc., New York.

Kraus, E.H. (1934) Memorial of Frank Robertson Van Horn. American Mineralogist, 19, 101-105.

Kubbinga, H. (2012) Crystallography from Haüy to Laue: Controversies on the molecular and atomistic nature of solids. Acta Crystallographica A, 68, 3-29.

Kuhn, T. (1996) The Structure of Scientific Revolutions. University of Chicago Press, Chicago.

Lalena, J.N. (2006) From quartz to quasicrystals: probing nature's geometric patterns in crystalline substances. Crystallography Reviews, 12, 125-180.

Langmuir, I. (1919) The arrangement of electrons in atoms and molecules. Journal of the American Chemical Society, 41, 868–934.

von Laue, M. (1912) Eine quantitative Prüfung der Theorie für die Interferenz-Erscheinungen bei Röntgenstrahlen. Verlag der Königlichen Bayerische Akademie der Wissenschaften, 363-373.

von Laue, M. (1962) My development as a physicist: An autobiography. In Ewald, P.P., Ed. Fifty Years of X-ray Diffraction. International Union of Crystallography, Glasgow. pp. 278-307.

Levison, W.G. (1917) Proceedings of Societies. American Mineralogist, 2, 67-68.

Lewis, G.N. (1908). The osmotic pressure of concentrated solutions, and the laws of the perfect solution. Journal of the American Chemical Society, 30, 668–683.

Lewis, G.N. (1916). The atom and the molecule. Journal of the American Chemical Society, 38, 762-785.

Lewis, G.N. (1926). The conservation of photons. Nature, 118, 874–875.

Lima-de-Faria, J. (1990) Time-maps of crystallography. In Lima-de-Faria, Ed., Historical Atlas of Crystallography, Kluwer Academic Publishers, Dordrecht, pp. 5-42.

Lindley, D. (2015) Boltzmann's Atom: The Great Debate that Launched a Revolution in Physics. The Free Press, New York.

Mach, E. (1883) Die Mechanik ihrer Entwicklung. F.A. Brockhaus, Leipzig.

Mach, E. (1919) The Science of Mechanics. Trans. McCormack, T.J. Open Court Publishing, Chicago.

Madelung, E. (1909) Molekulare Eigenschwingungen. Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse, 100-106.

McLaren, A.C. (1991) Transmission electron microscopy of minerals and rocks. Cambridge University Press, Cambridge.

Melhado, E.M. (1980) Mitscherlich's discovery of isomorphism. Historical Studies in the Physical Sciences, 11, 87-123.

Melhado, E.M. (1981) Jacob Berzelius: The Emergence of his Chemical System. University of Wisconsin Press, Madison. Cambridge University Press, Cambridge.

Melhado, E.M. and Frdngsmyr, T., Eds. (2003) Enlightenment science in the romantic era: The chemistry of Berzelius and its cultural setting (Vol. 10). Cambridge University Press, Cambridge.

Mendeleev, D. (1879). The periodic law of the chemical elements. The Chemical News, 40, No. 1042.

Mendeleev, D. (1891) Principles of Chemistry, Vol 1. Translated by G. Kamensky, Longmans, Green & Co., London.

Michel, F.M., Ehm, L., Antao, S.M., Lee, P.L., Chupas, P.J., Liu, G., Strongin, D.R., Schoonen, M.A., Phillips, B.L. and Parise, J.B. (2007) The structure of ferrihydrite, a nanocrystalline material. Science, 316, 1726-1729.

Miers, H.A. (1902) Mineralogy: An Introduction to the Scientific Study of Minerals. MacMillan and Co., London.

Miers, H.A. (1918) The old and the new mineralogy. Journal of the Chemical Society, Transactions, 113, 363-386.

Mitscherlich, E. (1819) Über die Kristallisation der Salze, in denen das Metall der Basis mit zwei Proportionen Sauerstoff verbunden ist. Abhandlungen, Akademie der Wissenschaften, Berlin, pp. 427-437.

Mitscherlich, E. (1821) Über das Verhältniss zwischen der chemischen Zusammensetzung und der Krystallform arseniksaurer und phosphorsaurer Salze. W. Engelmann, Leipzig.

Mitscherlich, E. (1822) Sur la relation qui existe entre la forme crystalline et les proportions chimiques. I. Mémoire sur les arseniates et les phosphates. Annales des Chimie et des Physique 19, 350–419.

Montgomery A. (1951) Peter Zodac and *Rocks and Minerals*. Rocks & Minerals, 26, 451-453.

Moore, D.M. and Reynolds, R.C. Jr. (1997) X-ray diffraction and the identification and analysis of clay minerals. 2nd Ed. Oxford University Press, Oxford.

Moore, P.B. (1990) Brief history of chemical crystallography. I. Inorganic compounds. In Lima-de-Faria, Ed., Historical Atlas of Crystallography, Kluwer Academic Publishers, Dordrecht, pp. 5-42.

Morrow, S.I. (1969) One hundred and fifty years of isomorphism. Journal of Chemical Education, 46, 580-583.

Moseley, H.G.J. (1913) The high-frequency spectra of the elements. Philosophical Magazine, 26, 1024-1034.

Moses, A.J. and Parsons, C.L. (1900) Elements of Mineralogy, Crystallography and Blowpipe Analysis. 2nd Ed. D. Van Nostrand Company, New York.

Moses, A.J. and Parsons, C.L. (1916) Elements of Mineralogy, Crystallography and Blowpipe Analysis. 5th Ed. D. Van Nostrand Company, New York.

Navrotsky, A. (2004). Energetic clues to pathways to biomineralization: Precursors, clusters, and nanoparticles. Proceedings of the National Academy of Sciences, 101, 12096-12101.

Neumeier, G. A brief history of mineral magazines. Newsletter of the New York Mineralogical Club. http://www.newyorkmineralogicalclub.org/history/minutes/Introduction%20--%20A%20Brief%20History%20of%20Mineral%20Magazines.pdf

Niaz, M., Rodríguez, M.A., and Brito, A. (2004) An appraisal of Mendeleev's contribution to the development of the periodic table. Studies in the History and Philosophy of Science, 35, 271-282.

Nieto, F. and Livi, K.J. (Eds.). (2013). Minerals at the Nanoscale (Vol. 14). The Mineralogical Society of Great Britain and Ireland.

Notes and News (1946) The Crystallographic Society. American Mineralogist, 31, 84.

O'Day, P.A., Rehr, J.J., Zabinsky, S.I. and Brown, G.J. (1994) Extended X-ray absorption fine structure (EXAFS) analysis of disorder and multiple-scattering in complex crystalline solids. Journal of the American Chemical Society, 116, 2938-2949.

Ostwald, W. (1904) Faraday Lecture: Elements and compounds. Journal of the Chemical Society, Transactions, 85, 506-522.

Parsons, A.L. (1943) Memorial of Thomas Leonard Walker. American Mineralogist, 28, 167-173.

Pauling, L. (1929) The principles determining the structure of complex ionic crystals. Journal of the American Chemical Society, 51, 1010–1026.

Perutz M.F. (1990) How W.L. Bragg invented X-ray analysis. Acta Crystallographica A, 46, 633-643.

Pfeiffer, P. (1917) Crystals as molecular compounds. Zeitschrift für anorganische chemie. 97, 161-174.

Phair, G. (1969a) The American Mineralogist: Its first four years. American Mineralogist, 54, 1233-1243.

Phair, G. (1969b) The founding of the Mineralogical Society of America. American Mineralogist, 54, 1244-1255.

Phillips, A.H. (1912) Mineralogy: An Introduction to the Theoretical and Practical Study of Minerals. MacMillan, New York.

Phillips, A.H. (1916) New zinc phosphates from Salmo, B. C. American Journal of Science, 249, 275-278.

Pojman, P. (2011) Ernst Mach. In Zalta, E.N., Ed., The Stanford Encyclopedia of Philosophy. URL: <https://plato.stanford.edu/archives/win2011/entries/ernst-mach/>.

Pope, W.J. (1935) William Barlow 1845-1934. Obituary Notices of Fellows of the Royal Society, 1, 367-370.

Pough, F.H. (1949) Memorial of Herbert Percy Whitlock. American Mineralogist, 34, 261-266.

Rhodes, R. (1986) The making of the atomic bomb. Simon and Schuster, New York.

Rogers, A.F. (1921) Introduction to the Study of Minerals and Rocks. McGraw-Hill Book Co., New York.

Rutherford, E. (1911) The Scattering of α and β Particles by Matter and the Structure of the Atom. Philosophical Magazine. 21, 669–688.

Senechal, M. (1990) Brief history of geometrical crystallography. In Lima-de-Faria, Ed., Historical Atlas of Crystallography, Kluwer Academic Publishers, Dordrecht, pp. 43-59.

Smits, A. and Scheffer, F.E.C. (1917) The interpretation of the "Roentgenograms" and Roentgen spectra of crystals. Proceedings of the Koninklijke Akademie van Wetenschappen te Amsterdam, 19, 432-338.

Solly, R.H. (1894) An Elementary Introduction to Mineralogy. C.J. Clay and Sons, London.

Sohncke, L. (1888). Erweiterung der Theorie der Krystallstructur. Zeitschrift für Kristallographie-Crystalline Materials, 14, 426-446.

Stockwell, C.H. (1927) An X-ray study of the garnet group. American Mineralogist, 12, 327-344.

Taber, S. (1916) The growth of crystals under external pressure. American Journal of Science, 246, 532-556.

Thomson, J.J. (1904). On the structure of the atom: an investigation of the stability and periods of oscillation of a number of corpuscles arranged at equal intervals around the circumference of a circle; with application of the results to the theory of atomic structure. Philosophical Magazine, 7, 237-265.

Turner, S. and Buseck, P.R. (1979). Manganese oxide tunnel structures and their intergrowths. Science, 203, 456-458.

Van Melsen, A.G. (1960) From atomos to atom: the history of the concept atom. Harper and Brothers, New York.

Van Tendeloo, G., Van Landuyt, J. and Amelinckx, S. (1976). The α→ β phase transition in quartz and AlPO4 as studied by electron microscopy and diffraction. Physica Status Solidi (A), 3*3*, 723-735.

Veblen, D.R. (1983) Microstructures and mixed layering in intergrown wonesite, chlorite, talc, biotite, and kaolinite. American Mineralogist, 68, 566-580.

Veblen, D.R. and Buseck, P.R. (1979) Chain-width order and disorder in biopyriboles. American Mineralogist, 64, 687-700.

