

3 / *The Petrographic Years: 1907–1921*

IN THE SPRING OF 1907 Goldschmidt began his first major research work, which was to result in his doctor's thesis. It was a 483-page monograph, entitled *Die Kontaktmetamorphose im Kristianiagebiet* (The Contact Metamorphism in the Kristiania Region). Published in 1911, it is a classic in the literature of geology.

The Oslo (Kristiania before 1925) region is a graben, a trough of younger rocks downfaulted between blocks of ancient Precambrian¹ gneisses. The oldest rocks in the graben are Lower Paleozoic (Cambrian-Silurian) shales, marls (calcareous shales), and limestones. These rocks were later intruded in Permian times by magmas, mainly syenites of different types. The intrusions heated the intruded rocks and brought about the extensive mineralogical changes comprised under the term "contact metamorphism." The resulting rock types are known collectively as hornfels. These rocks are extremely fine-grained and their mineral identification demanded a remarkable facility in the use of the microscope, a facility which Goldschmidt demonstrated throughout his life.

As Goldschmidt pointed out in the introduction to his monograph, the Oslo region was uniquely suited to this investigation. The geology had been studied and recently remapped by his teacher, W. C. Brøgger, with many coworkers; the contacts between the intrusives and the sedimentary rocks were well exposed in many places, in quarries, mines, and road and railway cuttings; and extensive collections of minerals from the contact zones were available for study in the university collections. For the first couple of years he concentrated on field work and on the investigation of the mineralogy of the contact zones; more than half of his thesis consists of detailed descriptions of 83 minerals. As he noted in his preface:

"The greater part of the geological work was completed in the summer of 1909. . . . Since the spring of 1910, after I had established the mineralogical composition of the hornfelses, I devoted myself to the problem, which I had considered important since the

beginning of my research, namely the principles governing the mineral associations in these rocks" (translated from German).

As a result of his comprehensive studies Goldschmidt concluded that the mineral association of a specific hornfels is completely determined by the composition of the original material and the pressure and temperature of recrystallization. Considering the series of rocks ranging in composition from shales to limestones, the resulting hornfelses will exhibit a corresponding range of definite and predictable mineral compositions. On this basis he established a series of ten hornfels classes, characterized by specific mineral associations as follows (in order of increasing calcium content):

1. andalusite-cordierite
2. andalusite-cordierite-plagioclase
3. cordierite-plagioclase
4. cordierite-plagioclase-hypersthene
5. hypersthene-plagioclase
6. hypersthene-plagioclase-diopside
7. plagioclase-diopside
8. plagioclase-diopside-grossular
9. diopside-grossular
10. diopside-grossular-wollastonite

Along with these specific minerals, the rocks also contained quartz, orthoclase, and often biotite.

This sequence can be visualized in terms of an ACF diagram (Fig. 1), in which *A* signifies Al_2O_3 , *C* is CaO , and *F* is $(\text{Mg,Fe})\text{O}$; the corners of the triangular diagram represent 100% of the specific component; the diagram presupposes the presence of excess SiO_2 , present as quartz. ACF diagrams were devised by the Finnish geologist Pentti Eskola² while working with Goldschmidt in Oslo, 1919–20.

The ACF diagram not only illustrates the observed mineral associations, it also provides the explanation for the non-occurrence of conceivable mineral associations. Thus andalusite and hypersthene do not occur together, since they would react to give the intermediate compound cordierite; similarly wollastonite and anorthite are incompatible, reacting to form grossular.

