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Viktor Moritz Goldschmidt (1888–1947) and Vladimir Ivanovich Vernadsky (1863–1945): The father and grandfather of geochemistry?

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ABSTRACT

Vladimir Ivanovich Vernadsky (1863–1945) and Viktor Moritz Goldschmidt (1888–1947) are indisputably the two most important founders of and theoreticians within geochemistry. In 1910 Vernadsky provided the first definition of geochemistry, and therewith the basis of the scientific discipline concerned with the processes governing the distribution of the elements in the Earth System. In 1911, Goldschmidt, then 25 years younger, and commonly considered as the 'Father of modern geochemistry' in the western world, defended his Ph.D. thesis 'Die Kontaktmetamorphose im Kristianiagebiet' (The contact metamorphism in the Kristiania area). His thesis and his 'Geologisch–petrographische Studien im Hochgebirge des südlichen Norwegen' (Geological and petrographic studies in the mountains of southern Norway) published in the following years were primarily dedicated to answering questions about the mineralogy and petrology of the area. With the foundation of the Raw Material Laboratory of Norway in 1917, of which he was the first director, Goldschmidt carried out a systematic program of chemical analysis of rocks, soils and minerals and, therewith, began to address fundamental questions about geochemical processes. Goldschmidt's lecture 'Der Stoffwechsel der Erde' (The metabolism of the Earth) published in 1922 subsequently opened the era of investigation of the distribution of the elements in the Earth's crust, meteorites and solar system and of the laws controlling this distribution. With this new approach, Goldschmidt followed the definition of process-controlled geochemistry which had been formulated by Vernadsky 12 years earlier.
In this study the influence of Vernadsky on Goldschmidt's oeuvre has been analyzed by referring to private correspondence, biographical publications and other documents. The exchange of letters, hitherto largely unknown, proves that exchange of scientific ideas between the two men took place over a long period. Goldschmidt invited Vernadsky for several visits to Oslo in 1927 and to Göttingen in 1932. The exchange is documented in 38 surviving letters written between 1913 and 1939, justifying the conclusion that Goldschmidt's work was substantially inspired and influenced by Vernadsky, at least after 1922. However, Vernadsky's influence on Goldschmidt was mostly restricted to the theoretical background of geochemistry and the processes responsible for distribution of elements in the Earth's crust rather than analytical developments and documentation of element distributions.

1. Introduction

Geochemistry is a relatively young discipline within the geosciences, having developed at the turn of the 20th century and first defined in its contemporary understanding by Vernadsky in 1910 (Krüger et al., 1990; Vernadsky, 1910;). Vernadsky was obviously not the first scientist, who addressed geochemical questions. Three schools contributed decisively and almost simultaneously to the establishment of geochemistry as a scientific discipline. First, there was the US-American school under the leadership of Clarke (1847–1931), second, the Russian-Soviet school under Vernadsky (1863–1945) and Fersman (1883–1945), and, third, the Norwegian–German school under Goldschmidt (1888–1947) (e.g. Krüger, 1983).

Clarke and his colleagues postulated that the quantitative determination of the chemical composition of the earth is the principle objective of geochemistry. In 1889 Clarke published the first extensive collection of rock analyses, followed in 1908 by the compilation of 'The data of geochemistry' (Clarke, 1889, 1908). In 1922, together with Washington, he published 'The average chemical composition of igneous rocks' (Clarke and Washington, 1922). The school around Clarke and Washington and their successors focused on the collection of précis analyses and on the classification of the 'present chemical state' of geological objects (Herlinger, 1927; Krüger, 1983; Larsen, 1941).

The Russian-Soviet school around Vernadsky promoted the aim of geochemistry as the investigation and explanation of the laws governing the distribution of the chemical elements in the Earth's crust. At the turn of the 20th century Vernadsky developed geochemistry as an independent science originating with fundamental mineralogical

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and chemical questions. In his 'History of the minerals of the Earth's crust' in 1898, he presented initial concepts of the dynamic nature of geochemical processes, but without formulating the ideas clearly (e.g. Krüger, 1983). It was not until 1909 that Vernadsky defined geochemistry as a new and independent geoscientific discipline (Vernadsky, 1910). The development of the idea of the process-controlled distribution and migration of chemical elements in the Earth's crust can be traced through his publications (Vernadsky, 1909, 1924, 1927a, 1930). From 1926 Vernadsky included the geochemistry of living organisms in his studies (Vernadsky, 1926) and, finally, the impact of human activity on geochemical processes (Vernadsky, 1944).

The Norwegian–German school of geochemistry around Goldschmidt evolved from crystal chemistry and petrography, in the narrower sense the application of thermodynamics to metamorphic rocks. Goldschmidt, on his appointment as head of the Raw Material Laboratory of Norway in 1917, began systematic analysis of minerals, rocks, meteorites and soils. From 1922, utilizing his broad knowledge of crystal chemistry, he started to investigate the laws governing the distribution of elements as conceived in Vernadsky's definition of geochemistry. In the western world, Goldschmidt is often regarded as the "father of modern geochemistry" (e.g. Mason, 1992), a view that fails to acknowledge Vernadsky's earlier contribution to the foundation of geochemistry as an autonomous geoscientific discipline.

The aim of the present paper, which was presented at the Vernadsky conference organized by the Leibniz-Sozietät der Wissenschaften e.V. in Berlin in March 2013, is to summarize the main achievements of Goldschmidt's scientific career in the field of geochemistry and the history of his scientific correspondence and exchange with Vernadsky to demonstrate the influence this had on Goldschmidt's work. Evidence from 40 surviving letters and other documents is reviewed and discussed.[1] The biographical data and scientific achievements of Goldschmidt, which form the main thread of this paper, have been obtained chiefly, if not otherwise specified, from the book 'Victor Moritz Goldschmidt: Father of modern geochemistry' by Brian Mason (Mason, 1992) and from the Goldschmidt archive of the Norwegian State Archive in Trondheim, Norway. Mason was himself a geochemist and one of the last pupils of Goldschmidt.

