INTRODUCTION.

Pegmatites have received considerable attention from petrologists and mineralogists during recent years, and many papers on various subjects pertaining to these multifarious bodies have been contributed to the geological literature. These contributions have brought out a wealth of new details regarding the minerals and mineral associations of pegmatites; they have widened the field of study by including new types and thus made possible a comprehensive system of classification of pegmatites; they have also to some extent modified the genetic theories, especially by emphasizing the late-magmatic phases of the genetic processes; but they have not, so far, produced any radical change in the generally accepted ideas of pegmatite genesis.

The majority of writers still agree on the magmatic origin of pegmatites and all seem to realize that the "life history" of pegmatites is one of evolution through several stages, varying conspicuously even within the same paragenetic group.

These leading ideas were established more than forty years ago largely through the writings of W. C. Brøgger.

Brøgger's conclusions were based on studies of the syenite pegmatites and granite pegmatites of Southern Norway. On simple evidence of geologic, petrographic, and mineralogic observations,

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1 No attempt will be made to review the literature, but references to the more important publications of recent years that have come to my attention are given at proper places.

Brøgger succeeded in proving the magmatic origin of pegmatites and in establishing definite stages of evolution. Thus the magmatic, the pneumatolytic, and the hydrothermal stages were expressively mentioned as representing crystallizations at successively lower temperatures and with increasing influence of volatile substances. Recent studies by other investigators have elaborated, without actually changing, the genetic theory of pegmatites thus first clearly expressed by Brøgger.

In the recent discussions of genetic processes the problems are dealt with chiefly from a geochemical point of view, the discussions being based on petrogenetic theories supported by mineralogic and petrographic evidence. With all these contributions, however, the subject has not been exhausted; even in the field of geochemical study of pegmatites there are numerous unsolved problems, and when considered from other points of view the pegmatites offer a rich field for study.

In the present paper some of these other problems will be briefly discussed. Special attention will be given certain genetic problems that can be most profitably discussed by laying stress on the structural features and on various aspects of the relationship between the pegmatites and their containing rocks: the mode of occurrence of the pegmatites. I will base the discussion on examples from the pre-Cambrian pegmatites of Southern Norway, more especially the area southwest of the Oslo region (largely "Sörlandet"), but the results may hold true for other pegmatites as well.

The more important points to be considered are the following: 1) Form and dimensions of pegmatite bodies and the attitude of these bodies especially in relation to structural features of the containing rocks or to geological features of the area in which they occur. 2) Distribution of pegmatites in various types of rocks with emphasis on the selective distribution of certain types of pegmatite in certain types of rocks. 3) Certain features of the structure of pegmatites. 4) A few types of paragenesis of pegmatites in comparison with the mineral association of the containing rocks. These points will not be treated in the sequence mentioned, but will be discussed at proper places in the general presentation of the subject.
The term pegmatite.

It may be well first to indicate what kind of geologic bodies are included in the term pegmatite in this discussion. The term is now often used simply to denote unusually coarse-grained rocks of igneous origin, and this may be the most suitable definition for the general purposes of petrography, but for the consideration of fundamental genetic problems it would be convenient to modify the definition in some respects. Obviously, when the very nature of the genetic processes are discussed, no definite theoretical solution of the problems involved, such as the assumption of an igneous origin of the pegmatite, should be taken for granted; the definition of the body whose genesis is to be explained should be based, as far as possible, on observable facts only.\(^1\)

As a definition, stringent enough to have a meaning still loose enough to be comprehensive and at the same time reasonably detached from petrogenetic theories, I would suggest the following: Pegmatites are mineral associations crystallized in situ, decidedly more coarse-grained than similar mineral associations in the form of ordinary rocks and differing from these in having a more irregular fabric of the mineral aggregates. This definition will be used in the present discussion.\(^2\)

This definition would include: “ordinary granite pegmatites”; all other types of pegmatites bearing comagmatic relations to definite families of igneous rocks, like syenite and gabbro pegmatites; many types of coarse-grained mineral associations endemic in metamorphic rocks (see p. 42); coarse-grained quartz lenses; and certain other

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\(^1\) This is perhaps an unduly severe application of the simple rules of formal logics in a field where circumstantial reasoning is often inevitable; it should willingly be granted, for instance, that the theory of the igneous nature or at least the magmatic origin of all ordinary pegmatites may well be given the rank of an observed fact, nevertheless it is believed that a strict adherence to elementary logical principles in this case may serve to clarify the discussion.

\(^2\) It should be noticed that a definition of this kind does not in any way contradict a geochemical petrogenetic definition like the one recently suggested by Fersmann (Z. Kr. Abt. B. 41, 64, 1931). The two definitions simply serve different purposes. Fersmann's is a summary of conclusions arrived at by logical reasoning on the basis of a theoretical interpretation of facts, whereas the definition here stated is a preamble of facts on which to build conclusions.
types of minor geologic bodies. In this discussion only pegmatites of quartz bearing mineral associations will be considered.

Any one who has had the opportunity to observe numerous bodies of this kind in the field must have been struck by the following general facts: The bodies here called pegmatites vary widely not only with regard to mineral associations, but also with regard to structure and mode of occurrence. However, it soon becomes clear to the field observer that on the basis of mode of occurrence, with some regard to other features, it is possible to classify these pegmatite bodies into a relatively small number of types (some of which will be considered in this paper). At the same time it is easily realized that all pegmatite bodies as a whole differ characteristically from an other group of minor geologic bodies of common occurrence: the igneous dikes.

**Remarks on igneous dikes.**

Such igneous dikes (e.g. diabase) occur in the same area and in the same kind of rocks as those containing the pegmatites, and a comparison between the two groups of bodies is natural. Viewed against the background of the simple relations of the igneous dikes certain features of the pegmatites will stand out more distinctly than they otherwise would. It may be worth while, therefore, to recapitulate very briefly some of the well known characteristics of the igneous dikes with special reference to those occurring in the same pre-Cambrian areas as the pegmatites here dealt with.

The most numerous dikes in the pre-Cambrian of Southern Norway are those of diabase and the most striking ones, owing to their width and great length, those of rhombporphyry (larvikite porphyry). These dikes are all younger than the pegmatites; they are the youngest igneous rocks in the area; in all probability they belong to the post-Downtonian igneous series of the Oslo region, a neighbouring region of the area here considered, the rhombporphyry representing one of the oldest members and the diabase the youngest.

It is characteristic of these dikes that they usually show distinct preferences for certain directions of strike and often have nearly vertical dips; thus the rhombporphyry dikes strike almost due north, several diabase dikes near Arendal strike northeast, some near
Kragerö strike east, others north. Many of these dikes have been traced over long distances along the strike, the rhombporphyry dikes up to 80 km\(^1\) and the diabase dikes up to 5 km. The rhombporphyry dikes may be as much as 50 m wide, the diabase dikes seldom more than 6—8, exceptionally up to 30 m wide.

All these younger dikes have parallel walls with fairly straight-lined courses. They all show the usual phenomenon of border zones against the country rocks. Every dike seems to be persistent in composition and structure all along its observed length. It is also to be noted that the dikes show no preference for any particular type of containing rock; they run indiscriminately and continuously through any combination of rock types.

According to well established theories dikes like these have been formed by intrusion of magma into fissures in older rocks. Some of the fissures may have extended upwards as far as to the surface of the Earth, thus perhaps becoming feeding channels for eruptions of lava, all have obviously had direct communication with the underlying magma basin through openings wide enough to permit a rapid flow even of a relatively viscous magma. The larger fissures have been formed by action of regional forces producing tensional tangential stresses in the Earth's crust. It is obvious that the igneous dikes have been formed in the upper parts of the Earth's crust, the zone of fracture. At the moment of intrusion the temperature of the surrounding rocks must have been relatively low.

These long established interpretations of the genesis of dikes should be clearly remembered when the genesis of pegmatite bodies are considered.

**Examples and discussions of pegmatite bodies.**

Compared with the simple structure and mode of occurrence of igneous dikes the corresponding relations of pegmatite bodies present a picture of confusion. It is true that many of these bodies apparently have some of the essential characteristics of dikes, such as parallel walls, but a large number of them have forms of such undefinable irregularity that by no stretch of the definition of the

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\(^1\) A dike running from Åmodt to Begndal. An other rhombporphyry dike has been traced from near Grimstad northward for more than 30 km.
term is it possible to classify them as dikes. When other features are considered no pegmatite body to my knowledge answers the description of a typical igneous dike.

In the discriptions given below some types of pegmatite are demonstrated. The examples are selected to show the great diversity of pegmatite bodies especially with regard to structure and mode of occurrence.

1. Large pegmatites in granites.

In a recent publication Vogt has pointed out that "within the granite itself great granite pegmatites are extremely rare, but small, as a rule very small pegmatites, on the other hand unusually frequent".

Vogt describes one pegmatite of extraordinary size and structure and a few of more ordinary type, all occurring within the same pre-Cambrian granites of Østfold. In other areas of pre-Cambrian granites I have observed three pegmatites large enough to be workable as feldspar deposits (all insignificant) and only a few others. One of these three occurs in the non-foliated Grimstad granite, the others in foliated granite. They are not essentially different from the numerous pegmatites cutting metamorphic rocks outside the granite fields, and a description of them will serve no purpose of this paper. I may only mention that none of these bodies appears to have any considerable length. Although they have fairly parallel sides they taper off within a short distance and are actually more lens-shaped than dike-shaped. This feature they have in common with the smaller bodies described below and with many of the larger pegmatites outside the granites.

1 The various subdivisions of the section of descriptions are not meant to indicate any definite system of classification.


3 I can fully confirm Vogt's observations from my own experience over a large area of pegmatite bearing rocks. In fact I find that, considering the great abundance of granites in the pre-Cambrian areas of Southern Norway, no other group of rocks contain a smaller number of pegmatites of such size that they are easily observable in the field. Some statistical data on the relative abundance of pegmatites in various groups of rocks are given elsewhere in this paper (p. 47).
2. Small pegmatites in granites.

The small pegmatites in granites occur either as irregular lumps grading into the normal granite, or as dike-shaped bodies with sharp boundaries against the granite. The irregular bodies need no consideration here.

The small dike-shaped pegmatite bodies run in many different directions through the granite, and sometimes they intersect one another. Vogt describes a few examples of such intersections.

A case of pegmatites of different composition, still both "granitic", intersecting one another, I have observed at Normandvik, Dyvåg (Fig. 1). In a hornblende-biotite granite of the type that is common along the south coast of Norway there is an inclusion of amphibolite, and the intersection between the two pegmatites occurs in this inclusion as shown in the sketch. The older pegmatite consists largely of microcline and a little plagioclase; it contains relatively little quartz, and its only femic mineral is hornblende. The younger pegmatite consists also largely of microcline, but is richer in quartz than the older one and contains magnetite in conspicuous amounts besides a little biotite.

Sometimes these little pegmatites are associated with aplites, the two occurring either in the same body, which then has a zonal structure, or in separate bodies. When the body is zoned the border zone is usually a pegmatitic aggregate of feldspar, quartz, mica, etc., while the central part is an aplite; exceptionally the reverse is the case; there are always sharp boundaries between the two parts. When the pegmatite and aplite occur in individual bodies they may intersect one another. In Vogt's examples of such intersections the pegmatite is the younger body. I have seen examples also of the opposite relation (for instance in a little granite quarry near Gjeving, Dyvåg).

