Ore deposits produced by magmatic segregation, with special reference to the nickel ores of the Sudbury district, Ontario

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Ore Deposits Produced by Magmatic Segregation,
with Special Reference to the
Nickel Ores of the
Sudbury District,
Ontario.

by

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ORE DEPOSITS PRODUCED BY MAGMATIC SEGREGATION,
WITH SPECIAL REFERENCE TO THE NICKEL ORES
OF THE SUDBURY DISTRICT, ONTARIO.

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Introduction.

Part I.

Nickel-Copper Deposits.

The Sudbury District.

Other Nickel Deposits.

Part II.

Titaniferous Iron Deposits.

Magnetites of the Adirondack Region, New York.

Titaniferous Magnetites.

Non-Titaniferous Magnetites.

Part III.

Other Igneous Deposits.

Chromite.

Corundum.

Diamond.

Segregation Veins.

Part IV.

Differentiation of Rock Magmas.
Introduction.

In recent years the theory of the origin of ore deposits by magmatic segregation has taken strong hold upon students of economic geology. The segregation theory was a bold departure from the earlier views that all ore bodies were the result of concentration by circulating meteoric waters, and it has furnished the most satisfactory explanation for the origin of certain deposits which have been found intimately associated with igneous rocks.

In this paper the writer makes no radical departure from the views held at present on the process of magmatic differentiation; he has simply introduced types of ore deposits produced by a direct segregation of the ore minerals from a molten magma. Special reference has been made to the Sudbury Nickel District since that is one of the largest and most important regions in which the ores are presumably of igneous origin, and one upon which the author has done some field work from which were drawn the conclusions outlined in the body of this paper.

Type deposits of iron, chromium, aluminum, and diamond that have been formed by magmatic segregation are discussed, and conditions favorable for the formation of deposits of gold, silver, lead, zinc, tin, and other rare metals as a result of extreme differentiation are given.

In conclusion the problem of differentiation of rock magmas is briefly considered and the factors or agencies operating are discussed.
PART I.

NICKEL-COPPER DEPOSITS.

The Sudbury District.

No attempt will be made to outline the general geology of the Sudbury district for such information regarding the region has already been published in reports by A.C. Coleman (2), of the Ontario Bureau of Mines and A.E. Barlow (6), of the Canadian Geological Survey. The discussion is limited to a consideration of the methods of occurrence and origin of these most interesting sulphide deposits.

A resume of the two views held in regard to the origin of the Sudbury ore deposits may be briefly stated as follows:

1. That the sulphides are primarily of igneous origin, having separated from a molten norite magma by a slow process of differentiation, the ores having segregated at the bottom of the eruptive and at the margin of a synclinal basin in obedience to the laws of magmatic solutions.

2. That the sulphides are entirely of secondary origin, having been deposited along the brecciated margin of the eruptive by aqueous solutions. The sulphides replaced the rock and also acted as a cement, the ore-bearing solutions having been introduced sometime after the intrusive had cooled and had been fractured.

All geologists who have advocated the igneous theory concede that there has been solution and redeposition subsequent to the formation of the ores, resulting generally in enrichment of the sulphides and alteration of the original norite rock; that the greatest amount of such alteration has taken place in the offset deposits and that many of
the marginal deposits remain today nearly as they were formed, very little change having taken place through aqueous agencies since the time of formation.

On the other hand, the advocates of a secondary origin for these sulphide deposits fail to recognize any factor other than circulating waters for their deposition.

The men who have done the most detailed geological work in the region are Dr. A.E. Barlow and Dr. A.P. Coleman. Both are strong advocates of the igneous theory of origin for the ore bodies. Their conclusions are based principally upon field evidence. Opposed to their views, and a strong advocate of an aqueous origin for the sulphide deposits, is Doctor Dickson. His conclusions are based principally upon laboratory study of polished surfaces of the ores.

The metallographic methods used by Doctor Dickson are intensely interesting, but they show only the present condition of the ores and not necessarily the primary conditions under which the sulphides were formed. It may not be amiss to quote at this point his concluding remarks (2). "Aside from the main contention that the deposits are replacements, any arguments advanced as to the actual source, manner of concentration and paragenesis of the ores may be regarded as largely tentative and as inviting discussion, by which we may hope to arrive at more definite conclusions as to the actual processes and sequence of events, culminating in these remarkable bodies of ore as we find them today."

In his paper Doctor Dickson clearly and strongly presents his arguments to prove the secondary character of the ores. However, the weight of his conclusions would have been greatly increased if they
had been based not alone upon laboratory study, but upon thorough field work and laboratory studies combined. That laboratory studies without thorough field study may lead to error in solving the origin of the Sudbury ores is forcibly expressed by Doctor Coleman (2) in referring to the work of Dickson. He says, "Doctor Dickson seems to have been singularly unfortunate in the choice of his material for study since he has selected almost without exception the brecciated rock material enclosed in the ore, and judging from his photomicrographs and descriptions, has not studied the opposite phase in which the norite is thickly speckled with the ore particles. Many of Doctor Dickson's examples are from offset deposits and naturally enough for one who had but a short time for field work in the region, he does not distinguish their characters from those of the marginal deposits, which point more clearly to an origin from the molten norite."

The brecciation at the contact of the nickel-eruptive and the country rock, which consists of greenstones, granite, gneiss, and other rocks, is as one would expect as a result of an igneous intrusion. The deep-seated magma spreading out beneath the overlying Animikean sediments would have to stope its way, and many fragments of the intruded rocks would be broken off, some probably being assimilated in the norite magma. The enclosed rock fragments are both angular and rounded, the latter probably being the earlier fragments broken off, while the former may be referred to stoping action of a later stage when the magma had lost much of its heat and could no longer fuse the edges of the fragments.

The ore bodies are found in intimate relation with the norite, and this association is so persistent that one is forced to conclude that there must be some genetic relation between the sulphides and the
norite magma. The ore bodies occur at the margin of the eruptive rock and are of finer grain immediately at the contact than at some distance away. The rock in immediate association with the ore is much more basic in composition and finer in texture than the rock farther removed from the contact. As one proceeds from the margin toward the inner basin, the eruptive rock gradually becomes more acid and coarser-grained until the norite has changed to micropegmatite. At the same time the sulphides, which often occur in masses at the basic edge, change to pyrrhotite-norite with the sulphides disseminated throughout the rock. This in turn grades insensitively into norite practically free from sulphides, and in less than a mile from the basic edge of the southern range no sulphides at all are found in the eruptive rock. The transition between the normal norite and the pyrrhotite-norite furnishes unmistakable evidence that the sulphides were formed during the cooling and crystallization of the norite magma. The norite is unquestionably the original source of the ore.