The three columns of the time scale in Fig. 1 summarize important political events and the biographical data of Vernadsky and Goldschmidt which had a significant effect on the lives of both men. Both scientists were affected by the difficult times during and between the two world wars. The great achievements of both scientists are therefore even more worthy of recognition. Goldschmidt was Jewish and for that reason suffered discrimination and arrest and was almost sentenced to death by the Nazis. Only at the last second with the help of colleagues, friends and members of the Norwegian resistance, did he escape being transported to Auschwitz and gassed.

2. Goldschmidt's childhood (1888–1906)

During childhood, Goldschmidt's family was traveling and moving (Fig. 2). Goldschmidt was born in 1888 in Zurich, but after five years the family moved to Amsterdam where his father Heinrich Goldschmidt accepted a position as lecturer in chemistry at the University of Amsterdam. Three years later the family moved to Heidelberg in Germany, where the father became professor of chemistry. The family spent four years in Germany, after which Heinrich Goldschmidt accepted a professorship at the University of Oslo in 1901 and Norway became the home country of the young Goldschmidt. From 1903 to 1905 Goldschmidt attended the secondary school in Oslo. During this period he developed a strong interest in mineralogy, certainly inspired by the work of his father. During an excursion in the summer of 1904 Goldschmidt found quartz crystals in Gudbrandsdalen north of Oslo. The crystals showed a strong thermoluminescence which is not common for natural quartz. Goldschmidt described the discovery to Professor W. Brøgger, who was a colleague and friend of his father and director of the Geological Institute of Oslo University. Brøgger recognized the potential of the young man and gave him more quartz samples to study. In 1906 this study resulted in Goldschmidt's first publication entitled 'Die Pyrolumineszenz von Quarz' (Goldschmidt, 1906). At that time he was only 19 years old.

3. The petrographic years (1907–1917)

In 1907 Goldschmidt commenced his first large scientific study, which, in 1911, resulted in his 483-page Ph.D. thesis, entitled 'Die Kontaktmetamorphose im Kristianiagebiet' (The contact metamorphism of the Kristiania area) (Goldschmidt, 1911). In his Ph.D. Goldschmidt described and interpreted the mineralogy of hornfels that formed at the contacts between Paleozoic sediments and Permian granites in the intra-continental Oslo graben. Goldschmidt was the first to recognize the relationship between the chemistry of the rock before metamorphism and the mineral paragenesis of the metamorphic product. He concluded, that the mineral content of the hornfels is the result of a thermodynamic equilibrium and, therefore, that the Gibbs Phase Rule could be applied. The rule defines how many mineral phases can occur in an equilibrium assemblage in a rock composed of a specific number of chemical components. The application of the Gibbs Phase Rule to rocks became known as Goldschmidt's Mineralogical Phase Rule. The application of the phase rule became the key to interpreting phase transitions and mineral reactions in metamorphic rocks. It also formed the basis for mineralogical phase diagrams that are used today for predicting the temperature and pressure conditions under which given mineral assemblages are formed in rocks. Goldschmidt initiated this revolution by the investigation of the pressure- and temperature-dependent reactions of calcite and quartz to form wollastonite and carbon dioxide (Goldschmidt, 1912a). The results of Goldschmidt's Ph.D. immediately attracted international attention, particularly in Western Europe.

While Goldschmidt worked on his Ph.D., Vernadsky, who was 25 years older, presented his paper 'The paragenesis of the chemical elements in the Earth's crust' at the 12th Congress of Russian physicians and natural scientists in Moscow in December 1909. In this presentation published in 1910 Vernadsky provided the first definition of geochemistry as an independent science (Vernadsky, 1910). It marks Vernadsky's strict dedication to geochemical studies. In contrast to his American colleague Frank Clarke, who in 1908 published the remarkable compilation 'The data of geochemistry', in his talk Vernadsky described geochemistry in terms of dynamic processes. Later, he condensed the statements from 1910 in the following definition: 'Geochemistry is the scientific investigation of the chemical elements, i.e. the atoms of the Earth's crust and, wherever possible, of the entire planet. This involves studying the history of elements, their distribution and migration in space and time as well as their genetic interactions on our planet' (e.g. Vernadsky, 1930).

After the completion of his Ph.D. Goldschmidt extended his regional studies to the south Norwegian Caledonides and applied his phase rule in order to determine the temperature and pressure conditions during the Caledonian orogenesis. The results were published in five volumes entitled 'Geologisch–petrographische Studien im Hochland des südlichen Norwegen' (Geological–petrological studies in the highlands of southern Norway) between 1912 and 1921 (Goldschmidt, 1912a, 1912b, 1912c, 1915, 1916, 1921b). In addition to studying metamorphic rocks, Goldschmidt carried out detailed investigations of magmatic rocks and developed the 'Stammbaum magmatischer Gesteine' (The family tree of magmatic rocks). The family tree of magmatic rocks is based on the

[1] Three sources of letters have been identified and used in the frame of this study. First, the Archive of the Russian Academy of Science (ARAN; 26 letters), second, the Goldschmidt Archive of the Norwegian State Archive, Trondheim, Norway (6 letters) and, third, the Columbia University Libraries, New York, USA (8 letters). Copies of all letters are provided in the accompanying file.

