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THE PEGMATITES OF THE DULUTH GABBRO.[1]

FRANK F. GROUT.

INTRODUCTION.

This paper describes some pegmatitic phases associated with the Duluth gabbro in Minnesota. The wide differences of opinion as to the origin of pegmatites, long ago led Williams to suggest that pegmatites form by two somewhat distinct processes.[2] It is therefore not suggested that the conditions of origin at Duluth apply to all pegmatites, but it is clear that these pegmatites were formed under conditions rather different from those commonly assumed for siliceous pegmatites.

DESCRIPTION.

The gabbro with which the pegmatites are associated at Duluth was intruded into diabase flows, and during some sort of movement, was differentiated into a series of bands of varying composition. Near the base, bands of periodotite are conspicuous, while higher up feldspathic bands are predominant.[3] There are patches in the banded gabbro, especially near the base and near the top, in which the gabbro minerals have grown coarse, with grains up to six inches in diameter; and since the borders of the patches are ill defined (Plate XIII., *B*) the masses are to be attributed to processes of segregation. Miarolitic cavities and a little biotite may be taken as indications of the presence of mineralizers but the biotite is scarcely more abundant than

[1] Published by permission of the directors of the United States Geological Survey and the Minnesota Geological and Natural History Survey. Part of a dissertation presented to the faculty of Yale University, in partial fulfilment of the requirements for the degree of doctor of philosophy.

[2] Williams, G. H., "Granitic Rocks of the Middle Atlantic Piedmont Plateau," U. S. Geological Survey, Fifteenth Ann. Rept., p. 684, 1895.

[3] F. F. Grout, Papers at the Geol. Soc. of America meeting, December, 1917.

in some common bands of the gabbro. The patches of notably coarse grain range from a few inches to many feet across and are estimated from incomplete exposures to be roughly ellipsoidal