A feature of these pegmatites worthy of notice is the following: As far as it has been possible to trace them for any distance they

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1 See Vogt, paper referred to on p. 6, especially the field sketches pp. 57–59.
always seem to taper out, ending in a point or a lamella of invisible thickness, thus forming apparently drawn-out lenses, a feature characterizing also the larger pegmatites in granites (see above).

Vogt points out how numerous these small pegmatite bodies are in the pre-Cambrian granite of Østfold (east of Oslo fjord). Of dike-shaped pegmatite bodies usually from 2 to 30 cm wide and at most a few m long, there may be 400 per sq. km and the quantity of pegmatite is estimated at 0.25—4 pct. of the surrounding granite.

My observations of these little pegmatite bodies have not been consistent enough for compilation of statistics, but I can confirm Vogt’s statement as to the great abundance of such pegmatites in pre-Cambrian granites. Thus in my field notes from a geological reconnaissance of the granite area of Flå (1920) I have recorded numerous occurrences of small pegmatite bodies in the granite. It is of interest to note that this granite is exactly the same kind of non-foliated granite as that of Østfold where Vogt’s observations have been made. Also various types of more or less foliated granite, especially abundant along the south coast of Norway (“Sørlandet”) contain small pegmatite bodies, but I have the impression that such bodies are less abundant in these rocks than in the non-foliated granites.

3. Small pegmatites in various rocks.

Buøen.

An interesting example of the co-occurrence of pegmatite and aplite is shown in a sketch from the northeast point of the island Buøen, near Eydehavn. (Fig. 2).

In a banded amphibolite there is a little dike-shaped body, A, containing a zone of pegmatite along the border and aplite in the middle. An independent dike B, containing only pegmatite, branches out from the border zone of the composite dike and is cut by another little dike, C, of pure aplite.

The sequence of events has here evidently been the following:
(1) Opening of two intersecting fractures, A and B. (2) Introduc-

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1 Vogt, pp. 56 and 60 in paper referred to on p. 6.
2 This petrographic identity of the two great granite bodies, separated by an area of other rocks about 100 km wide, has been realized long ago. See Kjerulf, Udsigt over det sydlige Norges geologi, Christiania 1879, p. 190, where H. Mohn’s field observations from 1859 are mentioned.
tion into these fractures of a magmatic solution from which crystallization of pegmatite took place, the pegmatite filling the entire fracture B, but leaving a passage filled with solution in the fracture, A. (3) Opening of another fracture, C. (4) Introduction into C and the central passage of A of a solution from which aplite crystallized.

Tveit.

Another example of an intersection of pegmatite and aplite is shown in a sketch (Fig. 3) from the neighbourhood of a feldspar quarry at Tveit, Evje (north of Kristiansand). There are many small bodies of pegmatite and aplite in the gabbro and foliated granite surrounding the large and extensively mined pegmatite bodies in this neighbourhood.

The intersection here shown occurs in gabbro. It is seen that in this case the pegmatite is the younger body. The aplite is slightly foliated, of a grano-dioritic type. The pegmatite is of the ordinary microcline-quartz bearing type, it shows no sign of having been exposed to stress. Evidently the aplite and pegmatite in this case are not genetically associated.

Flostaøen.

Complex intersections of small dike-shaped pegmatites and aplites are shown on a sketch map (Fig. 4) from the east side of the island Flostaøen (east of Arendal) about 1 km south-southwest of Kalvøsund.

The prevailing rock is a gabbro-diorite in somewhat variable development with regard to constitution and structure. This rock is

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1 For illustration and descriptions of the feldspar deposits see Feltspat I, Norges Geologiske Undersøkelse Nr. 128 A, 1926, pp. 70, 71, Fig.s 49, 51, and 52.
cut by an aplitic gabbro-diorite (1) which again is cut by an aplite (2) consisting largely of microcline with only a little quartz and very little dark minerals, and all three rocks are cut by pegmatite (3) containing microcline, quartz, considerable magnetite, and a little biotite.

It is worth noticing that the youngest body in this case, the pegmatite (3) is of the same type as the youngest body in a previous example from Normandvik. The two pegmatites occur in different (although probably comagmatically related) rocks and are located 13 km apart. These facts are of interest because they show that the activity causing the formation of these bodies cannot have been of a purely local nature.

Fig. 4. Sketch map from the east coast of Flostaøen, south-west of Kalvøsund. Dikes in gabbro-diorite. 1 Aplitic gabbro-diorite, 2 granite aplite, 3 microcline-magnetite pegmatite.

Flaten.

About 300 m southeast of the railway station Flaten in Åmli (north of Arendal) there are good exposures of a gray gneiss (perhaps a foliated granodiorite) containing numerous lenses of red granite and pegmatite, which are probably associated with a foliated red granite forming a marked ridge immediately southeast of the point mentioned.

A sketch of one of the little pegmatite lenses is reproduced (Fig. 5) because it illustrates well the structural features of many of these bodies. This pegmatite is cutting across the foliation of the
gneiss. It is seen that it has a noticeable, although not a very sharply marked, zonal structure, microcline perthite, plagioclase and biotite crystallizing along the borders and quartz in the middle.

**Miniature pegmatites.**

Other little pegmatite lenses in the same neighbourhood (Flaten) may be mentioned because they seem to give a definite hint as to the mode of emplacement of some of these bodies. As shown on the sketch of one of them (Fig. 6) the foliation of the gneiss does not conform to the outlines of the pegmatite lens; the pegmatite seems to have eaten into the gneiss from the narrow passage along the foliation, through which the solution responsible for the pegmatite found its way. These particular pegmatite bodies consist in most cases of almost pure feldspar, largely microcline perthite. The lenses may vary in width from a few cm down to mere streaks and in places where they are crowded, they impart to the containing rock the character of an injection gneiss.

Similar observations I have made at several places; thus in the same district, east of the railway station Rise, where the prevailing rock is a foliated quartzite. Certain bands of the quartzite contain "eyes" or lenses of pegmatitic character, ranging in size from 5 by 20 cm down to small specks. Some of the lenses consist of a mixture of plagioclase, potash feldspar, biotite, and quartz, others contain only feldspar and quartz, and some nearly pure quartz.
These relations seem to demonstrate quite plainly that siliceous solutions particularly rich in the constituents of potash feldspar have permeated the foliated rocks wherever they found suitable openings, forming in some places little lenses, eyes, and streaks, and in other places larger bodies with all the characteristics of pegmatites, acting, perhaps, in part by replacement and in part mechanically by pushing the containing rocks aside.

Observations and conclusions like these are not new in the geological literature. They are included here because they fill out the picture of the diversity of pegmatite bodies and add weight to certain points in the genetic theories to be considered presently.

Dal.

As a contrast to some of the miniature pegmatites just described I present a photograph (Fig. 7) of a pegmatite lens occurring in a strongly foliated gneiss at Dal on the island Flosta (east of Arendal).

1 It is convenient to use in these discussions the term solution instead of melt or liquid, because it is applicable without specifying conditions; it includes, for instance: all dry melts of mixed silicates, all magmas, and all hydrous solutions whether at low temperatures and pressures or in the supercritical range of high temperatures and pressures. The term melt or liquid would have their definite limitations, and in a considerable part of this discussion it is not necessary to assume any limiting conditions beyond the statement that magmatic solutions were the agents of transport and crystallization of the pegmatite material.

It is seen that the foliation of the gneiss bends around the lens-shaped body of the pegmatite; there is no indication of assimilation of the wall-rock.

In this case it looks as if the layers of gneiss were forced aside by the pressure of the liquid from which the pegmatite crystallized. An alternative explanation would be to assume that a lens-shaped opening for the solution from which the pegmatite crystallized was provided by orogenic forces, and this is an idea that cannot be disposed of as improbable; indeed I believe that this explanation may be applied not only to the particular example considered but also to numerous other pegmatite bodies occurring along the schistosity of foliated rocks.

**Terneholmen.**

On a little island rock, Terneholmen, located in the bay on the south side of the large island Skåtö, near Kragerö, there is a good exposure of a peculiar intersection of pegmatite bodies (Fig. 8).

In a gray plagioclase-quartz gneiss there are irregular pegmatitic “veins” consisting largely of quartz with some oligoclase and small amounts of magnetite, hornblende, biotite and epidote. The gneiss has fringes of biotite along its borders against the veins. The quartz-plagioclase pegmatite and the gneiss are cut by a pegmatite of the ordinary type, consisting largely of microcline perthite and quartz.

The quartz-plagioclase pegmatite has in places a distinct cataclastic structure, the quartz being strained (undulose extinction) and in part fractured and granulated, and the plagioclase having deformed twinning lamellae. The younger pegmatite shows no signs of having been exposed to any severe stresses.

**General remarks on small pegmatite bodies.**

The small dike-shaped pegmatite bodies cannot represent crystallization in tectonic fissures; their irregularity of direction and small dimensions seem to preclude such an interpretation. The little cracks in the granite and other rocks into which the magmatic material has been forced must have been formed by the action of “local forces”; they may have been cooling cracks due to stresses produced by

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1 This would be a mode of emplacement much like the one assumed for certain gold-quartz veins. See W. Lindgreen, Mineral Deposits 3d. ed. 1928, p. 629.
temperature gradients in the first formed shell of solid granite or in the adjacent wall rock, or they may possibly, to some extent, have been formed as a result of the volume change accompanying the crystallization of the magma. These cracks must have communicated with the magma during the period of solidification. Furthermore they have, in all probability, been the channels of communication between the magma and the openings in the rocks surrounding the granite in which numerous other pegmatite bodies have been formed. These outlying pegmatites constitute the great majority of all pegmatites of conspicuous size, and they are often found at a considerable distance from any granite that may have been their source.

In view of these facts, the conclusion seems necessary that all this communication between the magma and the openings where pegmatites are formed, either inside or outside the granite, to a large extent has taken place through very narrow channels. Further evidence for this conclusion is found in the following circumstances: The small cracks now filled with pegmatite have no visible interconnecting channels, and the granites with their adjacent rocks show very few traces of large continuous openings through which a widespread communication between the magma and its surroundings can have taken place. The pegmatites in general give the impression of being closed bodies; the openings giving access to the liquids from which they crystallized must have been of such fineness that they escape detection by field methods, they may have been almost capillary continuations of the visible cracks. This, in my opinion, constitutes one of the fundamental differences between pegmatites and ordinary igneous dikes and is a point to be considered when the genesis of pegmatites is discussed.

An other point of interest in this connection is the mutual intersections of the little pegmatite bodies in granites and other rocks and the peculiar co-existence of pegmatites and aplites in zoned bodies or in intersecting bodies. These relations seem to indicate that the process of pegmatite formation has extended over a considerable period of time and that it has been more complex than the process giving rise to the formation of ordinary igneous dikes. They seem to show that the formation of granitic pegmatites in the pre-Cambrian of Southern Norway has been caused by a number of distinct granite intrusions, each accompanied be expulsion of
DISCUSSIONS OF THE GENESIS OF PEGMATITES

Fig. 6. Sketch map showing lens of pegmatite in gneiss. Near Flaten, Åmli.

Fig. 7. Pegmatite lens in gneiss. Dal, Flosta.

Fig. 8. Sketch map from Terneholmen, Skåtö. Gneiss (1) cut by quartz-plagioclase pegmatite (2) and both cut by microcline pegmatite (3).
pegmatite forming solutions. It may not even be necessary to assume that the magmas from which the pegmatite forming solutions are given off, in all cases have been granitic. Many quartz-plagioclase pegmatites and pure quartz pegmatites, for instance, may well have crystallized from solutions derived from other magmas.  