Walker, T.L. (1923) The development of mineralogical methods. American Mineralogist, 8, 41-46.

Washington, H.S. (1925) The modern study of minerals. American Mineralogist, 10, 45-52.

Weiss, C.S. (1814) Uebersichliche Darstellung des verschie- denen naturlichen Abteilungen der Kristallisationssysteme. Abhandlungen der Koniglichen Akademie der Wissenschaften in Berlin, 289-344.

Wenk, H.-R., Ed. (1976) Electron Microscopy in Mineralogy. Springer-Verlag, Berlin.

Wherry, E.T. (1917a). Clay derived from volcanic dust in the Pierre in South Dakota. Journal of the Washington Academy of Sciences, 7, 576-583.

Wherry, E.T. (1917b) Review of two recent papers on crystal structure. American Mineralogist, 2, 36-38

Wherry, E.T. (1918) Abstracts of crystallographic literature. American Mineralogist, 3, 137-147.

Wherry, E.T. (1925) Bentonite as a one-dimensional colloid. American Mineralogist, 10, 120-123.

Whitlock, H.P. (1920) The Mineralogical Society of America. Science, 51, 219-220.

Wollaston, W.H. (1812) On the primitive crystals of carbonate of lime, bitter-spar, and iron-spar. Philosophical Transactions of the Royal Society of London, 102, 159-162.

Wollaston, W.H. (1813) The Bakerian Lecture: On the elementary particles of certain crystals. Philosophical Transactions of the Royal Society of London, 103, 51-63.

Wooster, W.A. (1990) Brief history of physical crystallography. In Lima-de-Faria, J., Ed. Historical Atlas of Crystallography, Kluwer Academic Publishers, Dordrecht, pp. 61-75.

Wyckoff, R.W.G. (1920). The crystal structures of some carbonates of the calcite group. American Journal of Science, 299, 317-360.

Wyckoff, R.W.G. (1921). The crystal structure of alabandite (MnS). American Journal of Science, 11, 239-249.

Wyckoff, R.W. (1925) Crystal structure of high temperature cristobalite. American Journal of Science, 54, 448-459.

Wyckoff, R.W.G. (1954) Some thoughts on the future of natural science, with illustrations from the growth of X-ray diffraction work in the United States. British Journal of Applied Physics, 5, 199-204.

Wyckoff, R.W.G. (1962) Reminiscences. In Ewald, P.P., Ed. Fifty Years of X-ray Diffraction. International Union of Crystallography, Glasgow. pp. 691-694.

Wyckoff, R.W.G. and Merwin, H.E. (1924) The crystal structure of dolomite. American Journal of Scienc*e*, 48, 447-461.

Wyckoff, R.W., Merwin, H.E., and Washington, H.S. (1925). X-ray diffraction measurements upon the pyroxenes. American Journal of Science, 59, 383-397.

Figure Captions

Figure 1: The Six Founders of MSA. A) Edward H. Kraus (from MSA Centennial website); B) Alexander H. Phillips (from Am Min Obit); C) Frank R. Van Horn (From Am Min obit); D) Thomas L. Walker (from Am Min obit); F) Edgar T. Wherry (from MSA web page).

Figure 2: A) René Just Haüy (engraving by Ambroise Tardieu) (open source from Wikipedia); B) Construction of pentagonal dodecahedron of pyrite by integrant molecules from *Traité de Mineralogie* (1801). (from Wikimedia commons)

Figure 3: A) Closest packing of atoms in a snowflake from Keppler's *Strena Seu de Nive Sexangula* (1611) [from Google Books]; B) Drawings of quartz crystals and their component "globular bodies" from Hooke's *Micrographia Restaurata* (1665) [from Google Books]; C) Arrangement of spherical bodies to explain cleavage angles in calcite from Huygens *Traité de la Lumière* (1690) [from Google Books].

Figure 4: William Wollaston's (1813) proposed construction of Haüy's polyhedral *molécules intégrantes* using spheres and ellipsoids. [Open access article]

Figure 5: The "Father of Atomic Theory" John Dalton (1808) correlated chemical with physical atomicity. Part 1 in this figure represents the arrangement of "particles" in water, and Parts 2, 5, and 6 portray the geometrical constraints of particles in ice. [From open access article]

Figure 6: A) William Barlow and B) William Jackson Pope [terms of https:// about jstor.org/terms]

Figure 7: Schemes for closest packing of spheres in crystals from Barlow (1883). [From Nature Publishing Group]

Figure 8: Barlow's (1898) model for cubic closest packed spheres with smaller spheres tangentially located within interstices. [From Zeitschrift für Kristallographie]

Figure 9: A) Dmitri Mendeleev (1834-1907); B) Ernst Mach (1838-1916). [From Wikipedia]

Figure 10: Photograph of Max von Laue (1879-1960) [from Wikipedia]

Figure 11: A) First X-ray diffraction pattern of copper sulfate [from http://what-when-how.com/proteomics/history-and-future-of-x-ray-structure-

determination-proteomics/]; B) First published X-ray diffraction pattern of sphalerite (Friedrich et al. 1913).

Figure 12: A) William Lawrence Bragg (1890-1971) (left) and William Henry Bragg (1862-1942) (right) (Acc. 90-105 - Science Service, Records, 1920s-1970s, Smithsonian Institution Archives). [Reprinted according to fair use copyright laws]. B) Reflection of X-ray pencils from parallel planes within crystal to generate diffraction spots (Bragg 1913a).

Figure 13: A) Ernest Rutherford (1831-1937); B) Niels Bohr (1885-1962) [From Wikipedia]

Figure 14: A) Paul Ewald (1888-1985) [from JSTOR archives]; B) Representation of X-ray scattering sphere in reciprocal space from Ewald (1913) [From Physikalische Zeitschrifte from Hathitrust.org]

Figure 15: Founders of *The American Mineralogist*: A) Samuel G. Gordon (1897-1952); B) Harry W. Trudell (1880-1964) [both from Mineralogical Record online archives]

Figure 16: A) Gilbert N. Lewis (1875-1946) [from Wikipedia]; B) Dot notation for H_2O, HI, and I_2 from Lewis (1916) [from Journal of the American Chemical Society]

Figure 17: Wherry's (1918) representations of the structures of A) diamond and B) body-centered cubic structures such as a-Fe. Note his inferred physical shapes of the atoms required by the unit-cell geometries to the right. [From Wherry 1918 in Am Min]

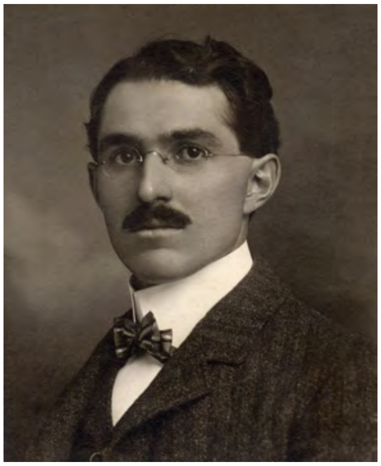
Figure 18: Lewis's sketches for the disposition of valence electrons around "cubical atoms," formalized in Lewis (1916). [From Wikipedia]

Figure 19: The Founders' Letter circulated in 1917. [From MSA Centennial website]

Figure 20: The announcement in the Nov. 28, 1919 issue of *Science* of the founding of the "Crystallographical and Mineralogical Society of America." [From Science magazine]

Figure 21: Aperiodic fine (A) and coarse (B) slabs in mixed-layer chlorite ("C")-mica ("M") intergrowths with *c** horizontal. Inset diffraction patterns show heavy streaking along 00*l* due to the fine intergrowths. Diagram at bottom shows the structure of the nonconventional setting for the C (chlorite) and M (mica) slabs outlined in HRTEM images. Reprinted from Veblen (1983). [From Am Min article]

Figure 24: Transmission electron microscope images of synthetic akaganeite (γ-FeOOH) nanoparticles. Published with permission of Kris Peterson.



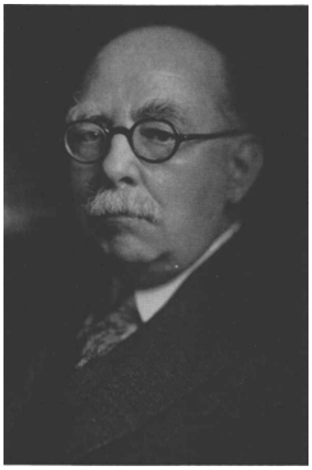
Edward H. Kraus (1875-1973)

Alexander H. Phillips (1866-1937)

Frank R. Van Horn (1872-1933)

Thomas L. Walker (1867-1942)

Edgar T. Wherry (1885-1982)



Herbert P. Whitlock (1868-1948)

Figure 1: The six founders of MSA.

René Just Haüy (1743-1822)

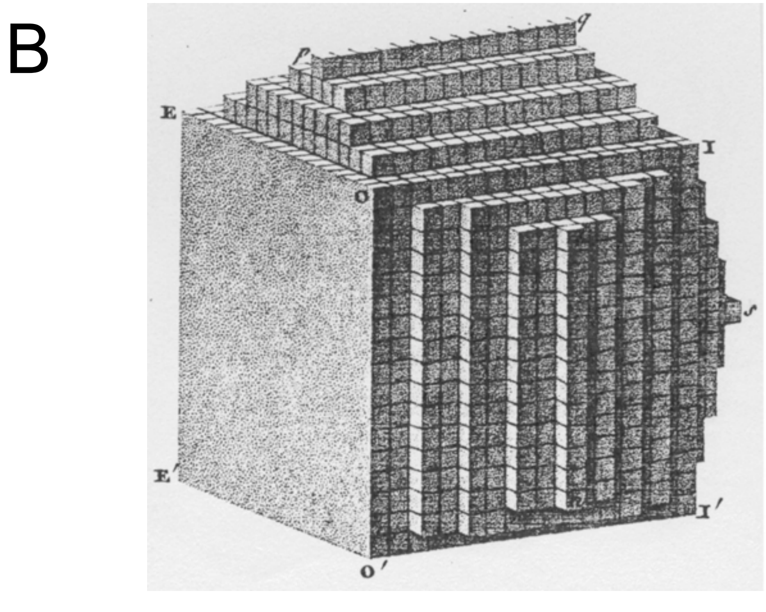


Figure 2: A) René Just Haüy (engraving by Ambroise Tardieu); B) Construction of pentagonal dodecahedron of pyrite by integrant molecules from *Traité de Mineralogie* (1801).