Just when the synclinal basin was formed is unknown, but more evidence points to the sinking of the Archean basement and consequently the upper sediments into the space formerly occupied by the magma during the time of eruption and during its slow cooling than to formation after the magma had solidified. From a consideration of this structure, the abrupt change from massive sulphides to barren country rock is as would be expected in the case of segregation of the ore bodies from a liquid magma. Through fractional crystallization, gravity, convection currents, and probably other factors, the heavy parts of the magma would settle to the bottom and the basic constituents would collect at the cooler parts, which would be at the contacts. The contemporaneous or subsequent formation of the synclinal basin, and the long period of
erosion to which the edges were subjected, would cause just such structural conditions and ore occurrences as are found in the field today.

The differentiation of magmas into a basic border zone and an acid core has been recognized and studied in many cases. The factors producing this separation and concentration are not agreed upon by petrologists, but that such conditions obtain in solidifying magmas is indisputable. The Sudbury laccolithic intrusion was subjected to this process of differentiation. If the magma separated into diverse parts, the acid being concentrated at the center and the basic segregating in the outer portions, would it not be reasonable to suppose that the heavy sulphides in a like manner separated from the basic portion of the magma? A magma rich in dissolved metals and sulphur is all that would have to be presupposed. Gravity would be an especially important factor in the concentration of the metals. Pyrrhotite and chalcopyrite are rock-forming minerals, and occur widely disseminated in many igneous rocks. In the case of the Sudbury laccolithic intrusion there was either an exceptionally large amount of dissolved sulphides present, or else the oxides of the metals were present in great abundance and at the time of segregation there was introduced a supply of sulphur (an element common to volcanic eruptions) which was more than enough to satisfy all the uncombined oxygen. In either case there would be no chemical difficulties in the way of the igneous formation of these ores.

The conditions under which the Sudbury laccolithic intrusion began to differentiate into an acid and a basic phase were those of considerable depth. The intrusion spread out between the Archean rocks below and the Animikean sediments above. These sediments, it is
estimated, had a thickness of nearly two miles, and, at such depth and under such conditions of pressure, the magma would cool very slowly, and there would be ample time for a complete separation. In such a case gravity would undoubtedly be an important factor in the settling of the heavy sulphides to the bottom and the collecting of the lighter acidic constituents at the top. Michel Levy's theory of the action of fluid mineralizers would aid in the concentration of the lighter or more acid substances above and the basic below. The basic constituents would also tend to concentrate at the edges of the intrusive sheet, probably in accordance with Soret's principle, which states, "If different portions of a homogeneous solution of a salt are kept at different temperatures for any considerable length of time, the salt will concentrate in the cooler portion of the solution." Both Vogt and Kemp favor this principle in the differentiation of a magma, and although many scientists have discarded this principle when applied to magmas, on the basis that such a process of molecular diffusion would require too long a time, it is considered to be a possible factor. Under such conditions of depth and of temperature as existed in the case of the Sudbury laccolith, the time required for differentiation by Soret's principle may not be a very serious objection to its application as one of the factors of differentiation of the Sudbury ores.

The magmatic waters which always follow extensive vulcanism are thought by the writer to have been of primary importance in the concentration of the large ore bodies. After the sulphides had undergone a process of segregation by gravity, and the magma was still in a molten condition, such concentrating action by the magmatic waters would be simply one of the factors of the magmatic differentiation
process, and could not be classed as after-action. There was, very probably, after-action also that caused further concentration of the ores by solution and redeposition in fractures produced by cooling and contraction of the magma, and probably by a certain degree of further settling of the synclinal basin. The action of the magmatic waters during cooling, which would cause a greater fluidity of the basic portion at the margin, would aid in explaining the great distances to which some of the apophyses extend into the country rock.

The richest deposits, many of which are almost pure sulphides, are found in embayments which extend into the Archean substratum. The most important deposit of this character so far worked is the Creighton mine. At this point an enormous body of sulphides rich in nickel and copper has been opened up. This deposit seems to afford an excellent example of concentration due primarily to gravity, the heavy sulphides having evidently settled into the depression and solidified as pure ore. That aqueous alterations and enrichment were of great importance in concentration, seems hardly possible as the ore and rocks are singularly free from fracturing.

Another factor which would probably aid in the differentiation of the magma is convection currents, resulting from unequal temperatures. The magma spreading out between the rocks would become cooler at the points of contact with the country rock. The upper and lower and outer edges would, therefore, be the coolest parts of the sheet, the outer margin especially, and a circulation would start between these points and the highly heated center. This process, combined with chemical affinity, would possibly constitute a factor well worth considering in the discussion of the relative importance of the various
factors in connection with the magmatic differentiation of the Sudbury ores.

The paragenesis of the sulphides is largely a matter of speculation, but a few orders of crystallization will be given. According to Fournet, in a molten magma of silicates in which sulphur has been dissolved, the sulphur shows affinity for the metals in the following order: copper, nickel, cobalt, iron, tin, zinc, lead, silver, antimony, and arsenic. From this we would expect to find that the ore minerals had crystallized in the following order: chalcopyrite, pentlandite, and pyrrhotite. The copper, nickel, and cobalt sulphides, which constitute but a small part when compared with the amount of pyrrhotite, should, therefore, be found concentrated in the pyrrhotite, and in many cases such relations are found, but more often the reverse occurs. In other places the intimate relation between the sulphides themselves and with the norite, points to a nearly contemporaneous solidification. Again, the relations show that the pyrrhotite antedated the pentlandite and the chalcopyrite since the pyrrhotite is often surrounded by the chalcopyrite. In consideration of the last described condition of occurrence it would seem that the chief factors controlling the solidification of the metals were the viscosity of the magma and the fusing points of the sulphides. Mr. David H. Browne (3) has brought out an excellent illustration upon this view and shows the possible manner by which such large and comparatively pure concentrations of the sulphides could have formed. He likens the fused magma to a matte pot filled with copper-nickel sulphides. The copper tends to move outward toward the cooler sides while the nickel is concentrated inward to the center. Study of the ore deposits at Sudbury seems to confirm the general
impression that the copper and nickel in the magma have followed to a large degree these same laws, and have distributed themselves in accordance with their viscosity and fusion points.