4. Large granite pegmatites in non-granitic rocks.

The more important types of non-granitic rocks of the pre-Cambrian area here considered may be superficially classified into the following three groups: Gneisses of many varieties (not including foliated granites), quartzites, rocks of the gabbro and diorite families (including amphibolites).

These rocks contain the great majority of those pegmatites that are easily observed in the field. As will be shown later these pegmatites are much more abundant in rocks of the gabbro groups than in any other group.

The pegmatites of this group show numerous variations with regard to constitution, structure and mode of occurrence. It is in this group we find what may be regarded as the prototype of "ordinary granite pegmatite", the pegmatite of feldspar and quartz deposits and at the same time the mother rock of many interesting minerals. Some of these pegmatites are very rich in quartz and may pass over into bodies of almost pure quartz, but the great majority of them consist of a mixture of feldspar, quartz, and various other minerals. The dominating feldspar is usually microcline.

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2 For petrographic descriptions of rocks of this type see: Carl Bugge, Kongsbergfeltets geologi, Norges Geol. Undersøkelse, Nr. 82, 1917. A detailed description of a restricted group of highly metamorphosed pre-Cambrian rocks is given by O. A. Broch, Ein Suprakrustaler Gneisskomplex auf der Halbinsel Nesodden bei Oslo, Norsk Geol. Tidsskr. 9, 81, 1926. Also in Arne Bugges paper, En forkastning i det sydnorske grunnfjell, Norges Geol. Undersøkelse Nr. 133, 1929, much valuable information about these rocks and especially about their distribution will be found. All these papers contain references to older literature.

3 A brief general characteristic of the constitution of these pegmatites is given in the English Summary of Feltspat I, Norges Geol. Undersøkelse Nr. 128 A, p. 136, 1926.
perthite which always is associated with more or less plagioclase (as a rule oligoclase). Seldom is plagioclase the dominating or only feldspar present. Of dark minerals biotite is nearly always present, although in varying amounts and often associated with black tourmaline, more rarely with muscovite. Exceptionally pyroxene or hornblende are the most conspicuous dark minerals.

The mineralogical geochemical classification of the pegmatites, which would have to be based on constitutional differences, with emphasis in part on the feldspars and common femic minerals and in part on the rare minerals, will not be discussed in this paper. I may only state that I have not been able to detect any systematic dependency between the constitution of the pegmatites on the one hand and their mode of occurrence on the other. It is justifiable, therefore, to deal with the mode of occurrence of this particular group of pegmatites regardless of the constitution, or at least without considering the minor constituents.

Of these pegmatites several subgroups of mode of occurrence might be kept apart, for instance: one including pegmatites occurring in massive rocks like gabbros, one including those cutting across the schistosity of foliated rocks, and one including lens-shaped or irregular masses running more or less along the schistosity of foliated rocks. However, since no distinct lines can be drawn between these subgroups, I prefer not to emphasize them by attempting any rigid classification of this group of pegmatites. Their mode of occurrence and structures will be illustrated by describing a few examples.

Arneviken.

A pegmatite body situated near an old schoolhouse south-southeast of the southern Arnevik farms on the island Flosta (east of Arendal) gives one of the most interesting examples of zonal structure in pegmatite that I have seen, and at the same time a good illustration of a fairly regular lens-shaped pegmatite. It is well exposed in a quarry from which a little graphic granite and quartz have been mined.

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1 A classification of this kind for the granite pegmatites of southern Norway is indicated in Brøgger's publication from 1906 (reference p. 1). Complete geochemical classifications of pegmatites have been suggested by Niggli (see Lehrbuch der Mineralogie 1920 p. 514) and more recently by Fersmann (reference p. 3).

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The country rock is a gabbro occurring as a narrow body between granite and gneiss. Along the contacts with the pegmatite the gabbro is noticeably altered, especially by biotitization of the dark minerals. The pegmatite body appears to form a flat lying lens entirely surrounded by the gabbro; it is dipping east at an angle of about 10°; it may be traced for about 100 m along the strike southwards and is exposed for about 30 m in the quarry where it is about 6 m thick. The zonal structure, as it appears in the quarry, is shown in Fig. 9. From the hanging wall downwards, the following zones are distinctly seen:

1) A plagioclase-quartz pegmatite, largely a graphic granite, containing numerous inclusions of magnetite in irregular lumps up to 5 cm in diameter. This zone, which is at most 20 cm wide, passes gradually into the next.

2) A zone of plagioclase graphic granite about 50 cm wide, containing scattered plates of biotite.

3) A zone about 1.5 m wide consisting of microcline perthite graphic granite with thin plates of altered (chloritized) biotite. This graphic granite shows a peculiar, banded structure with bands parallel to the hanging wall of the pegmatite, apparently due to the fact that the feldspar of the graphic granite cleaves along wavy faces with the crests of the waves running parallel to the hanging wall. The graphic granite itself shows considerable variation in texture, being in part very fine-grained and in part coarse-grained.

4) A zone up to 50 cm wide consisting of plagioclase graphic granite without magnetite, but with considerable biotite in plates oriented in a direction about perpendicular to the contact face.

5) An irregular, interrupted zone of relatively large crystals of microcline perthite, in part with well developed crystal faces protruding into the next zone. The microcline perthite is usually fresh, but at places altered to aggregates of muscovite and a green chlorite mineral.

6) A zone of pure quartz. Some of the biotite plates from zone 4 continues into the quartz, which at some places also contains vein-like or lump-formed bodies of sulphides (up to 20 cm in diameter), chiefly pyrite, some pyrrhotite and chalcopyrite. In the sulphide masses there are small cavities in part filled with an iron bearing carbonate (not pure siderite) and containing a few grains of magnetite.
The quartz zone forms the central part of the pegmatite, the symmetric continuation of the lateral zones, below the quartz, towards the footwall is seen at several places outside the quarry. As seen from the sketch some irregular individuals of microcline perthite are included in the quartz, indicating that the stages of crystallization of these two minerals cannot have been sharply separated.

The structure of this pegmatite body can hardly be interpreted in any other way than by assuming successive stages of crystallization from the wall-rock towards the center of the body, in the sequence described: beginning with magnetite bearing plagioclase graphic granite passing through three stages of biotite bearing graphic granite and, after an indistinct stage of individual microcline perthite, ending with quartz. Simultaneously with these main phases of crystallization minor crystallizations and reactions, such for instance as muscovitization of feldspar, formation of vein perthite in microcline, chloritization of biotite, and crystallization of sulphides, have been going on.

The border zone of plagioclase graphic granite and magnetite may possibly have been formed by partial replacement of the gabbro wall-rock. It looks as if the iron ore of the gabbro has been retained, recrystallized to relatively large individuals, while the other constituents have been removed, and replaced by quartz and plagioclase.
An other instructive pegmatite body occurs on a forest hill (Gloserhei) east of the farm Lyngrot in Froland, northwest of Arendal.

The surrounding rocks are largely feldspathic gneisses alternating with bands of amphibolite and quartzite; their strike is variable, but generally in a northerly direction, the dip is steep, usually towards east. The pegmatite body seems to form a big lens, striking about east and dipping north, i.e. cutting across the foliation of the containing rocks. At the surface the lens is up to about 140 m wide and is seen to extend several hundred m towards the west, where its outcrop is covered by the forest. The main mass of this pegmatite consists of feldspar and quartz, to a large extent forming a rather fine-grained graphic granite and to some extent an irregular mixture coarse enough to be a conspicuous pegmatite, still too fine-grained for commercial exploitation of feldspar.

The feldspar in the graphic granite is largely microcline perthite but also in part oligoclase. The pegmatite is cut by some dike-shaped bodies of aplite and contains a few coarse-grained parts with relatively large individuals of feldspar and quartz, but most of these parts are small. Only near the eastern end of the pegmatite is there a very large body of distinctly separated feldspar and quartz. It forms a smaller lens inside the big lens and consists of two separate bodies of coarse pegmatite, shaped like bivalve shells, enclosing a huge central lens of quartz. The pegmatite shells consist of microcline perthite and some strongly altered oligoclase, both forming individuals up to 2 m long, separated by still larger masses of quartz. Associated with the microcline are "secondary" muscovite and albite, some of the muscovite forming small euhedral crystals in quartz. The pegmatite contains some irregular plates of biotite. Subordinate minerals are tourmaline, magnetite, gadolinite, orthite, and xenotime. The central core consists of a very pure, light variety of rose quartz. This quartz lens is more than 100 m long and up to 30 m thick, while the shells may be 10—20 m thick, one extending along the entire northwest side of the quartz lens, about 100 m, and the other

1 For a map and a photograph of this pegmatite see: Feltspat I, Norges Geol. Undersøkelse, Nr. 128 A, 1926, Figs. 48 and 50.
one for about 80 m along the south side. The pegmatite has been extensively mined for feldspar.

The distinct zonal structure shown by this example demonstrates the same sequence of stages as in the preceding example, although there are striking differences in details. The most important stage in the evolution of this pegmatite, as far as quantity of material is concerned, is the first, the crystallization of the mixture of graphic granite and irregular pegmatite. This stage represents, as it were, an extended border zone. The next stage is also distinct, characterized by crystallization of individuals of feldspar together with biotite and the other minerals mentioned, and considerable amounts of quartz. There is not any strongly marked succession of minerals within this stage, although quartz is plainly the last mineral to crystallize. It is evident that reactions and crystallizations (replacement) have taken place during this stage. The third and last stage, crystallization of pure quartz, is essentially like that of the corresponding stage in the preceding example, only there have been no sulphides crystallizing in the quartz.

Ljøstad, Vegårshei.

A pegmatite body located in the forest about 1 km north-northeast of the farm Ljøstad, Vegårshem, northwest of Tvedstrand, shows the relations indicated in Fig. 10.

The pegmatite occurs along the schistosity of a strongly foliated gneiss, the exposed part of it forming a rather regular dike-shaped body. It dips about 45° north, is visible for about 50 m along the strike and is 3—4 m wide. Along the wall-rock there are irregular zones of graphic granite passing into a mixture of graphic granite and individual feldspar, and in the center there is a persistent zone of pure, light rose quartz. The feldspar, both in the graphic granite and in the separate individuals, is largely microcline perthite, but also in part oligoclase, the latter being altered along the margin
parts of the large individuals. Biotite and a little muscovite occur, mixed with the feldspar.

This pegmatite shows still another variation in the stages of crystallization: There is no sharp line between a border zone of graphic granite and a typical pegmatite zone with separate individuals of quartz, but the central quartz zone is the same as in the other examples.

**Kibbevik.**

East of the farm Kibbevik on the island Askerö in Dyvåg (east of Tvedestrand) there is a characteristic pegmatite body in gabbro.

The gabbro forms a relatively small lens in a plagioclase-quartz gneiss and the pegmatite forms a lens in the gabbro again; it is exposed in a little feldspar quarry¹.

The pegmatite lens dips about 30° northeast, is about 60 m long, and about 6 m wide over the greater part of its exposed length, tapering at both ends. It has a characteristic zonal structure: Next to the hanging wall there is a zone, less than 1 m wide, consisting of distinct crystals of oligoclase radiating out from the contact face and surrounded by quartz. Then there is a wider central zone consisting of large individuals of microcline perthite (up to 2 m long) together with large plates of biotite (up to 20 cm thick and 2 m in diameter), all in a matrix of quartz. The zone at the foot wall seems to be like that of the hanging wall.

In this pegmatite there is evidently a deviation from the general sequence of zoned pegmatites in as much as there is no border zone containing graphic granite, otherwise there is no striking irregularity; it is particularly to be noted that quartz crystallizes throughout both stages and is the last mineral to crystallize here as in most other pegmatites.