In his doctoral thesis Goldschmidt used the data on the mineralogical compositions of this sequence of hornfels to arrive at a general principle, which he called the *Mineralogical Phase Rule*. In this he was probably influenced by his father, earlier a colleague of van't Hoff, who had applied the Phase Rule to the study of salt deposits. The Phase Rule is a chemical principle enunciated by the American chemist J. Willard Gibbs in 1877. It is usually stated in the form of an equation $P + F = C + 2$, or, in any system at equilibrium the number of phases, *P*, (mineral species in the case of rocks) plus the number of degrees of freedom, *F*, (temperature, pressure, chemical composition) is equal

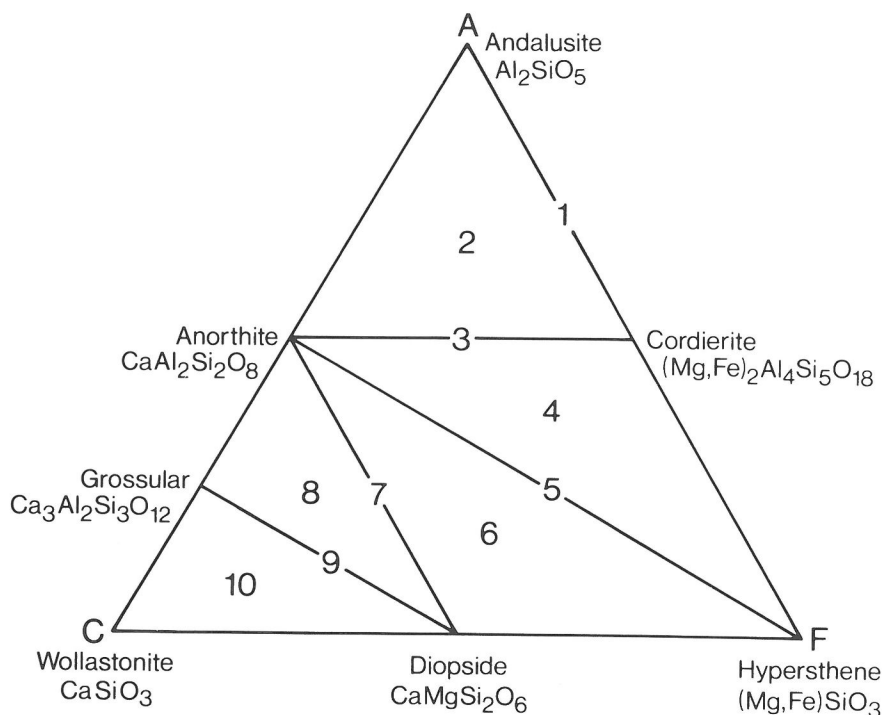


FIG. 1. ACF diagram illustrating the sequential mineral composition of Goldschmidt's ten classes of hornfels (Eskola, *Norsk Geol. Tidssk.*, vol. 6, p. 158, 1920). See text for additional details.

to the number of components, C , plus two. A simple example is the one-component system Al_2SiO_5 , which occurs naturally as the minerals kyanite, andalusite, and sillimanite. Each of these minerals is stable over a range of temperatures and pressures (Fig. 2). The phase rule predicts that the three minerals can coexist in stable equilibrium only when $F = 0$, i.e., both temperature and pressure are fixed. This is called the triple point, which for Al_2SiO_5 is at 500°C and 3.8 kilobars pressure, and it corresponds to a depth of about 13 km in the Earth's crust. But rocks crystallize over a range of temperatures and pressures, i.e., $F = 2$, and under these conditions $P = C$, i.e., only one of the three possible minerals will be present. This is borne out by experience, since rocks containing more than one of these minerals are very rare and usually show evidence of disequilibrium.

This is an example of Goldschmidt's *Mineralogical Phase Rule*, which states that in any rock the number of minerals will not exceed the number of components. This is a powerful tool in petrology in limiting the number of minerals present in a rock. Most rocks can be considered as within an eight-component system of O, Si, Al, Fe, Mg, Ca, Na, and K; these eight elements usually make up 99% of the common rocks. Seldom, if ever, will eight minerals occur in this sys-