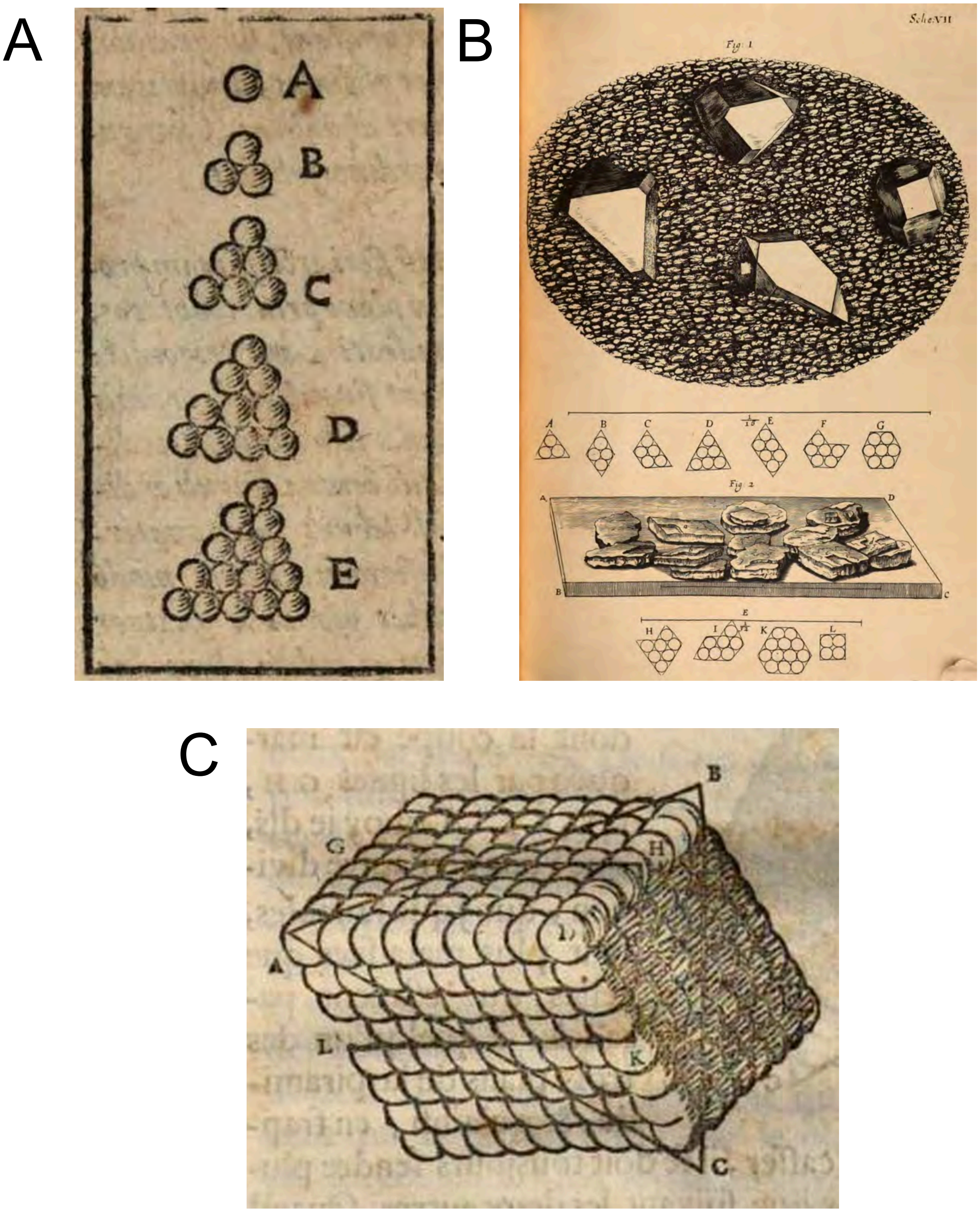


Figure 3: A) Closest packing of atoms in a snowflake from Kepler's *Strena Seu de Nive Sexangula* (1611); B) Drawings of quartz crystals and their component "globular bodies" from Hooke's *Micrographia Restaurata* (1665); C) Arrangement of spherical bodies to explain cleavage angles in calcite from Huygens *Traité de la Lumière* (1690).

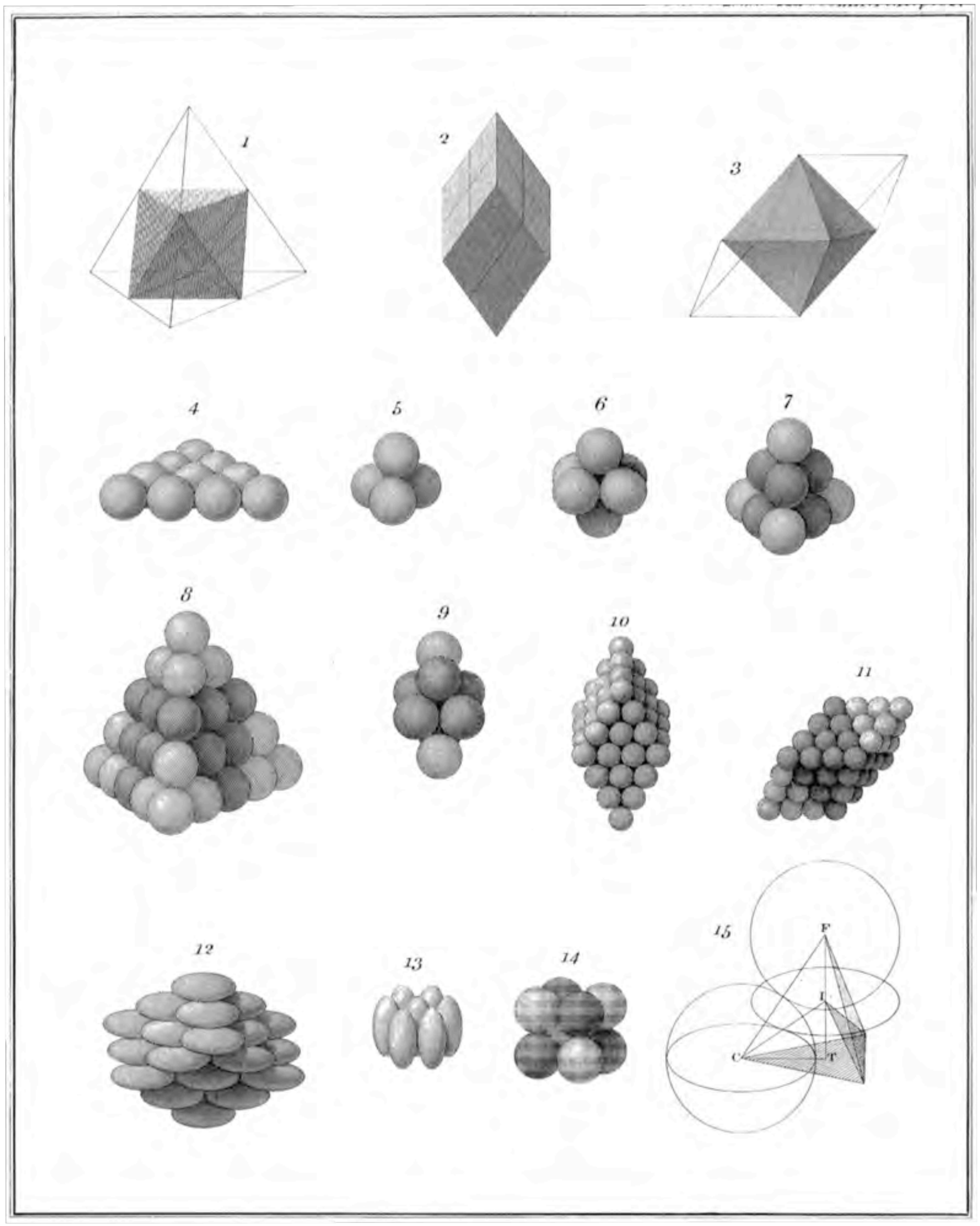


Figure 4: William Wollaston's (1813) proposed construction of Haüy's polyhedral *molécules intégrantes* using spheres and ellipsoids. [Open access]