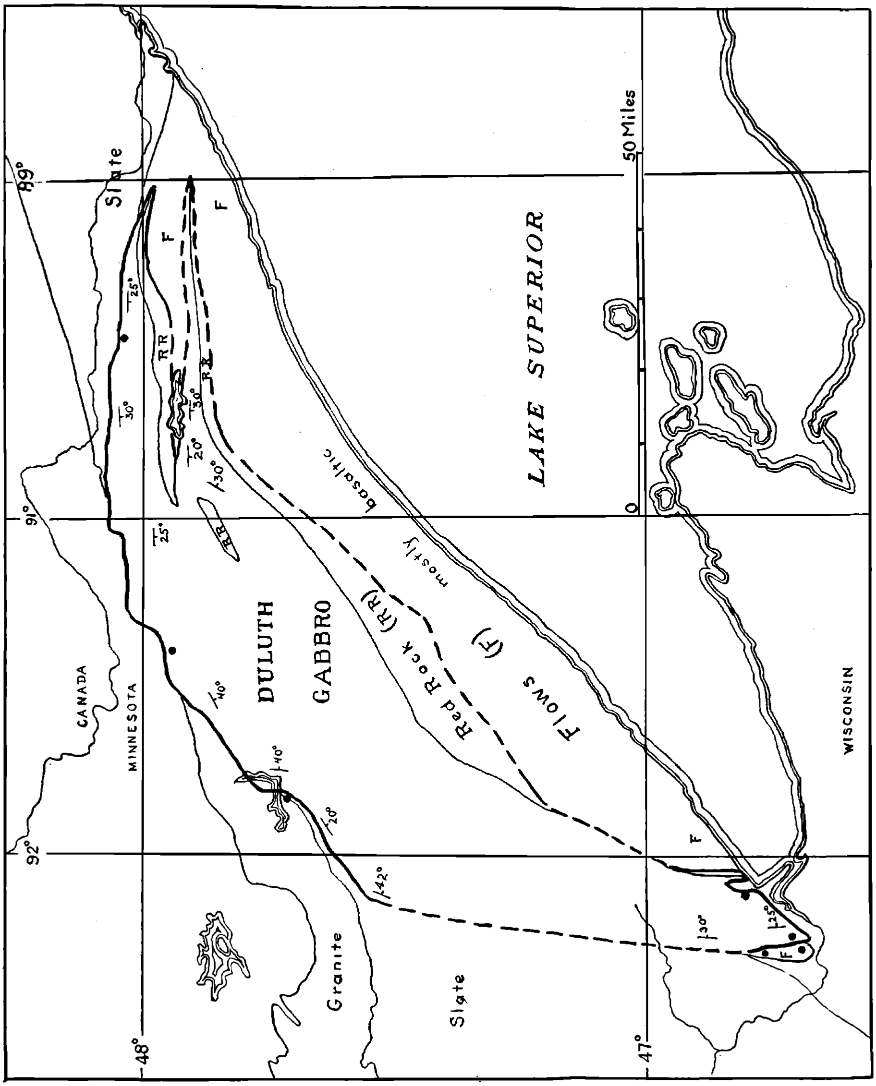


FIG. 30. Sketch of the area occupied by the Duluth gabbro, showing by small spots, the places in which pegmatite has been noted. Symbols of dip and strike are based on a banded structure in the gabbro; the "red rock" is considered a differentiate of the same intrusion.

to somewhat tabular in form. In many places near the base the patches are numerous. Specific localities are: east of the tunnel at Short Line Park, Duluth; on the Northern Power Company power line, half a mile west of Piedmont Avenue, Duluth; at Allen Junction; on an island in Poplar Lake; and at Lake Number Four. (See Fig. 30.)

There are also, just outside the gabbro, pegmatitic dikes ranging in size from the smallest stringers (Plate XIV., *B*) to dikes several feet wide. They extend downward from the gabbro into the floor rock, to a distance equivalent to about 100 feet from the former position of the gabbro. No such dikes appear inside the gabbro. The best exposures are east of the tunnel of the Duluth, Winnipeg and Pacific Railway near Short Line Park. Some of the dikes have the mineral composition of coarse gabbro, but others vary widely, some being granitic. Near Birch Lake the Mesabi iron formation close to the gabbro bears an abundance of disconnected pegmatitic stringers. (See Plate XIII., *A*.)

ANALYSES OF OLIVINE GABBRO AND ENCLOSED PEGMATITE, SHORT LINE PARK, DULUTH.

	Olivine Gabbro.	Pegmatitic Gabbro.
SiO_2	47.10	42.24
Al_2O_3	12.92	18.50
Fe_2O_3	12.95	4.68
FeO	9.46	14.50
MgO	3.08	2.76
CaO	10.29	10.36
Na_2O	2.61	2.19
K_2O	0.92	0.33
H_2O+	0.71	1.80
H_2O-	0.12	0.25
CO_2	——	1.67
TiO_2	1.38	1.16
P_2O_5	0.01	0.19
MnO	0.80	0.13
	101.62	100.76
Classification	Camptonose[4]	Auvergnose

Most of the minerals in the pegmatitic gabbro are much altered, but it is clear that some of the rocks have the same min-

[4] Assuming, as is evident, that some iron is oxidized.

erals as the adjacent olivine gabbro of normal texture. The pyroxene is augite and diallage; the olivine is conspicuous even in the field. Mr. George S. Nishihara has analyzed the gabbro and associated gabbro-pegmatite of Short Line Park. They are similar in many respects, but the pegmatite is more altered, containing much CO_2.

One instructive exposure is that of a curving four-foot pegmatite dike which shows in itself a complete gradation from gabbro sides to granite center. (See Plate XIV., *A*.) The walls of this dike consist of diabase altered to a granulitic or sugary texture. Its marginal phase, which is in places firmly attached to the wall, is an apatitic gabbro with feldspars an inch or more in length. Within two inches from the border the interstitial red granophyr appears among the large grains of plagioclase. This siliceous material increases in proportion toward the center but without the least sign of any contact between types, and finally at the center becomes a quartz-feldspar-hornblende rock with granitoid, rather than granophyric texture. There is no sign of any banding, nor of any fluxion structure such as would indicate any intrusive movement towards the end of the process of crystallization. There is even a slight tendency along the walls for the crystals to point out at right angles to the walls—a comb structure made up of plagioclase crystals. The types have not been fully analyzed but the variation in alkalies shows the great change in the character of the feldspar.