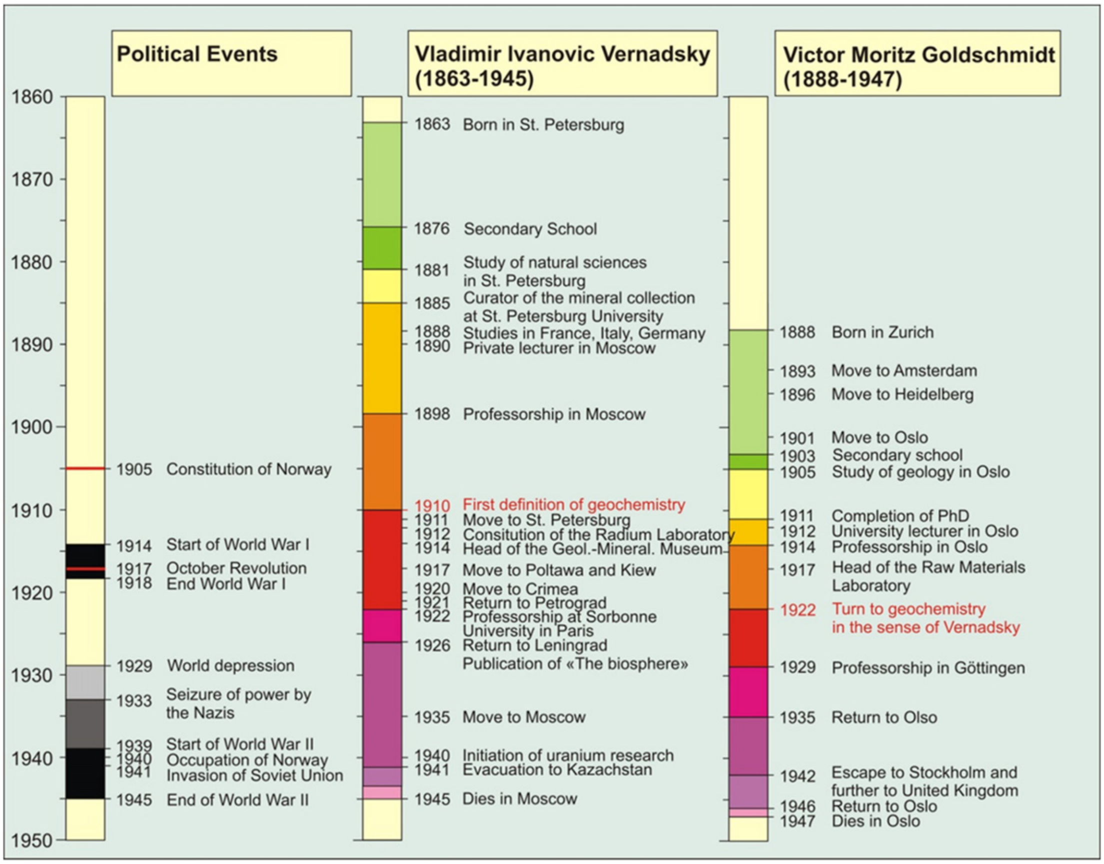


Fig. 1. Time scales showing the dates of the most important political events in relation to the lives of Goldschmidt and Vernadsky. The careers of both scientists were hampered by the difficult time during and between the two World Wars. The fact that Vernadsky was 25 years older than Goldschmidt is important. Goldschmidt devoted himself to geochemical studies following the principles embodied in Vernadsky's definition of geochemistry from 1910 and as late as 1922.

idea that all magmatic rocks evolved from primitive mafic magmas via fractionation. During this investigation he introduced the term 'trondhjemite' for leucogranitic, plagioclase-rich granites which occur in the vicinity of the city of Trondheim. All these studies were dedicated to petrological–mineralogical questions.

Fig. 2. Photograph from 1892/93 showing the young Viktor Moritz Goldschmidt and his father Heinrich Goldschmidt. By permission of the Goldschmidt archive of the Norwegian State Archive in Trondheim, Norway.

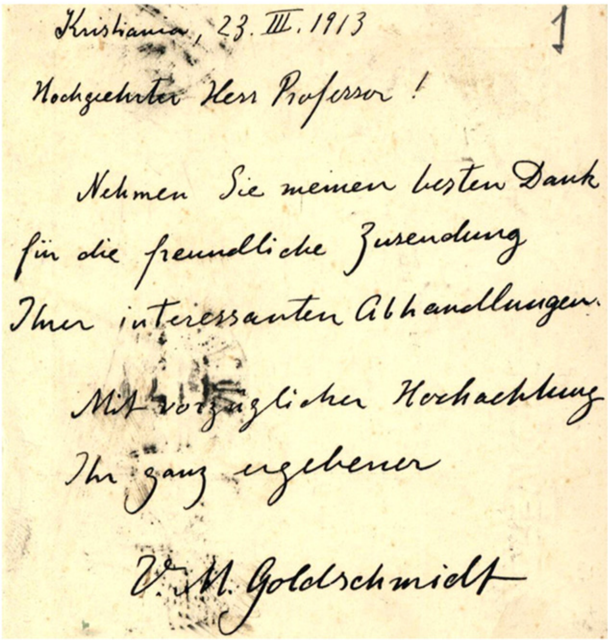
In 1914, at the age of 26, Goldschmidt received a personal professorship at the new Mineralogical Institute in Oslo. The reason for this unusual offer to Goldschmidt at such a young age was that the University of Stockholm had also offered him a professorship there. A position was set up for Goldschmidt because Oslo University wanted to keep their rising star.

The first recorded letter from Goldschmidt to Vernadsky, documenting their early scientific correspondence, dates from 1913 (Fig. 3). The letter, in which Goldschmidt expresses his thanks to Vernadsky for sending him his publications, is very formal and shows that the two scientists were not yet on familiar terms. Unfortunately, the next preserved letter dates from 1926. This letter has a different, very personal character indicating that Goldschmidt and Vernadsky had probably met between 1913 and 1926.

4. The years of research on raw materials (1917–1922)

The First World War led to a shortage of raw materials in Europe. Norway was not involved in the war, but was nevertheless affected by the shortage. As a consequence, the Norwegian government decreed the constitution of a raw material commission. The general task of the commission was to search for alternative raw materials which could replace conventional types of resources so that Norway could become more independent from the international market. In 1917 Goldschmidt became the first head of this commission.

Important tasks for the commission included the search for alternatives to bauxite for production of aluminium (clays and anorthosite), alternatives for the production of fertilizer, for example potassium minerals (biotite and K-feldspar) or carbonates and phosphates of



Kristiania, 23. III. 1913 1

Hochgeehrter Herr Professor!