**Berø.**

On the southeast side of the island Berø, near Kragerø, there is a large pegmatite body of irregular form and structure².

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¹ See Feldspar I, Norges Geol. Undersøkelse Nr. 128 A, Pl. XVIII, Fig. 62.
² This body has been mined for many years, the unsorted pegmatite being used as raw material in Portland Cement making. A brief description of the pegmatite is given in Norges Geol. Undersøkelse Nr. 122, 11, 1924. A photograph of the pegmatite body and quarry is reproduced in Feldspar I, Norges Geol. Undersøkelse, Nr. 128 A, Fig. 59, 1926.
DISCUSSIONS OF THE GENESIS OF PEGMATITES

The surrounding rocks are quartzite, gneiss, and amphibolite. In these rocks, largely in the amphibolite, the pegmatite occurs as a very irregular body, the outlines of which are shown on the sketch map (Fig. 11). It forms a prominent rock precipice with very steep slopes extending from the sea to a height of 65 m above sea level. It contains several large inclusions of amphibolite and has irregular branches shooting off into the containing rock as indicated on the sketch map.

Fig. 11. Sketch map of pegmatite occurring in amphibolite on the island Berø near Kragerø. Stippled areas pegmatite. The heavy line to the right is the shore.

This pegmatite contains no large individuals of feldspar or quartz. It consists, for the greater part, of a somewhat irregular and not very coarse-grained mixture of about equal amounts of microcline perthite and oligoclase, with a large amount of quartz. The prevailing dark mineral is a somewhat chloritized biotite, occurring in plates not over 15 cm in diameter. Muscovite forms small scales in the feldspar. Black tourmaline, in insignificant amounts, forms small groups of crystals irregularly scattered in the pegmatite. Of other minerals the following have been observed, all in small quantities: garnet, titanite, pyrite, pyrrhotite, chalcopyrite, apatite, and calcite.
An analysis of the pegmatite obtained on an average sample from the crushing plant has been published before\(^1\). It is given in Table I together with an approximate recalculation based on the known composition of the feldspars\(^2\) and an estimate of the probable composition of the dark minerals (chiefly biotite and chlorite).

A characteristic structural feature of this pegmatite is its lack of distinct zones. It contains a good deal of graphic intergrowths of feldspar and quartz, but not of the regular type of graphic granite occurring in many other pegmatites. These intergrowths seem to be scattered, without rule, throughout the pegmatite, and the same holds true for the other constituents.

In this pegmatite, thus, there is no evidence of the same general sequence of stages of crystallization as that characterizing the more or less distinctly zoned pegmatites, but neither is there evidence of a reversed sequence or of any sequence at all. It looks, decidedly, as if all minerals had crystallized more or less together. The crystallization of the entire pegmatite may be regarded as belonging to one stage, corresponding, perhaps, largely to the border zones of the zoned pegmatites.

Frøyna.

An other irregular pegmatite occurs on the island Frøyna in the Søndeled fjord (about 8 km west-northwest of Risør). It has good exposures in a quarry from which a considerable amount of feldspar has been mined.

The surrounding rocks are gneisses of various types, cordierite gneisses being prominent among them. The pegmatite cuts irregularly across the foliation of these rocks. It has roughly the shape of a lens dipping steeply towards southeast, extending from the fjord to a height of about 40 m above sea level where it forms the flat top of a prominent point of the island, and sending offshoots from this top down towards southeast. Its outlines are shown on the sketch map (Fig. 12).

The main minerals of the pegmatite are microcline perthite, andesine, and quartz; dark minerals biotite and a little muscovite.

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\(^1\) Norges Geol. Undersøkelse Nr. 122, 12, 1924.

\(^2\) An analysis of the microcline perthite is published in: The Genesis of certain types of feldspar, Norsk Geol. Tidsskr. 10, 146, 1928, (Table 3, analysis Nr. 9).
**DISCUSSIONS OF THE GENESIS OF PEGMATITES**

25

**Table 1.**

Analysis of pegmatite from the quarry of Dalen Portland Cement Co, on the island Berö, near Kragerö.

Analyst: E. Klüver.

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<td>TiO₂</td>
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<tr>
<td>BaO</td>
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Recalculation

Quartz: 44.2%
K-feldspar: 17.4%
Na-feldspar: 20.4%
Ca-feldspar: 8.4%
Microcline perthite: 22.1%
Oligoclase: 24.1%
Mica (including biotite, chlorite and muscovite): 8.4%
Apatite, calcite etc.: 1.2%

Total 100.302

**Table 2.**

Analysis of pegmatite from Fröyna, near Risör.

Analyst: E. Klüver.

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<td>CaO</td>
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<td>Cl</td>
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<tr>
<td>BaO</td>
<td>0.04</td>
<td>F</td>
</tr>
</tbody>
</table>

Recalculation

Quartz: 36.6%
K-feldspar: 38.7%
Na-feldspar: 13.9%
Ca-feldspar: 6.4%
Microcline perthite: 45.7%
Andesine: 13.3%
Mica (biotite and muscovite): 3.9%
Apatite, calcite etc.: 0.5%

Total 100.124
(alteration product); minor constituents apatite and calcite, both in very small amounts. The composition as stated in Table 2 has been determined by analyzing an average sample collected from debris at 20 different places in the quarry. An approximate recalculation of the analysis is given in the same table.

The larger part of the feldspar occurs as separate microcline perthite and andesine, both forming individuals of considerable size, and both entering to some extent into graphic granite of irregular distribution. A smaller part forms an unusual perthite consisting of intimately interwoven individuals of andesine and microcline perthite of total composition (in weight pct.) 25.4 Ca-feldspar, 37.7 Na-feldspar, 36.9 K-feldspar (56.6 andesine, of composition 43 Ca-f, 57 Na-f; and 43.4 microcline perthite of composition given below\(^1\). The composition of the andesine both in this complex perthite and in the separate individuals is 41—43 Ca-feldspar, 59—57 Na-feldspar. The composition of the microcline perthite is also the same in the complex perthite as in the free individuals: 1 Ca-feldspar, 14 Na-feldspar, 85 K-feldspar. It is seen from these figures (compare the figures mentioned with those of Table 2) that the ratio andesine: microcline perthite is much higher in the interwoven perthite than in the pegmatite as a whole.

As an explanation of the formation of andesine-microcline perthite I have suggested\(^2\) a simultaneous crystallization of andesine and an albite bearing microcline, the latter being a film perthite with thin lamellae of albite formed by exsolution on cooling. Assuming this explanation to be correct, the relations between these two feldspars are not unlike those of feldspar and quartz. Both pairs of minerals may at times form oriented intergrowths by simultaneous

\(^1\) For description and analysis of this feldspar see: The genesis of some types of feldspar, Norsk Geol. Tidsskr. 10, 181, 1928, (analysis Nr. 29, Table 3, p. 147).

crystallization (perthite, graphic granite)\(^1\) and at other times separate individuals, but there is no evidence against the assertion that also these separate individuals may have crystallized simultaneously. This seems to indicate that the factors deciding whether intimate intergrowths, or separate individuals, shall be formed, may be largely the physical conditions of crystallization. One may think of the crystallization as rhythmical rather than strictly simultaneous and may assume that for several reasons there will be changes in the rate of diffusion in the crystallizing solution. It becomes conceivable, then, how these changes may bring about fine-grained intergrowths, coarse-grained intergrowths and separate individuals of the same crystallizing minerals\(^2\).

5. General remarks on granite pegmatites.

Summary of features.

It appears from the preceding descriptions that some of the pegmatites have a decidedly zoned structure while others seem to be quite irregular. The distinct zones give evidence of a definite sequence of stages of crystallization, whereas the irregular structure seems to indicate that there has been no marked sequence, that the crystallization of the entire pegmatite belongs to one stage.

In the zoned pegmatites the first stage of crystallization is usually represented by plagioclase graphic granite, the next stage by a microcline graphic granite, then comes a stage of individual feldspar together with individual quartz, and finally a stage of quartz alone.

These stages are not always sharply separated, and in them, of course, all the other minerals of the pegmatites are included. Although never amounting to more than a few percent of the total pegmatite, these minor minerals are important factors in lending individuality to the pegmatite bodies: they vary conspicuously in paragenesis, crystal size, and distribution.

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\(^1\) That graphic granites, at least those of common occurrence in pegmatites, are products of simultaneous crystallization must be regarded as definitely established by the investigations of Vogt (see paper referred to on p. 6) and Fersmann (Z. Kr. 69, 77, 1928).

\(^2\) The same problem of simultaneous rhythmical crystallization has been discussed by Ussing (Meddelelser om Grønland, 14, 1894, pp. 88—94 and 98—100) whose discussion is reviewed in my paper, The genesis of some types of feldspar, p. 184 (reference p. 26).
The many variations in details of the main stages themselves should also be emphasized. A distinct succession of several stages of graphic granite, for instance, such as the example from Arnevik shows, is rather exceptional. Neither is it common that the stage represented by crystallization of individual feldspar is so insignificant as in the same example; usually both plagioclase and microcline perthite are included in this stage, and both in considerable quantities. Also the central quartz is subject to great variations; it sometimes constitutes almost the entire pegmatite and sometimes is reduced to scattered lenses or irregular lumps. Finally it should be mentioned that instead of regular zones of graphic granite along the borders many pegmatites, notably those that are not typically zoned, contain more irregularly distributed graphic granite and some have apparently very little ordinary graphic granite, but contain instead an irregular, relatively fine-grained aggregate of feldspar and quartz.

With all the variations indicated, the fact remains that the zoned pegmatites are always developed, more or less distinctly, in the stages indicated, beginning with graphic granite, passing through crystallization of individual feldspar and quartz, and ending with quartz.

**Aplite in pegmatite.**

A feature only superficially described in the foregoing sections is the occurrence of aplite in the pegmatite. The co-occurrence of pegmatite and aplite in small pegmatite bodies has been mentioned, but it has not been emphasized that aplite occurs also in many of the larger bodies. Sometimes it forms rather regular, almost dike-shaped bodies cutting sharply across the pegmatite, but as a rule it forms irregular masses scattered among the coarse-grained minerals. It is always characterized by a mineral association similar to that of the main part of the pegmatite, consisting essentially of feldspar (largely microcline perthite) and quartz with very little of dark minerals. As far as I have seen, these dark minimalis, and certain other common minor constituents, are the same in the aplite as in the pegmatite with which it is associated. In a garnet bearing pegmatite, for instance, I have seen garnet bearing aplite. Sometimes the aplite merges into a more coarse-grained mineral association having the composition and texture of aplite, but the grain size of a granite or a relatively fine-grained pegmatite.
A possible cause of aplite formation.

Spurr\(^1\) has suggested that aplites have crystallized from magmas drier than granite magmas while pegmatites, according to the prevailing theory, have crystallized from solutions (magmas) relatively rich in volatile constituents. I can see no observational evidence against this idea. Still, it remains a puzzle why pegmatites and aplites should occur together in such curiously intermingled bodies as those mentioned. Evidently the two have crystallized, geologically speaking, simultaneously and apparently under the same physical conditions, and both must have been derived from the same source, a granite magma. Why, then, should a granite magma, whose natural trend of evolution, according to present ideas, is toward concentration of volatiles in a pegmatitic restmagma, suddenly turn in the opposite direction? The answer may be that there have been local differences in physical conditions after all, and that these differences have sprung up within the granite or pegmatite magma, where they have caused a spontaneous separation of an aplite magma. The only way such a condition can be produced, as far as I can see, is by the sudden relief of pressure that must accompany each opening of a cooling crack or other fracture communicating with the magma\(^2\).