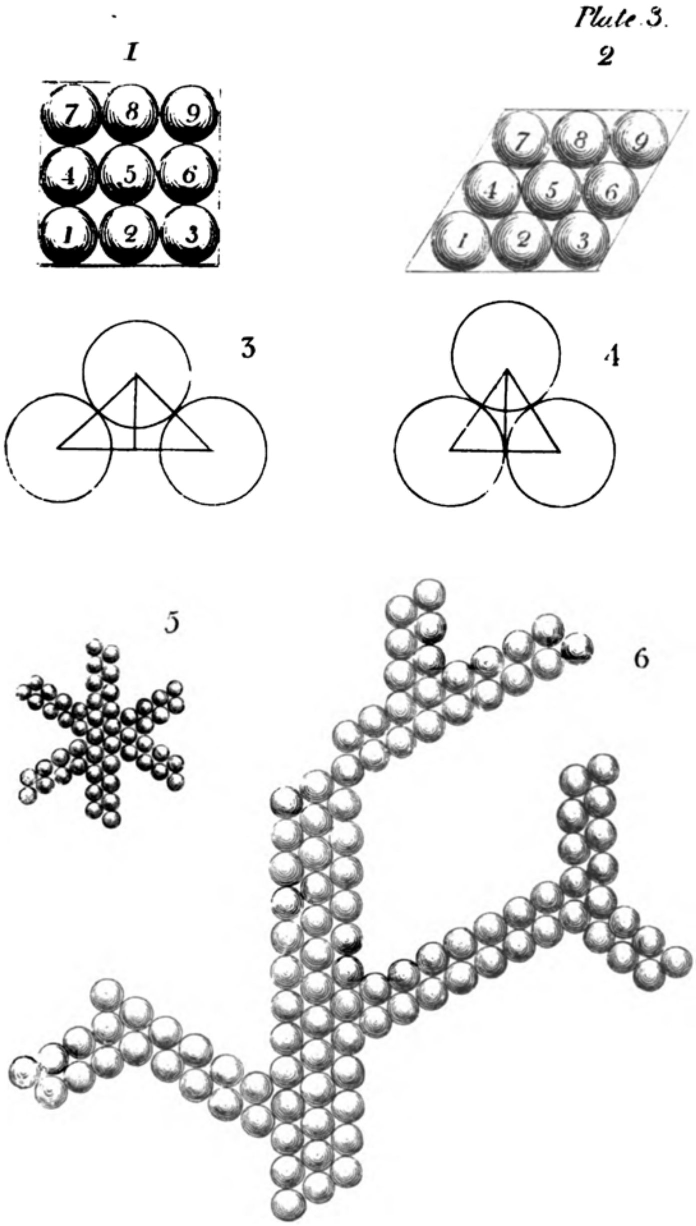
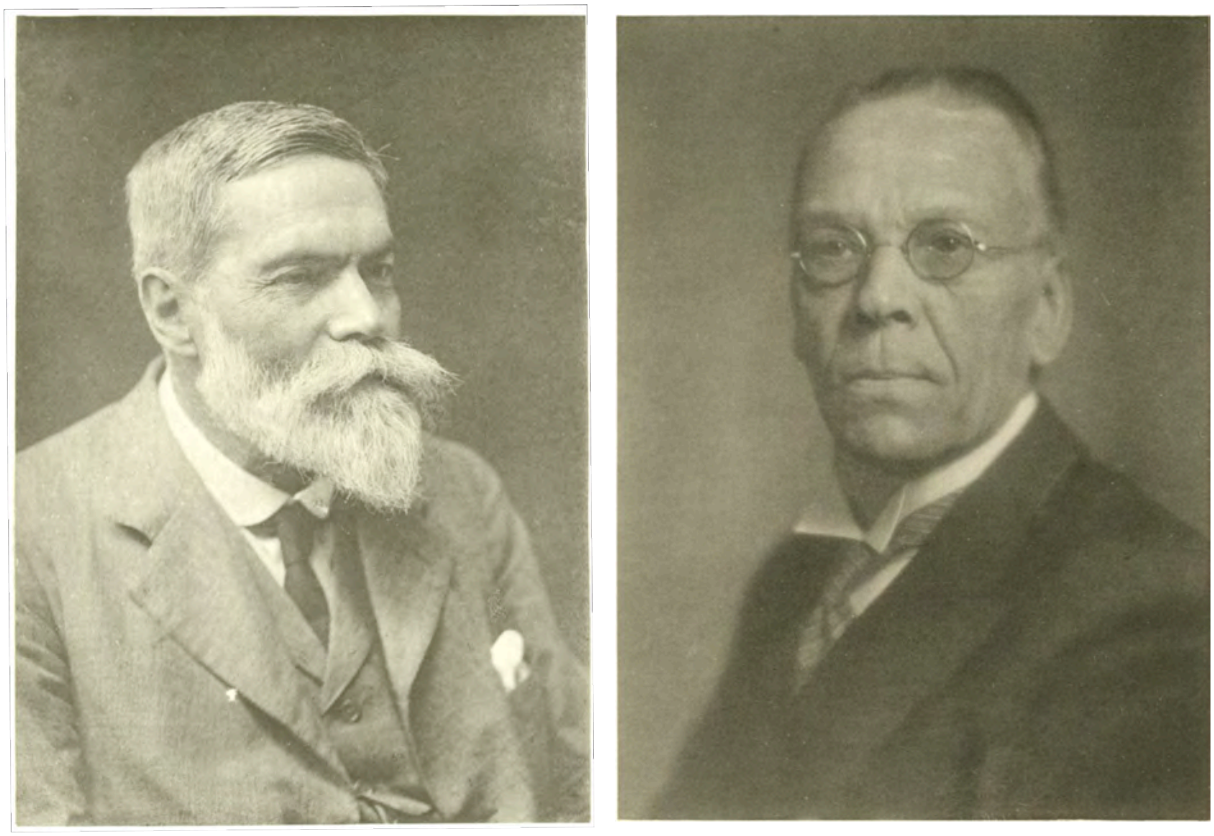


Figure 5: The "Father of Atomic Theory" John Dalton (1808) correlated chemical with physical atomicity. Part 1 in this figure represents the arrangement of "particles" in water, and Parts 2, 5, and 6 portray the geometrical constraints of particles in ice.



William Barlow (1845-1934)

William Jackson Pope (1870-1939)

Figure 6: William Barlow and William Jackson Pope

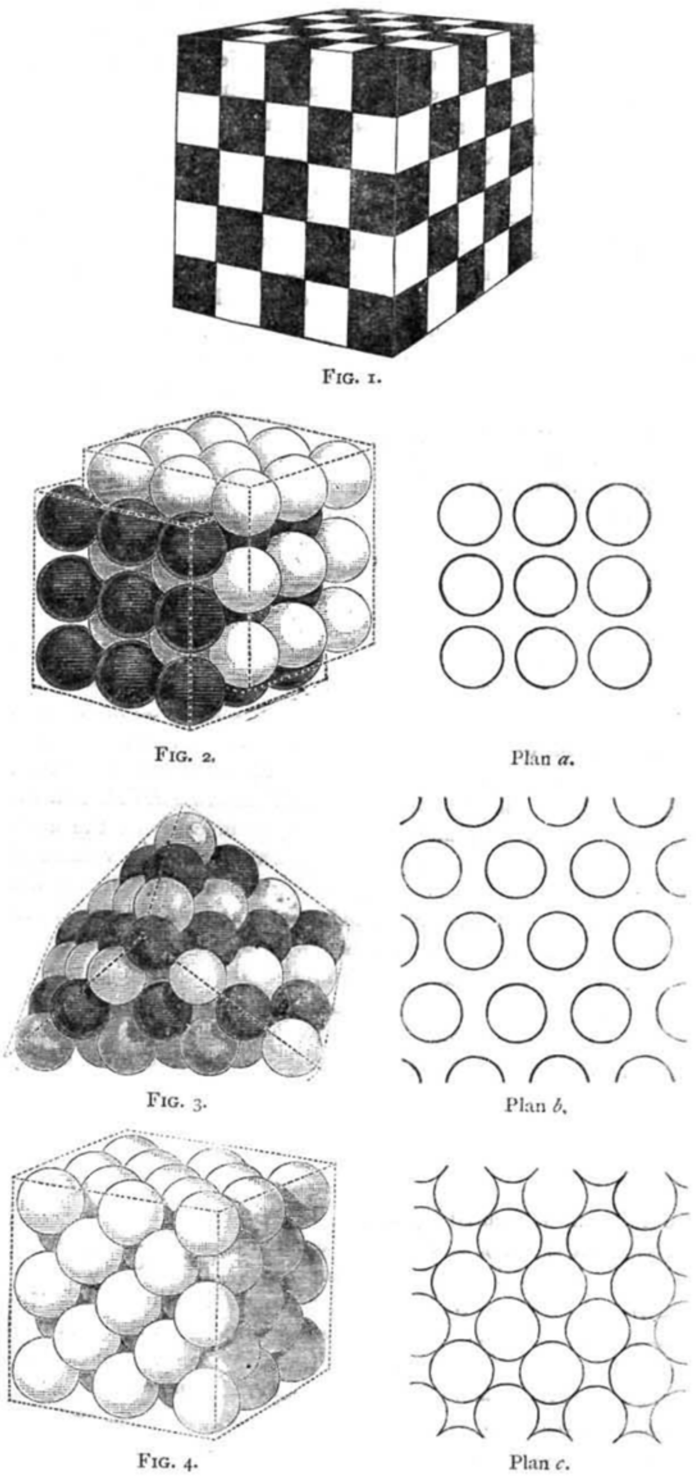


FIG. 1.

FIG. 2.

Plan *a*.

FIG. 3.

Plan *b*.

FIG. 4.

Plan *c*.

Figure 7: Schemes for closest packing of spheres in crystals from Barlow (1883).

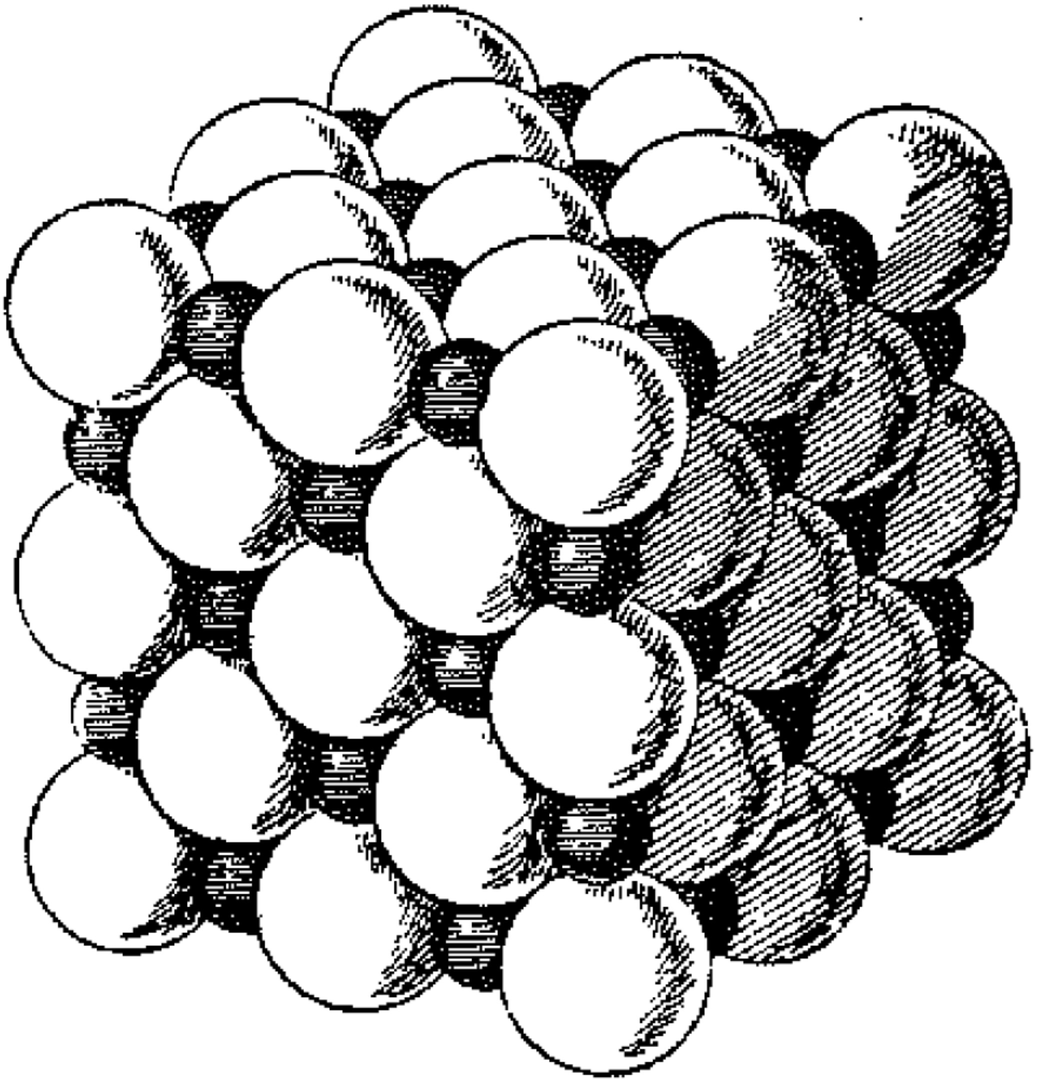


Figure 8: Barlow's (1898) model for cubic closest packed spheres with smaller spheres tangentially located within interstices.

