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# From the Ritter pile to the aluminum ion battery – Peter Paufler’s academic genealogy

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**Abstract:** This article highlights Peter Paufler’s academic genealogy on the occasion of his 80th birthday. We describe the academic background since 1776, which covers 11 generations of scientists: Ritter, Ørsted, Han-steen, Keilhau, Kjerulf, Brøgger, Goldschmidt, Schulze, Paufler, Meyer, and Leisegang. The biographies of these scientists are described in spotlight character and references to scientists such as Dehlinger, Ewald, Glocker, Röntgen, Vegard, Weiss, and Werner are given. A path is drawn that begins in the Romanticism with electrochemistry and the invention of what is probably the first accumulator. It leads through the industrialization and the modern geology, mineralogy, and crystallography to crystal chemistry, metal and crystal physics and eventually returns to electrochemistry and the aluminum-ion accumulator in the era of the energy transition. The academic genealogy exhibits one path of how crystallography develops and specializes over three centuries and how it contributes to the understanding of the genesis of the Earth and the Universe, the exploration of raw materials, and the development of modern materials and products during the industrialization and for the energy transition today. It is particularly characterized by the fields of physics and magnetism, X-ray analysis, and rare-earth compounds and has strong links to the scientific landscape of Germany (Freiberg) and Scandinavia, especially Norway (Oslo), as well as to Russia (Moscow, Samara, St. Petersburg). The article aims at contributing to the history of science, especially to the development of crystallography, which is the essential part of the *structural science* proposed by Peter Paufler.

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## 1 Introduction

Peter Paufler celebrated his 80th birthday on February 18, 2020. Throughout his academic career, he devoted himself primarily to crystallography, particularly as an editor and book reviewer for the German crystallographic journal *Zeitschrift für Kristallographie*, but also as member of the board of the German Society for Crystallography (*Deutsche Gesellschaft für Kristallographie*, DGK), as member of committees of the International Union of Crystallography (IUCr) and the European Crystallographic Association (ECA), and as chairman of the Association for Crystallography (*Vereinigung für Kristallographie*, VfK) in the former German Democratic Republic (GDR), the German Mineralogical Society (*Deutsche Mineralogische Gesellschaft*, DMG), and in particular the DGK. Therefore, this *Festschrift* is published in this journal to honor Peter Paufler’s efforts in the field of crystallography.



Courtesy of Peter Paufler

Nearly, on the same date, February 12, 2020, the Konrad Adenauer Foundation published a survey [1], according to which three quarters of the university teachers in Germany agreed with the statement: “Research also includes creative leisure. That is missing.” Accordingly, the 80th birthday of Peter Paufler may and should be an occasion of such

scientific leisure. In this sense, the authors would like to pursue the question that one encounters sooner or later after studying or during a doctorate, presumably also because of the advanced age: “Why do I do what I do?” In the context of answering this question, further questions arise, which then quickly develop in the direction of “meaning of life”. This article is the result of exactly this *mélange*. It also aims at encouraging young scientists to continue on their chosen scientific path and to orientate themselves with regard to research topics towards their *academic ancestors*, perhaps even taking them as fixed anchor points. This could help to achieve academic socialization within a discipline by establishing explicit links to the ancestors who may still be influential today [2]. Some studies (e.g., [3]) give statistical evidence that the academic lineage can even have an impact on the (published) scientific results.

In this article, we discuss this special aspect of shaping the academic and scientific biography: our *academic ancestors and relatives*. “In fact, certain views, methods, goals, etc., are passed on from the older ones to the younger ones; one is not always aware of this”, as Peter Paufler once summarized it [4]. Certainly, much has been passed on to us by our academic ancestors. For example, research topics, research methods, quality standards, management, presentation and lecture style, academic appearance, dealing with employees, and much more. And this, in turn, we pass on to our academic descendants. Here, the term “descendants” refers to students, close colleagues, and co-workers to whom we are in close contact through our teaching, mentoring, and cooperation. The Danish philosopher, theologian, and writer, Søren Aabye Kierkegaard, motivates this approach, but also points out the challenge [5]:

“It is quite true what philosophy says that life must be understood backwards. But beyond that, one forgets the other sentence that it must be lived forward.”

Supporting the challenge of living *forward* could be the sentence of the American novelist John Dos Passos [6]:

“A sense of continuity with generations gone before can stretch like a lifeline across the scary present.”

And finally, the words of the Russian writer Aleksandr Sergejevich Pushkin, again suggest [7]:

“To be proud of the glory of one’s ancestors is not only permitted but even required; to disregard it is shameful faint-heartedness.”

Accordingly, we focus on the academic genealogy of Peter Paufler and other outstanding scientists associated with it. On the one hand, Peter Paufler’s scientific roots will be described, and on the other hand, it will be shown how the scientific issues raised in this series – particularly referring

to crystallography – continue to have an impact on the topics of Peter Paufler and his academic descendants that have been dealt with to this day.

A path is drawn that begins in the Romanticism [8] with electrochemistry and the invention of what is probably the first rechargeable battery – the Ritter pile. It leads through the industrialization and the modern geology, mineralogy, and crystallography to crystal chemistry, metal and crystal physics. Eventually, the path returns to electrochemistry and the identification and characterization of novel battery materials for an aluminum-ion accumulator in the era of the energy transition. This article, however, in its brevity does not intend to provide a detailed biography and comprehensive appreciation of the scientific merits of the individual persons. Rather, the aim is to give a brief overview of scientific history and to highlight those references that are connected to Peter Paufler’s research profile, the authors’ work, and especially to crystallography in Germany, Norway, and Russia.

## 1.1 Academic genealogy and methodology

The presentation of historical developments can be carried out by genealogy, the study of ancestor research. For this purpose, a tree-shaped representation is commonly used to visualize relationships, a *family tree*, or a *table of relatives*. The latter, like in this article, includes not only the ancestors but also the descendants [9]. However, we will use the term *genealogy* here.

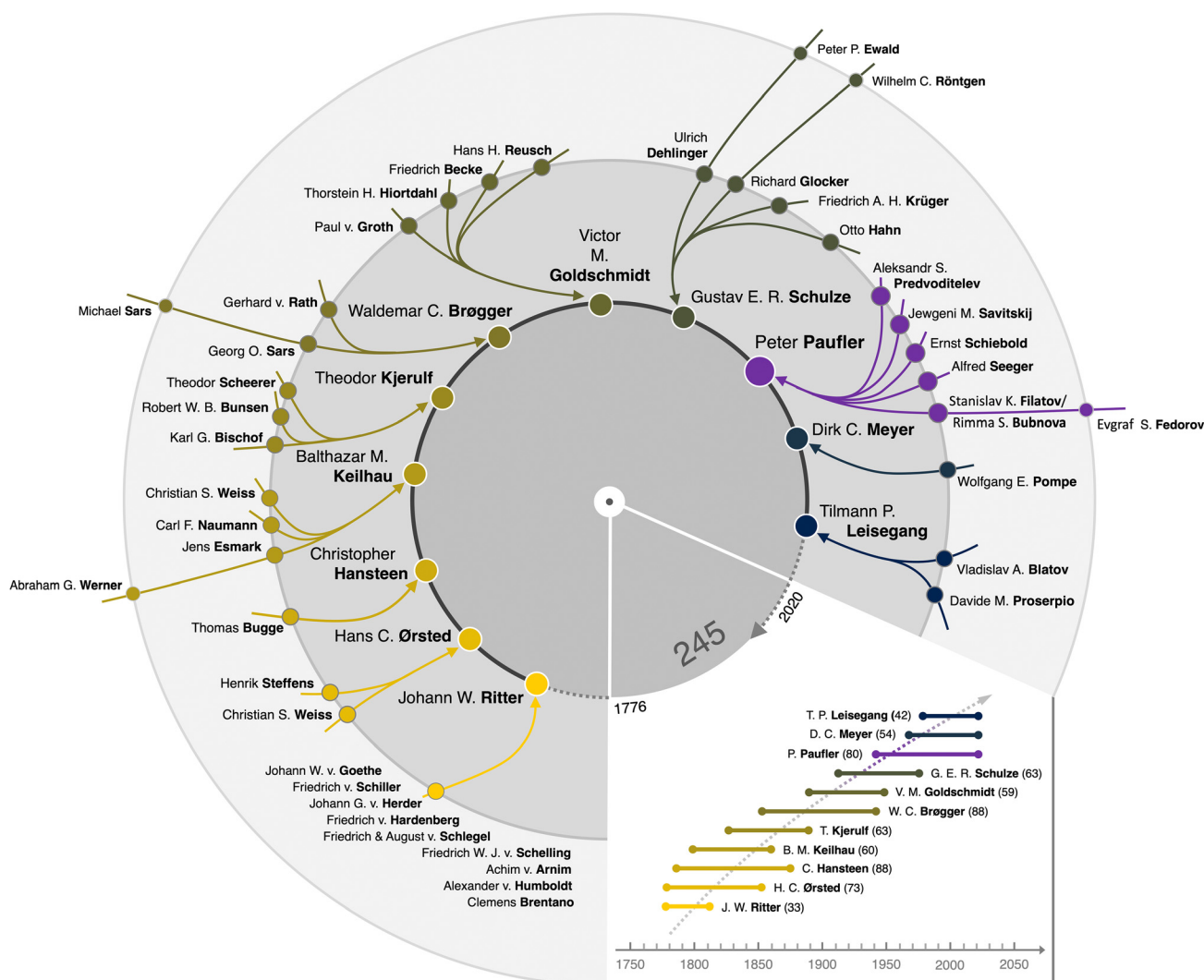
Peter Paufler’s extended but incomplete academic genealogy can be traced on the page of the project *The Academic Family Tree* [10], where he is embedded in the *crystallographic* genealogy. In order to set up such a genealogy, doctoral theses of a department are recorded there. The supervisors of a scientist’s theses, possibly his postdoctoral work and second doctorate (habilitation) are listed as his *parents*. Scientists who did their doctorate or habilitation with him or were supervised by him as post-docs are listed as his *children*. In this way, *scientific schools* can be identified, which often trace back to well-known scientists who founded or strongly influenced a science or a branch of it. Until the 18th/19th century, however, it was common in the natural sciences that no (written) doctoral theses had to be produced. In Norway or the whole of Scandinavia, for example, universities did not award any scientific degrees before the 19th century. They often advertised prize-winning topics to which every student could respond by writing and submitting a thesis on the topic. Students could also apply for a scholarship from the government. With this scholarship they could spend up to

4 years at different universities in Europe before applying for an amanuensis or professor position [11]. Instead of these, such works and student–teacher/mentor relations were used here to establish Peter Paufler’s academic genealogy.

In contrast to *The Academic Family Tree*, a connecting scientist, Balthazar M. Keilhau, is placed in between the crystallography branch (Theodor Kjerulf) and the physics branch (Christopher Hansteen). We start Peter Paufler’s genealogy (provisionally) with Johann W. Ritter. First, because of Ritter’s short lifetime that makes it difficult to determine his major academic influences in the sense of a teacher/mentor–student/mentee relationship and second, because scientific crystallography developed around this time. The thus determined academic genealogy is shown schematically in

Figure 1 as a dial-diagram. Here, the different *generations* are arranged clockwise on the inner circle. Other influential scientists are arranged on the middle and outer circle. Accordingly, the diagram can be read not only clockwise, but also from the outside to the inside in terms of different *generations*. The inserted section provides a chronological classification. Table 1 summarizes biographical key data.

The article is based mainly on monographs [12–19], the *Store Norske Leksikon* (<https://snl.no>), the *Norsk Biografisk Leksikon* (<https://nbl.snl.no>), the work and personal communications of Arne Bjørlykke (former director of the *Norwegian Geological Survey* and the *Natural History Museum* at Oslo University), and personal communications of Peter Paufler.



**Figure 1:** Peter Paufler’s academic genealogy. A similar presentation can be found in *The Academic Family Tree* project [10], although at least the scholar Baltazar M. Keilhau is not (yet) included. Starting with Ritter, the various *generations* up to Peter Paufler and his descendants are shown clockwise on the inner circle. Other scientists who greatly influenced the respective *generation* are arranged on the middle and outer circle. Accordingly, the diagram can be read not only clockwise, but also from the outside to the inside in the sense of different *generations*. A chronological classification can be found at the bottom right. The age reached for every person is indicated in brackets. A period of almost 245 years was recorded, while it is difficult to ascribe a dominant academic influence of a person to Johann W. Ritter at the latest.

Table 1: Biographical key data on the persons of Peter Paufler's academic genealogy.