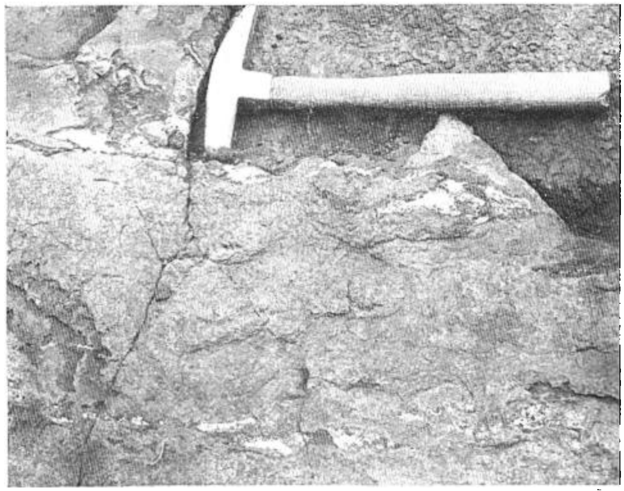
ALKALI CONTENT OF THE ZONES IN A PEGMATITE DIKE.

	Border Zone.	Median Zone.	Central Zone.
Na_2O	3.23	4.78	3.94
K_2O	1.71	2.34	6.32

PEGMATITES OCCUR AT THE OUTSIDE OF THE MAGMA.

The pegmatitic rocks thus far discovered in the gabbro are very close to the border. Many pegmatitic rocks related to the gabbro are in the floor rock below. It is to be emphasized that no pegmatite is found near the central parts of the mass.

In the occurrence as a border phase, the pegmatitic gabbro

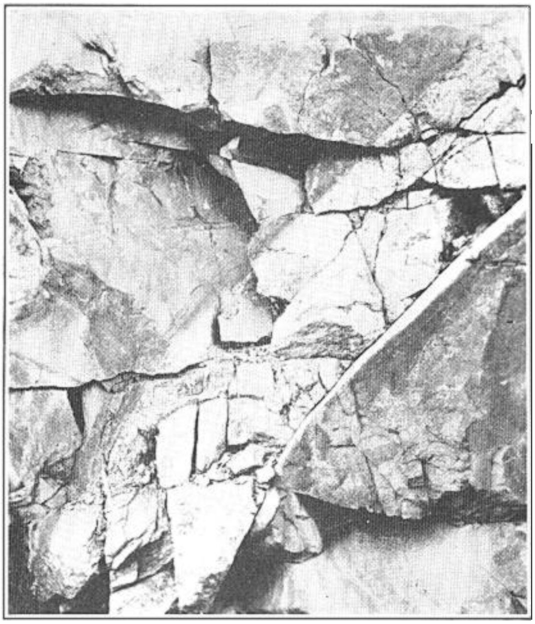


A.

Discontinuous stringers of pegmatite in the Mesabi iron-bearing rocks where they form the floor of the Duluth gabbro.

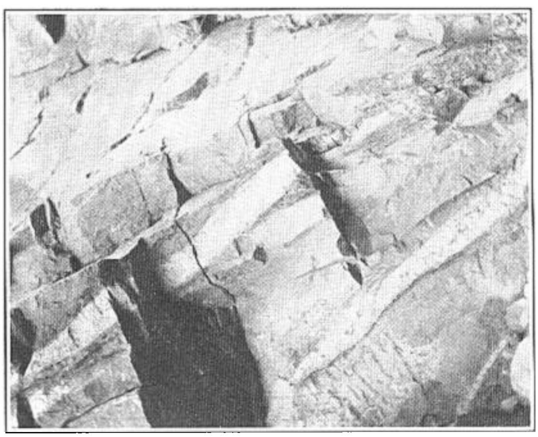
B.

Patches of coarse grain, near the base of the Duluth gabbro.



A.

Pegmatite dike, four feet wide. It varies in composition from coarse gabbro at the sides, to granite in the center.



B.