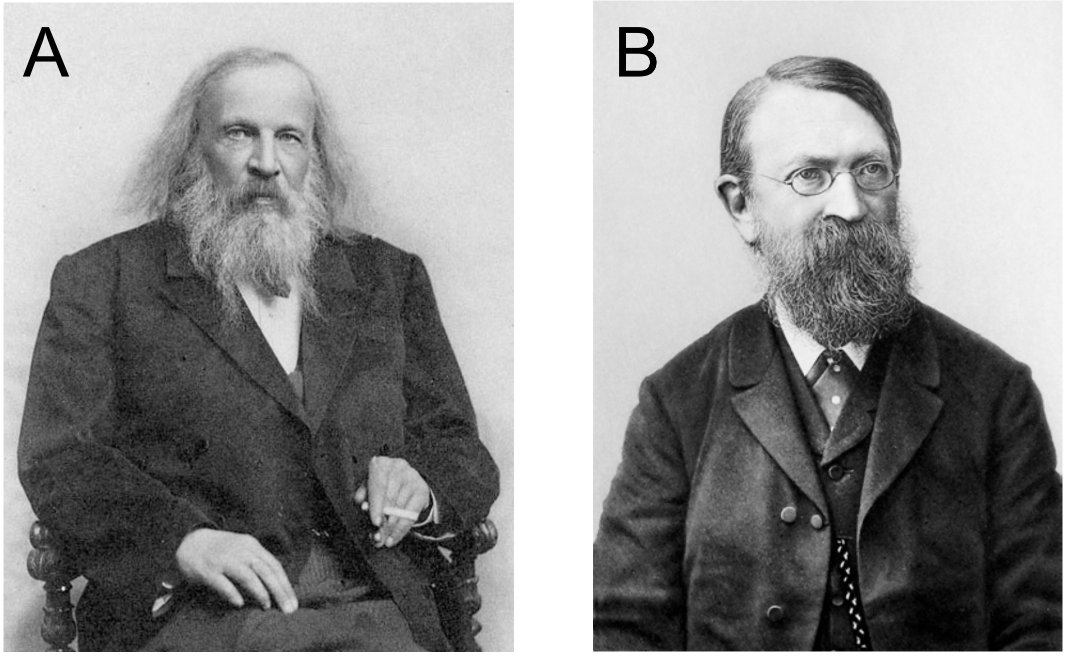


Figure 9: A) Dmitri Mendeleev (1834-1907); B) Ernst Mach (1838-1916).

Figure 10: Max von Laue (1879-1960)

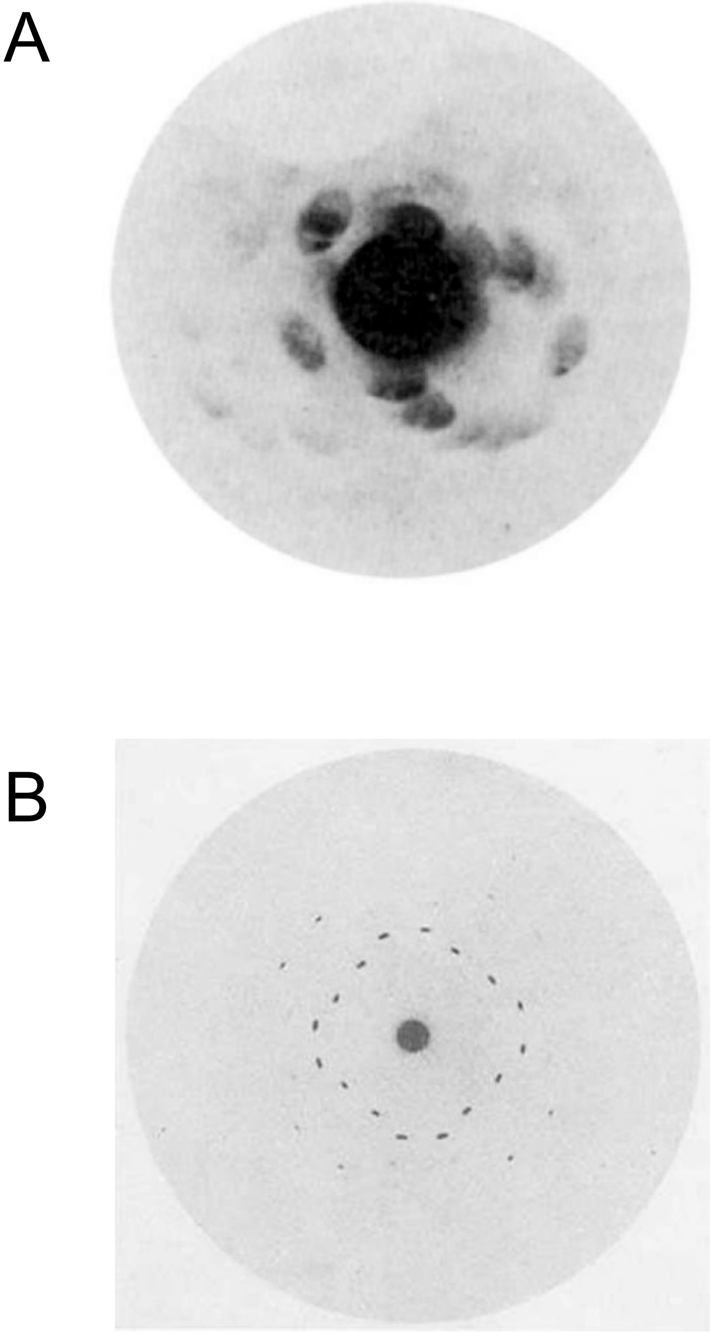


Figure 11: A) First X-ray diffraction pattern of copper sulfate; B) First X-ray diffraction pattern of sphalerite (Friedrich et al. 1913).

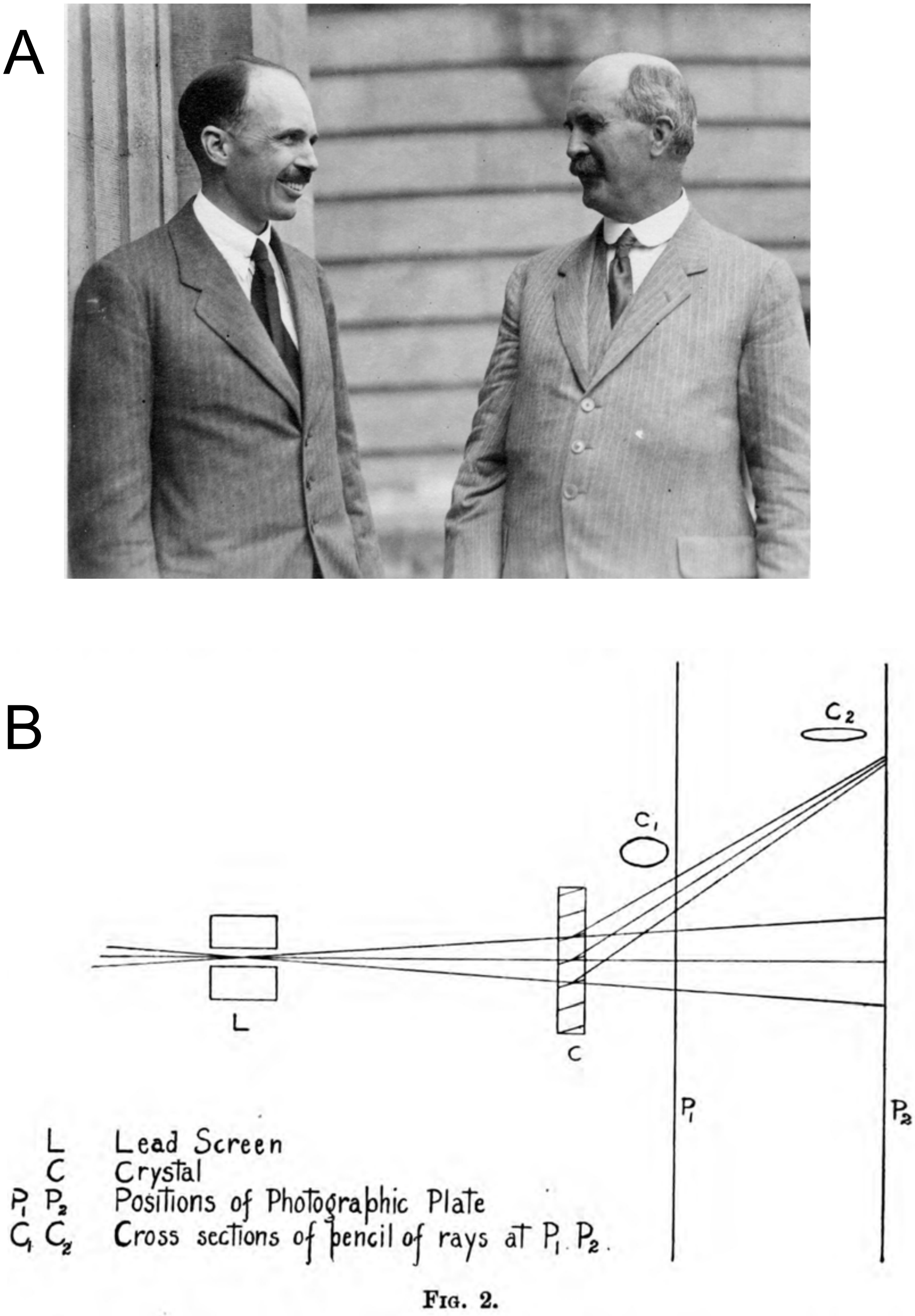


Figure 12: A) William Lawrence Bragg (1890-1971) (left) and William Henry Bragg (1862-1942) (right) (Acc. 90-105 - Science Service, Records, 1920s-1970s, Smithsonian Institution Archives). B) Reflection of X-ray pencils from parallel planes within crystal to generate diffraction spots (Bragg 1913a).