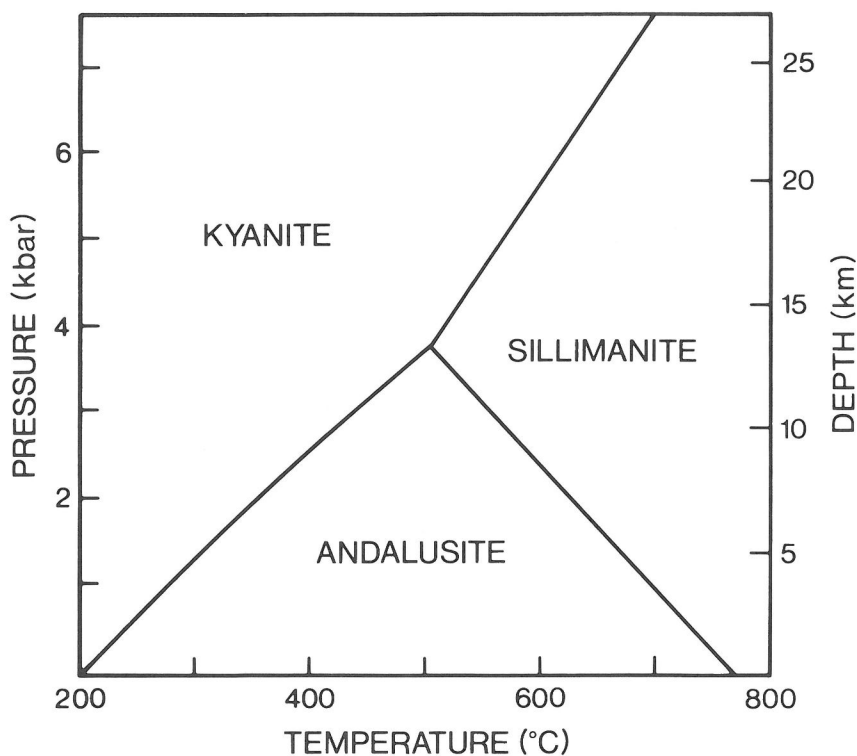
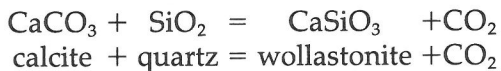


FIG. 2. Temperature–pressure relations in the Al_2SiO_5 system.

tem; several of these elements replace each other atom for atom in minerals, for example, Na and Ca in plagioclase feldspar, and Fe and Mg in ferromagnesian minerals, and are thus not truly independent components.

The Phase Rule has been of great utility in setting limits to the temperatures and pressures of rock formation. Goldschmidt initiated this in 1912 with his evaluation of this reaction:



a common metamorphic reaction whereby a siliceous limestone is converted into wollastonite. Using the limited data available at that time he determined a pressure–temperature curve for this reaction (Fig. 3). The curve for the equilibrium partial pressure of CO_2 divides the field into two parts, one of which (the lower part of the diagram) corresponds to the coexistence of calcite and quartz, and the other (the upper part of the diagram) to the field of wollastonite. Many analogous diagrams have since been determined and utilized in geothermometry and geobarometry (the determination of temperatures and pressures of reactions in the Earth's crust).

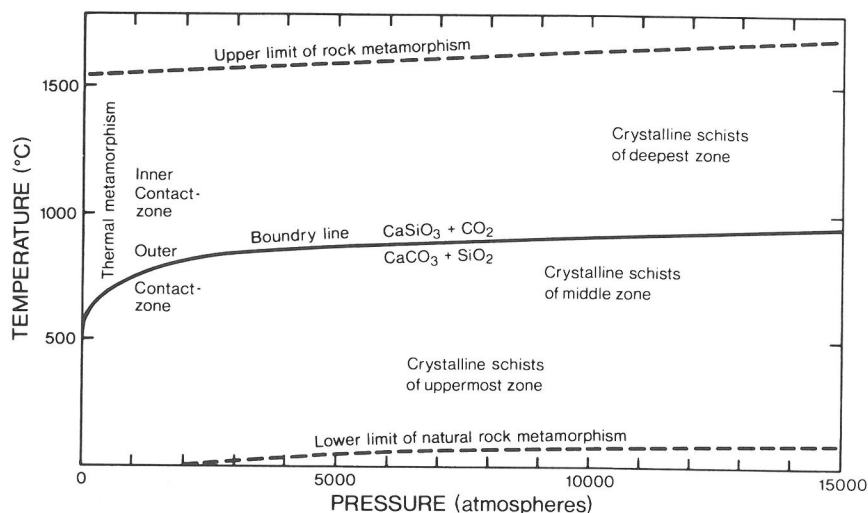


FIG. 3. Temperature–pressure relations in the CaCO_3 – CaSiO_3 – SiO_2 system (Goldschmidt, *Vidensk. Skrifter. I. Math.-naturv. klasse*, No. 22, p. 6, 1912).