Another factor which must be considered in the crystallization of the Sudbury intrusive is the law governing mass-action. Mass-action as recognized operates to produce many irregularities in the crystallization of a magma. The chemical equilibrium of a complex solution is very unstable and is easily displaced by such influences as temperature and concentration. To what extent mass-action influenced the order of crystallization in this magma cannot be stated, but it may have reversed Fournet's order to begin with, and later the magma may have reached the proportions of a eutectiferous solution, and subsequently crystallized according to the laws governing such a solution. Since the pyrrhotite is so much more abundant than the other sulphides, this law of mass-action may have been of primary importance in determining the order of crystallization of the ore minerals.

The metallographic studies of the ore bodies by Campbell and Knight (1) showed the order of formation of the sulphides to be, 1. pyrrhotite, 2. pentlandite, 3. chalcopyrite. But their work cannot be used in determining the order of primary deposition of the ores for their specimens show three periods of deposition of the sulphides, two at least of which are secondary since they occur in veins and along fractures in the pyrrhotite.

The men who favor most strongly the aqueous origin of the ores consider that there may have been a slight primary concentration of the metals with the intrusion of norite, but they consider such a concentration unimportant. Doctor Dickson does not attribute the source
of the metals to the norite, but favors a more distant source. The metals it is thought may probably have been minutely disseminated in the rocks through which the depositing solutions passed.

However, from a consideration of all the facts it seems clear that we must look for the source of the ore within the eruptive itself. At this stage we must recall the following facts: 1. Sulphides are known to be primary rock-forming minerals. 2. Magmas tend to differentiate into chemically and mineralogically diverse parts, the acid rocks forming the inner zone or core, the basic rocks the outer or border zone, this splitting up being due to fractional crystallization, action of mineralizers, variations in temperature and pressure, convection, or a combination of any or all of these and probably many other factors. 3. The sulphides are found at the borders of the basic border-zone, in embayments, and disseminated through the norite, the amount of ore being inversely proportional to the distance from the basic edge. 4. The sulphides are very intimately associated with the norite of the basin type, and with norite only. 5. The conditions were those of great heat and pressure, and there was present in all probability a large amount of magmatic water. 6. The ores throughout the district are remarkably uniform, consisting as they do of pyrrhotite, chalcopyrite, and pentlandite. If the ores had been formed by deposition from aqueous solutions, it seems hardly possible that such uniformity should exist. Replacement minerals such as are found in other copper and nickel fields are almost entirely lacking, and there is a marked absence of crystals of metallic minerals and drusy-covered cavities so typical of water action. 7. Professor Walker (2) says that in some places the rocks close to the ore bodies are greatly altered, the pyroxene having changed to hornblende.
Such a condition would show secondary aqueous action. Again, in many places the rocks close to the ore bodies show no alteration at all. Such a condition would show that the ores could not have been formed on such an extensive scale, as they are at present found, by aqueous solutions. Doctor Barlow (5) says that of his collection showing fresh and unaltered material, most of the specimens were obtained in the immediate vicinity of the various mines. Some containing as much as ten percent sulphides had undergone so little metamorphism as to permit of the positive identification of all the prevailing minerals, including hypersthene, enstatite, diallage, olivine, and labradorite. Sulphides frequently occur in portions of the norite which have suffered little or no dynamic metamorphism, and practically no hydro-chemical alterations.

**Conclusion.**

In drawing a conclusion as to the origin of the Sudbury ores, precedence must be given to the views of such men as Vogt, Coleman, Barlow and others who have studied deposits of copper-nickel sulphides both practically and theoretically, the relations shown in the field and the associations found to exist between ore and rock from laboratory studies. These men have shown in their reports evidence to uphold the igneous theory, and most other geologists who have studied the deposits in the field have agreed with these pioneers of the theory of ore deposits formed by magmatic segregation.

On the other hand, much credit must be given to Doctor Dickson in his work tending to prove an aqueous origin for the ores. His views are the strongest in support of such a theory.

In consideration of all the facts, it seems hardly conceivable
that these ore deposits could have been formed primarily by any action other than a direct segregation from a molten magma.

Other Nickel-Copper Deposits.

The Gap mine, Pennsylvania, has not been in operation since 1893 and therefore is of no commercial importance at present. The point of interest lies in the origin of the pyrrhotite deposits.

The occurrence of the ore body is quite similar to those of the Sudbury district, except that the evidences of water action are much more prominent. In many ways the ore strongly suggests a contact deposit, but after a study of both the Gap mine and the Sudbury ore bodies, the weight of the evidence is in favor of an igneous origin for both districts.

At the Gap mine, the amphibole in which the pyrrhotite occurs does not show a very much weathered surface. The latter condition would prevail if such a large body of ore had been formed by aqueous solutions. Kemp says (2), "If the ore has been derived from solutions along a crushed zone, it is remarkable that the amphibolite is most massive near the mine, while at the western end of the lens, where the gneissoid (i.e. most sheared) varieties occur, the ore fails."

The process of concentration may have been quite similar to the segregation of the Sudbury ores from the norite magma, the chief factors probably being fractional crystallization, gravity, and convection currents.

Vogt has given excellent descriptions of the occurrence of
pyrrhotite in Norway and in Sweden and has adduced strong evidence for the classification of these deposits as direct segregations from molten magmas. The ore bodies are very similar to those at Sudbury and the genesis is probably the same. What has been said in description of the occurrence of the Sudbury deposits may, with a few modifications and additions, apply equally well to the pyrrhotite ores of Scandinavia.

Campbell and Knight (1) found the same order of deposition of pyrrhotite, pentlandite, and chalcopyrite in the ores of the Gap mine and those from Norway and Sweden as was found to exist in the Sudbury ore bodies. If these deposits were entirely secondary in their origin, it seems hardly possible that the same conditions should exist and the same order of deposition followed in all of these fields; whereas, if the primary concentration of the ores has been from a molten magma, the various factors which have already been discussed may have operated equally well in each district, and the secondary alteration by aqueous solutions produce the same relations as are found to exist from metallographic studies. In fact, the uniformity in the order of deposition of the ores in these various localities is very strong evidence favoring an igneous origin of the ore deposits.
Titaniferous iron deposits are of world-wide distribution. Large bodies are found in New York State, Rhode Island, New Jersey, Minnesota, Wyoming, Colorado, in the Provinces of Ontario and Quebec, in Norway and Sweden, and in Brazil. Smaller occurrences are found in many other places.