Name	Type	Year	Title	City	Supervisor	Mineral	Academy of Science
J. W. Ritter * 16.12.1776 † 23.01.1810	—	—	—	Jena	—	—	Bavarian Academy of Sciences and Humanities
H. C. Ørsted * 14.08.1777 † 09.03.1851	Dissertation	1799	Über die Architektonik der Naturmetaphysik (About the architectonics of natural metaphysics)	Copenhagen	B. Riisbrigh	—	Académie des Sciences American Academy of Arts and Sciences Bavarian Academy of Sciences and Humanities Göttingen Academy of Sciences and Humanities Royal Danish Society of Sciences Royal Prussian Academy of Sciences Royal Society of Edinburgh Académie des Sciences American Academy of Arts and Sciences Bavarian Academy of Sciences and Humanities Göttingen Academy of Sciences and Humanities Royal Society of Edinburgh Russian Academy of Sciences Royal Norwegian Academy of Sciences
C. Hansteen * 25.11.1784 † 11.04.1873	Treatise	1812/1819	Untersuchungen über den Magnetismus der Erde (Studies on the magnetism of the Earth)	Copenhagen	H. C. Ørsted	—	
B. M. Keilhau * 02.11.1797 † 01.01.1858	Treatise	1821 1823	Efterretninger om et hidtil ubekjendt Stykke af det Søndenfeldske Norge (Information about a hitherto unknown piece of the Søndenfeld Norway) De Skandinaviske Formasjoner (The Scandinavian Formations Second Suite)	Oslo	C. Hansteen	Keilhaulite	
T. Kjerulf * 30.03.1825 † 25.10.1888	Treatise	1855 1857	Das Christiania Silurbecken, chemisch-geognostisch untersucht (The Christiania Silurian Basin, chemically and geognostically investigated) Om Dannelsesmaaden af de uskiktede Bjergarter (On the formation of the stratified rocks)	Oslo	B. M. Kellhau	Kjerulfine	Leopoldina Royal Swedish Academy of Sciences Thuringian-Saxon Association for Geography
W. C. Brøgger * 10.11.1851 † 17.02.1940	Treatise	1878/1879	Untersuchungen norwegischer Mineralien I & II (Studies of Norwegian minerals I & II)	Oslo	T. Kjerulf	Brøggerite	Académie des Sciences American Academy of Arts and Sciences Bavarian Academy of Sciences and Humanities Göttingen Academy of Sciences and Humanities Royal Danish Academy of Sciences

Table 1: (continued)

Name	Type	Year	Title	City	Supervisor	Mineral	Academy of Science
V. M. Goldschmidt * 27.01.1888 † 20.03.1947	Dissertation	1911	Die Kontaktmetamorphose im Kristianagebiet (The contact metamorphosis in the Kristiania area)	Oslo	W. C. Brøgger	Goldschmidite	Royal Society of Sciences in Uppsala Royal Physiographic Society in Lund Royal Norwegian Academy of Sciences Royal Swedish Academy of Sciences Royal Society of Science and Letters in Gothenburg National Academy of Sciences Prussian Academy of Sciences Royal Society Royal Society of Edinburgh Russian Academy of Sciences Göttingen Academy of Sciences and Humanities Leopoldina Russian Academy of Sciences
G. E. R. Schulze * 24.02.1911 † 05.10.1974	Dissertation	1933	Die Kristallstruktur von $BPO_4$ und $BAso_4$ (The crystal structure of $BPO_4$ and $BAso_4$ )	Goettingen	V. M. Goldschmidt	–	Saxon Academy of Sciences and Humanities
	Habilitation	1940	Zur Kristallchemie der intermetallischen $AB_2$ -Verbindungen (Laves-Phasen) (On the crystal chemistry of intermetallic $AB_2$ compounds (Laves phases))	Stuttgart	U. Dehlinger/ R. Glocker		
P. Paufler * 18.02.1940	Diploma thesis	1963	Zur Züchtung von Einkristallen intermetallischer Verbindungen (On the growing of single crystals of intermetallic compounds)	Dresden	G. E. R. Schulze	Paufferite	Leopoldina Saxon Academy of Sciences and Humanities
	Dissertation	1967	Zur Plastizität intermetallischer Verbindungen, insbesondere von $MgZn_2$ (On the plasticity of intermetallic compounds, especially $MgZn_2$ )	Dresden	G. E. R. Schulze		
	Habilitation	1971	Analyse des Mechanismus plastischer Verformung in spröden metallischen Festkörpern am Beispiel der intermetallischen Verbindung $MgZn_2$ (Analysis of the mechanism of plastic deformation in brittle metallic	Dresden	G. E. R. Schulze		

Table 1: (continued)

Name	Type	Year	Title	City	Supervisor	Mineral	Academy of Science
D. C. Meyer * 15.01.1966	Diploma thesis	1991	solids using the intermetallic compound MgZn <sub>2</sub> as an example) EXAFS-Untersuchungen an amorphen metallischen Legierungen (EXAFS investigations on amorphous metallic alloys)	Dresden	W. Blau		
	Dissertation	2000	Anwendung von Röntgen-Absorptionsspektroskopie und Röntgen-Diffraktometrie unter resonanten Streubedingungen zur Charakterisierung der strukturellen Nahordnung und des Phasenbestandes (Application of X-ray absorption spectroscopy and X-ray diffraction under resonant scattering conditions for the characterization of the structural short-range order and the phase composition)	Dresden	P. Paufler		
T. Leisegang * 27.10.1977	Diploma thesis	2004	Strukturuntersuchungen an Selten-erdverbindungen mittels Röntgenmethoden (Structural investigations of rare-earth compounds using X-ray methods)	Dresden	P. Paufler		Saxon Academy of Sciences and Humanities
	Dissertation	2010	Röntgenographische Untersuchung von Seltenerdverbindungen mit besonderer Berücksichtigung modulierter Strukturen: Die Antwort der Kristallstruktur auf Stöchiometrieabweichungen (X-ray investigation of rare-earth compounds with special emphasis of modulated structures: The response of the crystal structure on composition variations)	Dresden/ Freiberg	D. C. Meyer		



## 2 The academic genealogy of Peter Paufler

### 2.1 Johann Wilhelm Ritter (1776–1810) – physics and electrochemistry

Let us go back to the 18th century and start with the German physicist Johann W. Ritter (\*16.12.1776–†23.01.1810). Due to his short life and sociability, it is difficult to identify particularly influential scientists, although most of them are from his Jena period, where he began studying at the University of Jena in 1796. He once described the German mathematician, astronomer, and physicist Johann H. Voigt, who taught in Jena, as his “revered teacher” [16].

Ritter is regarded as “the most outstanding personality among the naturalists of early Romanticism in the Jena-Weimar cultural area” [16]. He was in close contact with famous personalities such as Johann W. von Goethe, Friedrich von Schiller, Johann G. von Herder, Friedrich von Hardenberg (Novalis), Friedrich and August von Schlegel, Friedrich W. J. von Schelling, Achim von Arnim, Alexander von Humboldt, and Clemens Brentano [16]. Ritter probably invented the prototype of the accumulator, the Ritter pile, while he was working on galvanism, which fascinated many people at that time [20]. Actually, he was operating a kind of fuel cell, as was shown later [21]. However, he realized that the galvanic processes are always linked to oxidation and reduction. Therefore, he is considered as the founder of scientific electrochemistry. Many of his other discoveries are almost unnoticed until today. This is probably due to his extensive presentation – in only 33 years of his life he left a total of about 5500 written pages – which reminds us of the writings of the Romantics with whom he consorted in Jena [16]. For example, he discovered the ultraviolet radiation at the higher energy end of the visible electromagnetic spectrum emitted by the sun. These research topics, ultraviolet radiation [22], spectroscopy (later, however, with X-rays [23]), and electrochemistry [24–26] are still in the focus of his academic descendants today (cf. Figure 2).

Crystallography, however, did not seem to impress him too much. Although he had been a friend of the German mineralogist and founder of geometric crystallography Christian S. Weiss – who was a student of the German geologist and mineralogist Abraham G. Werner in Freiberg – for a long time, the two did not interact in their scientific work [16]. Once, Ritter wrote about Weiss that he “has from an experimental point of view, certainly not even the slightest inclination to be a researcher, but on the other hand, perhaps, has an exceptionally large inclination to be an observer, but certainly not for all objects, but for his

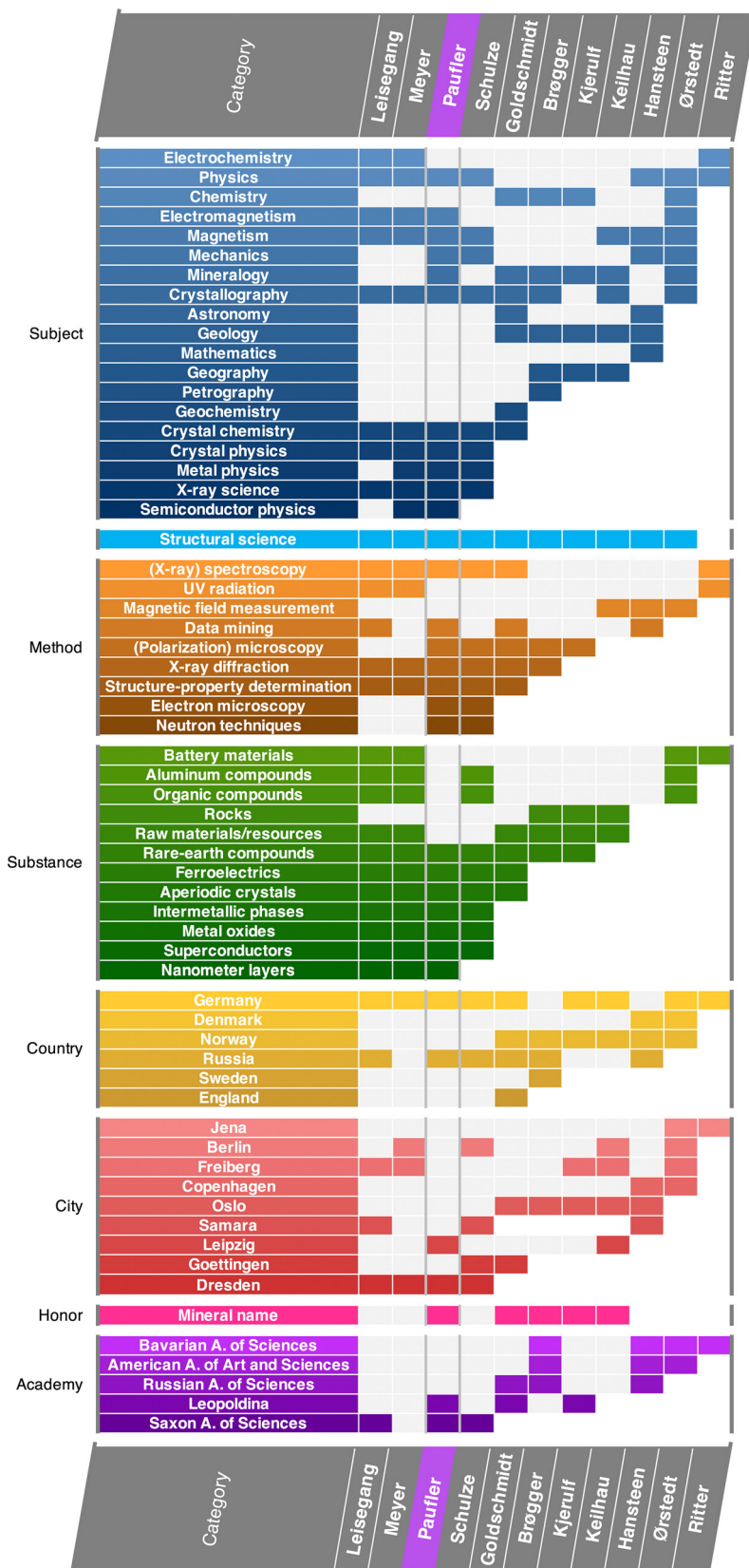
crystals only”. Ritter also complained to Weiss about his lack of patience when it came to perseverance with one of his works. Weiss, once in Paris, talked about Ritter not very diplomatically, which Ritter therefore resented. But this did not affect Ritter’s gratitude for Weiss’s helpfulness, who was “a friend who helped you in times of need [...], and with sacrifices, as no one else had done before”. Weiss had helped him with a large sum of money to pay off a considerable part of his debts in Jena.

Brentano once described Ritter as a “Moses” of research, capable of tapping “the pure crystal-clear source of wisdom” [16, 27]. For Goethe, too, Ritter was “an apparition to astonishment, a true heaven of knowledge on earth” [16, 26]. The German-Baltic chemist, philosopher and founder of physical chemistry Wilhelm Ostwald, however, did not find good words for him (and his friend and student Ørsted; see below). In his book “*Elektrochemie – ihre Geschichte und Lehre*” (“Electrochemistry – its history and teaching”) he wrote [28]:

“Meanwhile, despite the protest from this side, Ritter’s work seems to have caused quite a stir. It was spread in France by Ørsted, who at that time had visited Ritter and found a kindred spirit in him. For this physicist, who later became famous for his discovery of the deflection of the magnetic needle by electricity, was possibly an even worse natural philosopher than Ritter, and the great discovery which he made later shows how nature allows its secrets to be eavesdropped on at times in the most absurd ways. At the same time, however, it is shown here that a rare finding can succeed even with such people, but that the scientific exploitation of the treasure found requires other forces.”

Although Ostwald discussed Ritter’s early electrochemical work, he had not attempted to emphasize its importance as a precursor to the accumulator or fuel cell [21]. Ostwald’s assessment was probably also influenced by the later development of Ritter, who in Munich – working as a full member of the *Bavarian Academy of Sciences* since 1804 – became influenced by the German physician, mining engineer, and philosopher Franz von Baader<sup>1</sup>, a theosophist who also pursued mystical-theological thoughts. During his time in Munich, Ritter, with Baader’s support, was also engaged in underground electrometry, *i.e.*, dowsing [16]. It is possible that these increasingly unscientific tendencies of Ritter influenced Ostwald’s assessment. In the end, due to his early death, Ritter was unable to provide any further scientific contributions. He was probably so weakened by the many

<sup>1</sup> Baader studied at the *Bergakademie Freiberg* from 1788, where he was a student of Werner.



**Figure 2:** The more frequently recurring terms in the literature studied are summarized in categories of different color. It should be noted that the category “electromagnetism” includes electrical properties such as dielectricity and superconductivity, “mechanics” includes mechanical properties such as plasticity and hardness, “UV radiation” includes both their detection and their use in EUV lithography (EUV: extreme ultraviolet). The category “raw materials” concerns both their search and their inclusion in scientific considerations. One can see an increase or specification of the categories “subject”, “method”, and “substance class” from Ritter to Leisegang. Three time periods can be distinguished: (1) Ritter to Keilhau, (2) Keilhau to Goldschmidt, and (3) Schulze to Leisegang. This is made clear by the subjects, methods, and classes of material studied.



self-experiments<sup>2</sup> on the effect of electric current on the human body and certainly by his permanently precarious financial situation [16] that he died without ever having received a doctorate or being appointed to a chair.