It must be assumed that many such openings were formed practically simultaneously, but even so the total increase in available space for the magma may have been small. If equilibrium were reestablished at once the final effect on the magma would probably be negligible. This would be the case if only wide openings, permitting a rapid influx of liquid, were formed, or if the entire magma basin were subjected to a sudden expansion by deformation. The

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1. The Ore Magmas \(I\), 309, 1923.
2. The process may be compared with the opening of a valve between two inter-communicating high-pressure bombs, one containing a solution under a pressure of hundreds or perhaps a few thousand atmospheres and one being exhausted to vacuum.

The idea of volatile solutions advancing ahead of more viscous magma during injection processes is evidently old. For a thorough discussion of this idea see Fenner, reference p. 12 cf. p. 694. The phenomenon of a sudden opening of vacuum spaces is briefly discussed in a previous paper (reference p. 26, cf. pp. 142–145) in connection with perthite theories. A concise statement of fundamental ideas underlying problems like these is given by Merwin (Am. Min. \(16\), 93, 1931).
volatile vapours first given off to vacua would then soon be followed by the less volatile residual solutions, pressure would be equalized at once, and diffusion and convective currents would readjust possible differences in temperature and composition before any further crystallization had taken place. But such conditions seem to be exceptional: According to evidence presented before, there is every reason to believe that most of the openings communicating with the magma have been narrow and that possible intercommunication between those next to the magma and those far off has been established only through extremely fine passages. A rapid reestablishment of the disturbed equilibrium, therefore, is impossible, and in spite of the small expansion the magma must have had a chance to undergo local, sudden and temporary changes large enough to produce conditions for crystallization of aplite.

The process may be imagined to have been approximately the following: Assuming an initially homogenous pegmatite magma, the sudden opening of fractures at once produced a vesiculation at least in a part of the magma. This may have had two simultaneous effects: Gas bubbles would stream towards the openings and into the spaces formed, and residual magma would be pushed in the same direction. But the residual magma would be a very viscous liquid compared with the extremely mobile gases. As soon as obstacles like narrow fissures were encountered the gases would run away from the magma, and when the magma later had a chance to fill some of the openings, it was impoverished in volatile constituents, and, although the pressure in these openings now would rise gradually, the magma would be barred from taking the gases quickly back into solution; it would have become relatively dry, and when crystallizing it would form aplite.

It is easily seen how these conditions also may explain the intermingled aplite and pegmatite bodies. In most cases the aplite magma may have been preceded by a more fluid pegmatite magma which has partly crystallized from the walls of the opening before the aplite magma reached it; this is the rule at least for the large pegmatite bodies containing aplite in the interstices between the coarse-grained minerals. In some cases, however, this wave of pegmatite magma may have stopped crystallizing before it had filled completely or partly all accessible openings, leaving free passage for the still streaming aplite magma. The aplite would then fill the
remaining central parts of some passages, fill completely others in which no pegmatite had crystallized, and form a border zone in still others in which then a new wave of pegmatite might form the central part.

I wish to emphasize that the explanation here indicated, which may hold true for aplites associated with pegmatites in the manner described, may not be applicable at all to many other aplite bodies.

Possible explanation of some pegmatite forming processes.

Some such mechanism as the one just outlined may give the explanation not only of the association of pegmatite and aplite, as stated, but also of many of the other structural features characterizing pegmatite bodies, and may consequently throw light on the general process of pegmatite formation. A complete discussion of this intricate problem lies outside the scope of this paper, and could hardly be undertaken in any case, for lack of fundamental facts, but it may be of interest to try to draw some conclusions on the basis of specific simplifying assumptions.

Considering only granite pegmatites and disregarding the complication of aplite formation, the initial magma is supposed to be a pegmatitic restmagma after crystallization of granite. As soon as openings form suddenly in one way or another the magma will move into them in the manner indicated above. In the case of wide openings it will occupy these quickly, and virtually unaltered, and will start crystallization as an ordinary granite pegmatite. This may possibly give the explanation of some of the non-zonal, relatively fine-grained pegmatites. With narrow openings, however, and these evidently represent the most general case, there will be at least a temporary differentiation, as indicated in the discussion of aplites. Volatiles will separate from the magma and move through the openings at a rate varying greatly, depending upon the width and length of the passages. In extremely long and narrow passages even very mobile solutions (gases) will move slowly, and viscous solutions will be practically stopped. In such cases, therefore, there is a possibility of a permanent differentiation if crystallization begins before equilibrium in pressure is reestablished.

1 See R. A. Daly, Igneous Rocks and their origin, 368, 1914.
2 For brief remarks on this phenomenon with references to more complete discussions see paper referred to on p. 26, cf. pp. 142, 143.
The volatiles given off are actually mineral carrying solutions, probably largely hydrous solutions of silica and silicates. Their temperature at the moment of expulsion is practically that of the magma, but as they pass on they reach colder surroundings and may crystallize. Sooner or later further progress of solutions will stop, either because of the crystallization or because the fractures in the rock fade out. When this happens the pressure and concentration in the open passage will increase till the whole system (magma basin and openings) approaches a state of equilibrium. In a long and narrow passage this state will probably never be reached, crystallizations or reactions, therefore, may take place under different conditions at different parts of the passage, while the streaming solutions are gradually changing towards equilibrium. It is possible, for instance, that quartz may crystallize from a dilute hydrothermal solution at the relatively cold farther end of an opening while at the same time feldspar and quartz may crystallize from a more magmatic solution at the relatively hot end next to the mother magma. Later the conditions may have changed in such a way that resorptions of some minerals previously crystallized would take place. In this way, through complex changes of equilibrium conditions, not easily defined at the present state of knowledge, it becomes conceivable that the separation of volatiles by relief of pressure in narrow fractures may be one of the primary causes of the peculiar features of pegmatites.

It should be considered now how these conditions may become modified when the accessible openings are wide enough to give room for the large pegmatite bodies observed. It has been stated already, that if such wide openings communicated directly with the magma there would be little, if any, differentiation of the nature described. The only differentiation in such a case would be caused by crystallization; the process would not differ essentially from that of the crystallization of a granite. But, according to evidence given already (pp. 13, 14), most of the pegmatite bodies considered are not likely to have been formed in openings having such easy communication with the magma. Leaving out of consideration the problem of how the width of the openings occupied by the large pegmatite bodies may be explained, it is evident that the influx of solutions into them generally has taken place through relatively long and narrow passages like those already discussed. It is clear, then, that the width and length of these channels of supply, and not the dimensions of
the pegmatite chamber itself, will be the factors influencing the process of crystallization of such large pegmatite bodies. In that way it becomes possible to apply to the process going on in many of the large openings the same reasoning as that applied to the process of the long and narrow fractures.

Thus this process may help explaining such features as the zonal structure, the central quartz, and the shading of feldspar bearing pegmatites into quartz pegmatites. To account for these features it is evidently necessary to assume that crystallization has taken place from streaming and gradually changing solutions. The sudden opening of fractures communicating with the magma through narrow channels will produce these conditions according to the conclusions indicated above. However, in discussing this process it is necessary to consider also the effect of the simple crystallization from a stationary pegmatite magma. The residual solution must be supposed to be rich in volatile constituents, and if fractures open after the formation of such a residual solution it will be forced out in the way indicated before and may contribute to the formation of the structural features considered. Further it must be remembered that the process may be repeated when new fractures open from a local chamber in which crystallization has been going on for some time. The solutions thus given off may in turn form the source of a new differentiation, and so on.

In the preceding discussion it has been assumed that the pegmatite forming solutions entered into pre-existing spaces formed by sudden ruptures of the country rocks and held open by the strength of these rocks.

An other mode of emplacement, which seems to be the one most commonly assumed by previous writers, is the actual injection of solutions into spaces formed as the solution advanced, driven by an internal pressure strong enough to overcome the hydrostatic load and the strength of the rock. A necessary condition for such a process is that the rock has planes of relative weakness along which the solutions can find a path of least resistance. This is the case with foliated rocks and with rocks which have joints that are not actual vacuum cracks. From solutions forced into the rocks in this way volatiles cannot escape except by slow diffusion into the country rock unless the pressure produces sudden ruptures of the rock ahead of the advancing solution, in which case a vacuum crack is formed.
By a gentle injection of such solutions, therefore, no other essential
differentiation, than that produced by crystallization, is likely to
take place.

It seems reasonable to assume that the lens-shaped pegmatite
bodies running approximately along the schistosity of foliated rocks,
and also many of the very irregular pegmatite bodies, have been
formed by this process of emplacement, but no decisive proof of this
assertion can be offered. As before mentioned, these bodies, as a
rule, have no distinct zonal structure, and this may be ascribed to
an absence of abrupt changes in the crystallizing solutions.

6. Large coarse-grained quartz bodies.

At many places in the pre-Cambrian formations of Southern
Norway, notably within the southern extension of the so-called
Kongsberg-Bamble formation, one will find conspicuous bodies of
coarse-grained quartz, differing in several respects from the large
quartz bodies, associated with granite pegmatites, described in a
previous section. Most of the quartz bodies here considered occur
in gneisses or other metamorphic rocks, some in gabbro and very
few in granite. A few examples representing various types of mode
of occurrence will be briefly described.

Åmdal.

In the forest southeast of the farm Åmdal in Froland (north-
west of Arendal), on the western slope of the mountain Jomåsknuten,
there is a coarse-grained body of pure quartz.

The quartz body occurs in a gabbro in which it forms a very
irregular lens of large dimensions (only a part of it was exposed at
the time of my visit in 1928). The quartz is white and no other
minerals are seen in it, but it contains some inclusions of the sur-
rounding gabbro. The gabbro in the inclusions and along the contact
with the quartz is considerably altered (biotitization).

This pegmatitic quartz body has probably been formed by crys-
tallization from a hot hydrothermal solution rather than from an
actual magma. The solution must have entered through initial
fractures in the gabbro, perhaps assimilating some of the wall-rock
thereby producing a wider space for the subsequent crystallization,
the assimilated part being carried away by the circulating solution.
Kvitberg.

A conspicuous body of coarse-grained quartz occurs at the farm Kvitberg in Holt (about 13 km west-southwest of Risor).

The surrounding rocks are gneisses and amphibolites of variable development. The amphibolites are altered to a biotite bearing rock along the contacts with the quartz.

The quartz forms a roughly lens-shaped body the outlines of which are shown on the sketch map (Fig. 13) on which also another quartz body, at Nævestad, appears. At Kvitberg the quartz body forms a large hill rising from the shore of the Nævestadfjord to a height of about 130 m above sea level. (See Fig. 14). It has steep boundaries against the country rock. It is seen on the map that the southwestern end of the quartz body is divided into three branches cut off by the fjord (or possibly it may contain two large inclusions of gneiss).

The greater part of this large body consists of a very coarse-grained quartz of variable color: rose, purple, bluish, gray or white, containing some biotite in scattered plates, some small crystals of rutile evenly distributed throughout the quartz, very small quantities of tourmaline, some muscovite, traces of zircon, but no visible feldspar. I have no analysis of the quartz, but would estimate its average content of SiO₂ to not less than 98 percent.

At some places, notably along the eastern border of the quartz body (north of the farm), there is a relatively fine-grained granular
variety of quartz containing rounded grains of microcline, small amounts of sillimanite in bundles of fine needles, and a little zircon in very small crystals. This variety shows an indication of foliation, and if observed alone it would probably have been classified as a quartzite.