Nehmen Sie meinen besten Dank
für die freundliche Zusendung
Ihrer interessanten Abhandlungen.

Mit vorzüglicher Hochachtung
Ihr ganz ergebener

V. M. Goldschmidt

Fig. 3. This letter which Goldschmidt wrote to Vernadsky in 1913 documents the oldest preserved correspondence between the two scientists. Goldschmidt expresses his thanks to Vernadsky for sending him his publications. The letter is very formal, indicating that the scientists were not on familiar terms with each other. This early correspondence has not been reported previously. By permission of the Archive of the Russian Academy of Science (ARAN), Moscow.

the Fen carbonatite complex (Goldschmidt, 1919a, 1921c, 1921d; Goldschmidt and Johnson, 1922). The commission was also involved in developing processes for the production of titanium oxide from ilmenite for use as a white pigment (Goldschmidt, 1919b, 1921a). Today Norway remains the largest producer of titanium pigment in Europe. During this period Goldschmidt's research led to the discovery of the heat-resistant properties of olivine and its potential use as a refractory material. He filed several patent applications outside Norway which ensured him small sources of additional income. However, the real significance of Goldschmidt's discovery was recognized only after his death in 1947.

The Norwegian government provided substantial financial support to set up an analytical laboratory. Goldschmidt took only three years to establish one of the most modern chemical laboratories in operation at that time. Goldschmidt used the funds for the construction of an X-ray diffractometer for the determination and comparison of the crystal structures of poly-mineralic samples. This demonstrates Goldschmidt's innovative character because it was just one year after X-ray diffractometry of poly-mineralic samples had been developed (Debye and Scherrer, 1916). In 1958 the Raw Materials Laboratory became a department of the Geological Survey of Norway and, in 1962 the department was integrated with the chemical laboratory of the survey.

5. The turn to geochemistry (1922–1927)

The analytical opportunities that arose with the establishment of the Raw Material Laboratory inspired Goldschmidt to start the systematic chemical analysis of rocks, minerals, soils and meteorites. This marks Goldschmidt's turn to geochemical studies. Between 1923 and 1938 Goldschmidt published the 'Geochemische Verteilungsgesetze der Elemente' (The geochemical laws of the distribution of elements). The nine volumes of this work contain his greatest achievements (Goldschmidt, 1923, 1924, 1926; Goldschmidt, 1938; Goldschmidt and Thomassen, 1924; Goldschmidt et al., 1925a, 1925b, 1926a, 1926b). The publications are devoted to the determination of the distribution of elements in the Earth's crust, meteorites and solar system, and the processes responsible for the distribution. This new direction in research was a crucial development and turning-point in Goldschmidt's work that was launched when he presented 'Der Stoffwechsel der Erde' (The metabolism of the Earth) at the annual meeting of the Deutsche Bunsengesellschaft and Centenary of the Gesellschaft Deutscher Naturforscher und Ärzte in Leipzig in September 1922 (Goldschmidt, 1922). Goldschmidt formulated his new research concept as follows: "It is conceivable that the original state of the Earth was a homogeneous or nearly homogeneous mixture of the chemical elements and their compounds. Today, however, the Earth is in a far from the homogeneous state. The material distribution within the Earth has by no means reached a final state of equilibrium; we observe instead an active redistribution of matter and energy. The processes which have resulted in the inhomogeneity of our planet and still contribute to the migration of material I would summarize in the expression 'Der Stoffwechsel der Erde' (The metabolism of the Earth)." From now on geochemistry became his major field of research. Later, in 1945, Goldschmidt wrote a letter to Brian Mason about his turning towards geochemical questions: "I can very well understand that you (Brian Mason) are very much attracted by the petrology of metamorphic rocks. I was also bound by the same spell for very many years. And most of my results are still unpublished because I fell for the charms of geochemistry" (Mason, 1992).

Goldschmidt's new research approach resembles the definition of process-controlled, dynamic geochemistry given by Vernadsky in 1910. In the first volume of the 'Geochemische Verteilungsgesetze der Elemente' Goldschmidt cited Vernadsky (Goldschmidt, 1923). This is somewhat surprising because until that time Vernadsky published predominantly in Russian and Goldschmidt could not read Russian. (Goldschmidt mentions in his letter to Vernadsky on 23 November 1927, that he does not understand the Russian language.) Goldschmidt was therewith one of the few scientists in Western Europe who was aware of Vernadsky's studies, as revealed in the letter of 1913 (Fig. 3), and who also applied them. The letter from 1913 documents the earliest known correspondence between Goldschmidt and Vernadsky. Goldschmidt expresses his thanks to Vernadsky for sending him his publications. Unfortunately, the publications are not specified. Goldschmidt become presumably aware of Vernadsky's work through one of his early German publications, most likely through the article 'Über die gediegenen chemischen Elemente in der Erdkruste' published in the Zentralblatt für Mineralogie, Geologie und Paläontologie (Vernadsky, 1912). The note by Vernadsky in his diary that Goldschmidt became a corresponding member of the Russian Academy of Sciences in 1924 is another indication of their early scientific exchange (Rose-Luise Winkler, 2013, personal communication). At the end of the 1920s the correspondence became very personal. In 1927 Vernadsky visited Goldschmidt for several days in Oslo and later, in 1932, in Göttingen, showing how close their relationship had become. The closeness of their scientific communication at this time has barely been recognized. The only references to it were given by Krüger (1983, page 350) and Mason (1992, page 57). The striking similarity between Goldschmidt's new research approach and the definition of geochemistry given by Vernadsky in 1910 suggests that Goldschmidt was significantly influenced by Vernadsky. It is reasonable to propose that it was Venadsky's work which initiated Goldschmidt's turn towards geochemistry. The establishment of the Raw Material Laboratory was, of course, a precondition for carrying out precise geochemical analyses via mineral identification and chemical assays.