An igneous origin for the highly titaniferous magnetites is generally accepted. The intimate relation existing between the ore bodies and the basic plutonic rock, leaves little doubt that magmatic segregation has been of primary importance in the concentration of the ores.

The origin of the less titaniferous magnetites is not so well established. They are generally associated with acid rocks, and the presence of such minerals as apatite, fluorite, hornblende, and quartz is not unusual. In deposits showing such relations, circulating waters and pneumatolitic action have undoubtedly been instrumental in the formation of the ore bodies, although a primary concentration may have taken place by a direct segregation from a molten magma.

In some regions both types of magnetite deposits are found. Their intimate relations, both of occurrence and in chemical and mineralogical composition, point strongly to a common source for the eruptives. If given time, a deep-seated magma will separate into chemical units with no sharp line of demarkation between them. It seems necessary for such a process to operate if the eruptive sequence is to be explained. The amount of titanium in combination with the magnetite
is dependent upon the amount of lime and silica in the magma. If an excess of the lime and silica is present, much of the titanium will unite with them to form titanite. As a result, the magnetite when formed would contain little or no titanium and would therefore be very valuable as an ore.

The Adirondack region furnishes us an excellent example of both types of titaniferous magnetite deposits, and it will therefore be used as a type locality.

The Magnetites of the Adirondack Region, New York.

The iron ores of the Adirondack region are of two types, 1. the titaniferous, and 2. the non-titaniferous. The former carries quite a large percentage of titanium, and on account of the difficulty of treatment, is very little used at present. The latter usually contains a fraction of one percent of titanium which is not a serious objection in its metallurgy.

Excellent descriptions of the general geology of the region, the mines, and the occurrence of the ore bodies, have been given by J. F. Kemp (6) and D. H. Newland (1), so these details will not be repeated.

Titaniferous Magnetites.

The titaniferous magnetites of the Adirondack region are associated with very basic igneous rocks, gabbro and anorthosite. These rocks are the first of a series of igneous intrusions in the region. The later intrusions are more acid in character, being syenites and granites,
but it is quite evident that they were derived from the same source as supplied the basic rocks.

To understand the origin of these deposits a few facts relating to their occurrence must be presented. The earliest rocks of the region were gneisses and crystalline limestones. These were intruded first by a magma, which upon cooling produced the anorthosite rock. Of much later date, but very closely related to the anorthosite, is gabbro. This rock is abundant only within the area occupied by the former or in close proximity thereto.

The ore bodies are found in both the anorthosite and the gabbro. Those occurring in the former are undoubtedly concentrations within the anorthosite magma, for, as a rule, the ore grades from magnetite practically free from gangue minerals into magnetite and gangue intimately mixed in all proportions, depending upon the distance from the central ore body. Those occurring in gabbro generally appear as dikes cutting the anorthosite. The bodies found in such relations are usually small and of tabular form, grading into the normal gabbro at the edges. At Calamity Brook, near Lake Sanford, there is an excellent illustration of this type of deposit. A series of gabbro dikes rich in magnetite is intruded into the anorthosites.

As to the origin of the titaniferous magnetites, the relations existing between the ore and rock leave little doubt to the theory that they are a direct concentration from the molten magma. Also the mineralogical characters of the anorthosite and the gabbro would strongly suggest that they were derived from the same general source. Upon this assumption, there must have taken place a differentiation of the basic magma at depth. The magma was rich in iron and titanium, the latter
probably playing much the same rôle as silica. The exact nature of the causes of differentiation into an anorthosite and a gabbro phase is not fully understood, but that there is a tendency to split into different parts or probably layers, composed of different compositions, is undoubtedly the case, and gives us an explanation for the eruptive sequence.

Assuming this operation to have been in force for the magmatic reservoir beneath the Adirondack region, dynamic forces caused the anorthosite phase of the general magma to intrude the older gneisses and crystalline limestones of the region, in the form of a batholith. While this intrusion was cooling, there was a segregation of the iron oxide and a union of the iron and titanium, the latter probably acting as an acid. This segregation may have been caused by the operation of any or all of the various principles mentioned under the discussion of the Sudbury ore deposits. Probably the chief ones in force in this case were gravity, convection, and fractional crystallization.

Long after the cooling of the anorthosite magma, and probably after some dynamic metamorphism, the gabbro, rich also in iron and titanium, was intruded into the former as dikes and small bosses or stocks. In a similar manner, the metals were concentrated in the gabbro. The rich dikes found at Calamity Brook and elsewhere were probably almost pure ore at the time of intrusion.

The most important ore deposits of titaniferous magnetite are found near Lake Sanford, western Essex County. The ores have not been very extensively exploited up to the present time, and, on account of their high percentage of titanium, are of no great economic importance.
Non-Titaniferous Magnetites.

The non-titaniferous magnetites, or those carrying but a fraction of one percent of titanium, are the most widespread of the Adirondack iron ores. The deposits are found in several different kinds of rocks, all of which are acid or partly so. The wall rocks include gneisses of granitic, syenitic, and dioritic composition, acid pyritic, garnetiferous gneisses, hornblende and biotite schists, amphibolites, and occasionally crystalline limestones.

The ores show great variation in mineral and chemical composition. They range from impure lean varieties, consisting of magnetite intermixed with the constituents of the wall rocks, to those made up of pure magnetite. As a rule, the magnetites show very little effect of alteration, the only chemical change being that of oxidation resulting in some pseudo-hematite or martite.

The rocks associated with the non-titaniferous magnetite, as has been said, are acidic, in contradistinction to the gangue rock of the titaniferous ores. It is probably due to the acid gangue that the magnetites under discussion contain such small amounts of titanium, for it has undoubtedly united with calcium and silica to form titanite. The latter mineral, being found in considerable quantities in association with the ores, tends to confirm this theory.