While working towards his doctoral degree Goldschmidt took every opportunity to broaden his knowledge of geology and mineralogy. In the summer and autumn he did field mapping as an assistant on Norges Geologiske Undersøkelse (the Geological Survey of Norway). He spent the winter of 1908–09 at the University of Vienna, studying the techniques of optical mineralogy with Professor F. Becke.³ In December, 1909, he received a university scholarship in Oslo in mineralogy and petrology; this involved some teaching responsibilities, and from then on he lectured in these subjects, and led field trips with the students. After obtaining his doctor's degree in May, 1911, he spent the winter of 1911–12 with Professor Paul Groth,⁴ the foremost crystallographer of the time, at the University of Munich.

Professor Brøgger was concerned about his protégé's tendency to overwork, and evidently wrote to him about this when Goldschmidt was in Munich. Goldschmidt replied on February 17, 1912:

"Many thanks for your friendly letter, which I received today. I was really ashamed when I read it, and I promise to improve. I must admit that I may have worked excessively in January, because it was necessary to complete the crystal measurements at low temperatures. It was rather trying work, and I am glad it is finished.

Now, however, the manuscript is in the hands of Professor Groth, and I have been able to relax during the last few weeks. My only work is to try out the new four-circle goniometer which has been delivered by Fues [a German instrument company]. I must say that it is a great pleasure to work with this instrument. Crystal measurements now take fewer hours than previously days, and a high degree of precision is attainable. For example, a mono-

clinic crystal with many faces can be completely measured in 30 minutes. However, the greatest advantage is that one can not only measure the interfacial angles, but also the interzonal angles. The instrument is not expensive; it costs 150 marks and can be mounted on an ordinary goniometer, and can be removed in about two minutes.

Everyone who has seen the goniometer in use agrees that it is much better to work with than any of the older instruments.

Here in Munich it is already springtime; each day the sun shines warmer, and we work with open windows.

When I have completed the descriptions of the new goniometer and the quartz crystals from Finse [Norway], I shall continue with the low temperature measurements. I am going to measure crystal hardness and cleavability at -180°C . This research should be much less difficult than the angular measurements. I have been asked to lecture to the physicists on this subject on March 6. All this, however, is in the future, and at present I work only a few hours each day. The best indication that I am not overstrained is that I am sleeping well. As soon as I work too much I sleep badly, and so far that has not happened this winter. You can be quite sure that I am not sacrificing my health on account of my work.

Working here at the Institute is enjoyable in all respects, and Groth's assistants are all nice people, with whom it is a pleasure to collaborate. Professor Groth is always very friendly towards me; he sends you his warmest regards.

The collection of contact metamorphic rocks from the Kristiania region is already on exhibition; I am to select a corresponding collection of Alpine rocks, which will be forwarded during the spring.

I hope you are well. Thank you again for your friendly concern" (translated from Norwegian).

On his return from Munich Goldschmidt was appointed docent (assistant professor) in mineralogy and petrology at the University of Oslo from July 1, 1912.

After his experience with contact metamorphism in the Oslo region, he turned his attention to the wider and more difficult field of regional metamorphism, as it is developed in the cores of mountain ranges, such as those of southern Norway. Beginning in the summer of 1911 and continuing until late in 1916, he mapped large areas of the mountain country between Stavanger and Trondheim. In this work he was assisted by Mimi Johnson⁵ and Endre Berner⁶ (Plate 5).

In March 1914 Goldschmidt was elected to the Videnskaps-Akademi (the Norwegian equivalent of the Royal Society of London), one of the youngest persons so honored. Some of the Academy opposed this, on the grounds that there were older scientists equally qualified. Brøgger carried the day for Goldschmidt by saying:⁷ "I do not hesitate to say that I consider Victor Goldschmidt the most outstanding Norwegian mineralogist of today—myself not excepted!"