Such an intermingling of foliated quartzite and massive pegmatitic quartz I have observed at many places in this district. Sometimes the quartzite seems to form streaks or irregular bands or veins

in the pegmatitic quartz, and sometimes the latter forms lenses or veins along the foliation of the quartzite or cuts irregularly across it.

The quartz body at Nævestad shown on the sketch map is of the same general nature as that at Kvitberg and need not be described here. It is characteristic in running approximately along the strike of the surrounding gneiss.

The most reasonable interpretation of these remarkable quartz bodies, and several smaller ones in the same neighbourhood, seems to be that they are formed by a process of injection, possibly accompanied by replacement. The form of the body at Kvitberg seems to exclude its interpretation as a highly metamorphosed quartzite, although quartzite, as indicated, may have formed a part of the surrounding complex of foliated rocks.
Söisdal.

In the forest about 2 km south-southeast of the farm Söisdal in Froland (northwest of Arendal) there is a coarse-grained quartz body from which a considerable amount of pure quartz has been mined.

The surrounding rock is a banded gneiss with wide bands of amphibolite. Immediately east of the gneiss is a zone of impure quartzite about 500 m wide.

The quartz forms an irregular body extending in the direction north-northeast, roughly along the strike of the foliated rocks, but plainly intersecting them. The quartz is very coarse-grained, white or light gray and remarkably free from other minerals. It contains a few angular inclusions of a rock consisting largely of quartz and actinolite with some plagioclase and a little titanite and apatite.

This pegmatitic quartz body has probably also been formed by a combined injection and replacement process. The solution must have entered through initial fractures and has eaten its way into the wall rock, carrying away all but small traces of the original minerals and replacing them with quartz.

Lindviken.

At Lindviken, an old quartz quarry about one km east of the farm Kjendalen on the island Barmen, west of Risör, a vein of coarse-grained quartz is running along the strike of the prevailing gneiss, a banded quartz plagioclase gneiss with bands of amphibolite and of a microcline-bearing gneiss. The gneiss dips steeply towards north-northwest, and is cut off by a steep slope towards southeast which forms the coast of the island (see Fig. 15). Immediately northwest of the quartz body a large field of gabbro adjoins the gneiss, the gabbro undoubtedly forming an intrusive body in the gneiss.

The quartz body forms a pinching and swelling lens, from two to ten meters wide, and several hundred meters long. It consists for the larger part of a fairly pure, white or light gray quartz, but contains some plagioclase, forming irregular patches of quartz-plagioclase pegmatite with a little biotite; it also contains insignificant amounts of garnet.

The surrounding gneiss contains numerous smaller veins of quartz-plagioclase pegmatite or pure quartz along the strike, and also some cross-cutting veins of microcline bearing pegmatite.
This quartz body I would interpret much in the same way as the preceding examples: as formed by injection of a siliceous solution which possibly effected a replacement of a part of the gneiss.

**Lövdal—Orkjær.**

Some remarkable pegmatitic bodies, consisting largely of quartz and entirely included in granite, occur at the boundary between Dylvåg and Søndeled at the farms Lövdal and Orkjær, about 10 km southwest of Risør.

The granite is a coarse-grained fresh rock of the general type occurring along the south coast of Norway, but somewhat unusual in being practically devoid of foliation. Its constitution is characterized by: much microcline perthite, less oligoclase, medium quartz; of femic minerals orthopyroxene and green hornblende or hornblende and biotite (sometimes all three); minor constituents magnetite, apatite, zircon, and sometimes orthite.

The form and extension of two of the largest of the quartz bodies appear from the sketch map, Fig. 16. It is characteristic of these bodies that they form depressions in the landscape; the granite surrounds them with high walls at several places (Fig. 17). The boundaries between the granite and the quartz bodies are sharp, without indication of textural border zones either in the granite or in the quartz. At many places it is seen that the contacts are vertical. Nowhere have I seen dikes or apophyses from either body into the other or inclusions of one in the other.
As stated, the pegmatitic bodies consist largely of quartz, which occurs in anhedral individuals often measuring several cm in diameter. Insignificant amounts of albite, microcline, actinolite, zircon and apatite form small inclusions in the quartz; they frequently have euhedral outlines; especially the albite has the appearance of phenocrysts, often showing rectangular outlines. The entire quartz rock is much more friable than the quartz of ordinary pegmatites or other pre-Cambrian quartz rocks, the natural explanation of the fact that it forms depressions in the granite.

Bodies like these I have only observed at a few places, all in the same granite, and I have not seen descriptions of such bodies in the literature. The interpretation of their genesis is not obvious.

Fig. 16. Sketch map showing two large quartz bodies (dotted areas) surrounded by granite at the lake Folevand between the farms Løvdal and Orkjær, southwest of Risør. The double line indicates road between Laget and Gjeving.

It may be maintained that the quartz bodies simply represent large fragments of older quartz rocks included in the granite, and since quartzites, older than the granite, unquestionably do occur in this pre-Cambrian area, the idea cannot be disposed of as altogether unreasonable. However, the following facts speak against it: The absence of border structure in the granite at the contacts, and the absence of dikes or apophyses from the granite into the quartz body. On the strength of these objections I prefer not to regard these bodies as foreign inclusions in the granite.

My data are inadequate for strong arguments in favour of any definite genetic theory for these bodies. The following may be said to indicate that they have been formed by replacement: The texture of the quartz body, characterized by very small and in part euhedral inclusions of the minor constituents in the large individuals of quartz,
shows that the quartz in all probability has been formed under conditions differing from those prevailing when the minor constituents were formed. These minor constituents may have been residual minerals left over from the granite after the replacement process. Most of the potash feldspar, all biotite, and the ferromagnesian part of the hornblende may have been removed, and some albite, most of the apatite, zircon, and the lime-magnesia part of the hornblende (including some FeO bearing constituent) have been left, quartz being deposited in place of all the substances removed.

These replacing solutions may represent some late emanations from the granite magma itself, transported through fissures from the underlying magma basin to a place in the previously crystallized granite where they could remain for some time to react thoroughly with the minerals of the granite, then passing on, carrying away the substances dissolved and depositing quartz.

As an alternative explanation one could assume that the quartz bodies represent crystallization of a silica restmagma entrapped in the granite. This is a simpler explanation and would perhaps be given the preference by many geologists. However, the structural features mentioned do not harmonize well with such a mode of genesis, and for that reason I am inclined to support the replacement theory.

**General remarks on coarse-grained quartz bodies.**

Numerous other quartz bodies, some small and some of enormous size, occur in the same general district, around Risør, Tvedestrand and Arendal. Some of these bodies one would undoubtedly call quartzites, thereby indicating their nature as metamorphosed sedimentary rocks, others one would call quartz pegmatites or veins, while in many cases the mixed character of the body would make one hesitate before applying any term having a genetic implication, rather disposing of the matter by using the noncommittal term "quartz body".

It seems plain, however, that even those bodies, whose structure and mode of occurrence justify their classification as quartzites, during their metamorphosis have been affected by solutions of the same kind as those producing the pegmatitic quartz veins. One is almost forced to the conclusion that large parts of the area here considered (the Kongsberg Bamble formation) have been subjected to a truly
regional influence of circulating siliceous solutions, producing at some places an injection metamorphism in small scale, at other places a less distinct metarmorphism consisting for instance in a partial re-crystallization of quartzites, and at still other places being the agents of crystallization of numerous large and small bodies of pegmatitic quartz.

These widespread solutions have probably been dilute hydrothermal solutions containing silica as the predominating solute. Silica

Fig. 17. Lövdal, Dyvåg. From the road (about in the center of the circular quartz body Fig. 16) northeast of the farm, looking north. The wall in the background is granite, the lighter rock in the foreground is quartz pegmatite.

magmas cannot be regarded as a likely source of these quartz bodies, although such magmas under other circumstances may have caused the formation of large rock bodies extremely rich in quartz.\(^1\)

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\(^1\) It is of interest in this connection to mention V. M. Goldschmidt's description of magmatic quartz dikes, presumably representing the last product of differentiation of the opdalite-trondhjemite magmas of the Stavanger region. (Die Injektionsmetamorphose im Stavanger-Gebiete. Vidensk. Selsk. Skr. I Mat. Naturv. Kl. 1920, No. 10, p. 31). These dikes are fine-grained, rather aplitic than pegmatitic in texture, and form regular sills or even small lacolites in the surrounding schists, in these respects differing from the coarse-grained quartz bodies here considered and therefore probably formed under different conditions. Thus the acceptance of a truly magmatic origin of the quartz bodies in the Stavanger region does not contradict the explanation of the pre-
With regard to the source of these circulating solutions several opinions may be maintained, but I see no reason why the solutions should not have been genetically associated with some or all of the magmas which at various periods have been present in the formations considered; gabbros, diorites or granites are nowhere far away from the quartz bodies.

The gabbro magmas may have been the source of most of these bodies. In the particular region considered (the Kongsberg Bamble formation) the gabbros, as far as I have seen, are always older than the granites, and both are intrusive in the foliated metamorphic rocks. The fact that the quartz bodies considered are very common in the foliated rocks, rare in the gabbros, and, with the few exceptions that can be otherwise explained, not present in the granites at all, thus is in agreement with the idea that most of the quartz bodies have originated from the gabbros. Their scarcity in the gabbros may have a similar reason as the scarcity of large granitic pegmatitic bodies in the granites, a matter alluded to before. As stated already the source of the solutions which may have formed the quartz bodies in granite is assumed to have been the granite magma itself.

7. Pegmatites endemic in metamorphic rocks.

Among bodies included under the description “pegmatites endemic in metamorphic rocks” the following may be mentioned as being relatively common in the pre-Cambrian formations of Southern Norway: Coarse-grained lenses or irregular lumps of a plagioclase-cordierite bearing mineral association in plagioclase-cordierite gneisses, large garnet bearing masses in garnet bearing gneisses, epidote bearing microcline-quartz pegmatite in epidote bearing microcline-quartz-mica schists. These bodies have largely the same paragenesis as the Cambrian quartz bodies as formed by hydrothermal rather than by strictly magmatic solutions.

Some other statements in the same paper (p. 33) concerning schistose quartz bodies deserve emphasis: "Es ist möglich, daß auch einige größere Massen ganz schiefriger Quartzgesteine ihrem Ursprung nach mit diesen intrusiven Quartzzügen zusammengehören" — — — "Dies ist von Interesse für die Deutung so manchen Quartzschiefers in andern Gegenden des kaledonischen Gebirges". These significant statements should be born in mind also when the genetic interpretation of many of the puzzling quartz bodies in the pre-Cambrian formations are sought for.
rocks in which they occur and seem to owe their origin to the same genetic processes as those that produced the final metamorphism of the rocks. They are never of any conspicuous size, still they may be larger than many of the small bodies called pegmatite in the preceding descriptions, at the same time being sufficiently coarse-grained to justify the denotation pegmatite. Genetically they may be closely related to the miniature pegmatites occurring in gneisses and quartzites (see p. 11), these bodies being explained as formed by injection metamorphism. The principal difference in genesis may have been that in the miniature pegmatites referred to, the injected solutions have introduced new material into the initial rock, whereas in some of the pegmatites here considered the solutions may have been agents not so much for introduction or exchange of material as for recrystallization of material already present.

Good exposures of the cordierite and garnet bearing bodies may be seen at numerous places along the coast of Sörlandet. The data at my disposal are inadequate for detailed descriptions, but the following brief statements, based on field notes from my geological survey work, may give a general impression of the nature of these bodies.