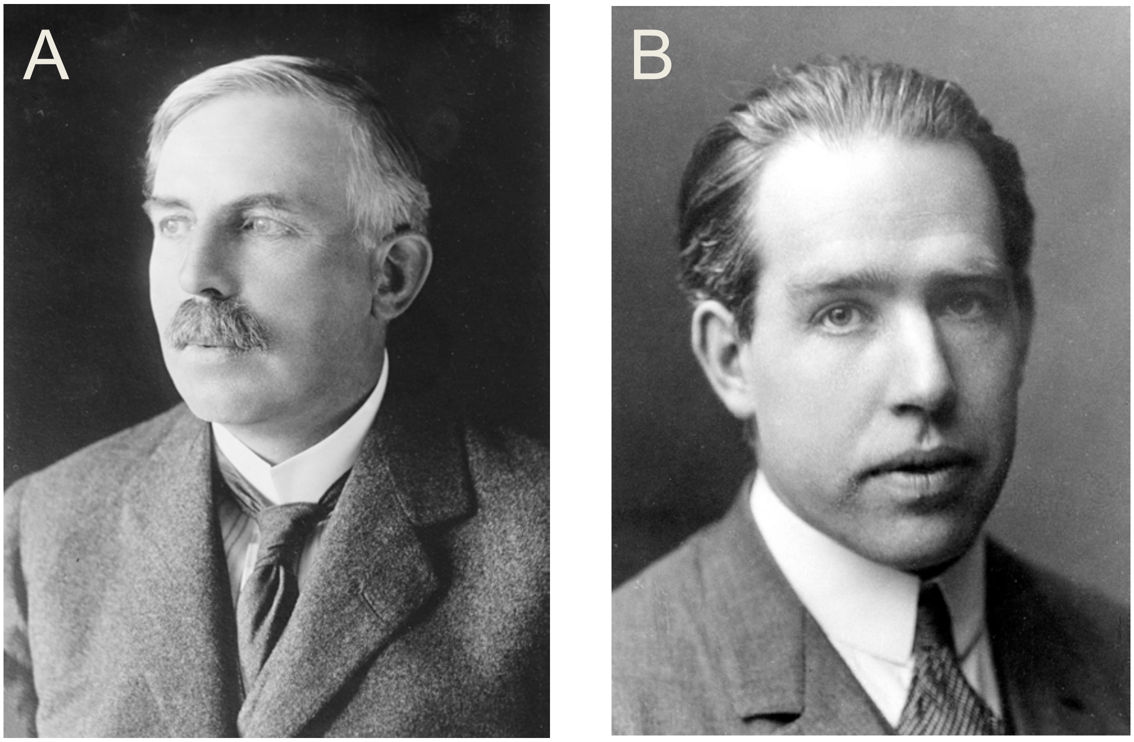


Figure 13: A) Ernest Rutherford (1831-1937); B) Niels Bohr (1885-1962)

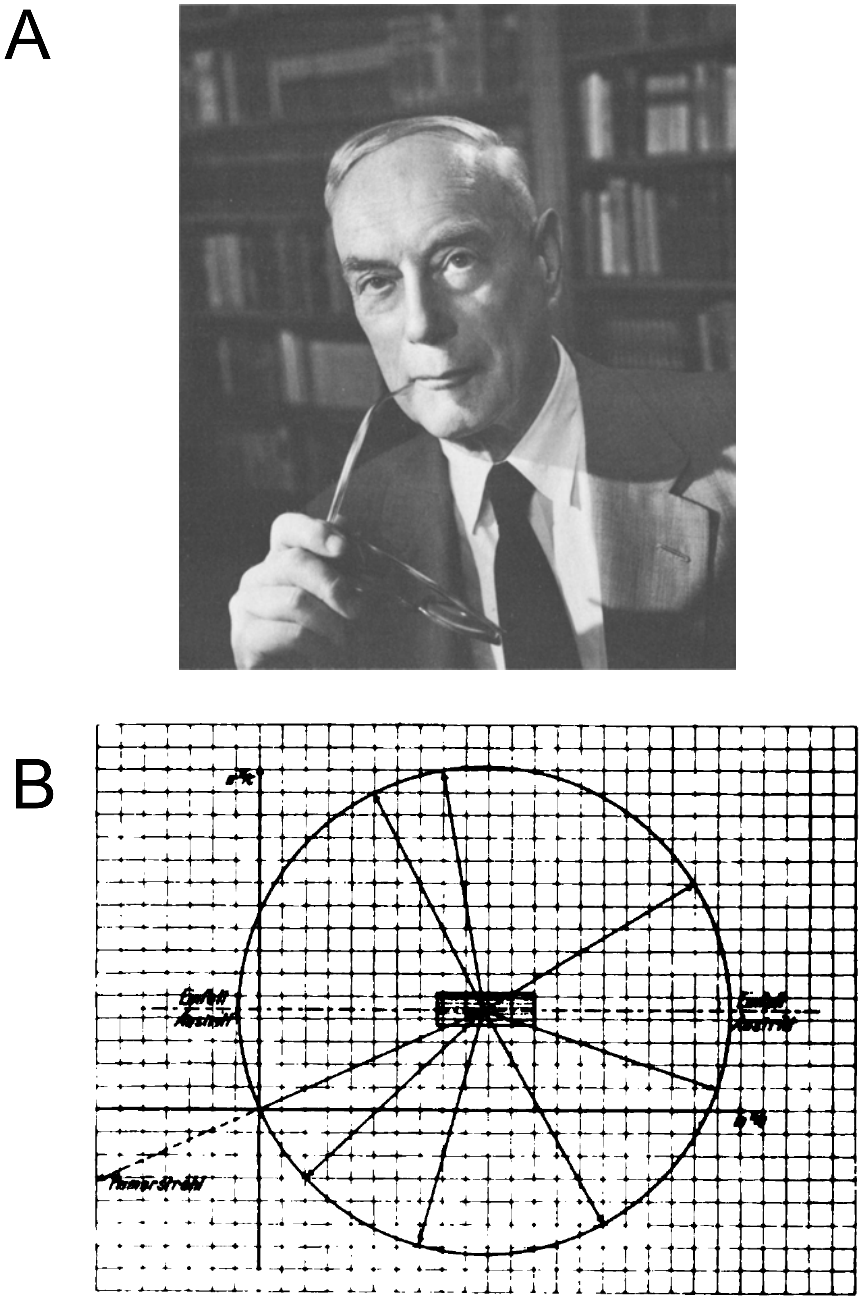


Figure 14: A) Paul Ewald (1888-1985); B) Representation of X-ray scattering sphere in reciprocal space from Ewald (1913)

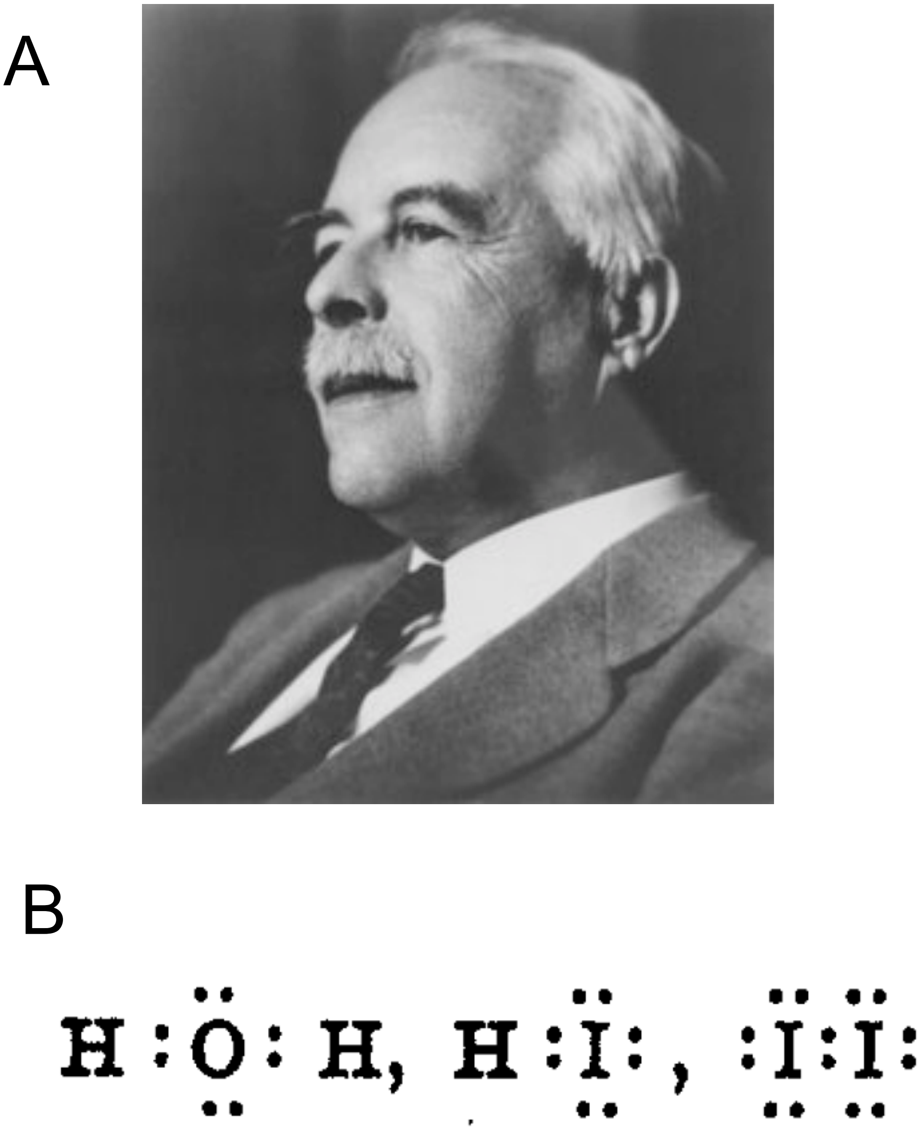


Figure 15: A) Gilbert N. Lewis (1875-1946); B) Dot notation for H_2O, HI, and I_2 from Lewis (1916).