Fluorite, apatite, hornblende, and other minerals of this class, are often found intercrystallized with the magnetite. Very frequently, also, pegmatite and vein quartz are present. Such associations point conclusively to pneumatolitic action and circulating waters being factors in the concentration of some of the ore bodies.

At some period subsequent to the gabbro eruption, the syenite,
granite, and other rocks closely related to them, were intruded into a large area. These acid intrusions are evidently not of contemporaneous age, but probably consisted of a series of eruptions spreading over considerable time. With almost all of these intrusives, magnetite bodies are found, a condition which shows the wide range and the abundance of the iron.

The mineralogical relations between these several acid types of eruptives point to a common source or reservoir in which there must have been a process of differentiation, thereby giving the eruptive sequence. In similar manner, there was a separation and concentration of the iron oxide during the process of cooling and crystallization. The forces operating to produce segregation probably varied with the different intrusives, but, in general, gravity, convection currents, fluid mineralizers, and fractional crystallization were factors influential in the formation of the ore bodies by a direct process of segregation.

There are many strong points in favor of an igneous origin for many of these ore bodies. The close association existing between the deposits and the wall rock, the gradation from bodies of pure magnetite to disseminated ore and gangue, and the high percentage of iron found in these acid rocks, give valid evidence in support of this theory. On the other hand, the presence of fluorite, apatite, pegmatite, and vein quartz, would lead one to conclude that the ore bodies were epigenetic in their origin. In some cases the magnetite deposits are probably of igneous origin, in others they may be due to contact after-action. Again, both processes may have been in force primarily, and subsequent metamorphism may have caused enrichment and other changes.
The non-titaniferous ore bodies are found, as a rule, on the outer margin of the acid intrusion. There may be an underlying geological basis for this distribution, and, if such relations could be worked out in greater detail, the origin of the deposits might be more clearly understood. In such case, the ore bodies may be shown to have been deposited by gaseous and aqueous solutions, the ore bodies replacing the country rock at the contacts. Kemp (7) thinks that the most reasonable explanation is that the ores are contact-deposits, formed by the influence and stimulus of the gabbro intrusion. If this theory be correct, the acid rocks were the original country rock of the region, and antedated the intrusion of the gabbro and anorthosite.

The writer is not in full harmony with this view, but favors magmatic segregation as of primary importance in the concentration of the ores. Such a theory could explain their occurrence in the bordering zones, through concentration by fractional crystallization. Assuming the magma to have had an excess of iron, during the process of cooling magnetite would have been one of the first minerals to crystallize. As fast as these crystals formed, they would be shoved to one side into the cooler part by further crystallization of the other minerals. This is the law of diffusion as described by Sorby. The ore bodies, being in the margin of the intrusive, would be subjected to alteration by the water and gases given off from the cooling of the acid magma, and the presence of such minerals as apatite, fluorite, hornblende, etc., would be a natural consequence.

The relation of the acid intrusions to those of the basic forms an interesting study. The presence of intermediate rocks shows a continuous series from the basic to the acid ends. All of the ores
contain titanium, the amount varying according to the kind of rock with which they are associated. The earliest rocks of the region were acid gneisses and crystalline limestone. The anorthosite and gabbro may have worked toward the surface by a process of magmatic stoping, the masses of country rock broken off sinking to the bottom. There they would dissolve and form a stratum of acidic magma with no sharp line of demarkation, but rather a gradation from the basic to the acid phases. We would expect then that subsequent eruptions would become more and more acid, and such was the order.

The association and origin of the Adirondack titaniferous iron deposits furnish us with the general occurrence of such ores throughout the world. They may be found with both acid and basic rocks, although the latter is of more common occurrence. Types of deposits of this character must not be confused with the ordinary magnetite which is found generally in metamorphic rocks, or in sediments in which the ferric oxide has been reduced by organic matter to magnetite. The titaniferous magnetite deposits are in practically all cases the result of concentration by direct segregation from a molten magma.

Two other large deposits of titaniferous iron in this country may be mentioned because they so closely resemble those of the Adirondacks. The vast gabbro area in Minnesota, north of Lake Superior, contains a number of masses of ore which are undoubtedly segregations within the intruded magma. The other is found on Iron Mountain in southeastern Wyoming. The titaniferous magnetites occur as large dikes of nearly pure metal which cut the older anorthosites. Still younger than the dikes, is a granite intrusion. The anorthosite, iron ore, and granite are very probably differentiation products of a common magma.
PART III.

OTHER IGNEOUS DEPOSITS.

Chromite.

Chromite is distributed widely, being found in nearly all localities in which peridotite, or its metamorphic equivalent, serpentine, is present. Chromite is also found in alluvial deposits, but primarily it is a constituent of basic igneous rocks. Probably the occurrences on our continent that have been most thoroughly studied are those in Canada, in California, and in the peridotite belt which extends in disconnected outcrops from Alabama to Maine.

The original association of the chromite has been the peridotites or closely related igneous rocks, although in many cases these rocks have been greatly changed by metamorphism. Just as ilmenite is usually associated with gabbro, anorthosite, etc., so the chromite is generally found in peridotite.

Chromite deposits are found in masses or pockets at the borders of the igneous intrusion, or in concentrated bodies well within the eruptive. The former seems to be the prevailing type in North Carolina while in California numerous large deposits occur some distance within the serpentine masses.

The manner of occurrence of the chromite bodies is strong evidence that they have been formed by a direct segregation from a molten peridotitic magma. Probably the most important factors producing concentration in this case are fractional crystallization, gravity, and convection currents. In a peridotite magma the minerals crystallizing first would be the oxides containing no silica, chief among which would
be chromite. The first crystallization would be in the cooler parts, that is at the contacts of the intrusive with the country rock. This difference in temperature would cause convection, and, as a result, new supplies of material would be brought to the outer boundaries and the chromic oxide would be further concentrated.

While concentration along the contacts was taking place, there would doubtless be a settling of the heavier parts of the magma, due to gravity, causing a concentration in the lower portion. Differences of temperature and basicity of the magma, together with convection currents and other movements, would cause a localization of concentration, thus resulting in the segregation of the basic minerals. The factor of gravity is undoubtedly very important in the formation of ore bodies composed of heavy metallic oxides and sulphides.

With the exception of the placer deposits, all chromite ore deposits of economic value have been formed by segregation from a molten magma.

Corundum.