Based on the new theory that the Earth was originally a globe of molten rocks, consisting of three immiscible melts: (1) nickel–iron, (2) iron sulfide and (3) silicate, Goldschmidt formulated a geochemical classification of elements into four groups: (1) Siderophile elements with an affinity to nickel and iron, (2) Chalcophile elements with an affinity to sulfides, (3) Lithophile elements with an affinity to silicates, and (4) Atmophile elements, which are normally present as gases (Goldschmidt, 1923). Later he extended the classification by adding a fifth group, the biophile elements (Goldschmidt, 1954). This classification formed the basis of Goldschmidt's new approach and, in the following years, he investigated the geochemical reasons for these affinities. Goldschmidt soon realized that the geochemical character of each element is related to its position in the periodic table of the elements which had been established by Mendeleev in 1869 (Mendeleev, 1869). In order to understand this relationship, he embarked on two tasks. The first was to determine the structure of crystals which controls the distribution of elements and the second was to analyze the precise chemical composition of minerals. Interestingly, Vernadsky was simultaneously but independently developing his own geochemical classification of elements (Vernadsky, 1922a). In contrast to Goldschmidt, Vernadsky considered in his classification the following properties of elements: (1) the presence or absence of radiochemical or chemical transformations of the element in the course of the Earth's history (2) the reversibility and irreversibility of these transformations and (3) the ability of the element to form chemical compounds or molecules composed of several different atoms in the Earth's crust. Based on these characteristics Vernadsky distinguished six element groups: (1) noble gases, (2) precious metals, (3) cyclic or organogene elements, (4) disperse elements, which commonly do not form bonds, (5) strongly radioactive elements and (6) the rare earth elements (Krüger, 1981; Vernadsky, 1922a). Vernadsky's classification, however, did not prevail whereas Goldschmidt's classification is still widely applied by geologists.

In the seventh volume of the ‘Verteilungsgesetze der Elemente’ in 1926, together with his colleagues Barth, Lunde and Zachariasen, Goldschmidt published the ionic radii of all elements known at that time and derived from these results the principles of ionic substitution in minerals (Goldschmidt et al., 1926b). This study is one of his most remarkable achievements. The incorporation of a foreign trace element by replacement of a major element at a specific site in the lattice of a given mineral is described as diadochic substitution and is governed by the four rules defined by Goldschmidt:

(1) The ions of one element can replace another in a crystal lattice if their radii differ by less than 15%.
(2) Ions whose charges differ by one unit can substitute as long as electrical neutrality of the crystal is maintained.
(3) If two ions compete in substitution, the ion with the smaller radius will preferentially enter the site.
(4) If two competing ions have similar radii, the ion with the higher charge will preferentially enter the site.

Later, however, it was shown that the last three rules cannot always be applied and, therefore, only the first is known today as Goldschmidt's rule of diadochic substitution. Another conclusion was that the maximum coordination number of an ion is determined not only by its charge, but also by the radii of bound anions.

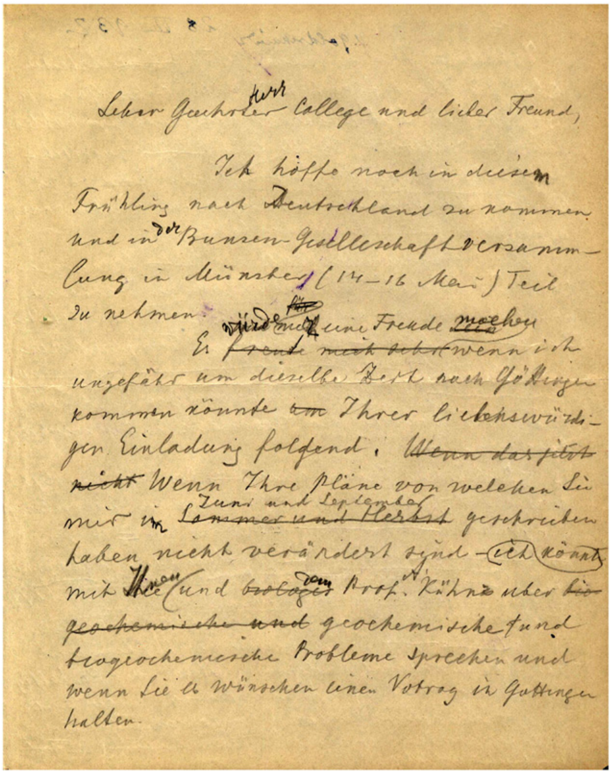
Vernadsky was, in this period, a guest professor to the Sorbonne in Paris (1922 to 1924): he published the first textbook of geochemistry ‘La géochemie’ in French (Vernadsky, 1924) and worked on his book ‘The biosphere’, which was published in 1926 (Vernadsky, 1926). The textbook of geochemistry comprises a collection of lectures that Vernadsky gave during his stay at the Sorbonne. The revised, German version of this book was published in 1930 (Vernadsky, 1930). These textbooks, and the presentations by Vernadsky and his colleague and former student Fersman at the ‘Russische Naturforscher Woche’ (Russian natural science week) in Berlin in June 1927, led to the wide recognition and popularization of the new field of geochemistry among European geoscientists (Krüger, 1983). Both Vernadsky and Fersman cited Goldschmidt in their lectures ‘Über den Kaolinkern der Aluminosilikate und ihre Stellung in der Erdkruste’ (On the kaolin core of aluminosilicates and their significance in the Earth's crust; Vernadsky) and ‘Die Migration der chemischen Elemente in der Erdkruste und ihre wissenschaftliche und praktische Bedeutung’ (The migration of chemical elements in the Earth's crust and its scientific and practical significance; Fersman) (Vogt, 1929). On July 15 1927 Goldschmidt wrote to Vernadsky, who at that time was staying at the radon baths in Oberschlema in Germany, to invite him on an excursion to the Oslo rift from 27 to 28 July. Vernadsky and Fersman visited Goldschmidt in Oslo for several days at the end of July 1927 (Krüger, 1983; Vernadsky, 1927b). During their stay they discussed, among many topics, the publication of an international geochemical journal with Goldschmidt. This project did not succeed due to lack of funding (Krüger, 1983; Vernadsky, 1927b).