Stringers of pegmatite gabbro in the basalt forming a floor under the Duluth gabbro.

resembles the more common siliceous pegmatites. In recent American descriptions the following are examples. The pegmatites of Maine are apophyses; less commonly, dikes in the granite.[5] At Barre, Vermont, dikes of pegmatite start from the granite surface and penetrate the schist.[6] At Marblehead and Swampscott, Massachusetts, pegmatites occur in apophyses but not in granite.[7] In New Hampshire the pegmatite is found to be less abundant in the granite and other plutonic formations than in the fibrolitic and other schists.[8] At other places in New England where the country rocks are both granite and gneiss, the pegmatites occur in the gneiss rather than in the granite.[9] In Colorado pegmatites are reported from many districts.[10] There is much pegmatite at Cripple Creek, but little in the Cripple Creek granite, of which the pegmatites are believed to be phases. In the Monarch district only a few pegmatites cut the granite but they are common as apophyses in the gneiss and schist. In the Montezuma district the pegmatites are found around the margin of the granite especially in connection with the metamorphics. In the Alma district pegmatites cut the gneisses and schists more than the granite. In Montana the pegmatites are rather closely associated with the margin of the Boulder batholith.[11] The relations are similar at Elkhorn,[12] as also at several places

[5] Bastin, E. S., "The Pegmatites of Maine," U. S. Geol. Survey Bull. 445, p. 14, 1911.

[6] Dale, T. N., "The Granites of Vermont," U. S. Geol. Survey Bull. 404, p. 13, 1909.

[7] Crosby, W. O., and Fuller, M. L., "Origin of Pegmatites," *Tech. Quart.*, Vol. 9, p. 351, 1896.

[8] Crosby, W. O., and Fuller, M. L., *Am. Geol.*, Vol. 19, p. 152, 1897.

[9] Dale, T. N., "The Granites of Massachusetts, New Hampshire, and Rhode Island," U. S. Geol. Survey Bull. 354, p. 158, 1908. Lahee, F. H., *Am. Jour. Sci.*, Vol. 33, p. 457, 1912.

[10] Lindgren, W., and Ransome, F. L., U. S. Geol. Survey Prof. Paper 54, p. 48, 1906. Crawford, R. D., Colo. Geol. Survey Bull. 1, p. 19; Colo. Geol. Survey Bull. 4, p. 50, 1913. Patton, H. B., Colo. Geol. Survey First Report, p. 132, 1909. George, R. D., Colo. Geol. Survey Bull. 3, p. 47, 1912.

[11] Barrell, Joseph, "Geology of the Marysville Mining District, Montana," U. S. Geol. Survey Prof. Paper 57, p. 58, 1907.

[12] Weed, W. H., and Barrell, J., U. S. Geol. Survey, Twenty-second Ann. Rept., Pt. 2, Plate 48, 1901.

in British Columbia[13] and abroad. In the Haliburton and Bancroft areas in Ontario, pegmatites are especially abundant in the thin covers of the intrusions.[14] According to several text-books these relations are common the world over.

Nevertheless, although the Duluth pegmatite resembles these other occurrences in its border position, it differs from many of them in the detail of its relations. For example, Bastin says in general summary of the Maine occurrences, that where pegmatites are abundant they seem to be in the *roofs overlying* batholiths; and this is apparently the general impression derived from occurrences elsewhere. However, since the floors of batholiths have not yet been closely studied, we can hardly state whether that floor also contains pegmatites. At Duluth more occurrences have been noted near the floor of the mass than near the roof. The formation of pegmatite is evidently not governed entirely by the conditions of roof.

PEGMATITES MAY FORM BEFORE MAGMA SOLIDIFICATION.

Many investigators attribute pegmatites to the residual watery-magma, or "mother liquor" left after partial crystallization.[15] As proof of their origin after solidification began, Barrell cites the fact that pegmatites occur in tension cracks in the granite magma.[16] Nevertheless, the proof that some pegmatite forms after partial solidification is not proof that they are in any sense a solidified mother liquor. If the process of crystallization left a mother liquor of pegmatite, its characteristic occurrence should be the central core of the mass, and not the border. As sug-

[13] Daly, R. A., "Igneous Rocks and their Origin," p. 369, 1914.

[14] Adams, F. D., and Barlow, A. E., Canada Dept. of Mines, Memoir No. 6, p. 140, 1910.