The corundum found in various parts of the country as a primary concentration from a magma rich in alumina, is associated principally with peridotites and closely allied rocks, with nepheline-syenites, with ordinary syenites, and also with granites. The occurrences in peridotite or dunite and in nepheline-syenite form the most important deposits. The former is the association in the belt of basic magnesian rocks extending disconnectedly from Maine to Alabama,
being especially well developed in North Carolina and Georgia; the latter in the southeastern part of Ontario, Canada.

The origin of the corundum deposits is very similar to that given for chromite. The magma was exceptionally rich in aluminum and lean in silica. The alumina, being one of the most insoluble constituents of the magma, would be among the first to crystallize. This would take place primarily at the contacts of the intrusive and the country rock, and further concentration at these points would result through the action of convection currents and the process of fractional crystallization. Concentration would also take place to some extent well within the magma, due to the action of various crystallizing factors.

In Montana, sapphires have formed in dikes through concentration of alumina within the molten magma.

Diamond.

It is with some misgiving that the writer includes diamonds in the category of "deposits produced by magmatic segregation." So little is known in regard to the primary occurrence and origin of these precious stones, that anything that may be said must be considered as somewhat speculative.

Diamonds are found in association with igneous rocks, principally in South Africa, in the Tulameen District, British Columbia, and in Pike County, Arkansas. Some are also found in stream placers in various parts of the world. The igneous rock is in nearly all
cases peridotitic, and is known as kimberlite. The intimate association of the diamond with this rock gives weight to the recently advanced theory of an igneous origin for all diamonds. Fersmann and Goldsmidt in their recent monograph on the crystalline form of the diamond, state, that all the diamond crystals known to us have been formed suspended in a molten mother-liquid (magma).

Orville A. Derby (1,2), in two excellent articles on the genesis of the diamond, advocates an igneous origin, but favors crystallization by the later action of mineralizers. To quote from his second paper, he says: "Diamond crystals have been formed suspended in a medium sufficiently mobile, or susceptible to solution (replacement), to permit their free, all-round development." The essential difference between these two views is in regard to the physical condition of the enclosing rock at the moment of the crystallization of the mineral. In either case the carbon is a primary constituent of the deep-seated magma. In the former the carbon exists in the magma as a liquid, and crystallizes contemporaneously with the olivine. In the latter view the carbon is in the gases associated with and undoubtedly derived from the magmatic solution.

It is on the strength of the conclusions reached by Fersmann and Goldsmidt that the diamond has been included with segregation deposits.

The formation of the diamond by a direct concentration within the molten magma is not a chemical impossibility, and many stones found seem to suggest such an origin. This deduction is given additional weight by the recent studies of Fersmann and Goldsmidt in which they point out the extreme delicacy of the saturation point for
carbon in a solution from which the material of the diamond crystals was derived. The growth of the crystals would be due to a condition of supersaturation. Even a slight change in the physical conditions or the chemical relations of the magma, might cause crystallization, or the reverse, that is resorption of the previously formed crystals.

That diamonds are not found more widely distributed through the peridotite areas of the world may be explained by the absence of the requisite conditions of carbon saturation of the magmas.

Diamond as a primary crystallization in a peridotite rock has been reported in the Tulameen District, British Columbia, where this mineral is found as idiomorphic crystals in chromite which occurs in small segregations in a partially weathered dunite. The diamonds found are small and while of no commercial importance up to the present time, their genesis is of great scientific interest.

From the fact that the diamond is found principally in the metamorphosed peridotite, and that this alteration has taken place to depths far below that which ordinary weathering could accomplish, the weight of evidence points to an epigenetic origin of most of the diamonds of economic importance. Derby (1,2) has recently advanced such a view, and it certainly deserves a great deal of consideration.

According to his theory, the peridotite was an intrusive, and, after it had cooled, was fractured to such an extent as to permit a sufficiently free circulation of subterranean solutions to produce extensive alteration of the rock. The circulating solutions introduced water and carbon, the former causing serpentinization of the olivine, the latter crystallizing in the form of diamond. This would take place at ordinary temperature and pressure, as has been proven by
Friedlander.

The conclusion to be drawn from the results of the latest researches on the origin of the diamond, is, that it is undoubtedly of igneous origin, forming either as a direct crystallization from the molten magma, by replacement, or crystallization from the subsequent gaseous emanations.

Segregation Veins.

During the process of cooling of a magma the mineral constituents assume a definite order of crystallization which is governed primarily by mass-action and by their solubility in the magma. The end product in most cases is a very silicious solution composed of magmatic water, residual silica, and various active mineralizers. In this end product is concentrated all of the rarer metals, such as gold, silver, lead, zinc, tin, molybdenum, etc., that did not go into combination with the basic metals which would ordinarily crystallize among the first minerals if present.

This residual solution would be a differentiation product of the parent magma. It may be a fluid mass of rock-forming minerals with varying amounts of occluded water, or it may be an aqueous solution heavily charged with mineral matter. Between these two extremes there are all gradations. But in any case we must consider this solution as a magma.

The influence of this end product, or sub-magma, upon the formation of ore deposits, is viewed in varying degrees of importance
by geologists. The crystallization of this solution is of primary
importance in the formation of pegmatite veins, and is probably also
one source of quartz veins. Whether these veins can be considered in
the light of ore deposits would depend entirely upon the degree of con­
centration of the metals in this end product of magmatic differentia­
tion. Pegmatites are the chief source of cassiterite and molybdënum,
and some of the rare metals are found in this association. Spurr (1)
has found many auriferous quartz veins, the formation of which he con­
siders was due to the precipitation of this residual silicious solu­
tion, and should, therefore, be classified as a segregation deposit.

A discussion of the value of such theories of magmatic differ­
entiation, as related to ore deposits, will not be attempted here, but
the thought opens up an interesting field for speculation and for fut­
ure study.

Summary.

From the preceding discussion, it is seen, that, while the
deposits due to magmatic segregation are made up of numerous minerals,
their economic importance is small when compared with the ore bodies
formed by sedimentation, by metamorphism, by contact action, by magmat­
ic circulations and emanations, by replacement, etc.