6. Inspiring times in Göttingen (1929–1935)

In 1929 the University of Göttingen offered Goldschmidt a professorship. He accepted promptly and moved with his father and mother and the housemaid to Germany in the same year. The years in Göttingen until 1933, when the Nazis came to power, were the happiest, most successful and productive years in Goldschmidt's life. The reasons were that his working group was made up of creative and efficient scientists and there was fruitful cooperation and exchange of knowledge with other local scientists of high international reputations in different disciplines. After his arrival in Göttingen, Goldschmidt immediately initiated the construction of several optical emission spectrographs. These spectrographs allowed him to determine concentrations of element as low as 1 ppm and less (Strock and Goldschmidt, 1936; Fig. 4). Between 1929 and 1935 Goldschmidt and his colleagues published more than 20 monographs about the geochemistry of germanium, gallium, scandium, beryllium, boron, selenium, arsenic, strontium, rare earth elements, precious metals (gold, silver, platinum group elements), alkali metals (lithium, sodium, potassium, rubidium, cesium, francium), borates und carbonates (Goldschmidt, 1930, 1931; Goldschmidt and Hauptmann, 1932; Goldschmidt and Hefter, 1933; Goldschmidt and Peters, 1931a, 1931b, 1932a, 1932b, 1932c, 1932d, 1933a, 1933b, 1933c, 1934; Goldschmidt and Strock, 1935; Goldschmidt et al., 1933, 1934).

Goldschmidt, in a letter dated June 18 1931, invited Vernadsky to visit his institute in Göttingen. Vernadsky replied that he gratefully accepted the invitation and was looking forward to discussing geochemical and biogeochemical problems, such as the carbon dioxide content of the oceans, the chemical composition of marine organisms, the radioactivity of geological materials, etc. (Fig. 5). Goldschmidt wrote, that he, unfortunately, would not be able to pay an honorarium, but he invited Vernadsky to be his house guest during the visit. After Vernadsky participated in the annual meeting of the Deutsche Bunsengesellschaft in

Fig. 4. This photograph shows two self-constructed optical emission spectrographs, named electric arc prism spectrographs, which Goldschmidt brought back from Göttingen to Oslo in 1935. The spectrographs were operated at the Geological Survey of Norway (NGU) until 1977. Today, after the Raw Material Laboratory was integrated into the Survey in 1962, the spectrographs are part of NGU's Goldschmidt exhibition. The emission spectrographs were the forerunners of modern mass spectrometers.



Lieber Geehrter College und lieber Freund,

Ich hoffe noch in diesem
Frühling nach Deutschland zu kommen
und in der Bunsen-Gesellschaft Versamm-
lung in Münster (14–16 Mai) Teil
zu nehmen. ~~würde mir~~ eine Freude machen
Es ~~Freude mich sehr~~ wenn ich
ungefähr um dieselbe Zeit nach Göttingen
kommen könnte ~~um~~ Ihrer liebenswürdi-
gen Einladung folgend. ~~Wenn das jetzt~~
~~nicht~~ Wenn Ihre Pläne von welchen Sie
mir im ~~Sommer und Herbst~~ Juni und September geschrieben
haben nicht verändert sind – ich könnte
mit Ihnen und ~~biologen~~ dem Prof. Kühn über ~~die~~
~~geochemische und~~ geochemische und
biogeochemische Probleme sprechen und
wenn Sie es wünschen einen Vortrag in Göttingen
halten.

Fig. 5. The oldest preserved draft of a letter from Vernadsky to Goldschmidt, dating from 1931 in which Vernadsky gratefully accepted the invitation by Goldschmidt to visit him in Göttingen. Note that Vernadsky wrote this letter in German. Later, from 1935 on, Vernadsky wrote in French to Goldschmidt. By permission of the Archive of the Russian Academy of Science (ARAN), Moscow.

Münster, Germany, he arrived in Göttingen on 15 June and gave several lectures at the university during his stay (Fig. 6).

The correspondence and scientific exchange between Vernadsky and Goldschmidt intensified after the visit to Göttingen. As an example, in two letters they discussed the isomorphism of epidote, a calcium iron aluminosilicate, and allanite, a calcium rare earth aluminosilicate. Vernadsky assumed, that the aluminium position in epidote could not be replaced by rare earth elements and, therefore, there was no crystallographic relationship between the two minerals. However, Goldschmidt could prove, on the basis of his substitution rules, that the calcium site is replaced by rare earth elements and not the aluminium site as suggested by Vernadsky. Thus, these two minerals form solid solution series, which was later proved by Ueda (1955) and Dollase (1971) (Fig. 7).

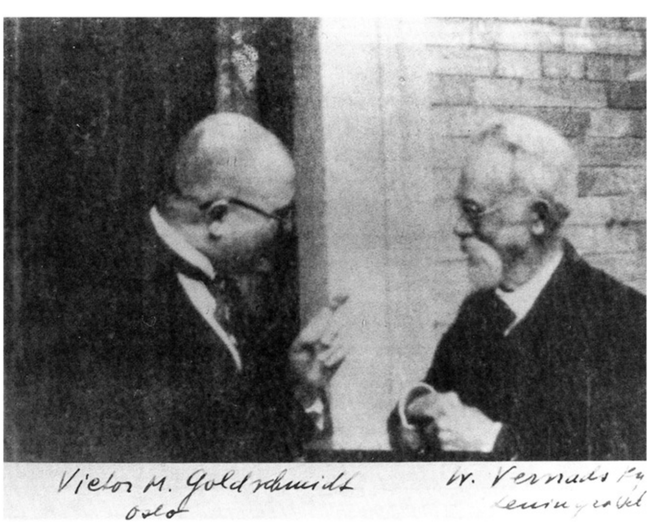


Fig. 6. Vernadsky (right) and Goldschmidt (left) in front of Goldschmidt's home in Göttingen in June 1932. Photo from Mason (1992).