## 2.2 Hans Christian Ørsted (1777–1851) – physics and electromagnetism

During Ritter's time in Jena, the Danish physicist and chemist Hans C. Ørsted (\*14.08.1777–†09.03.1851) travelled through Europe on a study trip between 1801 and 1804 [12, 29, 30]. He spent several months in Germany (Berlin, Göttingen, Weimar-Jena, and Freiberg) where he met the Norwegian natural scientist and philosopher Henrik Steffens, the German philosopher Schelling, and especially Ritter. Ørsted and Ritter have been friends for many years, "which, although for most of the time in the form of correspondence, was to remain a friendship for the rest of Ritter's life" [16]. "Close to the end of his life, Ritter confessed: You were still considered by my friends to be the most steadfast, faithful, and scientifically honest, and also the most prudent, and you remained such to me." [16] During Ritter's lifetime, "there was a lively exchange of ideas, designs, and experiments, which can only exist between colleagues who are friends." [16] Ritter's ideas and views on natural philosophy were among the cornerstones of Ørsted's later research on electromagnetism. "This happened in a continuation of Ritter's research and consequently of the path of knowledge initiated by him." [16] Later, Ørsted always referred to Ritter as his "honored teacher and friend" [16].

Just like Ritter, Ørsted also gained his first scientific experience in connection with a pharmacist's job. In 1794, he began studying at the University of Copenhagen, where he received his doctorate in 1799 with his doctoral thesis "On the architectonics of natural metaphysics" on the natural philosophy of the German philosopher Immanuel Kant [12]. In 1806, he was appointed associate professor of chemistry and physics and in 1817 full professor of physics in Copenhagen [12].

His discovery of the reciprocal link between magnetism and electricity, electromagnetism, was published in 1820 in his four-page work "*Experimenta circa effectum conflictus electrici in acum magneticam*" [31]. In addition, he investigated the compressibility of liquids and gases,

<sup>2</sup> He writes about his experiments on the new charge pile [20]: "If, instead of closing the gas tube, you close it with both hands, [...] properly moistened, [the electric circuit], then if you close it again and again in intervals of 1/4 or 1/3 s, you will probably receive 80–100 blows, the first of which will reach up to the elbows [...]."

and in 1822 he constructed a so-called piezometer (pressure gauge) for the first time. Due to his pharmaceutical background, Ørsted was always attracted to chemistry. In 1825, he was the first to succeed in representing aluminum in its pure form, as proved by the English chemist Humphry Davy [12]. He also worked continuously on an idea of the *interaction of fundamental forces* such as magnetism, electricity, chemistry (*cf.* Ritter), and light (*cf.* Hansteen) [12]. After a discussion with Weiss, he concluded that the one and the same fundamental force should explain both crystallization and electromagnetism [12]. Ørsted had a friendly relationship to Weiss and therefore also introduced him to Ritter. However, Weiss appeared so deeply absorbed in crystallography that Ørsted found him "crystallized himself" [12]. To follow Ørsted's ideas, for example when he compared the structure of matter with a stellar nebula, was probably not easy either [12].

To this day, magnetism or magnetic ordering [32] as well as electron correlation phenomena [33], i.e., electromagnetism in the broadest sense, aluminum [26], and the crystalline state [34] are main subjects of the work of his academic descendants (*cf.* Figure 2).

## 2.3 Christopher Hansteen (1784–1873) – magnetism and data mining

When Ørsted was appointed professor of physics, he wanted to establish a *school* of *physics* in Denmark. His first student became the Norwegian mathematician, physicist, and astronomer Christopher Hansteen (\*25.11.1784–†11.04.1873) [12]. A deep mutual friendship between the two developed. Ørsted supported Hansteen without selfish motives [12]. Conversely, Ørsted was the most important teacher for Hansteen [29], who once expressed his gratitude in a letter to Ørsted in 1814 [12]:

"It is with sincere gratitude that I think of the favors you have done me, my dear professor, and of how much a person's better acquaintances influence his or her way of thinking. Allow me to express my gratitude in these few (not hollow) words: it is rare to meet an upright person in whom neither head nor heart have any faults, and when it finally happens, one has the feeling of screaming: Eureka! [I found him!]"

Hansteen began to study law at the nearest University of Copenhagen in 1803, as Norway did not yet have a university. However, when Ørsted became his teacher, he devoted himself to studying astronomy, mathematics, and physics. Hansteen probably belonged to the group of "young hot-spurs with unconventional ideas about mathematics", as the Danish astronomer, mathematician, cartographer, and surveyor Thomas Bugge described the members of the new

generation of the university [12]. Bugge inspired Hansteen with the production of maps (geognosy and geography) and aroused his interest in geomagnetism. Like Bugge and Ørsted, Hansteen also became interested in magnetism. In 1809, he began his own investigations of geomagnetism and extensive literature studies, which he recorded in the form of detailed maps. The mathematician, physicist, and astronomer Carl F. Gauss remarked [29]: “[...] this highly deserving natural scientist has also given us a general map for the whole [magnetic] intensity. As grateful as one must be for this beautiful work [...]”. Hansteen “dared” to send a draft of a publication to Bugge and Ørsted to promote his research [29, 35]. He remarked [35]: “The attention which these two worthy men gave to my first attempt was very encouraging for me.” Bugge thereupon provided him with travel descriptions and ships’ logbooks from the archives of the East and West India Company.<sup>3</sup> With the help of the extensive literature, he then carried out data mining<sup>4</sup> on geomagnetism. The printed version of his work “*Untersuchungen über den Magnetismus der Erde*” (“Studies on earth magnetism”), published in 1819, comprised 502 pages and an appendix of 148 pages, listing the geomagnetic data on which the work was based. With his preliminary work he succeeded in answering a prize question raised in 1811 by the *Royal Danish Society of Sciences* in Copenhagen (author was Bugge [29]), whether “one or two magnetic axes are required to describe the earth’s magnetic field”. When Hansteen was able to demonstrate the necessity of two magnetic axes, he was awarded the prize in 1812 [12, 29]. A summary of his work was printed in Ørsted’s *Journal de Physique* [12, 36] and later, in an extended form, published as a book [37]. This made him internationally known [30], proved his adherence to scientific standards, and let him become professor of astronomy and applied mathematics at the newly opened University of Kristiania<sup>5</sup> in 1813 [36, 38]. In 1839, however, Gauss

presented a mathematical description that required only one magnetic axis instead of two [29, 39].

Other discoveries concerned the auroras, whose appearances he first linked to the earth’s magnetism, since they appeared around the earth’s magnetic poles [29], and which inspired Ørsted’s idea of the interaction of fundamental forces. The two also cooperated in the development of devices. They further developed Ørsted’s piezometer. Hansteen in turn lent Ørsted a so-called “Oscillationsapparat” (oscillation apparatus) to measure magnetic deflection [17]. Hansteen also carried out various expeditions, which he described in numerous articles and books. Especially his descriptions of a journey to Russian Siberia became popular, where he started in St. Petersburg and also travelled to the Volga region near the Samara oblast [36, 40]. Data mining, magnetism, and the relation to Russia – Hansteen was an honorary member of the *Russian Academy of Sciences* in St. Petersburg [29] – are further characteristics of his academic descendants until today [33, 41, 42] (cf. Figure 2).

Differences in opinion have arisen in his career and always arise with respect to the scientific knowledge gained. If the scientific convictions were criticized at that time, the scientists were criticized personally as well. Hansteen also did not shy away from criticism. However, he behaved with caution:<sup>6</sup> “If I have objected to the opinions of my dear friend [...], I hope you will understand that the dispute was not against persons but for the truth” [29].

## 2.4 Balthazar Matthias Keilhau (1797–1858) – geology, mineralogy, and crystallography

Originally, Hansteen wanted to undertake the aforementioned trip to Siberia together with the Norwegian geographer, geologist, and mountaineer Balthazar M. Keilhau (\*02.11.1797–+01.01.1858), who had been a lecturer in rock science at the University of Kristiania since 1826. Hansteen first was his teacher and then his mentor [29]. The faculty of the university, however, rejected Keilhau’s application for leave of absence, because he could not be dispensed with at the university for such a long time.

Keilhau, whose name describes a mining tool (“*Keilhau*”) and has its origin in Saxony, studied mineralogy at

<sup>3</sup> These were companies that were privileged to trade with India and Asia.

<sup>4</sup> In addition to the process of data collection, data mining also means “knowledge discovery in databases” (KDD) [150], whereby today this knowledge is used to realize a so-called “knowledge mining” based on “expert systems” [151].

<sup>5</sup> “After a great fire in 1624 the ancient capital of *Oslo* was rebuilt and named *Christiania* in honor of the reigning Christian IV of Denmark; this was changed to *Kristiania* in 1877, and the historical name *Oslo* was reinstated from January 1, 1925 [14].” In 1811 Norway received its first university, the Royal Frederick University, which was established in Christiania in 1813 and initially had a total of four faculties (law, medicine, philosophy, theology). The Kongsberg Mining Academy was then attached to the University of Christiania in 1814, and from then on it was possible to obtain a degree in mineralogy, and from 1860 on also at the new Faculty of Natural Sciences [30]. Since 1939 it is called the University of Oslo.

<sup>6</sup> Prudent criticism for the truth with a particularly careful choice of words was also a characteristic of Peter Paufler, as it is present in Leisegang’s memoirs.

the University of Kristiania, where he was the first student to graduate in this field in 1821 [17, 43, 44]. Keilhau was one of a group of young students that Hansteen gathered around himself [30]. Therefore, Keilhau kept good contact with Hansteen since the student days and often performed magnetic measurements for him during his travels [43]. Besides Hansteen, the Danish mineralogist and geologist Jens Esmark was another important teacher. He was the first professor for mineralogy and petrography to be transferred from the *Kongsberg Mining Academy* to the University of Kristiania in 1811. In 1814 the former was closed and became included into the latter [11]. The University then had to provide courses in mining and metallurgy. In the early days there was a conflict between applied science headed by Esmark/Scheerer (see below) and a group of natural philosophers headed by Hansteen/Keilhau. Esmark himself studied geology, also at the *Bergakademie Freiberg*, in 1791, where he was one of Werner's students. Esmark, for example, first discovered that Norway was once covered by glaciers. He was also the first to describe different types of rocks (Sparagmite, Norit, and Datolit) [44].

In 1823, Keilhau published a remarkable work "*De Skandinaviske Formasjoner anden Svite*" ("The Scandinavian formations second suite") in the first issue of the *Magazin for Naturvidenskaberne*, with Hansteen as one of the editors [30]. In 1825, his childhood friend, the famous Norwegian mathematician and co-founder of the group theory, Niels H. Abel,<sup>7</sup> successfully applied to the King of Norway for a travel grant for 2 years [17]. In 1825, Abel set off on a journey through Europe together with Keilhau and three other companions. Keilhau could deepen his knowledge of mineralogy with Weiss in Berlin and with the German geologist and crystallographer Carl F. Naumann in Freiberg [36, 45]. Keilhau probably remained very good friends with Naumann of the same age, because Naumann later translated geological articles from Keilhau into German and published them in Leipzig [17].

Once, Keilhau and Abel travelled from Leipzig to Freiberg by stagecoach. They started at noon and arrived in Freiberg at half past nine in the morning of the next day after covering a distance of about 100 km. And "the same evening [...] [they] were drinking terribly" [17]. With these often reported occasional "celebrations" they certainly managed to make the time of waiting for their calls to the University of Kristiania, which they expected at any time, more pleasant. In a letter to Keilhau in 1826, Hansteen wrote that his (Keilhau's) appointment as university

lecturer for mining at the University of Kristiania "would be alright" [17]. In the same letter, Hansteen also wrote a message to Abel: "I am somewhat overworked and rarely able to work. You have to accept this as a reason why I have waited so long for a reply. Rest assured that I and my family fully recognize all that is good and lovable about you, although we clearly see some small weaknesses." [17] Already at that time, the leading scientists were obviously heavily loaded with work, which has not changed 200 years later [1, 46].

In 1826, Keilhau became a university lecturer at the University of Kristiania "with the obligation to make scientific trips to the less explored areas of Norway as long as this is considered useful and necessary" [17]. He became the leading scientist there and is considered to be the founder of Norwegian geology including mineralogy [36, 43]. Keilhau was an explorer with a remarkable gift for observation [11]. This is probably because he also was a good painter. His drawings of observations gave his work an extra dimension. His paintings from Jotunheimen are said to be fantastic. He named the mountains Jotunfjellene (Jotun mountains), later changed to Jotunfjellen. As one of the last geognosts of Norway, he called his paintings often geognosy or geognostic maps because he focused on mapping earth materials instead of telling the geological story behind the rocks and sediments. In 1827, he started his most ambitious project on behalf of the Norwegian government: surveying and mapping Norway, including the more distant areas of Finnmark, Bear Island, and Svalbard. Beyond his knowledge on geology, especially his spirit of discovery was decisive for this project. Thus, he was probably the first to climb numerous mountains in the course of his life, despite "painful hits and wounds" [17, 43]. The completion of the project, which led to the three-volume work "*Gea Norwegica*" with geological maps of all of Norway, took a total of 23 years [44]. This work on Norwegian geology, produced between 1838 and 1850, includes extraordinarily detailed and artistic sketches, drawings, watercolors, and geological maps.

When Abel died early in 1829 of tuberculosis, Keilhau married his fiancée out of concern for her future, although he had never met her [17, 43]. In 1834, Keilhau succeeded Esmark as professor of geology, geognosy, and mineralogy in Kristiania [36, 44].

Just like Esmark, Keilhau was initially a *Neptunist* and follower of Werner, who assumed that all rocks were sedimentary rocks deposited from the waters of the oceans. Later, Keilhau had problems with this view due to the discovery of slate with Permian fossils. He then withdrew from both the *Neptunists* and the *Plutonists* (rocks have their origin in volcanic forces) and developed his own theory of transmutation/transformation of rocks, which

<sup>7</sup> He also worked temporarily at the *Bergakademie Freiberg* where he developed his fundamental work on elliptic functions.

says that slate can transform into granite without forming a melt [43, 30].<sup>8</sup>

His enthusiasm for geology and mineralogy has been passed on to his academic descendants (*cf.* Figure 2), who continued it with the inclusion of further scientific fields [47].