**Cordierite bearing pegmatite.**

On a little island in the Sondeledfjord, southeast of the farm Svenes (about 7 km west of Risör) the prevailing anthophyllite-cordierite bearing plagioclase gneiss contains numerous irregular bodies or veins consisting of clear oligoclase (in part aventurine), quartz, cordierite, anthophyllite, biotite, and a little apatite and hematite. These bodies sometimes cut across the foliation of the containing gneiss, but usually form roughly lens-shaped veins along the foliation. The boundaries between the pegmatite and the wall rock are never very sharp.

Similar observations are made at the southwest point of the island Frøyna not far from the place just mentioned. The cordierite in the pegmatitic bodies at this place is particularly conspicuous owing to its large individuals and its deep blue color. It is also worth stating that the anthophyllite bearing gneiss containing these bodies is strongly crumpled, a fact which indicates that forces which may have produced open fractures in the rocks have been active during the metamorphism.
Garnet-rich pegmatite.

At another place in the same neighbourhood, a little island rock west of the larger island Hannöen, the prevailing quartz-garnet bearing biotite schist (probably an altered amphibolite) contains relatively large bodies (some over 0.5 m in diameter) of a pegmatitic mineral association consisting of garnet, plagioclase, quartz, biotite, and a little cordierite and apatite. At some places there is a characteristic "graphic" intergrowth of garnet and quartz. Some of these pegmatitic bodies consist largely of garnet and quartz, others largely of plagioclase and quartz. One rather distinctly dike-shaped quartz-plagioclase pegmatite at this place is more than 1.5 m wide. All these pegmatite bodies and their containing rock are cut by a little dike-shaped body of plagioclase-quartz pegmatite carrying black tourmaline and muscovite as dark minerals.

Epidote bearing pegmatite.

One type of the bodies here considered, the epidote bearing pegmatites, I have described in an earlier paper. These pegmatites form lenses in a strongly foliated rock of wide distribution around Notodden. The rock has been described under various names, such as granulite and leptite; it is characterized by the following mineral composition: Large amounts of microcline perthite and quartz, considerable amounts of epidote and muscovite, some biotite, and small amounts of oligoclase, hematite, ilmenite, titanite, apatite, and calcite. The parallel arrangement of the small scales of muscovite gives the rock the appearance of a glistening mica schist.

The pegmatite bodies contained in this rock have almost the same mineral association as the rock itself, but the individuals are much larger than in the rock. The structural features of these bodies (described in the paper referred to) show that the epidote has crystallized first and has been fractured and partly corroded before the other minerals crystallized.

The most probable explanation of this characteristic combination of a metamorphic rock and pegmatite is the following: The whole system is produced by metamorphism in several stages. First the

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1 On Epidote etc., Arch. f. Math. og Naturvidensk., 31, Nr. 15, 1911.
2 This explanation is briefly indicated, as one of several alternatives, in the earlier paper referred to.
original rock, presumably a supercrustal rock, rich in quartz and potash feldspar\(^1\), has been subjected to the metamorphism which produced its foliation. This may first have been simply a mechanical deformation accompanied by granulation of the minerals, but it must have passed over into recrystallization actuated by solutions of magmatic origin permeating the rock. During this recrystallization period epidote was formed. In the greater part of the rock it had no chance to grow to anything but small individuals, but at some places the passages through which the solutions circulated must have been wide enough to permit the free crystallization of rather large individuals (several cm long) protruding from the wall-rock. Then, before any further crystallization took place, while the passages were kept open by the solution, some mechanical disturbances broke the epidote crystals, and chemical changes in the solution caused their corrosion. Finally the passages were filled by an orderly crystallization of microline perthite, quartz, and the other minerals constituting the pegmatite, the fractured epidote crystals being included in feldspar or quartz, or sometimes in calcite\(^2\).

Whether this last stage was simply a recrystallization produced by the solution, or it included a supply of material from the solution, or a replacement of material, are questions not easily answered. In all probability some of the microcline and quartz, and perhaps all the carbonate, have been supplied by the solution, and it is obvious that part of the epidote has been replaced by other minerals.

This example is of particular interest because it seems to demonstrate more plainly than most examples that processes of metamorphism and processes of pegmatite formation may be closely related phenomena. All the pegmatite bodies described in this section would correspond more or less closely to the contact pegmatites in Fersmann’s system of classification\(^3\).

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1 W. Werenskiold has suggested a rhyolite (Norges Geol. Undersøkelse Nr. 53, II, p. 25, 1909), but several other suggestions (cited by Werenskiold) have been made.

2 Calcite forms in part individual lenses, to all appearances of the same origin as the rest of the pegmatite lenses.

3 Z. Kr. Abt. B. 41. 80. 1931.
Distribution of pegmatites.

The regional distribution of pegmatites within the pre-Cambrian areas of Southern Norway can hardly be disputed; superficially stated these bodies occur practically everywhere. Still, on closer study it will be seen that they are not evenly scattered throughout the area or throughout all the subdivisions of the pre-Cambrian system; it is also evident that they show decided preferences for certain petrographic types of country rocks, and in many cases they seem to be regionally associated with certain rocks with which they are likely to be genetically associated.

With regard to the distribution of pegmatites within the various geologic subdivisions of the pre-Cambrian I have few systematic observations of my own, and there is very little information available in the literature. All that can be stated with certainty, therefore, is that there are observable discriminations between various parts of the pre-Cambrian formations with regard to their content of pegmatite bodies.

The regional association of granitic pegmatites and large granite bodies seems to be definitely established for certain areas, but is not easily proved for others. The granite of Østfold, for instance, is most certainly surrounded by numerous pegmatite bodies, as shown long ago. The same is the case with the large granite area of Flå. Along the coast of Sørlandet these relations are obscured by the complex geological structure of that region, relatively small granite bodies being intermingled with gneiss, gabbro and other rocks in which the great majority of the large feldspar bearing pegmatites occur. Even with regard to this area, however, one can safely state that the pegmatites always occur in close proximity to granites, because granites of various types have a regional distribution almost as general as pegmatites have. But in this area it is usually difficult to point out any particular granite body with which a particular pegmatite body may have been genetically associated.

1 Thus Arne Bugge (p. 112 in paper referred to on p. 16) has observed that conspicuous feldspar bearing pegmatites are absent within certain parts of the Kongsberg-Bamble formation and particularly numerous within others.
2 See Vogt (p. 66 of paper referred to on p. 6) where references to Brøgger and others are given.
Distribution in various country rocks.

An interesting feature of the mode of occurrence of pegmatites is
the striking preference, shown by the most conspicuous of these bodies,
for definite types of country rocks.

It goes without saying that the group of pegmatites described
as “endemic in metamorphic rocks” do not occur in any other rocks,
each type of pegmatite being restricted to its particular type of
country rock.

It has been mentioned that the most common type of quartz
pegmatite occurs abundantly in metamorphic rocks, but sparingly in
gabbros, and not at all in granites, and that a particular type of
quartz pegmatite has been observed in one definite type of granite
but nowhere else.

Table 3. Relative abundance of granite pegmatites
in various types of rocks.

1. Number of pegmatite bodies in pct. of total number observed.
2. Relative areas of rocks (pct. of total areas).
3. Number of pegmatite bodies per unit area of rock (the ratio 1:2 recalcul-
lated on a percentic basis).

<table>
<thead>
<tr>
<th>Type of rock</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gabbro and amphibolite</td>
<td>60</td>
<td>5</td>
<td>87</td>
</tr>
<tr>
<td>Gneiss</td>
<td>25</td>
<td>50</td>
<td>4</td>
</tr>
<tr>
<td>Granite</td>
<td>10</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>Quartzite</td>
<td>5</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>

With regard to the distribution of ordinary granite pegmatites
in various country rocks some interesting facts are brought out by
compilation of approximate statistics. On the basis of field notes,
made during geological survey work in an area of some 2000 sq. km
of pre-Cambrian rocks, I have prepared the statistics of distribution
contained in the first column of Table 3. The figures are based on
about 250 individual observations of pegmatite bodies large enough
to be easily noticed during general field work, most of them workable

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1 Includes all heavy femic rocks.
2 Includes all gneisses, but not foliated granites.
3 Includes all granites, foliated and non-foliated.
4 Includes also some pegmatitic quartz bodies.
feldspar deposits. The predominance of gabbros and amphibolites as country rocks of pegmatites is apparent from these figures, but a more correct expression of the relative importance of various groups of rocks is obtained by taking into account the relative areas of the rocks. There are no accurate data available for this purpose, but on the basis of fragmentary geological maps and my personal impressions from the field I have made the guesses put down in the second column of Table 3. The third column, then, gives the relative number of pegmatite bodies per unit area of rocks, and these figures express, as correctly as the data permit, the relative importance of the various rocks as country rocks of pegmatites. Even considering the high degree of inaccuracy of these figures the relations shown are too striking to be disposed of as incidental; they must be considered in formulating the genetic theories of pegmatites.

Possible explanations of selective distribution.

The predominance of the gabbro group as country rocks for granite pegmatites might be ascribed to a magmatic relationship between the gabbros and the pegmatites, but I can find no evidence for such an assumption and see no reason for a further discussion of it, so much the more so as I believe that a plausible explanation may be given on a different basis.

The problem may be resolved into several minor problems. First one must account for the source of the solutions from which the pegmatites crystallized. Then one must answer the questions of how the openings, in which the crystallization took place, were formed; how the solutions were transported from their source to these openings; and why the openings were so much more numerous in gabbros and amphibolites than in any other rocks.

The first sub-problem has been discussed already: In accordance with a general opinion among geologists it has been maintained that the granite pegmatites have crystallized from solutions originating from granitic magmas. As granite bodies are widespread and belong to several stages of intrusion these solutions have had a truly regional distribution within the area considered and have been present in an active state for a long period of time. An explanation of the transportation of the solutions has also been intimated: Cooling cracks in the first crystallized granite and its surrounding rocks are supposed to have been the main channels through which the solutions passed
from the magma to the openings in which the pegmatite bodies were formed.

Regarding the explanation of the formation and selective distribution of these openings there are several possibilities. It might be argued off hand that the openings were cooling cracks like the channels of supply just mentioned, and naturally such cracks are likely to have existed also in gabbros and amphibolites, if they have existed in other rocks; but then it is difficult to see any reason for the selective distribution of the pegmatite bodies.

The openings might be assumed to have been caused by stresses set up by orogenic forces in zones of intensive folding, and this, of course, is a possibility that cannot be disregarded; indeed it is probable that many of the openings giving access to pegmatitic material have been formed in that way.

In order to use this process as an explanation of the unequal distribution of pegmatites in various rocks one must assume that the rocks of the gabbro amphibolite group differ materially in elastic properties from the other rocks, in such a way that fractures would form more easily in these rocks than in the others. This is not an altogether unreasonable assumption, but the meager data now available on elastic properties of rocks do not give any definite proof of it. All that can be said, therefore, is that the process must be seriously considered as one of the possible explanations of the preferential position of gabbro and amphibolite as country rocks for granite pegmatites.

One hypothesis, which in my opinion also should receive consideration, takes account of the unequal thermal contractions that no doubt characterize the various rocks involved.