In 1914 the professorship in mineralogy at the University of Stockholm became vacant, and Goldschmidt applied for it. Of the four applicants he was placed first and was offered the position—a remarkable achievement in view of his youthful 26 years! The University of Oslo, not wishing to lose this rising star, prevailed upon the government to establish a Mineralogical Institute with a personal professorship for him. Professor Brøgger, who was active politically at that time, was probably largely responsible for this outcome. On September 28, 1914, Goldschmidt gave his inaugural lecture entitled, "On the Problems of Mineralogy." The following excerpt outlines his interests at that time.⁸

"What are the conditions for thermodynamic equilibrium (in geological systems), and why is it that we find some minerals in one occurrence and not in another? The answer is that equilibrium conditions depend upon three independently variable factors. The first of these is represented by the bulk chemical composition of the existing minerals; it tells us which starting material the mineral-forming processes had to work with. The two other factors are the temperature and the pressure under which crystallization took place. These factors depend upon the geological conditions of the mineral occurrence. From one given starting material different minerals may form, depending on the temperature and pressure. In some cases we may from purely thermodynamic reasoning predict the temperature and pressure which must exist in order for certain mineral associations to be formed. One example of this, to which I once called attention, is the formation of calcium-rich silicates at the expense of calcium carbonate. This process can only take place within a certain pressure and temperature range. Thus, we have a method to determine the physical conditions, temperature and pressure, which have existed in the crust of the earth during mineral formation.

It is of course of great interest to be able to determine the physical conditions under which an individual mineral has been formed. It is of much greater importance not to limit such investigations to one single occurrence, but to study thoroughly a sizeable area in order to investigate the temperature–pressure distribution during a certain geological era.

Such an investigation, no doubt the first of its kind, is being performed by myself in the Norwegian mountain areas, from Ryfylke [near Stavanger] to Trondhjemsfjorden, in order to determine the temperature and pressure conditions in this part of the earth's crust during the formation of the Norwegian Caledonides at the beginning of the Devonian. The procedure of such a systematic investigation is as follows: rock specimens are collected a few kilometers apart and each specimen is studied by optical methods to recognize certain signs indicating the temperature and pressure

which existed in the locality in question during the formation of the rock. The sum of all observations gives us a picture of the temperature–pressure distribution during the formation of a mountain chain.”

The results of these investigations in the Norwegian mountains were published between 1912 and 1921 in a series of five monographs with the common title *Geologisch-petrographische Studien im Hochgebirge des südlichen Norwegen*. The first two are purely geological, on a Cambrian conglomerate at Finse, and on the deformation of the Precambrian basement during the Caledonian orogeny. The third describes the metamorphic rocks of the Trondheim region, accompanied by a map showing the distribution of the various grades of metamorphism, as determined by the occurrence of distinctive index minerals such as chlorite, biotite, and garnet.⁹ He compared and contrasted the relationship between the contact metamorphism of the Oslo region and the regional metamorphism in the Trondheim area. The fourth monograph deals with the igneous rocks associated with the metamorphic rocks in the Norwegian mountains. He introduced the concept of *Gesteins-Stamm* (*rock kindred*) to denote a series of genetically-related igneous rocks within a geologically limited region. He distinguished three such kindreds in the Norwegian mountains, each with characteristic features. These were the “green rock kindred” (basic lavas and intrusives of the Trondheim region and on the west coast), the “Bergen–Jotun kindred” (the anorthosites and related rocks in Jotunheim), and the “opdalite–trondhemite kindred” (opdalite is a name introduced by Goldschmidt for a rock whose composition corresponds closely to the mean composition of igneous rocks, and trondhemite is his name for a white plagioclase-rich granite, now recognized world-wide in many similar regions). The final monograph, published several years after the completion of the field work, describes the injection metamorphism of the Stavanger region. Here are found mixed rocks of metamorphic and igneous material in a form suggesting that granitic magma was injected between layers of metamorphic rock, and he called these rocks injection gneisses (now generally known as migmatites, a name introduced for similar rocks in southern Finland). The nature and origin of migmatites is still a controversial field of great geological interest.¹⁰