## 2.5 Theodor Kjerulf (1825–1888) – chemistry and social relevance

The Norwegian geologist Theodor Kjerulf (\*30.03.1825–†25.10.1888) was a self-confident, hard-working, and open student of Keilhau in Kristiania. In 1843, he began his studies of geology/geognosy with Keilhau, whose lectures inspired him [48]. From 1841 on, the German chemist, geologist, and mineralogist Theodor Scheerer, who had studied at the *Bergakademie Freiberg* and in Berlin, was also in Kristiania, amanuensis and later professor for metallurgy and mineralogy, and thus Kjerulf's teacher in these subjects [30]. Kjerulf once asked his teacher Keilhau how to pursue an academic career in geology. Keilhau advised him to travel and study as much geology and chemistry as possible and then to apply chemistry to geological problems [44]. Thus, Kjerulf was allowed to go to Iceland in 1850 to find arguments for Keilhau's theory of transmutation. However, Kjerulf returned as a *Plutonist*, and his stay in Iceland led to a break in his close collaboration with Keilhau. From then on, the two of them continued to work together, but very critically. Nevertheless, according to Keilhau's original recommendation in 1851, Kjerulf travelled to Germany, among other places. He spent a year with the German geologist and chemist Karl G. Bischof and half a year with the German chemist Robert W. B. Bunsen to study chemistry and its applicability to geology. After his return in 1852, he was able to argue even better with Keilhau, since even chemistry proved that *Neptunism* was wrong with regard to metamorphic and magmatic rocks [48]: "Keilhau became pale, he was disappointed, not to say angry." Keilhau then tried to stop Kjerulf's scholarship and forbid him to

lecture at the university and to use its mineralogical collections [44]. However, Keilhau received little or no support from colleagues for these measures. Conversely, the young, dynamic Kjerulf was increasingly supported at the university, especially by Hansteen, Keilhau's mentor and former teacher, who now became Kjerulf's mentor [43].

Firmly believing that "science [is] only a small section of the sunlit road – front and back are dark" [35] and "scientific conflicts [...] can only be solved scientifically" [49], Kjerulf wrote a long letter to the *Norwegian Ministry of the Interior* in 1857 to explain his dispute with Keilhau and to secure his further financial support, among other things, for a trip to Iceland [49]. The following quotation shows his close relationship with Keilhau:

"One evening in the autumn of 1848, when I returned from an excursion, I met with Keilhau. I then told him about my engagements, which, by the way, were still very little independent. I came to him from that time more often. He encouraged me to continue. We made plans together. He submitted my applications [for scholarships and prizes]. He advised me on chemistry – 'chemistry above all' – and travel. I took this seriously. [...] I told him that Iceland is completely volcanic. He was uncomfortable to hear. But an apparently good relationship remained. I travelled to Bonn, Siebengebirge, Eifel, Harz, Freiberg, South Tyrol, Heidelberg. I worked tirelessly for 1 year with Bischof, 1/2 year with Bunsen, the two chemists, who just started chemistry in geological direction. So at that time I had no reason to leave a path that seemed promising to me and which was the path of my choice."

Finally, Kjerulf reproached his former teacher Keilhau for studying alchemy [49, 35]. In an expert opinion, Hansteen made a very positive statement in Kjerulf's favor and considered it desirable that "a younger man who combines youthful vigor and warm zeal for [Iceland] can conduct this study in more detail, which the country's own children must take on as a duty to carry out." [49]

In 1850, Kjerulf was appointed associate professor at the University of Kristiania and after Keilhau's death he succeeded to the chair of geology in 1858 [44]. This happened after he won a prize in geology addressing the dispute between *Neptunists* and *Plutonists* with the article "*Om Dannelsesmaaden af de uskiktede Bjergarter*" ("On the formation of the unstratified mountains") [50], published in the journal *Nytt magasin dor Naturvitenskaberne* in 1857 [30]. As Keilhau's successor, he curated the mineralogical collections of the university, which again gave him unhindered access to rock samples. Rare-earth minerals such as cerite moved into the focus of attention [44]. Kjerulf also had the talent to inspire his students so much that after one of his lectures on Vesuvius they immediately started planning an excursion to Italy [51].

<sup>8</sup> The conflict between Neptunists and Plutonists was bitter [11]. The Permian intrusive in the Oslo area played an important part in the discussion. The Neptunists wanted magmatic rocks to be older than the sediments. In the Oslo area there are several contacts where granites intrude into shales with fossils. The famous meeting between the Plutonist Charles Lyell and Keilhau is described by Holtedahl [Holtedahl O. Charles Lyell's visit to Norway 1837 with remarks on the history of the 'granite problem' in the Oslo region. Studies on the igneous rock complex of the Oslo region, 19. Skr. Nor. Vidensk.-Akad. Oslo. Mat.-Naturv. Kl. Ny Ser. 1963, 12, 24].



He recognized the needs of society for geological knowledge [52] and contributed significantly to the systematic and detailed mapping of Norway's geology. His maps were not only to be a synthesis of existing regional geological maps, but were to be used as a useful tool for the exploration of ores, the extraction of raw materials for the construction of roads and buildings, and for cultivation [51]. He thus laid the basis for the foundation of the Norwegian Geological Survey (*Norges Geologiske Undersøkelse*, NGU) in 1857, the first director of which he became in 1858. Kjerulf managed to put an end to the discussion about *Plutonism*, *Neptunism*, and transmutation in Norway and thus to introduce Norway into modern scientific geology [15], which from then on was to be based on quantitative chemical analysis and microscopy [51].

In his research, Kjerulf included chemistry more comprehensively according to the recommendations of his teacher Keilhau. Kjerulf's academic descendants even intensified this approach (*cf.* Figure 2). The utilization of knowledge for society is another aspect that was added and is still an important motivation for the research of his academic descendants [53]. The cerium compounds, or rare earths in general, have remained an important class of materials until today [33, 54, 55].

Kjerulf will also be remembered for his students – W. C. Brøgger, H. H. Reusch, and J. H. L. Vogt (see below), A. T. Helland (geologist), T. H. Hjortdahl (geologist), and O. E. Schiøtz (physicist) – with whom he founded the golden era in Norwegian geology [11].

## 2.6 Waldemar Christofer Brøgger (1851–1940) – crystallography and physical chemistry

Among Kjerulf's most famous and versatile students was the Norwegian mineralogist, geologist, paleontologist, and archaeologist Waldemar C. Brøgger (\*10.11.1851–†17.02.1940). He studied at the center of Norwegian science at the University of Kristiania in 1869. He was very enthusiastic about Kjerulf's excursions, so he soon came under his special influence [15, 30, 36]. Brøgger once in a preface of his work wrote [56]:

“It is not only for this reason alone, however, that I feel it is my duty to express my sincere thanks to my highly esteemed teacher, but also for the warm interest which he has devoted in every way to the present work: firstly, by always providing me with the necessary means for research trips, then because of the rare liberality with which he, as head of the geological investigation, left

me as much as possible free hands for the work, and also, in some cases, tried to facilitate the course of the investigation by giving estimable instructions [...]. Just as I first felt attracted to the study of geology by his witty conception, so I owe all gratitude to my great teacher, in that I first learned to observe from him. May I therefore be allowed at this point to express my heartfelt thanks to Prof. Dr. Th. Kjerulf.”

Kjerulf took him and his friend and fellow student and later geologist Hans H. Reusch on various excursions. The student papers on this topic, among others on trilobites [57], attracted so much attention that they were published in German and English. In 1875, two new assistant positions for the two promising young geologists were established at the NGU, whose director was Kjerulf [36]. In 1877, Brøgger was sent by Kjerulf on another trip to the Hardangervidda plateau. Again, Brøgger wrote a report describing the geology of this area. However, his work was contrary to those of the NGU and its director. Kjerulf, who had arranged for the NGU to finance the trip, was therefore able to withhold the report, which led to a break in the close relationship between Kjerulf and Brøgger. Brøgger was only able to publish this report 11 years later, after Kjerulf's death. Nevertheless, during his academic career, Brøgger built on Kjerulf's work, continued it in all areas, and finally surpassed his teacher in the elaboration [58]. Brøgger, whom the Norwegian historian Halvdan Koht entitled “Chief of Norwegian Science” and who was also called the “Bismarck of Norwegian Science” [58], became the most important proponent of knowledge for the good of society, as he had learned from his teacher Kjerulf. According to this, a modern Norway should use the available natural resources and rely on hydropower and mining, as Brøgger stated [58]. He “was so talented [...] as a specialist in almost all areas of geological science” [18] that he was the dominant figure in Norway's natural sciences from the late 18th century until 1930 [15].

Brøgger's father was a printer who foresaw the increasing importance of science in Norway. Among the family's friends was the Norwegian biologist and theologian Michael Sars, father of the historian Ernst W. Sars and the zoologist Georg O. Sars. This must have had a strong influence on Brøgger in his childhood, as he decided to study zoology at an early age [58, 59]. Hence, he started his scientific career as a zoologist but soon came under the inspiring influence of Kjerulf and thus to mineralogy and geology. He devoted himself to the exploration of the rare earths containing pegmatites of Fredricksvarn and the Langesundsford [59–61]. The mineralogical investigations of the Langesundsford then became the main subject of his research during his time as professor of mineralogy and geology at Stockholm University, which he joined in 1881



[15, 59]. His inaugural lecture in 1882 was entitled “The importance of crystallography for modern petrography and – through it – geology” [59]. During this period, crystallography – probably also inspired by a collaboration with the German geologist and mineralogist Gerhard vom Rath [62] – became a focus of Scandinavian science. Brøgger’s Institute of Mineralogy soon became the most active mineralogy institute in Northern Europe [59]. In 1890, he followed the call to the chair of mineralogy and paleontology at the University of Kristiania as successor of the late Kjerulf [15]. He was dean of natural sciences several times and from 1907 to 1911 first rector of the university. In 1917, he resigned from his professorship to devote himself to research and the organization of science. In addition to his scientific work, he gained merits as founder of institutions, including a museum, and research manager [36]. He was a member of numerous academies of sciences worldwide.

Most of Brøgger’s memoirs were devoted to detailed crystallographic, optical, and chemical studies of the more than 70 pegmatite minerals described in his 898-page monograph [14, 59]. Thus, he examined rare-earth minerals, such as the rare-earth silicate Hellandite and its twinnings, in detail with crystallographic methods [59]. He gave many first descriptions,<sup>9</sup> especially using polarization microscopy,<sup>10</sup> which he introduced as a new physical method in mineralogy [15].

Around 1915, Brøgger included another new technique in his work: X-ray diffraction (XRD). It was introduced to Norway in 1913 by the Norwegian physicist Lars Vegard who first worked as a lecturer and from 1918 as professor of physics at the University of Kristiania. There, he built Norway’s first diffractometer [63] and transferred the method to mineralogy. Vegard stated in one of his articles [64]: “The crystals used were two fine stages [silver crystals], which were kindly lent to me by Professor W. C. Brøgger of the Mineralogical Laboratory.” Rare-earth compounds, crystallography, chemistry, XRD, transfer of scientific knowledge to applications, and research management are important aspects of Brøgger’s scientific career, which he has passed on to his academic descendants (*cf.* Figure 2).

One of Brøgger’s outstanding students was the Norwegian geologist, mineralogist, petrologist, and metallurgist Johan H. L. Vogt [36]. In 1876, Vogt first went to the *Royal*

*Saxon Polytechnic School*<sup>11</sup> in Dresden to study engineering, but left it after one year [11]. He decided to start studying geology in Kristiania under Kjerulf, where he graduated in mineralogy in 1880. Following Brøgger to Stockholm in the same year, he began to study metallurgy with Richard Åkermann [11]. Later he also studied at the mining academies in Freiberg and Clausthal and at the University of Leipzig. In 1886, he was appointed professor for metallurgy and mining science at the University of Kristiania [15]. He established theoretical geology, applied physical chemistry, and experimental studies, with chemistry being his main field of activity [15]. He became famous for his work on the application of melt facies diagrams in metallurgy to geological processes while his main interest was the immiscibility between sulphide and silicate melts and ore formation.

## 2.7 Victor Moritz Goldschmidt (1888–1947) – crystal chemistry and X-ray analysis

Another outstanding, if not the most famous, student of Brøgger was the Swiss born geochemist Victor M. Goldschmidt (\*27.01.1888–†20.03.1947). Brøgger was so convinced of Goldschmidt that he acted not only as a teacher but above all as his mentor and finally nominated him for the Nobel Prize in Chemistry in 1929 [65]. But Brøgger was not the only one to propose Goldschmidt. In total, he was nominated 10 times, among others, by the two Nobel Prize winners, the German physicist Max Planck and the German chemist Fritz Haber. Goldschmidt once described Brøgger as follows [52]:

“He was not only an outstanding scientist and teacher, but also a scientific personality who was above us all. And we, who had the opportunity to learn from him or to participate in a small part of his work, are deeply grateful for everything he gave us.”

Goldschmidt began studying geology, mineralogy, chemistry, physics, mathematics, zoology, and botany at the University of Kristiania in 1905. The deep friendship with Brøgger began in 1906. In 1910, Goldschmidt undertook an excursion to the Langesundsfjord together with Brøgger and the German mineralogist Paul von Groth, the leading crystallographer of that time and founder of the *Zeitschrift für Kristallographie*. Goldschmidt paid him a visit in

<sup>9</sup> Brøgger also introduced the term “metamict” for the first time, with which he described a class of minerals that have a crystal form but are amorphous from a structural point of view [152].

<sup>10</sup> In this context, Leisegang recalls Peter Paufler’s inquiries as to whether the new samples had already been characterized under the polarization microscope.