7. Goldschmidt's return to Oslo and the last years (1935–1947)

In 1935 the repression and humiliation of the Jewish community in general and of Goldschmidt as an individual by the Nazis and their supporters became so terrible that Goldschmidt decided to give up his professorship in Göttingen and moved back to Oslo. Back at his former institute Goldschmidt was shocked by the miserable state of his former laboratory because of the lack of maintenance and interest in geochemistry. He expressed his indignation in a letter to Vernadsky (Fig. 8). In this letter he wrote that he had no more money to re-establish the laboratory because his private property had been confiscated by the Nazis. Vernadsky wrote in an earlier letter that if the Nazis remained in power, the excellence of research being done in Germany would ultimately cease.

Because of financial problems, Goldschmidt focused on raw material research in the following years. However, due to increasing health and budget limitations, and the generally difficult political and economic situations, Goldschmidt was not able to update the analytical equipment at the Raw Material Laboratory completely. In 1938 Goldschmidt published the ninth and last volume of the 'Geochemische Verteilungsgesetze der Elemente'. He referred to the publication as his 'Ninth Symphony' comparing it to the Ninth Symphony by Ludwig van Beethoven. The paper describes the distribution of chemical elements in magmatic rocks, meteorites, the solar system and the cosmos. He also sent a copy to Vernadsky who expressed his gratitude in a letter (Fig. 9). This letter is the last preserved written correspondence between the two scientists. The loss of contact was caused by the outbreak of the Second World War, the persecution of the Jews and the tense political situation between the Soviet Union and the countries of Western Europe.

On April 9 1940 Germany occupied Norway and began persecution of Jews in Norway. On October 25 1942, Goldschmidt was arrested and transported to the Berg concentration camp near Tønsberg south of Oslo. There Goldschmidt became sick and was sent to the county hospital. On November 5 he was released from the camp as a result of an initiative by the Ministry of Agriculture that wanted to use

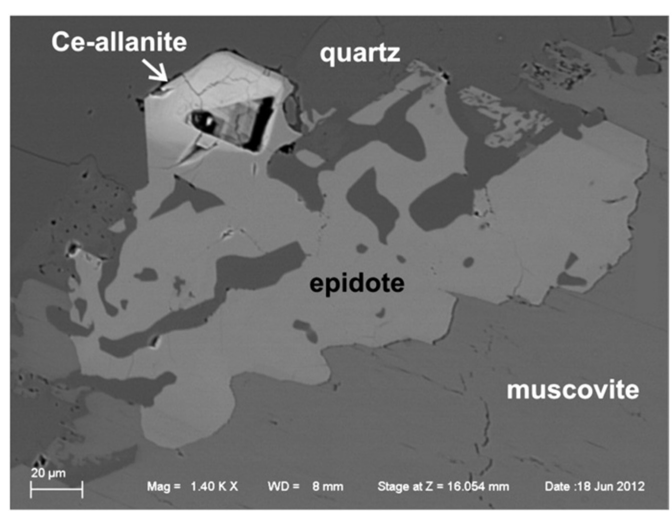


Fig. 7. Backscattered electron image illustrating the compositional transition of epidote (intermediate gray) to Ce–allanite (pale gray and zoned parts of the epidote crystal) supporting Goldschmidt's proposal that the two minerals form a solid solution series. This sample is from the leucogranite at the Sullins Wiseman mine at Spruce Pine, North Carolina (Müller, research in progress).

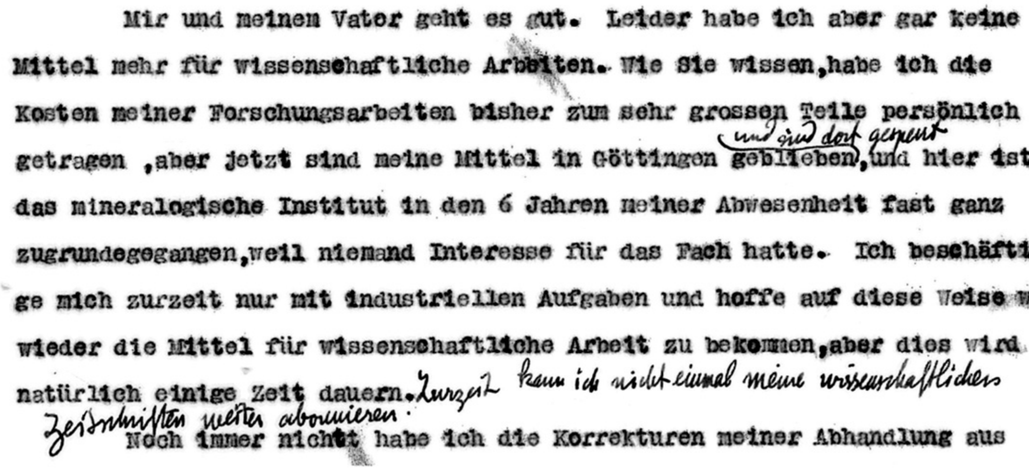

Mir und meinen Vater geht es gut. Leider habe ich aber gar keine
Mittel mehr für wissenschaftliche Arbeiten. Wie Sie wissen, habe ich die
Kosten meiner Forschungsarbeiten bisher zum sehr grossen Teile persönlich
getragen, aber jetzt sind meine Mittel in Göttingen geblieben, und sind dort gesperrt, und hier ist
das mineralogische Institut in den 6 Jahren meiner Abwesenheit fast ganz
zugrundegegangen, weil niemand Interesse für das Fach hatte. Ich beschäfti-
ge mich zurzeit nur mit industriellen Aufgaben und hoffe auf diese Weise
wieder die Mittel für wissenschaftliche Arbeit zu bekommen, aber dies wird
natürlich einige Zeit dauern. Zurzeit kann ich nicht einmal meine wissenschaftlichen
Zeitschriften weiter abonnieren.
Noch immer nicht habe ich die Korrekturen meiner Abhandlung aus