In a previous paper¹ I have tried to show how the principle of unequal thermal contraction in heterogenous associations of minerals may explain certain phenomena of perthite formation. The same principle can obviously be applied to heterogenous associations of rock bodies. The ideas underlying this principle may be briefly set forth as follows:

It is assumed that a limited rock body A (Fig. 18 a) is surrounded by another rock body B, and that A has a larger thermal contraction than B at least for a certain temperature range. It is

further assumed that the two bodies occur in the zone of fracture in the Earth's crust, and that the cooling of the entire complex takes place at such a slow rate that no stresses large enough to fracture the rocks need arise on account of temperature gradients. Under these conditions open spaces may nevertheless be formed in one way or another when the rocks cool through the temperature range stated. If there is no restraining force along the contact between the two rock bodies, A will loosen from B, and a space will form along the contact (Fig. 18 b). If, on the other hand, a sufficiently large frictional force is present along the contact faces, caused for instance by pressure exerted by B on A, cracks will be formed transversal to the direction in which the free motion along the contacts has been restrained (Fig. 18 c). If contraction along the contacts is partly free and partly restrained, the cracks will have a variable and irregular course, and this is most likely to be the case with actual rock bodies.

This principle may be applied to any combination of rock bodies fulfilling the conditions specified. Of special interest is the combinations of minor bodies of gabbro and amphibolite with surrounding rocks rich in quartz, because generally speaking, it represents the actual field relations obtaining in the area considered, where gabbros and amphibolites practically always are in contact with quartz bearing gneisses or quartzes, sometimes also with granites. Gabbro or amphibolite included in quartzite will represent almost an ideal case, provided that the cooling takes place in the region of high temperature quartz, say from 800° to 600° C. Throughout that range the volume of quartz is practically constant whereas all other common rocks, as far as our present knowledge goes, will contract on cooling¹. Thus conditions are present for formation of openings in the gabbro and amphibolite or along the contacts between these rocks and quartzite.

When the surrounding rock is only partly composed of quartz these relations will be modified, but there is every reason to believe that the presence of considerable amounts of quartz in a rock will

¹ For data on the thermal contraction of amphibolite see: S. Kozu, B. Yoshiki and Koichi Kani. Sc. Rep. Tohoku Imp. Un. Ser. III, vol. III, p. 150, 1927. Data on gabbro for the temperature range considered are not available, but there is no reason to doubt that also this rock has a considerable contraction.
influence its contraction properties in the direction supposed, also these rocks forming a matrix less contractible than the included bodies of gabbro or amphibolite.

It should be emphasized that the main point in this explanation is the peculiar volume constancy of high temperature quartz; the relations postulated are not likely to be very marked in the temperature range of low quartz or in any temperature range if only quartz-free rocks are involved.

![Fig. 18. Imaginary lenses of gabbro in quartz.](image)

If the hypothesis indicated can be upheld when exact data bearing on it become available it may be applicable also to many other combinations of rocks than those here considered.

**General conclusions.**

In this section an endeavour is made to present in connected form the general conclusions that may be based on the foregoing descriptions and special discussions. Some of these conclusions represent long established results, but they are restated in view of the confirming evidence contained in the observations given in this paper; others represent modifications of old ideas, and some may be new. It should be remembered that the features here discussed are those observed in the pre-Cambrian pegmatites of Southern Norway, but the genetic principles involved may find application to pegmatites in general.

The basis for all theories of pegmatite genesis at the present time is that these bodies owe their origin to the activities of deep-seated magmas. It has been established beyond doubt that there is a comagmatic relationship between certain types of pegmatite and definite types of igneous rocks; the existence of such bodies as granite pegmatites, syenite pegmatites, and gabbro pegmatites, cannot be disputed. In some cases the distribution of pegmatites, such, for
instance, as the crowding of granite pegmatites around large bodies of granite, gives additional support to this idea of a genetic association between pegmatites and definite magmas. But at the same time it is also true that the pegmatite bodies differ in composition from any assumed parent magma; they are products of differentiation. Sometimes the differentiation is carried so far that the relationship of a pegmatite with a definite type of parent magma cannot be easily established on chemical or mineralogical basis. This is the case, for instance, with many of the pegmatitic quartz bodies of which a few examples have been described. For geological reasons some of these quartz bodies may be assumed to have originated from gabbros, while others are more likely to be products of differentiation from granites, although their compositions in either case may be almost the same.

The granite pegmatites offer particularly instructive examples of transitional stages of differentiation. This is demonstrated both by their composition and by their structure. Some of them, notably the small ones, are little different from coarse-grained granites, sometimes shading directly into normal granites. Others may have nearly the composition of granites, but differ essentially in structure. Still others may differ widely in both respects.

A clue to the understanding of many of the peculiar features of pegmatites may be found in the influence of the long and narrow fractures which, according to inference from field observations, have formed the communicating passages between the magma and the more remote and relatively large openings where many pegmatites crystallized. It is thought that the initial pegmatite magma has undergone differentiation by giving off volatiles (i.e. dilute mineral solutions) to these narrow vacuum cracks. The mobile volatiles have passed on much more quickly than the relatively viscous residual solution, and have had a chance to precipitate minerals before the temporary disturbances of equilibrium, caused by the sudden opening of cracks, have been equalized. It is pointed out in the foregoing discussion how this process may explain such features as the mixed pegmatite and aplite bodies, the zonal structure of many pegmatites, and the passing of granite pegmatites, through stages of dominating bodies of central quartz, into bodies of almost pure quartz, and also possibly may be one of the reasons for replacement phenomena. The numerous possibilities of structural variations afforded by this
process makes it particularly attractive as a basis for interpretation of pegmatite genesis. At the same time it is maintained that the usual crystallization differentiation, causing concentration of volatiles in residual solutions, must be reckoned with, but this process cannot well explain such features as the association of aplite and pegmatite, the zonal structure, or the grading of pegmatites into individual bodies of quartz, unless it be combined with a process in which a stream of changing solutions is involved. Mention should also be made of the possibilities of repeated cycles of differentiation, each residual solution contained in a local pegmatite chamber being able to start a differentiation of its own if its conditions of crystallization change, as they undoubtedly will when new fractures are opened.

For some pegmatites one has to assume not only a differentiation from a possible parent magma, the identity of which may be uncertain, but also a reaction between the pegmatite forming solution and the country rock. This may have been a simple process of assimilation, most of the assimilated substance having lost its mineralogical identity in the wandering solutions; but it may also have been a true metasomatic replacement. Of the former case some of the pegmatitic quartz bodies described may be mentioned as examples. Of the latter case the pegmatites here described offer few clear examples as far as replacement of the country rock is concerned, whereas the replacement at later stages is unmistakable in all pegmatites carrying potash feldspar (e. g. formation of replacement perthite).

In a certain group of pegmatitic bodies here called “pegmatites endemic in metamorphic rocks”, comprising various types such as garnet, cordierite or epidote bearing pegmatites, the reaction with the country rock has been more a recrystallization than an assimilation or replacement. These bodies are supposed to have been formed as injection bodies and for most of them it is not necessary to assume any appreciable supply of material from the solution, but it seems essential that solutions have been active to form fluxes for the recrystallization.

The openings in which pegmatites crystallized may have been formed in several ways. As pointed out, these openings cannot have been of the same kind as the regular tectonic fissures in which

1 See, however, the examples from Arnevik, p. 17.
igneous dikes usually have crystallized, but many of them may owe their existence to orogenic forces. As a possible mode of formation of openings in relatively small bodies of gabbro and amphibolite surrounded by quartz bearing rocks, is suggested a differential thermal contraction in the temperature range of high-quartz, where quartz has a constant volume while other minerals and rocks contract on cooling. This mode of formation would explain why granite pegmatites occur so much more frequently in gabbros and amphibolite than in any other rocks. Cooling cracks, caused by steep temperature gradients may have formed openings for the numerous small pegmatite bodies occurring in granites and neighbouring rocks, and have been the channels through which most of the transportation of solutions from the magma to the larger openings in the surrounding rocks has taken place. The possibility that some of the larger openings now occupied by pegmatites have been formed by widening of narrow fractures through processes of assimilation is also indicated.

The features of the pegmatites considered in this paper show plainly that these bodies must have been formed under conditions differing widely from those under which typical igneous rocks were formed. Comparing the pegmatites for instance with the igneous dikes mentioned before, one will find very few similarities, although both groups of bodies are supposed to have a magmatic origin. This difference, as intimated before, must be ascribed to physically different environments caused by the geologic conditions under which the respective groups of bodies were formed.

The fissures of dikes have been feeding channels either for surface flows or for intrusive bodies formed near the surface; in either case they have been kept steadily open, affording an easy flow of the magma, and the magma has given off its volatiles in part gradually during the passage and in part by exhalations at the surface. Such conditions obtain when parts of the Earth’s crust are subjected to tensile stresses of regional dimensions, which will be the case in regions of continental uplift or gentle anticlinal folding. In a vertical section through such a region there will be an upper zone of tensional stresses underlain by an intermediary, neutral zone of no stress and a deeper zone of compressive stresses. The upper zone, then, must be the seat of dike formation, and the magma basins from which the dikes are fed must have been located within the same zone.
If the conclusions drawn in this paper hold true, pegmatites have not been formed in any zone of tensional stresses, but have been restricted to zones where fractures would form, because of temperature gradients, or because of differential contractions in adjoining rocks, or because of compressive stresses. Such zones are formed in regions subjected to orogenic forces and to the influence of nearby magmas. Because openings formed under these conditions have not been continuously wide, but must have had narrow interconnections, and because they have sprung up by intermittent ruptures, the injection of pegmatite forming solutions into them has taken place in spasmodic waves. As a consequence there has been at least a temporary exhalation of volatiles into the openings and a possibility for permanent differentiations.

A feature of the granite pegmatites described in this paper deserving special mention is the general absence of strongly marked replacement phenomena. Apart from the universal phenomena of muscovitization and albitization of feldspar the granite pegmatites of Southern Norway show no examples of mineral replacement of the kind so well described from many American localities\(^1\) and indeed very few distinct features that need be ascribed to replacement. Another striking feature of the Norwegian pegmatites is the total absence of lithium bearing minerals\(^2\), and since the replacement phenomena of the American pegmatites are particularly distinct in bodies rich in lithium minerals the conclusion seems obvious that these phenomena are conditioned by presence of lithium compounds in the magma. This does not mean that lithium compounds are the only ones parttaking in the replacement, but merely implies that the magma containing such compounds is capable of yielding the hydrothermal solutions necessary for the replacement processes. In magmas devoid of lithium the differentiation in hydrothermal direction has stopped at an early stage, albite and quartz being the last minerals to form in the great majority of the pegmatites formed from such magmas.

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2 A pink mica, occurring at one locality and reported as lepidolite, has been proved to be muscovite colored by traces of manganese.
The term pegmatite

Examples and discussions of pegmatite bodies

Distribution of pegmatites

1. Large pegmatites in granites
2. Small pegmatites in granites
3. Small pegmatites in various rocks
   - Buøen
   - Tveit
   - Flostaøen
   - Flaten
   - Miniature pegmatites
   - Dal
   - Terneholmen
   - General remarks on small pegmatite bodies
4. Large granite pegmatites in non-granitic rocks
   - Arneviken
   - Lyngrot
   - Ljøstad
   - Kibbevik
   - Berø
   - Frøyna
5. General remarks on granite pegmatites
   - Summary of features
   - Aplite in pegmatite
   - A possible cause of aplite formation
   - Possible explanations of some pegmatite forming processes
6. Large coarse-grained quartz bodies
   - Åmdal
   - Kvitberg
   - Søisdal
   - Lindviken
   - Lövdal-Orkjaer
   - General remarks on coarse-grained quartz bodies
7. Pegmatites endemic in metamorphic rocks
   - Cordierite bearing pegmatite
   - Garnet-rich pegmatite
   - Epidote bearing pegmatite
   - Distribution of pegmatites
   - Distribution in various country rocks
   - Possible explanation of selective distribution
   - General conclusions

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