<sup>11</sup> In 1828, the *Technische Bildungsanstalt zu Dresden* was founded, which was renamed *Königlich Sächsisches Polytechnische Schule* in 1851, *Königlich Sächsisches Polytechnikum* in 1871, *Technische Hochschule (TH) Dresden* in 1890, and finally *Technische Universität (TU) Dresden* in October 1961.

the winter of 1911. The Langesundsfjord area, with its rare-earth containing pegmatites, which Brøgger intensively researched, became an important research interest for Goldschmidt, too [65]. The work carried out in this context and others were included in his doctoral thesis, which appeared in 1911 in the form of a 483-page monograph entitled “Die Kontaktmetamorphose im Kristiania-gebiet” (“The contact metamorphosis in the Kristiania area”) [66]. As early as 1914, he became professor and director at the Mineralogical Institute of the University of Kristiania. During his 15 years in Kristiania, Brøgger and Vogt [65] certainly had the greatest influence on his research. Goldschmidt summarizes the academic influences on his personality and his research in his speech at the award ceremony of the Wollaston Medal in 1944 – the highest award of the Geological Society of London – as follows [14]:

“First of all, I wish to give expression to my feelings of appreciation for the highest award in the science of geology. In awarding me the Wollaston Medal, the Council of the Geological Society has placed me near my old teacher, colleague and friend, Waldemar Christopher Brøgger, who was not only the greatest geologist of Norway, but also one of the most righteous men I have met.

I consider the award to be an honour also to the five teachers to whom I owe my education in science—besides Brøgger, they were my father Heinrich Jacob Goldschmidt, the physico-chemist, Hans Henrik Reusch, the geologist, Thorstein Hallager Hjortdahl, who taught me crystallography and mineral analysis, and Friedrich Becke, at whose Institute in Vienna I studied petrographic optics one autumn and winter. Both Brøgger and Becke were Wollaston Medalists, and, looking through the list of the awards of the Wollaston Medal, I find also my old friends Paul von Groth, Gerard de Geer, Albert Heim and Alexand[r] Evgen[’e]vich Fersman, the foremost organizer of geochemistry in the Soviet Union. In that great country, through the work of my friends Fersman, Vernadsky and other great scientists, the practical importance of geochemistry was recognized so early by the authorities that the Soviet Union could develop her industrial strength with the full weight of her powerful resources. [...]

Besides the great Brøgger we appreciate early work by his predecessor Theodor Kjerulf, by the mineral chemist Teodor Scherer, as well as in more recent times by Johan Herman Lie Vogt, professor of metallurgy, whose application of physical chemistry to igneous rocks earned him the Wollaston Medal. Even in the first half of the nineteenth century, Kjerulf’s predecessor, Balthazar Mathias Keilhau, the author of admirable geological maps, wondered about problems of metamorphosis and granitization, but paid little attention to chemical evidence, as do even some modern representatives of that line. [...].”

John D. Bernal took up the scientific influences on Goldschmidt and compiled them in the form of a *structural chemistry family tree* [67].

In 1929, Goldschmidt accepted a call to Göttingen,<sup>12</sup> where a group of outstanding physicists was also interested in joint working [68]. Due to the increasing persecution of Jews by the National Socialists, he was forced to return to Kristiania in 1935 because of his Jewish ancestors. When the Germans then occupied Norway, he escaped to Sweden in 1942, then to England in 1943. In Great Britain, he worked at the Agricultural Research Council at the Macaulay Soil Research Institute in Aberdeen and at the Rothamsted Experimental Station in Harpenden on agricultural problems [14, 68]. Finally, he returned to Oslo in 1946 and died there in 1947 at the age of 59, due to the complications of a leg operation and presumably also due to his poor health, which had been aggravated by his escape experiences [14].

Goldschmidt combined various sciences during his academic career, thus creating the field of structural chemistry. His work on the relative abundance of elements, atomic and ionic radii, interionic distances, the effect of the radius ratio on the coordination number in crystals, the replacement of ions in minerals, and the lanthanide contraction – a term he introduced [65] – can be found in many textbooks on chemistry. He created the basis for modern crystal chemistry and geochemistry to interpret the properties of inorganic substances [65].

XRD and X-ray absorption spectroscopy (XAS) had already become his most important methods for the determination of crystal structures and elemental contents in Kristiania [14, 67], most likely inspired by Brøgger and the availability of Vegard’s X-ray diffractometer. Another trigger for XRD and XAS was his work as a consultant in connection with a customs dispute between Norway and England around 1918, during which he also made contact with the British physicist and Nobel Prize winner William H. Bragg [67]. An outstanding student of Goldschmidt in X-ray analysis was the Norwegian-American physicist and crystallographer William H. Zachariasen. He carried out

<sup>12</sup> Brian Mason impressively describes the *unparalleled galaxy of talents* [14] that were active in Göttingen at that time: “The mathematical tradition was carried on by Hilbert, Courant, Landau, and others. The organic chemist Wallach (Nobel Prize, 1910) was living in retirement, and his successor Windaus (Nobel Prize, 1928) was at the height of his career; his colleague in chemistry, Zsigmondy, had received the Nobel Prize in 1925. The Physics Department was guided by the triumvirate James Franck (Nobel Prize, 1925), Max Born (Nobel Prize, 1954), and R. Pohl. Prandtl, one of the founders of modern aerodynamics, was one of Göttingen’s great men, as was Tammann, the physical chemist who was still active in retirement. The zoologist Kuhn and the astronomer Kienle became great personal friends of the Goldschmidts. This galaxy of talent, alas, was to be cast to the winds after the Nazi takeover in 1933.”

X-ray structure analyses on rare-earth compounds within the *Metallurgical Project* as part of the *Manhattan Project* [33] and dealt with the “Theory of X-ray diffraction in crystals” [69]. With the help of XRD, Goldschmidt determined crystal structures of more than 200 compounds with 75 elements, from which he extracted atomic and ionic radii – thus performing data mining – which served as the basis for his laws on the geochemical distribution of the elements on Earth and in the Universe [65]. Goldschmidt also worked on problems in astronomy (The Goldschmidt Classification), focusing on the genesis of the elements and the study of the earth’s formation, a recurring topic of his [66]. Goldschmidt’s work, especially his observations from a physical point of view and in terms of atomic physics [68], formed the basis for later Nobel Prizes. For example, his table of cosmic frequencies, which was important for later theories about the atomic structure (“magic numbers”) and the origin of the elements.

During his high school graduation, in 1904, Goldschmidt was already working on the phenomenon of pyroluminescence on quartz, which he published in 1906 with the support of Brøgger [14]. He also showed remarkable foresight regarding the importance of man-made carbon dioxide emissions [14]:

“The carbon cycle is of especial interest because it demonstrates the great significance that the industrial combustion of coal and other fuels has already had on the carbon dioxide content of the atmosphere. The amount of carbon dioxide which each year is added to the atmosphere by the combustion of fuels is two hundred times greater than that contributed by the world’s volcanoes. This demonstrates that human activity in our time is a highly important geochemical factor.”

The shortage of raw materials during World War I led him, as chairman of the Raw Materials Commission and director of the Raw Materials Laboratory, to investigate Norway’s mineral resources on behalf of the Norwegian government in 1917 [14]. With financial support from the Norwegian government, he developed the use of olivine instead of quartz in the metallurgical industry and obtained numerous patents worldwide. After his return from Germany, he received considerable income from these patents [11, 14].

Many of Goldschmidt’s research topics (data mining [53], rare earths [33, 55], crystal chemistry [41, 42], pyroelectric effect [24, 25], and raw material considerations [53]) are still important topics for Peter Paufler and his academic descendants (*cf.* Figure 2).

In 1938, Goldschmidt claimed to have an intensive working day [14] – just like Hansteen: “I work from 7.30 in the morning often to 2 a.m. the next day, with only a few minutes for meals, weekdays and Sundays, on my university responsibilities, on my industrial interests, and in

the preparation of manuscripts.” Brøgger expressed concern early on about his *protégé’s* tendency to overwork and wrote to him about it. But Goldschmidt assured him: “I must admit that I may have worked excessively in January [...] and at present I work only a few hours each day.”

## 2.8 Gustav Ernst Robert Schulze (1911–1974) – metal physics and X-ray science

Goldschmidt had his most productive period in Göttingen, where he supervised a large number of students and employees at the Mineralogical-Petrographic Institute [14]. During this time, the German metal physicist and crystal chemist Gustav E. R. Schulze (\*24.02.1911–†05.10.1974) also studied and graduated with him as one of his best students [19].

Schulze began studying physics in 1931 in Berlin and then moved to Göttingen. There, he attended lectures of the German mathematician and physicist Max Born and, thus, was introduced to crystal physics. However, he specialized in the Mineralogical-Petrographical Institute with Goldschmidt, where he learned crystallographic techniques such as X-ray crystal structure analysis – a method that became increasingly popular in the 1920s [63] – and methods of crystal chemistry [19]. He completed his doctorate in 1933 with a doctoral thesis on “The crystal structure of  $\text{BPO}_4$  and  $\text{BaSO}_4$ ”. It was among the best work of the year in Göttingen.

When the National Socialists came to power, it became more and more difficult for Schulze’s teacher, Goldschmidt, to continue his work undisturbed. He advised Schulze to accept a research grant from the German Research Foundation for the Kaiser Wilhelm Institute (KWI) for Chemistry in Berlin, which was directed by Otto Hahn. According to Goldschmidt,<sup>13</sup> the best opportunities for further scientific development were offered there [19]. Goldschmidt must have had a correct presentiment here, because Hahn received the Nobel Prize for Chemistry in 1944. In 1934, Schulze built up a workstation at Hahn’s laboratory for the recording of X-ray powder diffraction patterns according to the Debye-Scherrer technique and measured metal oxides. However, already in 1935, he changed to the German physicist Friedrich A. H. Krüger at the Institute of Physics at the University of Greifswald, probably because of a significantly higher income [19]. In Greifswald, the electrical and magnetic properties of solid bodies were investigated, whereby Schulze turned his

<sup>13</sup> Unfortunately, the authors could find no evidence of subsequent communication between Schulze and Goldschmidt.

attention in particular to the magnetic properties in relation to the crystal structure [19]. He did not stay there for long either – it was probably a challenge even then to find a permanent position immediately after completing a doctorate – and moved to the KWI for Metals Research in Stuttgart in 1938. There, he came under the influence of the German physicists Richard Glocker and Ulrich Dehlinger. Glocker, who had completed his doctorate with the German physicist and Nobel Prize winner for physics Wilhelm C. Röntgen, was director of the Institute for Metal Physics at KWI and at the same time professor of radiology at the *Technische Hochschule* (TH) Stuttgart. Dehlinger received his doctorate from the German physicist Paul P. Ewald and his second doctorate (habilitation) from Glocker. He was one of the pioneers of metal physics [70] – with his habilitation thesis he introduced the term “*Verhakung*” (“hooking”) and thus gave the impetus for dislocation theory [71]. Dehlinger worked as Glocker’s assistant at the TH Stuttgart and as head of department at the Institute of Metal Physics at KWI. Later, Dehlinger succeeded Ewald and the Austrian physicist and Nobel Prize winner for physics (1933) Erwin Schrödinger as professor of theoretical and applied physics at the TH Stuttgart.

Schulze worked on general questions of crystal physics and chemistry with Dehlinger and Glocker [72]. He dealt with metal physics, the real structure of crystals, and their mechanical properties and finally wrote his habilitation thesis “On the crystal chemistry of the intermetallic  $AB_2$  compound (Laves phases)”, a field he always kept in focus from then on. Overall, he “had a very fruitful time in Stuttgart with Ulrich Dehlinger” [4]. In 1940, he was appointed lecturer for experimental physics at the TH Dresden<sup>11</sup>. During World War II, he was exempted from military service because of his one-sided visual impairment. However, he worked as a consultant for the *Reichs-luftfahrtministerium* (Reich Aviation Ministry) on the side. He advised on questions of microstructure and recrystallization behavior of aluminum and magnesium alloys [72]. Due to his membership in the *Nationalsozialistische Deutsche Arbeiterpartei* (NSDAP) (National Socialist German Workers’ Party) he was not allowed to continue work at the TH Dresden after the war. In 1946, he became head of the thermodynamic department at *Junkers Flugzeug- und Motorenwerke AG* (Junkers Aircraft and Motor Works) in Dessau. However, shortly afterwards he was deported together with his family and about 2000 other people from Junkers (as well as BMW and Askania) to the then Soviet Union. He was taken to the internment camp *Upravlencheskiy Gorodok* near Kuibyshev (today: Samara), where the world’s largest hydroelectric power plant was to be built and where the military aircraft manufacturer *Mikojan-Gurewitsch* (MiG) was transferred to from Dubna

near Moscow in 1941 as part of Moscow’s World War II evacuation measures. After the war, this factory was transferred to the Space-Rocket Centre “Progress” (RKTs *Progress*), one of the largest Russian aerospace engine companies, which to this day has developed many aviation turbojet, turboprop, and liquid rocket engines, some of which were first in the world and part of the Soyuz series, considered as one of the most reliable launch vehicles in the world. Between 1946 and 1953, Schulze was head of the thermodynamic department and involved in the development of engines [19]. In 1953, he was transferred to *Save-ovo*<sup>14</sup> near Moscow before he was finally appointed professor with a teaching assignment for special fields of physics at the TH Dresden in 1954. Due to the Soviet internment and subsequent return to the GDR, he most likely experienced a special influence, which was not reflected scientifically however; a concrete reference to topics of thermodynamics and aviation is missing, probably due to secrecy. From 1958, he worked as professor of radiology and metal physics, from 1970 as professor of experimental physics at the *Technische Universität* (TU) Dresden.<sup>11</sup>

From then on, Schulze’s research areas included metal physics, crystal chemistry, crystallography, and X-ray science. He was mainly concerned with metals and intermetallic phases, focusing on the mechanical properties (strength), which were of particular interest for applications [72]. He probably received his first inspiration from Goldschmidt, who worked on the description of the hardness of quartz crystals as early as 1912 and later on the dependence of hardness on interatomic distances, valence, and structure type [14]. Schulze advanced this area with Dehlinger. Another interesting topic was superstructures, which are characterized by additional diffraction or satellite reflections, which Dehlinger already observed in his X-ray diffractograms of mechanically stressed metals and described as “lattice ghosts” [73]. An unpublished review article by Schulze on this subject suggests that he intended to expand the topic further [19]. He also worked on the mass determination of small particles to calculate the real density of compounds, which he had already begun with Goldschmidt using the micropycnometer. Thus, the combination of structure and stoichiometry by means of XRD and chemical analysis formed his scientific anchor points. His student Peter Paufler (see below) reports [19]: “Since mainly intermetallic phases were to be investigated, the researcher always had to base his considerations on the

<sup>14</sup> Here, his work was probably also done for *Mikojan-Gurewitsch* (MiG). Today, its successor is *MKB Raduga Dubna* which produces various military missile technologies.



corresponding phase diagram.” This, as well as other aspects, has been transferred to the following generations until today. In addition, in 1957, Schulze began to use neutron diffraction to determine the magnetic moments and thermal oscillations (phonons) on intermetallic phases. In the 1960s, his institute advanced to become the leading scientific institute for the development and production of X-ray fine structure and spectroscopy equipment by decision of the GDR Council of Ministers. On the one hand, this restricted his research. On the other hand, he was finally allowed to invite Dehlinger to the GDR in 1961 for an honorary doctorate at the TU Dresden and was awarded the National Prize of the GDR in 1967 [19]. Furthermore, he carried out studies on the influence of stoichiometric deviations on structure and properties (magnetic, phononic, mechanical) and then also used electron microscopic analyses. Later he added superconductivity to his research portfolio.