Figure 16: Founders of *The American Mineralogist*: A) Samuel G. Gordon (1897-1952); B) Harry W. Trudell (1880-1964)

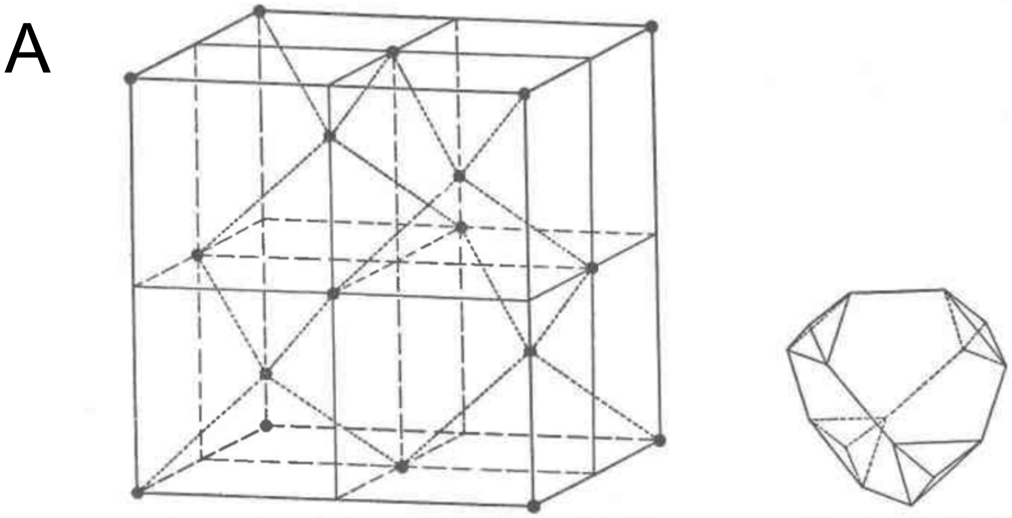


FIG. 1. Eight-atom cell of diamond lattice; valence of atoms 4, in directions shown by dotted lines.

FIG. 2. Shape of each atom[3] (when all are alike).

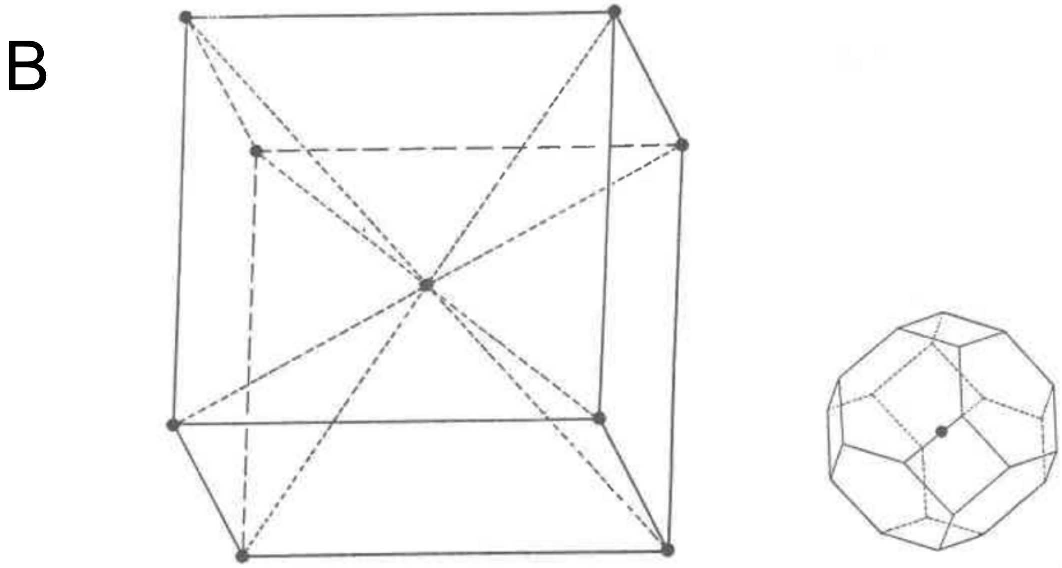


FIG. 5. Two-atom cell of body-centered cubic lattice; valence of atoms 8, in directions shown by dotted lines.

FIG. 6. Shape of each atom (when all are alike).

Figure 17: Wherry's (1918) representations of the structures of A) diamond and B) body-centered cubic structures such as α-Fe. Note his inferred physical shapes of the atoms required by the unit-cell geometries to the right.

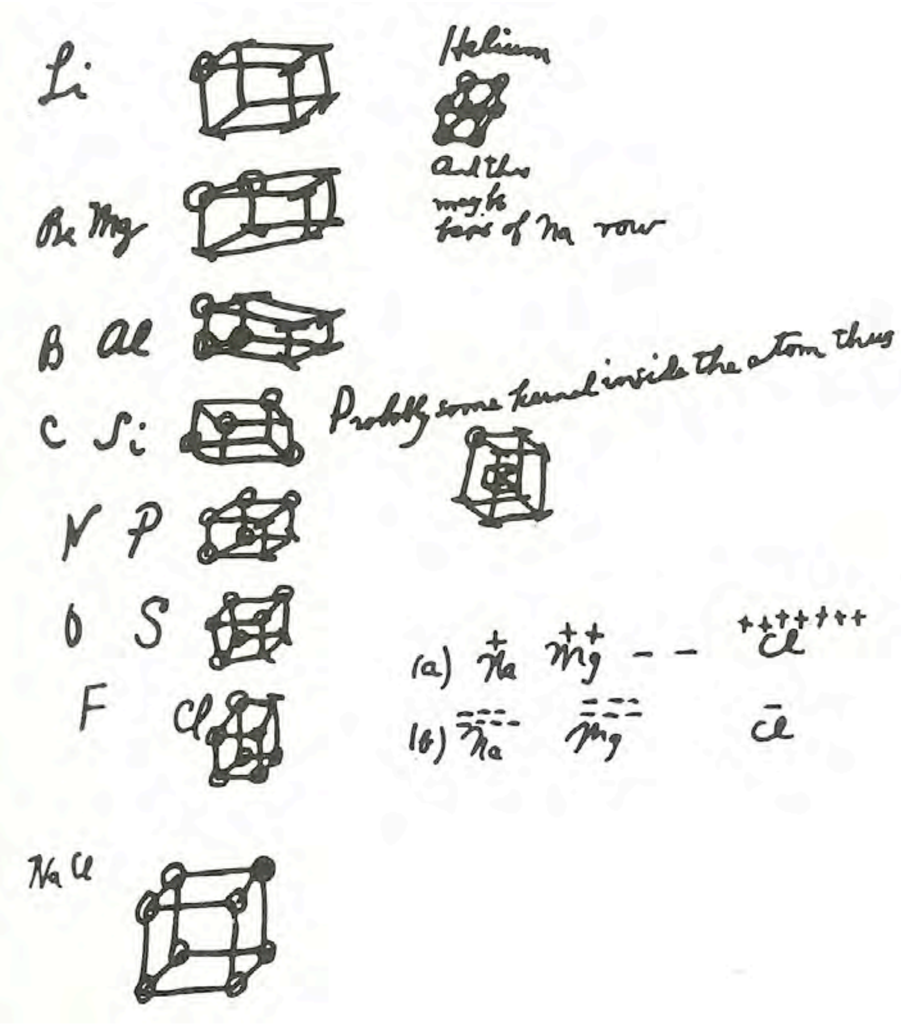


Figure 18: Lewis's sketches for the disposition of valence electrons around "cubical atoms," formalized in Lewis (1916).

Ann Arbor, Mich., February 5, 1917.

For several years past, some of those attending the annual meetings of the Geological Society of America have discussed the advisability of organizing a separate society composed of persons whose interests lie more especially in the field of Mineralogy. The feeling has been growing that the founding of a Mineralogical Society would do much to stimulate greater interest in the subject and also give wider recognition to the work being done in this field in America. Accordingly, the undersigned, who were in attendance upon the meetings of the Geological Society of America, at Albany, in December, 1916, discussed this question very thoroughly, and it was agreed that the time has come when an organization which might be called "The Mineralogical Society of America" should be formed at as early a date as possible.

While many of the advantages resulting from such an organization are apparent to all interested, the undersigned felt that perhaps the greatest benefit to be derived would be the founding by the society of a journal to be devoted exclusively to the publishing of mineralogical papers. As is well known, there is great need for a dignified medium of publication for the increasing volume of mineralogical investigations which are being carried on in America. Naturally such a publication must be started on a modest basis, and appear perhaps at first as a quarterly. Members of the society would of course receive the Journal free of charge.

With respect to organization and means of publication, mineralogists in America are far behind their colleagues in Europe, but we feel confident that you will respond promptly and favorably to our appeal to unite with us as a charter member in perfecting the organization of this society, the standards of which are to be on a par with those of the Geological Society of America. In order to insure the publication of a journal, which would naturally have a somewhat limited circulation, it was thought advisable that the annual dues be placed at $10.00.