Goldschmidt expounded on his concepts of the evolution of igneous rocks in a short monograph entitled *Stammestypen der Eruptiv-geseine*, published in 1922. This is illustrated in Fig. 4. Discussing the progressive crystallization of a magma he wrote:

“Among the first products of separation are minerals with low solubility in the silicate magma and high melting points, such as chromite and olivine, then follow other iron ores, together with the bulk of pyroxenes and plagioclase feldspars; amphibole and biotite succeed the pyroxenes, the calcic plagioclases are followed by sodic

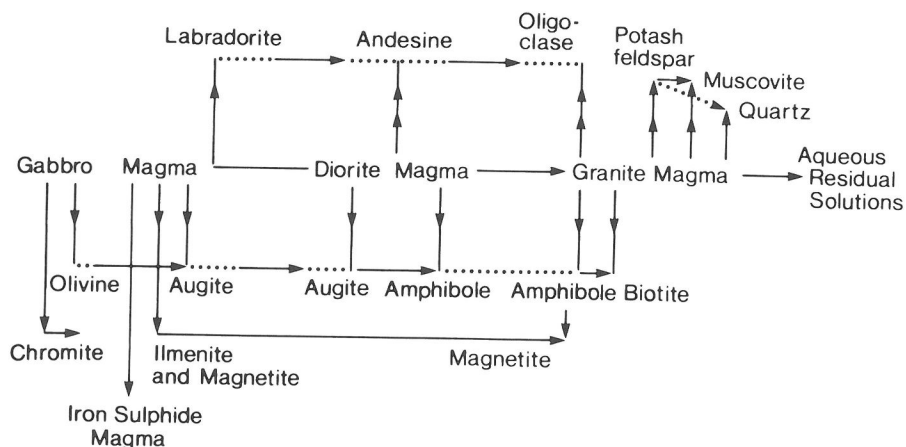


FIG. 4. The evolution of igneous magmas through fractional crystallization (Goldschmidt, *Vidensk. Skrifter. I. Math.-naturv. klasse*, No. 10, p. 6, 1922). The first-formed minerals (e.g., chromite) and rocks (e.g., gabbro) are on the left, and the final crystallization products (aqueous residual solutions) on the right.

ones and by potash feldspar, with quartz and muscovite. Finally, only pegmatitic magmas and aqueous solutions remain as a kind of mother liquor of the magma, from which crystallize coarse pegmatitic dikes and hydrothermal mineral veins, and from which also gaseous constituents may escape, giving rise to pneumatolitic minerals" (translated from German).

In a remarkable example of parallel thinking, the same concepts were published simultaneously by N. L. Bowen in his paper entitled "The reaction principle in petrogenesis" (*J. Geol.*, vol. 30, p. 177–196, 1922). Bowen's thesis was based largely on experimental work on the crystallization of silicate melts, which were carried out by his colleagues and himself at the Geophysical Laboratory in Washington, D.C., during the previous decade. In his monograph Goldschmidt refers appreciatively to Bowen's work.

In June 1922 Goldschmidt took an international group of distinguished geologists on a tour of the Stavanger area to demonstrate his injection gneisses and other features. The group included the following: F. Becke (Austria); C. E. Tilley (England); L. H. Borgström and H. G. Backlund (Finland); O. Andersen, O. A. Broch, C. Bugge, S. Foslie, C. F. and N. H. Kolderup, I. Oftedal, and Th. Vogt (Norway); and H. von Eckermann, A. Gavelin, P. J. Holmquist, H. Johansson, and P. D. Quensel (Sweden). An album of photographs from this excursion is preserved in the Goldschmidt Archives and a second copy in the Geological Museum in Oslo. In his instructions to the participants he recommended that they bring with them a half-bottle of brandy for medicinal use during the excursion, since at that time Norway was experimenting with a modified form of Prohibition.