The important segregated ores are nickel, chromium, titanifer­
ous iron, platinum, and diamond in ultra-basic rocks; gold, silver, lead,
zinc, tin, molybdënum, and some of the rarer metals in ultra-silicious
rocks; iron and copper in medium, and in both acid and basic rocks;
corundum in medium and in ultra-basic rocks. This list may be increased from time to time, but will probably never constitute a very important class.
Since the formation of ore deposits by magmatic segregation is but a phase of the differentiation of rock magmas, it may be well to discuss, briefly, the opinions held today regarding differentiation and the various factors which influence this important process.

If the Planetesimal Hypothesis is accepted in explanation of the earth's origin, the earth must be considered as essentially a solid throughout, and not as a globe with a solid crust and a molten interior. Under this new conception, the explanation of the eruptive sequence of igneous rocks is a difficult one and somewhat hypothetical. The phenomena of the order of intrusions and extrusions have led to the advancement of many theories to explain the manner and cause of eruptions. In most of them, the process of magmatic differentiation is offered to explain the variations so often found in the igneous rocks of a small area, while again, the same reasoning is just as applicable in the explanation of large petrographical provinces. Nothing more than a very brief discussion of the subject will be attempted in this paper, and only in so far as this problem is related to the ore deposits described above, will any details of the process of magmatic differentiation be given.

By magmatic differentiation is meant the separation or splitting up of a homogeneous rock magma into chemically and mineralogically diverse parts. The conditions under which the magma must exist, and the factors necessary to produce differentiation, are not well understood, and it is doubtful if experimental work will ever fully reveal the conditions which obtain at depth.
That such a process as differentiation is taking place, or rather has taken place, is evinced by a study of the intrusions and extrusions of igneous rocks in many volcanic regions. The rocks within a comparatively large area often show such close resemblances, mineralogically and chemically, that all must have had a common source. Again, the conditions and gradations of the rocks in some laccoliths and batholiths show that there has been a differentiation or separation of the magma in place, subsequent to intrusion. This leads to a consideration of two kinds of differentiation, that occurring at depth; that taking place in situ after eruption from depth as a homogeneous magma.

In considering the movement of the magma from deep within the earth towards the surface, ribbons of lava are conceived to be wending their way upward in narrow fissures caused by earth movements, and, probably, by assimilation. Daly advances the theory of magmatic stoping and subsequent assimilation as the manner in which the magma moves toward the surface, and in view of the fact that there probably exist large reservoirs of lava well below the surface, such a process as stoping seems essential if the formation of these magma basins is to be explained. Probably no great amount of differentiation takes place during the general movement of the lava from the center of the earth, unless it be through the assimilation of foreign material; but as this upward movement must necessarily be slow, diffusion probably works effectively against such a separation.

By differentiation in place, is meant a separation of the magma into chemical units occurring within a reservoir which exists comparatively near the surface. Such basins may exist considerably
deeper than the limit of the zone of fracture, which is approximately six miles, because the lava has a density practically the same as the surrounding rocks, and consequently rock flowage would not operate to cause a dispersion of the liquid magma. From such reservoirs, fed from below by many stringers of lava wending their way upward, come the intrusive and extrusive lavas. To illustrate, the magma which existed beneath the Sudbury nickel basin was the reservoir; the laccolith was the intrusion.

That the factors influencing differentiation at depth and differentiation in situ after irruption are very similar, can readily be seen, the only difference being that in the former the process would be slower than in the latter, due primarily to the more uniform temperature of the magma and the surrounding rocks. Just what the conditions are under which magmatic differentiation is produced, no one has been able to state. It is probably due to a combination of many factors which vary in importance in different volcanic districts.

Magmas are regarded as solutions of rock-forming materials. To what extent these solutions are miscible, and under what conditions they become immiscible, cannot be stated from our present limited knowledge of the subject. Some writers claim that magmas are completely miscible only at temperatures considerably above the fusion point. At such high temperatures even sulphides and silicates are thought to be miscible. Other writers claim miscibility at any temperature higher than the fusion point of the magma. The evidence seems to favor the former view, but certain magmas may be conceived to be immiscible at any and all temperatures.

The more important processes of differentiation are,
follows: 1. Separation by gravity in still molten magma. 2. Soret's principle. 3. Convection currents. 4. Assimilation of foreign materials. 5. Action of fluid mineralizers. 6. Fractional crystallization. In considering the relative importance of these, it must be recalled that the conditions most likely to affect a magma are changes of temperature, changes of pressure, and loss or addition of gases. These three factors are all important in both the differentiation and the crystallization of a magma.

1. Separation by gravity in still molten magma. This principle has been appealed to by a number of writers to account in part for differentiation. Its importance must be confined to those magmas which are not completely miscible. In such cases the solution would separate into layers, the heavier part being at the bottom, the lighter part above. Sulphides and other accessory minerals are extremely insoluble in magmas, and, only at high temperature, and probably considerable pressure, would the magma exist in a homogeneous state. Gravity was probably a factor of paramount importance in the segregation of the sulphides at the bottom of the Sudbury laccolithic sheet and in the concentration of many of the titaniferous magnetite deposits.

In the case of the differentiation of a homogeneous magma into acid and basic phases, the factor of gravity would be negligible. The magma would be in a miscible condition, and, since magmas act in all respects like ordinary solutions of mineral matter, they would, also, to a certain degree, be ionized, the ionization depending upon the concentration. In the ionic condition, molecular concentration could operate only to a very limited extent.
Since conditions of high temperature and miscibility prevail at depth, differentiation by gravity in still molten magmas would not operate as effectively there as under near-surface conditions of temperature, pressure, and gas content.

2. Soret's principle. The application of Soret's principle to account for magmatic differentiation has been long held as being of considerable importance, but in recent years Backstrom, Becker, and others, have shown that its influence would be practically negligible. The factors of time, temperature, and viscosity are the strongest arguments against this hypothesis. It has been shown that molecular diffusion in such a viscous solution as a rock magma would require almost unlimited time to be effective, while the variations in temperature would be so small that no pronounced osmotic pressure gradient would be set up. The osmotic pressure in a liquid is proportional to the absolute temperature as well as to the concentration. In the cooler parts of a magma, therefore, the osmotic pressure is less than in the warmer parts. As a result, equilibrium would be destroyed and there would be movement of the molecules toward the cooler part, resulting in concentration near the borders. Since the osmotic pressure is proportional to the concentration, theoretically it would be higher in the cooler parts than in the warmer parts. As a result, there would be movement from the parts of concentration to the more dilute portion of the magma. These two factors, then, temperature and concentration would work in opposition, provided the entire magma were in a fluid condition. But if crystallization of the more insoluble minerals (which in general are the more highly infusible) were in operation at the borders, the basic molecules, which were brought to the
borders, would crystallize and become concentrated, while the more acid material, in order to maintain equilibrium, would diffuse toward the inner parts of the magma reservoir. In such a case, osmotic pressure, due to differences in temperature and concentration, instead of working antagonistically would be additive in its effect. While diffusion would be extremely slow, when we consider the great length of time that a large body of magma may remain in a fluid state when under proper conditions of depth, Soret's principle should not be entirely discarded when we sum up the factors influencing magmatic differentiation of certain lava intrusions.