In 1963, he took over the Institute of Mineralogy and Geology at the TU Dresden, with a break until 1967, and was also intensively involved in the “tracing” of “historical sources of individual phenomena” and “their holistic considerations” [19]. He was actively involved both nationally and internationally in the National Committee for Crystallography of the GDR and the German Association for Crystallography (VfK) as well as through his chairmanship of the “Sub-Commission Metal Physics” of the Academy of Sciences of the GDR. His book “Metal Physics” [74], published in 1967, is certainly another testimony to his expertise and the special position of Dresden in the field of metals research [19]. In 1974, Schulze prematurely retired due to illness.

Schulze – and as is probably inherent to physicists and as is characteristic of Peter Paufler’s ancestors starting with Ritter and Ørsted and actually across the entire line – dealt with fundamental questions of life, such as the finiteness of the Universe, the theory of harmony, or thoughts on religion in connection with quantum theory and the theory of relativity. The examination of this broad range of topics and their relation to current problems has always been praised in expert opinions. “His special inclination and ability to present scientific facts in an understandable way combined with the joy of basic research” [4] was certainly a reason that directed his attention towards a career as a university teacher at an early stage. Goldschmidt and Hahn already confirmed to him “an unusual disposition for crystal structure investigations” and “his thorough crystallographic knowledge”. Dehlinger praised Schulze’s abilities “to process large empirical material from a physical and atomistic point of view and to present the results in an orderly manner” and thus supported the appointment as professor at the TH Dresden “in the warmest way” [19].

Schulze was very popular among his students and staff not only because of his wonderfully readable “*Lehrbriefe*” (teaching letters). They “always regarded him as a role model because of his comprehensive education and his culturally rich leadership style and passed on many of his esteemed views to the next generation” [19]. Education was a value in itself, as a colleague, the German electron microscopist Dietrich Schulze, described [75]: “His relationship to it [...] is expressed in the [...] lecture ‘Max von Laue and the history of X-ray fine structure investigation’ [...]: ‘Now another side of Laue’s nature: He was not only a specialist scholar, but also an educated person in the best sense’, whereby *education*, according to a definition given by him [G. E. R. Schulze], is what remains after one has forgotten all that is learned.”

“Unlike a number of his fellow FR [*Fachbereich*, English: department] physics teachers, he did not behave in an odd or unpredictable way, nor did he scare people about exams or other personal contacts. Despite his many obligations, he regularly informed himself in the laboratory about the progress of his diploma and doctorate students [...]” as his student Peter Paufler described him [19]. Another student added [76]:

“Of course, it happened that he unexpectedly showed up at their [his students’] workplace and asked ‘embarrassing’ questions about the progress of the ongoing investigations. Who would not know what it is like to work day and night on for weeks, and how you feel when you are asked about it directly. However, every such conversation always included professional and objective advice from the teacher. Moreover, it was simply comforting for the ‘candidate’ when he was finally told without ‘dishonest’ digression: ‘If you don’t have complexes during your doctorate, you’re not normal.’”

In an obituary of Schulze it says [19]:

“Professor Schulze opened up the beauty of the world of crystals to many of us, which was made possible by the fortunate combination of chemistry, mineralogy, crystallography, and physics that his doctoral supervisor V. M. Goldschmidt at the University of Göttingen at that time combined.”

Schulze passed on a large variety of topics to his descendants, including crystal chemistry (e.g., [41, 42]), crystallography (e.g., [23, 33, 34, 77]), metal physics and intermetallics (e.g., [33, 55, 78, 146]), superconductivity [33, 79], X-ray science (e.g., [23, 80, 81]), especially a broad interest in science, and integrity.

## 2.9 Peter Paufler (1940) – physics, crystallography, and structural science

The author of Schulze’s obituary and his most famous student is the German physicist and crystallographer Peter



Paufler (\*18.02.1940). He describes Schulze as “my academic teacher” [4], who as a mentor also “protected him from various politically motivated attacks” [82], which he could not or did not want to avoid in the former GDR (cf. [19]).

Peter Paufler began studying physics at the TU Dresden in 1958 and graduated in 1963 with a diploma thesis entitled “On the growth of single crystals of intermetallic compounds”. In 1967, he received his doctorate under Schulze “On the plasticity of intermetallic compounds, especially  $MgZn_2$ ”. From 1963, he was a research assistant and then senior assistant at the Institute of Radiology and Metal Physics at the TU Dresden, which Schulze headed. In 1970, he became a university lecturer for experimental physics and habilitated on the topic “Analysis of the mechanism of plastic deformation in brittle metallic solids using the example of the intermetallic compound  $MgZn_2$ ” in 1971. Through Schulze’s relationship with Dehlinger, Peter Paufler developed a close relationship to the Max Planck Institute (MPI; formerly KWI) for Metals Research, especially to the German solid-state physicist Alfred Seeger, whom he also met regularly at the Leopoldina [4]. After Schulze retired from teaching due to illness, Peter Paufler took over as head of the teaching team for solid state physics, which was responsible for the education of all physics students at the TU Dresden [82]. As successor of the German mineralogist and crystallographer Hermann Heinrich Neels, Peter Paufler accepted an appointment as professor for crystallography at the University of Leipzig (then: Karl-Marx-University) in 1978, where he also became director of the Institute for Crystallography, Mineralogy, and Materials Science. Later, in 1991, he followed a call to the TU Dresden, where he remained professor for crystallography at the Institute of Crystallography and Solid State Physics (German: *Institut für Kristallographie und Festkörperphysik*, IKFP; later: Institute for Structural Physics, ISP) until his retirement in 2005 [82].

Peter Paufler was conscientiously and continuously involved in numerous honorary activities and scientific associations [83]. In 1983, he became chairman of the VfK, in 1994 chairman of the DMG, and in 2001 chairman of the DGK [84]. In 2005, he was awarded the Carl-Herrmann medal, the highest award in the field of crystallography of the DGK, in recognition of his scientific life’s work, in particular his countless theoretical and experimental contributions to physical and material science crystallography and in special appreciation of his sincere attitude even under difficult political circumstances [85]. Once asked by one of his students what was decisive for his academic career, Peter Paufler replied [4]: “Even if coincidences often played a role, targeted efforts combined with one’s own flexibility finally led to success.”

For Peter Paufler, the time in Leipzig was “of considerable importance” for his academic background, because he originally had to reorient his research topic unintentionally from metal physics to semiconductor physics, since new appointments in the GDR were allowed little leeway and were rather expected to adapt to the local research direction [4]. Nevertheless, he experienced the new field “soon as very attractive” [4]. A further aspect of his time in Leipzig was the access to mathematical crystallography and mineralogy, which allowed him to get to know the way of thinking and working in the field of geosciences, which, according to him, is still different from the physical sciences today. For this reason, he says, there is still a gap between the representatives of the physical and geoscientific communities. However, a trend towards convergence and cross-fertilization is discernible [4], which is certainly visible in Peter Paufler’s academic genealogy. In Leipzig, Peter Paufler’s network of influential scientists expanded to include the German mineralogist and materials scientist Ernst Schiebold and the German mineralogist, crystallographer, and petrographer Friedrich Rinne [4], although he never experienced the latter, he benefited from the inventory of the Leipzig institute, which still contains important working and illustrative materials (e.g., the mineral collection). A highlight of the Leipzig period was the 1986 International Summer School on Crystallographic Computing, organized by Peter Paufler, which was the first time that electronic data transfer took place between computers from Leipzig and the *Fachinformationszentrum* Karlsruhe across the inner-German border. In 2006, Peter Paufler was awarded the honorary doctorate of the University of Leipzig in recognition of his merits to the development of crystallography in Leipzig [4].

As is certainly true for the Norwegian physicist Hans-teen and for Schulze, Peter Paufler’s stays in Russia had an important scientific influence. Following Schulze’s advice, Peter Paufler, then lecturer at the TU Dresden, had applied for additional studies at the Lomonosov University in Moscow,<sup>15</sup> “in order to improve my personnel file, which was not excellent in terms of politics at that time” [4] (cf. [18]).

From Lomonosov University (MGU), where Peter Paufler had worked in the Laboratory for Dislocations of the Chair of Molecular Physics – the head of which was then

<sup>15</sup> “Going to the Soviet Union at that time meant a decline in the personal standard of living and a considerable burden on the family. The insight into Soviet or Russian everyday life and scientific world, the personal acquaintance with Russian colleagues and employees, Russian culture, and the resulting sincere friendships outweighed the privations by far”, as Peter Paufler describes [4]. “The insights behind the scenes of the socialist system, which was tried to be copied in the GDR” were of lasting value for him.

the Russian physicist Aleksandr S. Predvoditelev – he managed to gain access to the Institute of Metallurgy of the USSR Academy of Sciences in Moscow by handing over documents about the Dresden work on Laves phases as an incentive [4]. “At that time, around 1970, the institute was extremely hostile to foreigners and therefore difficult to access because of the highly classified research conducted there.” [4] Since research on intermetallic compounds was being conducted there on a large scale, Peter Paufler’s efforts were directed towards establishing contact with the director and Russian physicochemist and metal physicist Yevgeny M. Savickij (Sawitzki). “Savickij’s method of predicting intermetallic compounds with electronic computers [86] proved to be very fruitful, even if the computing power was very low at that time” [4]. After initial restraint and an invitation of Savickij including other representatives of his institute to Dresden, especially to the Institute for Ultrapure Metals (later: Institute for Metal Physics und Pure Metals; today: institutes of the *Fraunhofer Gesellschaft*) and the Institute for Solid State Physics and Materials Research of the Academy of Sciences of the GDR (today: Leibniz Institute for Solid State and Materials Research), the tensions loosened. Peter Paufler subsequently organized a joint research on superconductivity and superconducting intermetallic compounds [87] and several monographs were the result of this close collaboration [88, 89, 90].

From his own positive experience, Peter Paufler had advised capable researchers during his time in Leipzig to carry out additional studies in the then Soviet Union, because Western countries were unreachable [4]. Among them were Detlef Klimm and Gert Klöß. Klimm, now a senior researcher at the Leibniz Institute for Crystal Growth in Berlin and co-author of the new edition of the book “Introduction to Crystallography” [91], had learned about the method of plastic deformation by standing ultrasonic (US) waves at the same institute at MGU as Peter Paufler, which he transferred to Leipzig. In this laboratory, the US technique had been cultivated under the direction of Natalija A. Tjapunina. After the early death of Predvoditelev, she took over the laboratory. Klöß became professor of applied mineralogy at the Institute for Crystallography, Mineralogy, and Materials Science at the University of Leipzig after various interim stops. In this respect, he is a successor of Peter Paufler, although not the immediate one. He has conducted research at the Kharkov State University (today Kharkiv National University, Ukraine) on the influence of plastic deformation on thermal conductivity.

A further connection to Soviet Russian science was established for Peter Paufler by working on a project at the Joint Institute for Nuclear Research (JINR) in Dubna. Here,

the focus was on intermetallic compounds. The neutrons available there were used to measure phonon spectra and magnetic structures. This was done in the course of several 14-day measuring visits to a group at the reactor constituted by German scientists of the Central Institute for Nuclear Research Rossendorf (today: *Helmholtz-Zentrum Dresden-Rossendorf*, HZDR). The relations between the TU Dresden and the JINR Dubna were very diverse [4].

Throughout his scientific career, Peter Paufler maintained contacts with Russian scientists. Accordingly, 30 years of cooperation and friendly relations have linked Peter Paufler with the geologist, crystallographer, and material scientist Stanislav K. Filatov (Department of Crystallography, Geology Faculty, St. Petersburg State University, SPb SU) and the physicist, crystallographer, and material scientist Rimma S. Bubnova (I. V. Grebenshchikov Institute of Silicate Chemistry, ISC, Russian Academy of Sciences, RAS), of the *St. Petersburg crystallography school* [92, 93].

Between 1998 and 2006, up to five PhD students from SPb SU worked in Peter Paufler’s institute on joint projects, investigating the crystal structure, thermal phase transitions, and thermal expansion of mixed (K, Rb)-, (K, Cs)-, and (Rb, Cs)-borosilicates in crystalline and glassy state [94–100], alkali borates [101, 102], Aurivillius phases [103], *etc.*, using powder and single crystal XRD methods. Corresponding new data on mechanical properties, densities, and refractive indices were also determined [104–107]. Three doctoral theses were concluded in this context in St. Petersburg, two of them at SPb SU by Maria G. Krzhizhanovskaya [108] and Natalia A. Sennova [109] and the third at ISC RAS by Maria I. Georgievskaya [110]. The first of these doctorate students is now associate professor of the Department of Crystallography at SPb SU.

In 1998, Aleksandr A. Levin took up a postdoc position with Peter Paufler. Levin graduated from the Faculty of Physics of SPb SU in 1986 and then worked at ISC RAS under the supervision of the physicists and crystallographers Yuri I. Smolin and Yuri F. Shepelev [111, 112], who were among the founders of X-ray structural analysis in Russia. He brought important knowledge about XRD to Peter Paufler’s group<sup>16</sup> and contributed significantly to the establishment of powder XRD and X-ray reflectometry, applied to the thermal behavior of intermetallic Fe-Al multilayers [113] and Fe-Cr thin films [78], which Levin is now continuing at the Ioffe Institute (A. F. Ioffe Physical-

<sup>16</sup> Leisegang was able to learn the practical knowledge of X-ray diffraction in essential parts from him.