[15] See, *e. g.*, Van Hise, C. R., "A Treatise on Metamorphism," U. S. Geol. Survey Mon. 47, p. 728, 1904. Harker, A., "Natural History of Igneous Rocks," pp. 294 and 323, 1909. Daly, R. A., *op. cit.*, p. 268. Barrell, J., Conn. Geol. and Nat. Hist. Survey Bull. 13, p. 88, 1910. Pirsson, L. V., "Rocks and Rock Minerals," pp. 178, 179, 1911. Williams, G. H., U. S. Geol. Survey, Fifteenth Ann. Rept., p. 684, 1895. Lindgren, W., "Mineral Deposits," pp. 717–718, 1913.

[16] Barrell, Joseph, "Geology of the Marysville Mining District, Montana," U. S. Geol. Survey Prof. Paper 57, p. 58, 1907.

gested above, pegmatites are rarely if ever found near the centers of large batholiths. The relative abundance of emanations from a magma at different stages is uncertain. The magmatic emanations that have been most carefully studied are probably those of contact deposits of metallic ores. It seems likely from these that emanation occurred at several stages, probably in part from liquid magma, and in part from magma from which crystallization had removed more or less anhydrous material, leaving a residue rich in water.[17] Since metalliferous emanations may form before crystallization it is unreasonable to assume that no pegmatitic emanation could develop at an equally early stage. Several features of the Duluth pegmatites indicate that they did form early.

1. It is mentioned above that no pematite dikes have been found in the main gabbro mass, but that many are close outside the border. If any of the gabbro had been solid and cooling when the pegmatitic material was generated, it would have been a favorable place for tension cracks and therefore for pegmatite dikes. Their absence suggests that the gabbro was not solid when they escaped, and it is probable that crystallization had not even begun.

2. An even stronger argument is based on the composition of the dikes and their position under the gabbro. It might be suggested by some, that the pegmatitic gabbro was a product of the basal part of the magma while the more siliceous pegmatites were derived from a higher more siliceous horizon. But this is wholly improbable, for the pegmatites, both basic and siliceous, occur *all together* at the base, not at any higher horizon, except just at the top; and if a siliceous emanation from the top reached down to the base—15,000 feet below—it would surely leave some traces of pegmatite on the way down; and none are found.

3. According to a current theory, during the solidification of average gabbro, olivine is probably one of the first essential minerals to crystallize in large amounts. In a slowly cooling magma the olivine crystals collect near the bottom, and the liquid be-

[17] Lindgren, W., "Mineral Deposits," pp. 666–668, 1913.

tween the crystals becomes progressively more basic.[18] At Duluth the field occurrences seem to meet the demands of this hypothesis; the rock near the bottom is a banded peridotite. It is very clear that during crystallization the bottom of the mass became more basic, changing from gabbro to peridotite. But when did the pegmatites form? They certainly do not resemble the peridotite; some of them are gabbro, but others are more siliceous, rather than more basic. It seems much more probable that a siliceous emanation came from the liquid original gabbro of medium composition, than from the partly crystalline peridotite with its mother liquor growing more and more basic.

Furthermore, the dikes of differentiated pegmatite show that if there was any change in composition of the emanation from time to time, the siliceous portion must have been the later, for it forms the center of the dikes. Since the granite emanation was a late emanation, and yet earlier than the accumulation of the early olivine crystals, the pegmatite dikes must have formed before the main magma crystallized.

In general, it seems likely that pegmatites escape from a fluid magma into the walls. If it happens that the borders of the magma begin to crystallize before the escape is complete, pegmatites will be found in the borders of the intrusion; otherwise, almost wholly in the wall rocks.

MINERALIZERS IN PEGMATITE MAGMAS.

Pegmatites are the source rocks for a number of hydrous minerals like muscovite, and minerals containing rare elements, like tourmaline, wolframite, and the lithium minerals; and this fact is the main support of a theory that the magma or solution from which they formed was high in "mineralizers." The idea is supported by the presence of miarolitic cavities and comb structures, like the structures of veins formed from water solution. Since water reduces the viscosity of a magma allowing free diffusion, the coarseness of grain may also be considered a sign that water was present. The above-mentioned tendency for peg-

[18] Bowen, N. L., "Later Stages of the Evolution of Igneous Rocks," *Journal of Geology,* Supplement, December, 1915, pp. 27 and 83.