3. Convection currents. Differences in temperature and pressure of a magma, together with the shape of the enclosing walls, cause convection movements. The value of such agencies in the process of differentiation have been discussed with varying degrees of emphasis by different writers. That such movements would be instrumental in the concentration of like molecules, or even of minerals which have crystallized, seems reasonable. Since there are always some differences in the temperatures of a magma there must be movements within the body to produce equilibrium. These would, necessarily, be more prominent in magma reservoirs near the surface than in those at depth.

4. Assimilation of foreign material. The strongest advocate of this process is Daly. He has shown (1) how the eruptive sequence may be accounted for through the application of his theory of magmatic stoping. For example, we may consider a basic magma stoping its way toward the surface through a granite or gneiss. Large blocks are broken off, and, upon sinking to the bottom, are dissolved. As
long as there is movement upward there would be a continued increase in
the amount of acidic material at the bottom of the magma. There would
be some intermixing of the basic and acid parts through diffusion and
also gravity, but as long as there was a pronounced movement upward,
there would be no great amount of intermixing. Eruption may then take
place either as intrusion or as extrusion, the acid phase closely fol­
lowing the basic, or with a distinct or even a long period between.
Such an explanation would account for the eruption of varying lavas
from one volcanic vent. A similar process may take place by the up­
ward movement of magmas of any composition. While assimilation proba­
biy does operate to produce chemical diversities within a magma, and may
account for the sequence of eruption in some instances, it is not con­
sidered to be the most important factor producing magmatic differentia­
tion.

5. Fluid mineralizers. This theory has been advanced by
Michel-Levy. In brief, it accounts for differentiation chiefly by a
circulation, at high temperature and pressure, of the fluid mineral­
izers which entangle the lighter substances of the magma and concen­
trate them near the top of the fluid mass. The heavier basic mater­
ial would, therefore, be in greater proportion at the bottom, an order
corresponding with a common order of ejectment during eruptions. There
are exceptions to this order, but, nevertheless, this theory should be
considered as probably one of the factors aiding in the differentiation
of rock magmas. The functions of these mineralizers will be consider­
ed in more detail in connection with the discussion of fractional crys­
tallization.

6. Fractional crystallization. Fractional crystallization
is probably one of the most important factors in the separation of rock magmas into normally acid and basic parts.

The order in which the mineral matter crystallizes from a molten magma is dependent upon four essential conditions primarily, the relative abundance of the mineral matter in solution; the solubility of the minerals; their fusion points; the amount of fluid or gaseous mineralizers present. In normally proportioned magmas, the less soluble substances will crystallize first. But in magmas which contain an abundance of certain elements, the order of crystallization is often controlled by mass-action. Similarly the presence of large quantities of mineralizers may influence the early crystallization of some minerals, while their tendency to lessen the viscosity of the magma may cause certain minerals, which, owing to their abundance may tend to crystallize first, to remain in the fluid condition through great changes of temperature and pressure. Thus the order of crystallization may greatly influence the eruptive sequence.

In a body of magma, the contacts with the inclosing rocks are necessarily cooler than the inner parts. Crystallization would, as a rule, occur first at the boundaries. As already mentioned, convection currents would be set up, other materials would be carried out to the borders, and additional crystallization of the less soluble minerals would occur. In this manner, the basic portions of a magma are often concentrated at the borders of an intrusion. Such conditions would obtain only where the remainder of the magma was so viscous that the action of gravity would not cause the solid basic minerals to sink to the bottom.

Fractional crystallization may also operate from many centers
to produce differentiation. If conditions existed within the magma such that certain minerals reached the point at which they are no longer soluble in the magma, they would begin to crystallize at innumerable centers. As a rule, the basic minerals would be the first to crystallize in this manner and gravity would cause them to sink towards the bottom. If crystallization continued, there would be practically a complete differentiation by such a process. If conditions favorable for eruption were present while the magma in the upper part of the reservoir was still fluid, the first phase would be acid. The release of pressure would probably cause a resorption of the basic material, thereby giving a succeeding basic phase to the eruption. If the magma in the upper part of the reservoir were in a very viscous condition, and a considerable release of pressure occurred, the lower basic part might remelt and erupt through the upper viscous part giving a reversal to the order of eruption. Again, the order of eruption would depend largely upon which part of the magma basin had been tapped. Between the possible conditions cited above, there would be all gradations.

The application of these principles governing magmatic differentiation has been discussed in connection with the study of the various type deposits. The conclusion reached from such studies shows that in no case was the separation due entirely to any one factor, but rather to a combination of factors. For example, in the Sudbury magma there may have been differentiation at depth previous to the laccolithic intrusion. After the formation of the laccolith, further differentiation may have taken place. Again, the magma may have been homogeneous at the time of irruption and differentiation
have taken place entirely within the laccolith. The latter view was taken in the general discussion of the formation of the ore deposits.

In the magnetite region of the Adirondack mountains, there was, undoubtedly, differentiation at depth, and considerable periods of time between the intrusions of the various sub-magmas. Subsequent to the irruptions, segregation of the heavy oxides took place.

The other type deposits described embody the same principles of differentiation that have been briefly discussed, but the most important factors operating to produce differentiation vary in nearly every case.

In recapitulation, it may be said, that, owing to the difficulty of field observations and the impossibility of reproducing in the laboratory such conditions as exist in nature, conclusions reached from a study of magmatic differentiation are almost entirely inductive. The problem which confronts the petrologist forms one of the most intricate in chemical geology, and opens a large field for research on the border lines between the sciences of geology, physics, and chemistry.
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