Technical Institute of RAS) in St. Petersburg. The time with Peter Paufler was very fruitful and more than 30 journal papers were published on topics such as borosilicate glasses [98–100] or structural effects induced by electric fields [114–116]. One of the most interesting investigations according to Levin was to examine pieces of a genuine Damascene sabre with unusually high mechanical strength. The quantitative composition and structural properties were comprehensively investigated by XRD [117, 118], electron microscopy [119], and mechanical testing [120], which showed the existence of carbon nanotubes in Damascus steel [121]. This series of work can be regarded as one of Peter Paufler's masterpieces that beautifully summarizes his "structural science" school as well as his ancestors' influence.

This fruitful St. Petersburg–Dresden collaboration continues to the present through ongoing research visits [122, 123]. In a recent review of the legacy of the Russian mathematician, crystallographer, and mineralogist Evgraf S. Fedorov [123], Paufler not only outlined the historical significance of Fedorov's derivation of the 230 space groups, but also emphasized the historical roots of German–Russian scientific cooperation in crystallography. He meticulously analyzed 72 of Fedorov's publications of *Zeitschrift für Kristallographie* and, since he himself played a leading role in German crystallography, this enabled him to demonstrate the atmosphere of free relations between Russian and German scientists [124]. First of all, between Fedorov and the mathematician Arthur M. Schoenflies, the author of the independent derivation of space groups, and between Fedorov and Groth. The relations between the scientists of both countries were of a purely scientific and deeply human character. With regard to the intergenerational connection, Paufler named this review about the author of the modern doctrine of crystalline matter "E. S. Fedorov promoting the Russian–German scientific interrelationship". It is remarkable, that Peter Paufler thus, for many years, closely collaborated with Fedorov's academic descendants: Bubnova, Filatov, Levin, Krzhizhanovskaya, and their students. A new mineral species, "Pauflerite", with the chemical formula  $\beta\text{-VO}(\text{SO}_4)$ , named in honor of Peter Paufler, symbolizes the results of this German–Russian collaboration. Pauflerite was first discovered at the Tolbachik volcano (Kamchatka peninsula, Russia) and described by members of Filatov's scientific school [125, 126].

As it is true with Peter Paufler's academic ancestors, especially Schulze, Goldschmidt, and Brøgger, Peter Paufler's research topics thus cover a broad spectrum: crystal physics [115], crystal chemistry [41], crystallography [127], mineralogy [47], art and archaeology [121], and history of science [123]. His scientific work focuses on the mechanism

and theoretical treatment of the plastic properties of solids (quasicrystals, thin films, and glasses) [22, 105, 106, 128], methodological work in the field of nanohardness measurements [128, 129] and X-ray analysis methods with emphasis on the use of synchrotron radiation [130], semi-conducting III-V compounds [131], structure-property relationships, superconducting intermetallic (rare-earth) compounds [41, 54, 132], quasicrystals [128, 133, 134], and modulated structures [77]. An important monograph is the book "Physical Crystallography" [135] from 1986, which was already then advertised in the West German journal *Physikalische Blätter* [136] and can still be found on the desks of his academic descendants.

Peter Paufler supervised numerous graduation theses and thus left his mark on many students. For example, Andreas Kupsch, one of his last doctoral students [134], wrote that he "substantially benefited" from Peter Paufler's "scientific stimulations, the open-minded discussions and his ability to methodize the maze of experimental findings" and further:

"He always conveyed his pure and unselfish passion for science to his students like me along with his attitude of humanity."

Although loaded with many tasks and responsibilities,<sup>17</sup> Peter Paufler also took time for cultural training. In this context, Levin recalls that Peter Paufler had invited him and Mrs. Levin once to the Semper Opera House, the anniversary exhibition of porcelain in Meissen, and the museum in Moritzburg, among other places. Conversely, when Peter Paufler once again took part in a conference in St. Petersburg, a visit to the Mariinsky Theatre and the Hermitage was also obligatory. After one of these visits, Mrs. Levin, herself active in the field of art, confessed that Peter Paufler really does understand art and music and that he is a man of art in science, as was the case in the Renaissance.

One of Peter Paufler's many responsibilities was linked to his appointment to the TU Dresden in 1991, in the course of Saxony's<sup>18</sup> general university renewal. He became spokesman and vice-dean for physics, which was associated with the chairmanship of an expert commission for the evaluation of scientific personnel. In 1992, the dean of the faculty founded the IKFP and Peter Paufler had been entrusted with the management. This also

<sup>17</sup> "My scientific life always took place between two scientific conferences." his student Dirk C. Meyer remembers a saying of Peter Paufler [138].

<sup>18</sup> The provisions of the German unification contract regarding employment in the public sector had to be implemented while the university(ies) were still in operation (cf. [19]).

meant that the supervision of existing diploma and doctoral students was adapted to the new personnel structure (with “professors of new law”). It was a special honor that Peter Paufler could host the 15th European Crystallographic Meeting in “his home institute” in Dresden in these turbulent times in 1994.

## 2.10 Dirk Carl Meyer (1966) – structural science, X-ray and crystal physics

In the eventful period at the beginning of the 1990s, the German physicist and structural scientist Dirk C. Meyer (\*15.01.1966) came under the influence of Peter Paufler. In his doctoral thesis Meyer wrote [81]:

“...the results and publications would not exist without his scientific guidance. I particularly enjoyed the scientific openness of the work under the direction of Prof. Dr. Peter Paufler. [Through him] methodological developments were always inspired and made possible. The resulting free working atmosphere with simultaneous support and guidance, which is also important from a human point of view, was a gift to me during the entire time. [...] In addition, I have been able to recall the earlier work of personalities such as Prof. Dr. Gustav E. R. Schulze, [...] as an incentive and orientation.”

Meyer began studying physics at the TU Dresden in 1986 and graduated in 1991 with a diploma thesis on “EXAFS investigations on amorphous metallic alloys”. The experiments on Extended X-ray Absorption Fine Structure (EXAFS) were first performed on a laboratory instrument, then soon at the German Electron Synchrotron (DESY) in Hamburg [81]. Meyer specialized in X-ray, metal, and semiconductor physics as well as in detector developments. Peter Paufler encouraged him to further develop the DAFS method (diffraction anomalous fine structure), which was initially abbreviated BREFS (Bragg reflectivity extended fine structure), as it was a crystallographically rich source of information that was initially little known. He successfully further developed this method, mainly at DESY in Hamburg. In addition to thin metallic multilayers for X-ray mirrors, under Peter Paufler’s supervision, his attention was also drawn to the GaInP/GaAs layer system for optoelectronics and which Peter Paufler had already worked on in Leipzig. Finally, Meyer received his doctorate in 2000 under supervision of Peter Paufler with a doctoral thesis on the “Application of X-ray absorption spectroscopy and X-ray diffractometry under resonant scattering conditions for the characterization of the structural short-range order and the phase composition” [81]. It casts a spotlight on his practical thinking that

his thesis contained 10 filed patents mainly related to detector developments. He used to work then as research assistant at the IKFP and from 2004 on as head of the independent junior research group Nanostructure Physics at the ISP. In the same year, he was awarded the Max-von-Laue Prize of the DGK. In 2007, he received an appointment as junior professor for nanostructure physics at the TU Dresden. In 2009, he was appointed full professor for experimental physics at the Chair of Compound Semiconductors and Spectroscopy at the *TU Bergakademie Freiberg* (TU BA Freiberg), a prominent place that was already part of the biography of most of his academic ancestors. There, he became director of the Institute of Experimental Physics (IEP) and Vice Rector between 2010 and 2015.

In Freiberg, Meyer started to establish a research line on functional oxides. This includes their use for new and innovative materials for high-performance components. The development of functional materials for data storage and sensors as well as for energy and material conversion, especially electrochemical energy storage, moved into the focus of interest. Apart from the synthesis of materials, a main subject is the establishment of structure-property relations by X-ray and synchrotron radiation probing. His institute developed rapidly and with it the research topics of the institute, which reach from basic research to applications today. He was able to build up a large research group in a short period of time, while also serving as Vice Rector. In addition, he founded the new Center for Efficient High-Temperature Material Conversion (*Zentrum für effiziente Hochtemperatur-Stoffwandlung*, ZeHS) in Freiberg. Meyer, who is the editor of the newsletter of the DGK, hosted the annual meeting in 2013, where he initiated the foundation of the new working group “Young Crystallographers”. It developed well and quickly became an important, lively, and inspiring part of the DGK.

Meyer’s research topics were further influenced by his student work at the HZDR [137], his intensive work at the Hamburg Synchrotron Radiation Laboratory (DESY-HASYLAB), where he worked as a user and on the conception and construction of equipment for synchrotron beamline experiments; later he contributed to the design of the Chemical Crystallography Beamline at PETRA III. When Meyer started scientific exchange with the working group of the German physicist Wolfgang E. Pompe, Pompe gave him further impulses for his research. He encouraged Meyer, for example, with regard to the material class of pyroelectrics with his typical “Let’s go!” (German: “Los jetzt!”) [138]. Impulses for nanometer multilayers and X-ray and EUV (extreme ultraviolet) mirrors also came from the Fraunhofer



Institute for Material and Beam Technology, Dresden (*Fraunhofer-Institut für Werkstoff- und Strahltechnik, IWS*).

Meyer's fields of work, thus, include crystallography, crystal physics, electrochemistry, materials science, and X-ray science. The focus of his work is on methodological developments of various X-ray and synchrotron analysis methods, in particular the combination of XAS and XRD and their application to crystalline materials [23, 81, 130, 131]. He continued the work, deepened by Schulze, on the development of X-ray equipment and then combined XRD and XAS with the application of external electric fields to investigate structure-property relationships of crystalline materials [114–116, 139]. Further focal points of his work are thin films, nanometer multilayers for optical and electronic [22, 140] as well as magnetic applications [78, 113, 130], oxide semiconductors, especially pyro- and piezoelectrics, for data storage and sensors as well as for energy and material conversion [24, 25, 34] and storage [42, 53, 141], the influence of defects of the crystal structure on the physical properties, and rare-earth compounds [55, 132]. Beside harmonic principles of elemental crystals [142], crystalline solids and quasicrystals, he especially worked on amorphous solids [98–100, 104].

According to the authors' experience, Meyer's talent for switching from academic conversation to easily understandable descriptions is remarkable, especially when addressing his students or with the realization of complicated design work in the workshop.

## 2.11 Tilmann Peter Leisegang (1977) – structural science, crystal chemistry, and data mining

The research topics and further aspects raised in Peter Paufler's academic genealogy shall be concluded with Tilmann P. Leisegang (\*27.10.1977), who became the first doctoral student and member of the independent junior research group founded by Meyer in 2004. In his doctoral thesis, Leisegang describes the influence of Meyer [33], who "introduced me to scientific work, always challenged and supported me intensively, but also gave me the creative freedom to develop my scientific skills." He continues: "The work under his leadership was particularly rewarding because he always developed innovative ideas, from which a motivation arose that enabled me to go beyond the normal level and take on scientific challenges. [...] The time of collaboration and the scientifically valuable discussions, which were always conducted in a friendly manner and which also went beyond this framework, have

had a great impact on me." These words show once again the special character of the student–mentor relationship in the sequence of Peter Paufler's genealogy.

Leisegang, who had begun his studies in physics at the TU Dresden in 1999, first met the IKFP to prepare a student lecture on X-ray reflectometry under the supervision of Meyer. He then worked with Meyer and as student assistant in cooperation with the IWS on nanometer multilayers for applications in the EUV and X-ray range. Leisegang specialized in crystallography. He attended lectures on crystallography and single-crystal XRD by Peter Paufler and on X-ray physics by Meyer. He graduated in 2004 with a diploma thesis on "Structural investigations of rare-earth compounds using X-ray methods", with Meyer and Paufler supervising the work. Subsequently, Leisegang worked as a research assistant in the Collaborative Research Center SFB463 "Rare-earth transition metal compounds: structure, magnetism, and transport". After Meyer moved to the TU BA Freiberg, Leisegang received his doctorate there in 2010 at the IEP with a doctoral thesis on "X-ray investigation of rare-earth compounds with special emphasis of modulated structures: the response of the crystal structure on composition variations" [33]. In 2012, he was awarded the Max-von-Laue Prize of the DGK.

Meyer probably had the greatest influence on Leisegang's academic career, partly because the two of them have spent almost 20 years together in intensive research and research management. Meyer wrote [143]: "It was a great pleasure and support for me that Mr. Leisegang, after obtaining his degree in physics from Prof. Paufler [...] in 2004, dared to take the risk of joining the 'Junior Research Group Nanostructure Physics' that I had founded, thus creating a seed for rapid and coherent growth."

Beginning in 2011 at the TU BA Freiberg, Leisegang mainly contributed to increasing the general research intensity at the IEP and establishing the new field of battery research and electrochemistry, particularly solid electrolytes, high-valent ion batteries, and pyroelectrocatalysis. He supported this by ensuring financial support, setting up the infrastructure including an additional branch office, organizing conferences, workshops, and trade presentations to bring respective knowledge to Freiberg and to promote the new research field, and through international networking. In this regard, another great influence on Leisegang's work has the Russian crystal chemist Vladislav A. Blatov. He introduced Leisegang to modern methods of crystal chemistry [41, 53, 144] during the guest visits at the Samara Center for Theoretical Materials Science (SCTMS; Samara, Russia) since 2015. A very fruitful and close collaboration in the emerging field of solid electrolytes and friendship began. In this context, the Italian chemist and



scientific advisor of the SCTMS Davide M. Proserpio must be mentioned, who introduced Leisegang to the philosophy of science and gave him access to international cooperation through his wide spread network [146].