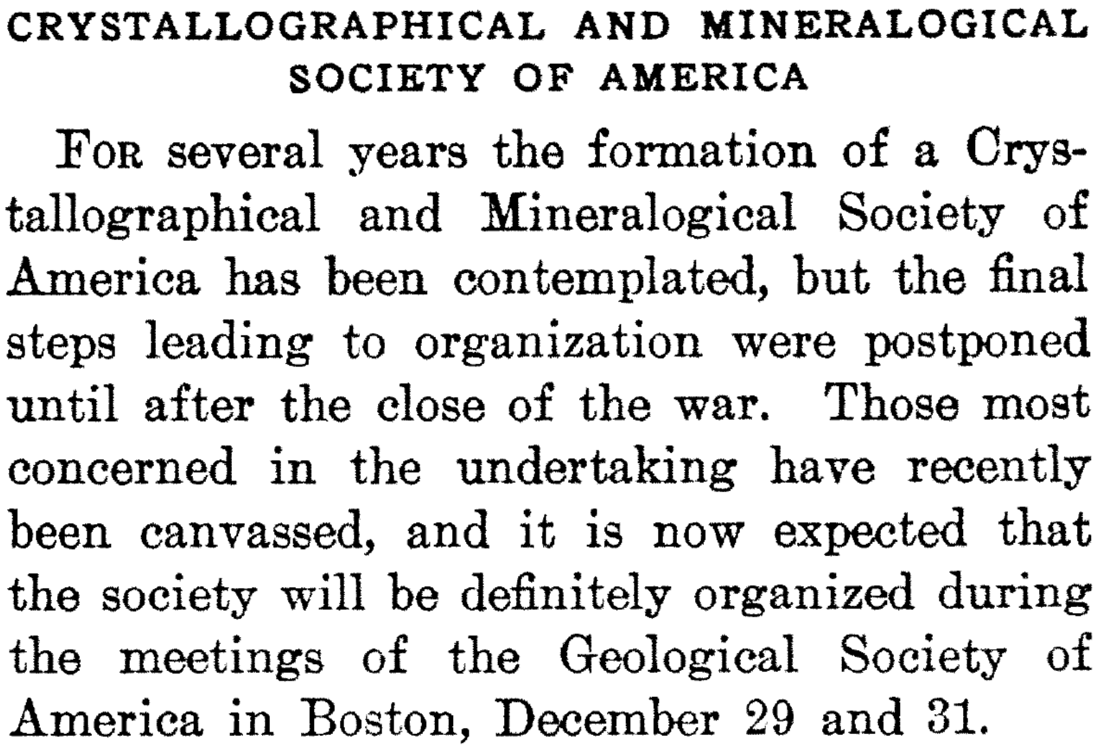
This letter is being addressed to a selected list of mineralogists in the United States and Canada, and if a sufficient number of favorable replies is received, it is planned to complete the organization sometime during the current year.

Professor Edward H. Kraus, Ann Arbor, Michigan, has been designated to conduct the correspondence looking toward the organization of the society. He will be glad to hear from you at your earliest convenience.

Very sincerely yours,

Edward H. Kraus,
Alexander H. Phillips,
Frank R. Van Horn,
Thomas L. Walker,
Edgar T. Wherry,
Herbert P. Whitlock.

Figure 19: The Founders' Letter circulated in 1917. [From MSA Centennial website]



CRYSTALLOGRAPHICAL AND MINERALOGICAL SOCIETY OF AMERICA

For several years the formation of a Crystallographical and Mineralogical Society of America has been contemplated, but the final steps leading to organization were postponed until after the close of the war. Those most concerned in the undertaking have recently been canvassed, and it is now expected that the society will be definitely organized during the meetings of the Geological Society of America in Boston, December 29 and 31.

Figure 20: The announcement in the Nov. 28, 1919 issue of *Science* of the founding of the "Crystallographical and Mineralogical Society of America."

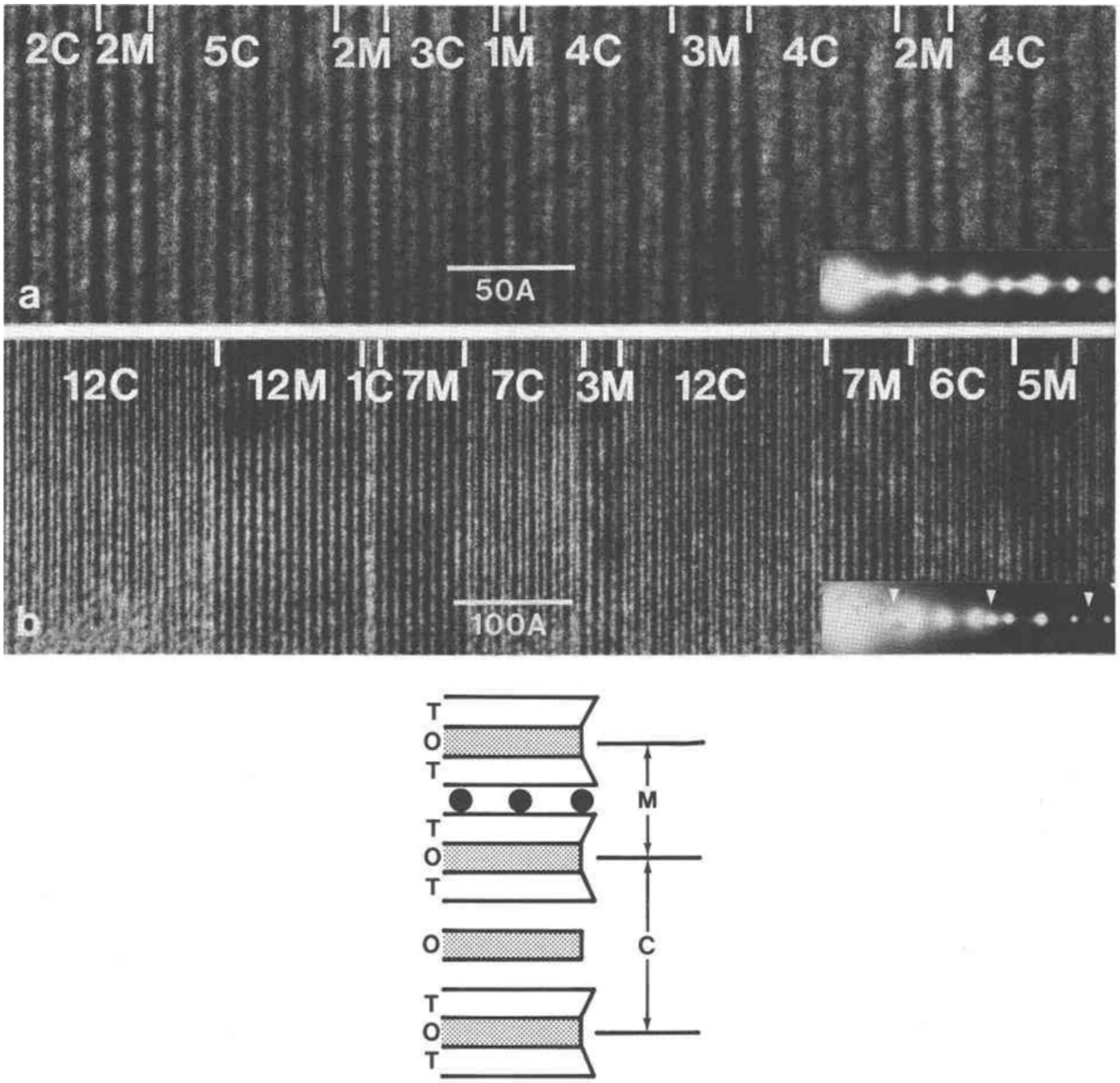


Figure 21: Fine (A) and coarse (B) slabs in mixed-layer chlorite ("C")-mica ("M") intergrowths with *c** horizontal. Inset diffraction patterns show heavy streaking along 00*l* due to the fine intergrowths. Diagram at bottom shows the structure of the nonconventional C (chlorite) and M (mica) slabs. Reprinted from Veblen (1983).

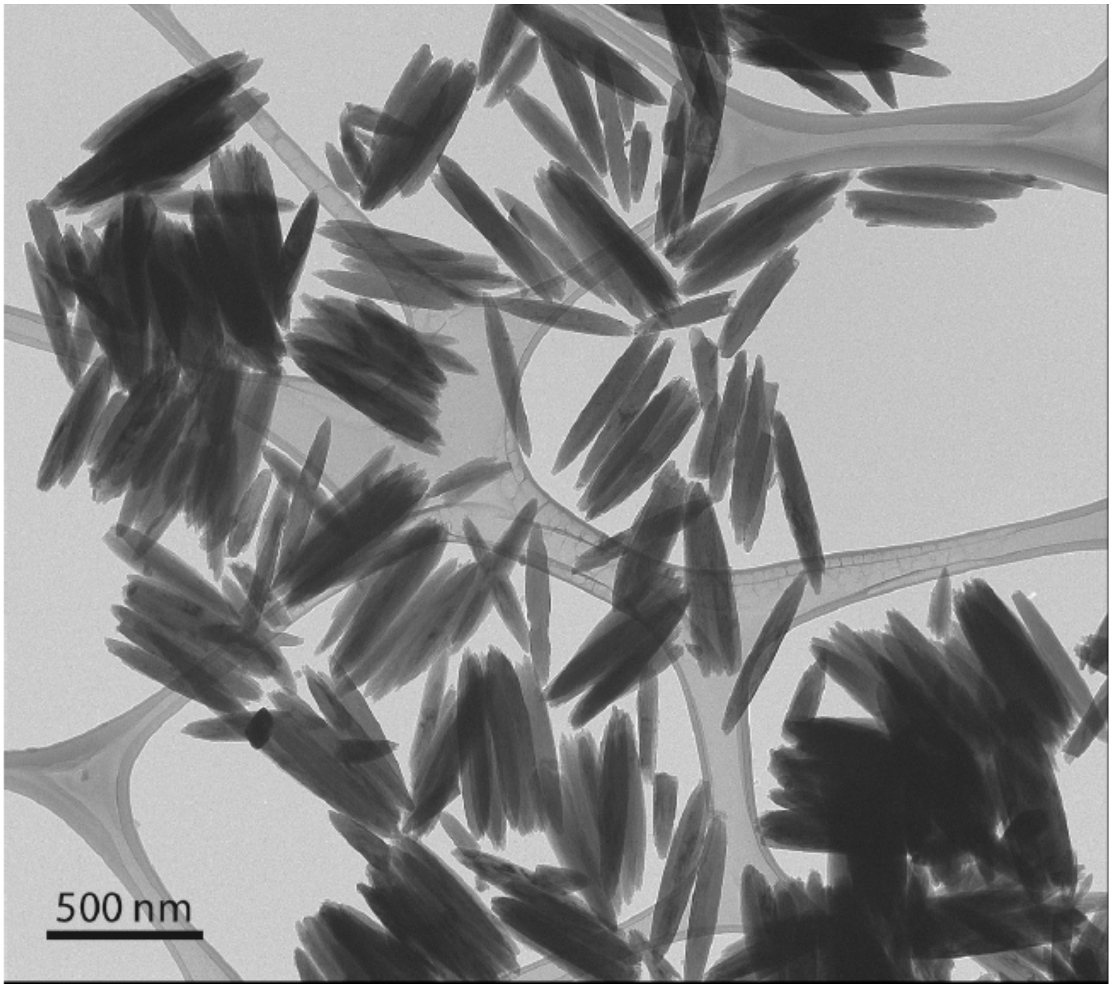


Figure 22: Transmission electron microscope images of synthetic akaganeite (γ-FeOOH) nanoparticles. Published with permission of Kris Peterson.