matites to escape from the magma on all sides may be a still further indication of gases escaping from solution, for such border positions would be the logical points for gases to escape under such tension. However, the proportion of water which will yield notable effects is in some doubt. In many pegmatites rare elements, hydrous minerals, and cavities are not conspicuous. W. H. Emmons found schist inclusions in a pegmatite, in such a position as to indicate that they did not sink—the magma did not contain water enough to greatly reduce its density.[19] Similar conditions are reported from Boulder County, Colorado.[20] There are thus two arguments against any invariably high proportion of water; if it was present it must have almost wholly escaped from some pegmatites; and if it was present it must have had very little effect on the density of the magma. It seems more probable that conspicuous pegmatite may develop in some conditions with only a small per cent. of mineralizers.[21]

The Duluth pegmatites are coarse, yet rare or hydrous minerals are not specially abundant; there may be mentioned a few grains of monazite and locally some concentrations of apatite. Miarolitic cavities were seen in a few siliceous pegmatites. The diabase walls of the pegmatite must have been almost impervious to water, and certainly contained little water to contribute to the pegmatite. The rocks seem to have developed without much concentration of water.

THE MECHANICS OF PEGMATITE SEPARATION.

On the theory of pegmatite "mother liquor," the mechanics of separation depend on crystallization and possibly filterpressing; but it is here argued that some pegmatites separate before magma crystallization. Under what circumstances may a magma furnish a fluid differentiate with some extra water? It is questioned by some whether water can diffuse out from a fluid magma, and suggestions have even been made that it is more

19 Referred to by E. S. Bastin, *Jour. Geol.,* Vol. 18, p. 310, 1910.

20 George, R. D., "Tungsten Area of Boulder County," Colo. Geol. Survey Bull. 1, pp. 20–22, 1910.

21 This agrees with the conclusions of Bastin in Maine, *op. cit.*, p. 45.

likely to pass in.[22] However, the physical chemistry of the combination is fairly well outlined.

The solubility of a gas such as water changes with variations in pressure, temperature and composition. Given a magma, we may well assume from any theory of its origin, as well as from its later behavior, that it contains in solution, some water; the amount probably varies in different cases. Little can be said as to whether there is any approach to saturation at the depth of magma formation, but it is clear that at a time of intrusion, both temperature, pressure, and composition may change a good deal. The pressure becomes less; the wall rocks and magma tend to equalize their temperatures; there may be solution of the wall rocks to modify the composition; and finally when crystals grow the residual liquid changes in composition because of their removal. Each of these changes affects the concentration of the dissolved water. At an early stage the pressure change is probably the most important.

As a laccolitic magma heats its walls, any water in the wall rock will be heated far above critical temperature, and if the wall is impervious the pressure of the vapor will be enormous—a pressure that would seem to be great enough to drive the vapor into the magma, forcing it into solution. But it must be remembered that solution depends not only on pressure but composition. If the magma is already saturated with gas at a certain pressure, more gas will dissolve only as the pressure increases. Is there no limit to the pressure a gas may exert, forcing itself into solution? Two may be suggested. (1) If the roof is not too strong it may be lifted. (2) If the magma is forced into the chamber by the greater pressure behind it, the pressure of gas must not exceed that pressure of intrusion or it will stop the intrusion, forcing the magma back to the deeper reservoir.

The question then is whether or not the magma is saturated with water at the pressure of laccolitic intrusion. If it is anywhere near the saturation point under the deeper conditions of magma generation, the intrusion to much shallower chambers must relieve the pressure to such a degree as to leave it greatly

[22] Crosby and Fuller, *op. cit.*

supersaturated. The known transfer of material at some contact deposits is proof enough that there was supersaturation in those cases; and it is likely that similar conditions are common where the records are less clearly preserved. No doubt conditions vary, but it is almost certain that many intrusions give off quantities of water.

As a whole it seems much more likely that water escapes from a magma than that the wall rocks contribute any to the magma, though both cases may occur. If the contact rock is impervious, the watery separate from a magma might collect as an upper layer of slightly lower specific gravity; if the rock is porous or fractured, the watery fluid might escape on any side, top or bottom, wherever a thin fluid may penetrate more readily than a viscous magma.[23] Such separates are therefore to be expected on all sides, but the chief accumulations would probably occur under an impervious roof.