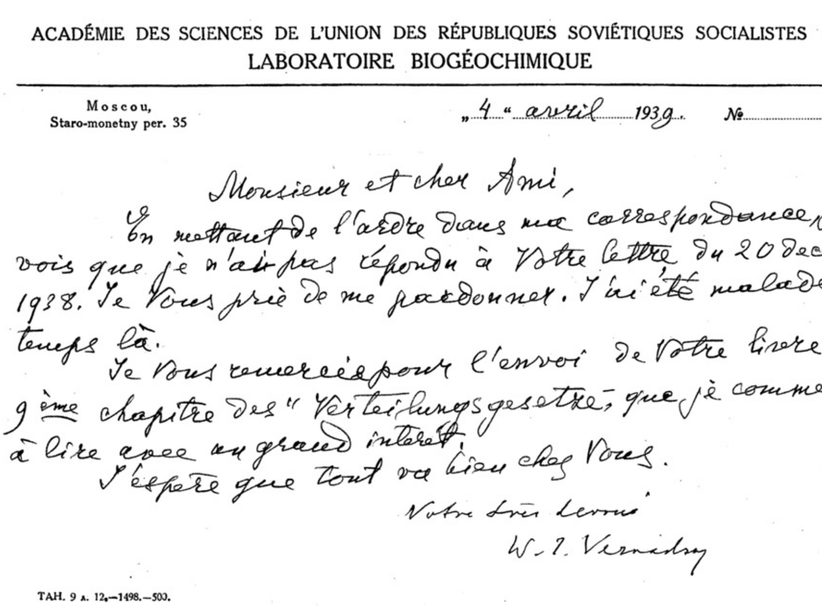
Fig. 8. Excerpt from the letter from Goldschmidt to Vernadsky dated December 27 1935. By permission of the Goldschmidt Archive of the Norwegian State Archive in Trondheim, Norway.

Goldschmidt's expertise for the development of production of agricultural fertilizer. On 26 November Goldschmidt was arrested again and was transported on the following day to the Oslo harbour, where he and 532 other Jews were to be sent on the ship 'Donau' to Stettin and from there to Auschwitz. At the last minute, as a result of request by his colleagues, pointing out the economic importance of his research, Goldschmidt was called out from the waiting line to continue to work for the Raw Material Laboratory. After arrival at Auschwitz 345 of the 532 Norwegian Jews were gassed immediately. On December 18 1942 Goldschmidt was picked up by members of the Norwegian resistance and smuggled to Sweden.

Goldschmidt stayed in Sweden for two months and, on March 3 1943, he was flown to London at the initiative of the British government. During his stay in the United Kingdom he attended many conferences, gave lectures, worked on his book 'Geochemistry', and provided information about the raw material plans of the Nazis in Norway to the British Secret Service. In 1946 Goldschmidt returned to Oslo, seriously ill. He died there on 20 March 1947. 'Geochemistry' was published posthumously in 1954 (Goldschmidt, 1954).

8. Summary

In 1922 Goldschmidt began a systematic analysis of minerals, rocks, soils and meteorites with the aim of investigating and defining the geochemical rules governing the distribution of chemical elements on Earth and in the solar system. In this approach he applied the dynamic process-controlled definition of geochemistry that Vernadsky had formulated twelve years earlier. In the same year Vernadsky began with chemical analysis of living matter and studied its influence on the geochemical cycle, thus extending geochemistry to the field of biogeochemistry (Vernadsky, 1922b). As a logical consequence he developed the concept of the biosphere in 1926. It can be concluded, that Vernadsky with his global and universal geochemical concepts was always one step ahead of Goldschmidt. Goldschmidt's strengths were his systematic methodical approach, the application of the most modern analytical instruments which he partly designed and built himself, and his strong interest in understanding the rules governing the distribution of elements by the application of crystal chemistry. The methodical ideas developed


ACADÉMIE DES SCIENCES DE L'UNION DES RÉPUBLIQUES SOVIÉTIQUES SOCIALISTES
LABORATOIRE BIOGÉOCHIMIQUE

Moscou,
Staro-monetny per. 35

„4" avril 1939 №

Monsieur et cher Ami,
En mettant de l'ordre dans ma correspondance je vois que je n'ai pas répondu à Votre lettre du 20 decembre 1938. Je Vous prie de me pardonner. J'ai été malade ce temps là.
Je Vous remercie pour l'envoi de Votre livre – 9ème chapitre des "Verteilungsgesetze", que je commence à lire avec un grand intérêt.
J'espère que tout va bien chez Vous.
Votre très devoué
W. I. Vernadsky

TAH. 9 A. 12.–1498.–500.

Fig. 9. The last preserved letter from Vernadsky to Goldschmidt dating from April 4 1939 in which Vernadsky thanked Goldschmidt for sending him the ninth volume of the 'Geochemische Verteilungsgesetze der Elemente' (The distribution laws of elements). By permission of the Goldschmidt Archive of the Norwegian State Archive in Trondheim, Norway.

Goldschmidt independently from Vernadsky. With his analytical equipment Goldschmidt was world-leading in performing geochemical analyses of natural substances. Goldschmidt drew his conclusions on the basis of an enormous amount of precise chemical and crystal chemical data that he obtained through his own scientific research, whereas Vernadsky compiled, processed and generalized various databases and arrived at universal conclusions with philosophical implications. Thus, Vernadsky's influence on Goldschmidt was mostly restricted to the theoretical background of geochemistry and the processes responsible for distribution of elements in the Earth's crust rather than analytical developments and documentation of element distributions.

In this study, based on the correspondence preserved in 38 letters and other archival material, it has been shown that a long-lasting scientific exchange took place between Goldschmidt and Vernadsky dating at least from 1913 onwards. The conclusion has been reached that Goldschmidt adopted and deepened some of Vernadsky's original theoretical geochemical concepts. Vernadsky's diaries are now in the process of publication and, no doubt, further studies will provide new perspectives on the scientific collaboration between these two remarkable men.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gexplo.2014.02.006.

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