Leisegang thus deals with crystal physics, crystal chemistry, and crystallography and since 2012 especially with electrochemistry [25, 26, 42, 145] and data and knowledge mining [42, 53, 141, 145]. An essential technique is single crystal XRD, which he learned from Peter Paufler and the crystallographer Gernot Zahn at the IKFP. He used this method for structural investigations of structural finesses, in particular of aperiodic crystals [33, 77, 146]. Further topics are the use of nanometer multilayers as optics for EUV lithography [22] and X-rays, the discovery of new ion conductors for solid state electrolytes and intercalation electrodes [42, 53, 141] and for high-valent ion accumulators, especially an aluminum ion accumulator [26], intermetallic rare-earth compounds [33, 55, 132, 146], pyroelectrics [24, 25], *etc.*, [139].

This closes the circle – for the time being – from Ritter’s pile, as probably the first accumulator, to current research on aluminum-ion batteries and from Ritter’s discovery of ultraviolet radiation to advanced EUV optics, as Leisegang’s research topics.

### 3 Conclusion

Brogger stated in the preface of his extensive work “The Silurian levels 2 and 3 in the Kristiania area and on Eker, their structure, fossils, stratigraphic faults, and contact metamorphoses” [56]:

“When I now look back on the finished work before me, which thus only gradually acquired its present scope, it is only with an unsatisfactory feeling that I now send it out into the world. Some of it is still unfinished, some of it should have been more fully and exhaustively investigated, more precisely and concise justified. [...] Then the relatively short time that I was able to devote to the preparation of this treatise may serve as an excuse, since it had to be completed before I took up my new position in Sweden; this circumstance also explains why some things were included that, strictly speaking, probably do not belong in the plan of the work.”

A similar feeling manifests itself in Leisegang. Because with more than 11 biographies of the main persons of the academic genealogy and more than 70 biographies of other persons in context, it is rather a life task to grasp, describe, and interpret everything comprehensively. Nevertheless, in the following we will attempt to summarize and interpret several observations.

First, the academic genealogy is summarized schematically in Figure 1 (references to influencing and

contemporary scientists) and Figure 2 (thematic references) as well as in Table 1 (key data). Figure 1 visualizes that several persons always had an influence on the research interests and work of the respective scientist. This includes leading scientists of their time, such as Bunsen, Groth, Röntgen, Weiss, or Werner, who have made significant discoveries and thus founded a research field or *school*. Political and societal conditions have left their mark as well. However, the cross-generational influences of ancestors and individual scientists evidently are and remain dominant. The chronological references in Figure 1 show that a *teacher*, if he was allowed to reach a high age, for example Hansteen at the age of 89, had an influence on the *students of students*. Thus, Hansteen had a great influence on Keilhau as well as later, then as a mentor, on Kjerulf. Leisegang also draws a parallel here with regard to his academic relationship to Peter Paufler, especially with regard to the Saxon Academy of Sciences.

Figure 2 compiles selected thematic references that have been frequently encountered in the literature review. It shows that the range of topics and, thus, the disciplines have expanded and become more specific. This is characteristic for that time period [8], when significant new ideas were introduced that lead to the creation of really new disciplines, such as crystallography. As stated by Arne Bjørlykke in [147] for instance: “Scientists were natural scientists first and geologist and botanists second” and since then “science became ever more specialized, resulting in a situation where an individual scientist would only study individual” topics such as a certain class of material or method. He adds that “today, natural science is on the march again.” On the other hand, more topics can be dealt with today, which is related to the available financial means as well as to improved living conditions (there has not been a war on the territory of the members of the European Union for 75 years) and improved computational and scientific infrastructure (computers [144], Internet, and synchrotrons). Certainly, tradition has an influence here as well, which lives on in us through our ancestors. Following Peter Paufler’s recommendation [148], it might be advantageous to speak of *structural science* as a summary of the individual disciplines observed here.<sup>19</sup> In this sense, all but Ritter have dealt with structural science (*cf.* Figure 2).

In Peter Paufler’s genealogy, specific sub-disciplines such as crystallography, metal physics, X-ray science, and

<sup>19</sup> Accordingly, Peter Paufler’s Institute of Crystallography and Solid-State Physics (IKFP) became the Institute for Structural Physics (ISP) in 2003.

crystal chemistry have developed from the main subjects geology and mineralogy, while subjects such as mathematics, astronomy, geography, petrography, and geochemistry have not established as main disciplines. In turn, however, crystallography became an almost universally important discipline up to today.

Furthermore, three time windows can be defined: (1) Ritter to Keilhau, (2) Keilhau to Goldschmidt, and (3) Schulze to Leisegang. This is evident by looking at the disciplines, the methods, and the classes of material processed. Presumably, this is an outcome of the respective prevailing zeitgeist. While in the time window (1) the physical interactions (electricity, magnetism, galvanism, light) were in the foreground, period (2) can be understood as a reaction to the strongly increasing importance of industrialization, where raw materials and their mining and utilization became more and more relevant, especially with regard to the two world wars (1914–1918 and 1939–1945). The focus was then set on the composition and structure of the rocks and how they could possibly be used economically. In period (3), in line with the sharp increase in the global population and the rapid technological developments being made after World War II, improved and new materials for applications and products then became increasingly important, and in the context of the energy transition, electrochemistry again. Apart from technological inventions, the societal and political demands and challenges have particularly influenced the development of crystallography in the last three centuries and up to today.

According to Figure 2, Peter Paufler's academic genealogy can be characterized by the following relevant subject areas, methods, and substance classes, which are still part of the research portfolio of Peter Paufler's academic descendants: physics, magnetism, and crystallography as well as (again) electrochemistry, (X-ray) spectroscopy, XRD, and rare-earth compounds.

The biographies reveal that scientists traveled more frequently and longer in the past. On the one hand, this is because that, for example, in Norway at that time travelling was a prerequisite for obtaining a professorship [11] and, on the other hand, to the fact that travelling was not always allowed in the former GDR due to political circumstances [4]. From a geographical point of view, Germany and Norway are the main locations, with a strong connection to Russia. The latter can also be seen in the affiliations of Hansteen, Brøgger, and Goldschmidt to the Russian Academy of Sciences. The influential locations of Peter Paufler and his academic descendants are thus particularly associated with Oslo, St. Petersburg, Samara, and Moscow, with Jena in Thuringia, Göttingen in Lower Saxony, and with the Saxon cities of Dresden, Freiberg, and Leipzig.

During their stays, each of the scientists was individually influenced by the methods learned and friendships made in these locations. It can therefore be assumed that *institutions* or *schools* are of equal importance in shaping the academic and scientific biography. The geologist, geographer, and environmental scientist Davis A. Young writes [18]: "...of particular importance are the BA Freiberg, home of Werner, Nauman, and von Cotta; the University of Kristiania (Oslo), where Kjerulf, Brøgger, Vogt, Goldschmidt [...] taught." However, Young here refers to the development of petrology as a subfield of the Earth sciences between mineralogy and geology. This certainly applies to the development of the *Paufler School* in a similar way. With regard to crystallography and structural science, important impulses are related with these places.

Indeed, cooperation between universities in Europe goes back 300–400 years [11]. The cooperation between Norway/Denmark and Saxony especially started already in 1550, when the Danish King initiated import of mining specialists from Saxony and Sweden with the purpose to import the Saxon mining law and to increase the exploration activity. After Kongsberg Silver Mines started in 1621, Norwegian miners were sent to Freiberg for education purposes. The developments of mining academies and mining schools played an important role and many of them turned into Technical Universities (Hochschulen).

Almost all scientists were members of one or more academies of sciences, received high honors, and many of them were even honored with a mineral named after them. Besides Keilhau, Kjerulf, Brøgger, and Goldschmidt, a mineral was also named after Paufler: Keilhauite, Kjerulfine, Brøggerite, Goldschmidtite, and Pauflerite, respectively. This certainly interesting aspect underlines the importance of Peter Paufler and his ancestors for geology, mineralogy, and crystallography.

It is noticeable that no women appear in the direct line of Peter Paufler's academic genealogy, which is probably related to the fact that in the past few female scientists were trained or allowed to be trained or could/have worked as such at a university. The German structural scientist Julia Dshemuchadse (associate professor at the Department of Materials Science and Engineering at Cornell University) can be mentioned here as the first woman in this context, whose academic career follows Peter Paufler with receiving her diploma with Meyer's group in Dresden and her doctorate under the supervision of the Austrian crystallographer Walter Steurer in Zurich, Switzerland.

It is also striking that in the past, a stay abroad or the answering of a scientific prize question was sufficient to be appointed to a chair, rather than a long list of publications,

teaching experiences, or funds raised. However, scientists have probably always worked much, as can be seen from the letters quoted.

There are no Nobel laureates to be found among the scientists in direct line, but in secondary branches at least the four Nobel laureates, Born, Bragg, Hahn, and Röntgen, as well as the 10 Wollaston Medal winners, Becke, Bischof, Brøgger, De Geer, Fersman, Goldschmidt, Heim, Groth, Naumann, and Vogt, have influenced the academic genealogy of Peter Paufler.

While the time in which Ritter lived appears to have offered more freedom for scientists. In Goldschmidt's era, in the face of National Socialist Germany, times became increasingly challenging in terms of political developments. Especially during World War II and afterwards, Goldschmidt, Schulze, and Peter Paufler faced various challenges such as infrastructure destruction, internment, political repressions, and travel restrictions. After the end of Germany's partition, it became increasingly easier to develop oneself more freely in scientific terms, which is evident in Peter Paufler's diverse committee work, in Meyer's creative way of addressing a multitude of topics, and in Leisegang's stronger expansion of his international network.

In Leisegang's point of view, numerous aspects have been interesting: The German-Russian inspirations, the influence of world events on research activities, and that other scientists faced similar challenges in terms of limited time and financial resources, multiple changes of location, time for the family, political conditions, criticism, or disputes. The many words of thanks for the *teachers* furthermore underline the importance of free, personal development. They also show that the ability of teachers to systematize as well as their sincerity are further aspects for a successful development of young scientists.

If one wanted to summarize Peter Paufler's academic genealogy with his individual research disciplines, in particular geology, mineralogy, and physics, in a single sentence, the following aphorism by Ritter, taken from his lecture "Physics as Art" [149], would be appropriate:

"... the Earth itself was first an artist and poet before it became a physicist, and the individual only repeats the history of the whole."

The fact that, in addition to a successful science, other *ingredients* are needed for a happy life becomes clear in a memory of Goldschmidt by Nils H. Houge [14]:

"I remember standing in the garden with him and looking at the children at play. He then said: 'Dr. Houge, you are a lucky man.' I

answered that he too, as a famous scientist, had much to be pleased about. His answer was: 'I can tell you one thing. Sometimes I regret that I never went out and drank beer with my fellow students.' So, everything has its price."

## Epilogue by T. Leisegang

I started working on this article in February 2016 during a research stay in Samara. Peter Paufler had told me shortly before that Schulze was interned in Samara after the war and sent documents about it. I immediately immersed myself in these at the hotel until late at night and in the following nights. My research quickly brought me to Goldschmidt and to the idea of setting up an academic genealogy. All in all, more than 4 years have passed now, and I managed to complete it almost in time for Peter Paufler's 80th birthday. Two situations about Peter Paufler are fixed in my memory:

**Situation 1 (in the office):** This situation concerned the presentation of my very first single crystal X-ray structure refinement results of various rare-earth compounds in his large office. In view of my excitement for this first working meeting, I had previously spent several nights in the institute to check all data, absorption corrections, refinement variants, and electron density maps. I entered Peter Paufler's office with great respect and admiration. I first stopped in front of his large desk with a large black chair in front of a huge *shelf of knowledge* dominating the entire room, filled with countless graduation theses, folders, and textbooks, neatly labeled and arranged. I studied the desk, which was lined with stacks of the latest books, articles, and all kinds of other papers and folders. However, the stacks seemed *fresh*, as I could not detect any dusty or yellowed papers. As a young student, I was impressed by this bastion of knowledge. Peter Paufler took the floor and asked me to sit down at his guest table in his very friendly manner, still somewhat absorbed in his last thoughts. He was then immediately attentive and listened to my explanations without interruption, allowing me to formulate my findings and thus reflect on them again, and finally shared his assessment and recommendations for further activities with me. In the end, I felt a little exhausted but happy to have his interest, his assessments, and especially one of his valuable theses in my hands, which contained important information that helped solving a problem concerning the absorption correction.

**Situation 2 (at the train station):** I guess it was the journey to Leuven (Belgium) for the 23rd European Crystallographic Meeting in 2006. Peter Paufler and I were waiting for the train to Leuven at Brussels airport. I sat

down next to him, a little indecisive as to whether he would rather be alone. But we immediately came into conversation, in which he told me about his time as a scientist in the GDR. One of his international conference participations had to pass different levels of approval and some hearings had to be fulfilled before the approval for participation was granted. If the permission to travel to Western countries had been given, the scientist still had to follow a certain code of conduct. This could mean that one was not allowed to talk to certain scientific colleagues. Peter Paufler once did not adhere to it and was observed by *watchdogs*. Back in Leipzig he had to explain himself to the rector of the university. I fondly remember the conversation because Peter Paufler spoke to me in a pleasantly calm voice, vividly, and with his sophisticated formulations – with sentences that first form a suspenseful arc before a point is set –, and willingly answered my sometimes very personal questions.

Dear Professor Paufler, I have recognized the *spirit* of Professor Schulze and all his academic ancestors at your institute at the TU Dresden, in your teaching, your appearance, and in your work. You have shaped me in this sense during my studies, as student in your lectures, as research assistant at your institute, and as scientist afterwards. With this article I would like to express my gratitude to you, especially with all the words of thanks that have been quoted. I have always perceived you as a very interested, well-read, enthusiastic, serious, trustworthy scientist. Your drive, your creativity, your tireless commitment to science, your alert mind, and your sense of justice are and will always be an example. I would like to conclude with a quotation from Goethe (Iphigenia 1,3):

How bless'd is he who his progenitors  
With pride remembers, to the listener tells  
The story of their greatness, of their deeds,  
And, silently rejoicing, sees himself  
The latest link of this illustrious chain!

Dear Professor Paufler: Congratulations on your 80th birthday!

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