The exact nature of this watery fluid is not so clearly known. It is above the critical temperature of water, but possibly not above the critical temperatures of a concentrated water solution. Above critical temperatures, pressure causes a great contraction and increase in density, so that the fluid may occupy less volume than liquid water at ordinary temperatures. Being in contact with molten magma, it is also a very active solvent, and may well contain enough rock minerals to produce pegmatite. Credit is given Arrhenius[24] for the suggestion that between the mineral fusion and watery phases there is only limited mutual solubility. Pegmatites are a strong argument for the correctness of this idea. Whether the watery phase is to be considered a gas, or an immiscible liquid, may well be left for the physical chemist to decide after a study of strong solutions at high temperatures; but the evidence is very clear that *something separates.* The watery phase is likely to remain liquid longest. The various magma constituents will be divided between the two phases according to their solubilities.

[23] Such separation is discussed by Fenner, C. N., "Gneisses in the Highlands of New Jersey," *Jour. of Geology,* Vol. 22, pp. 694–702, 1914.

[24] Geol. Fören. Förh., Vol. 22, pp. 395–415, 1900.

THE DIFFERENTIATION OF PEGMATITES.

The variability in pegmatite dikes both lengthways and sideways has been observed at many localities. The gradation from feldspar rock to quartz rock has been of special interest in the study of quartz veins. The change is commonly thought of as due to the crystallization of the feldspar from the solution before it got far from the magma source, while the quartz stayed in solution farther. Where quartz forms a central zone in a pegmatite dike it is attributed by some to a change in the character of the emanation rather than to differentiation in place. Nevertheless it is noteworthy that the fluidity indicated by the coarseness of grain and supposed presence of water would be a great aid to differentiation even without later or long continued intrusions. Any such later movements would be likely to produce a banded structure or internal contact, but differentiaiton has occurred in dikes that show no such structures. Even in the absence of coarse grains, dikes have differentiated,[25] but strongly contrasted differentiates are reported mostly from larger dikes. Pegmatites may show, in a narrow dike, a change from pure feldspar sides to pure quartz center; or as at Duluth, a change from gabbro sides to granite center. The latter case, though no more extreme, results in rock types which are less often related in outcrop than quartz and orthoclase.

Bowen explains the occurrence of dikes with basic borders by the passing of magmas of gradually changing composition.[26] The same idea has strong support in the pegmatites in the fact that the crystals have grown so very large that the supply of material was probably maintained by a magma movement of some sort. Bowen sharply contrasts differentiation *in situ,* with the continued passage of magma of changing composition. At Duluth the antithesis indicated by such terms finds no place.

[25] Geikie, A., "Structural and Field Geology," pp. 203–204, 1905. Lawson, A. C., "Differentiation of Dikes," *Am. Geol.,* Vol. 7, p. 153, 1891. Bücking, H., "Jahrbuch k. preuss. Landesanst.," 1887, Taf. V. Winge, K., "Geol. Fören. Förh.," Vol. 18, p. 187, 1896. Daly, R. A., "Igneous Rocks and their Origin," pp. 77, 78, 246, 402, 1914. Harker, A., "Natural History of Igneous Rocks," p. 146, 1909.

[26] Bowen, N. L., *op. cit.,* p. 14.

There was probably slow movement and considerable convection circulation to assist diffusion during crystallization, but the differentiation took place in the dike, not in the magma chamber from which the dike came; for that magma was becoming a peridotite, while the center of the dike was becoming a granite.

SUMMARY.

Pegmatites occur associated with the Duluth gabbro, having formed on all sides of the mass, largely as emanations into the wall rock. Distinct dikes are found only outside the contact of the gabbro. This fact, in connection with the siliceous nature of some pegmatites and the peculiarly basic nature of the gabbro near by, indicates that the pegmatite magma separated from the gabbro magma, before crystallization had begun to produce basic segregations. That is, the two magmas separated as two fluids, rather than as a separation of crystals from a fluid. The pegmatite magma seems to have carried only a moderate amount of mineralizers, and yet enough to facilitate the growth of large crystals, and a sharp differentiation, for some dikes vary from granite to gabbro in a space of two feet.