PRINCIPLES OF CLASSIFYING GRANITE PEGMATITES, AND THEIR TEXTURAL-PARAGENETIC TYPES[1]

by

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For over 15 years, this author has returned, on many occasions, to the problem of a textural-paragenetic classification of rare-metal granite pegmatites. This subject was best covered in Izvestiya of the Academy of Sciences, S. S. S. R., ser. geol., No. 2, 1952.

In recent years, the author has observed and studied many additional pegmatite fields in the Soviet Union and abroad — in China, Morocco, India, Spain, and the United States. An analysis of field data, coupled with information on this subject by the personnel of the Institute of Mineralogy, Geochemistry, and Crystallography of Rare Elements, as well as by the personnel of other Soviet organizations, and added to a study of foreign literature on pegmatites [8, 9], fully corroborates the truth of the principles of our textural-paragenetic classification of granite pegmatites.

We know now the importance of structure, texture, and mineral paragenesis in a classification of granite pegmatites, in their origin, spatial distribution relative to mother intrusions, in determining the regularities of the distribution in them of rock-forming and rare-metal minerals, and consequently the geochemistry of their component elements. At the same time, we have become aware of shortcomings in earlier variants of the textural-paragenetic classification, and of the new problems calling for solution.

One of the most important problems is the role of pegmatites with large accumulations of albite and spodumene, in a textural-paragenetic classification. In earlier variants, these pegmatites were included in the fourth rare-metal-replacement type, as its youngest member and consequently as the youngest product of the pegmatite process in general ([4], Figure 2, top).

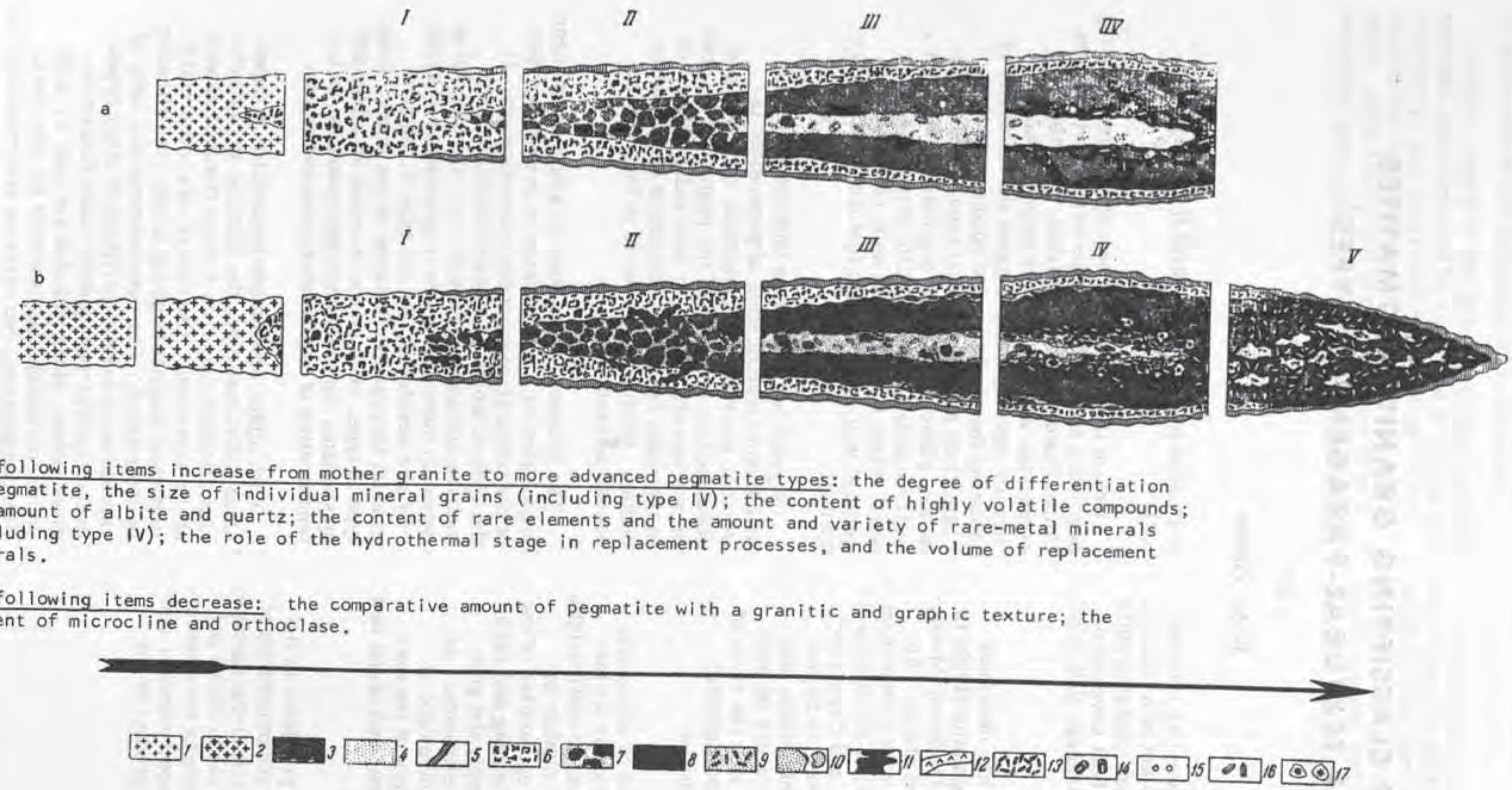
Recent discoveries of new spodumene-bearing pegmatite fields of this type in the Soviet Union, United States, Canada, Africa, and other countries, as well as their intensive commercial development, suggest the necessity of isolating these albite- and spodumene-rich pegmatites as an individual type V. Since the name, albite-spodumene pegmatite, has been well established in scientific literature, we shall retain it, inasmuch as it reflects, in a general way, the specific features of its paragenesis.

Of great importance in understanding the origin and classification of pegmatites is whether their albite-spodumene varieties are developed as a branch of the pegmatite process or are merely a more or less independent link in the chain of over-all evolution of pegmatite bodies. Evidence on hand is in favor of the second alternative.

The following facts point to albite-spodumene pegmatites as a continuation of preceding types of the textural-paragenetic classification: 1) the classic fields of albite-spodumene pegmatites always contain veins of other pegmatite types; 2) those fields where pegmatites of types I-IV are developed, but not type V, show a gradual increase in features of the latter, from type to type, such as the increase in albite and spodumene, up to commercial amounts; an intensification of replacement processes; etc.

With albite-spodumene pegmatites grouped as an individual type, the textural-paragenetic classification acquires a more finished aspect; at the same time, the role of this industrially important pegmatite group in our classification is determined. For completeness and unity of exposition, a brief description of other types in the textural-paragenetic classification is given below, along with that for type V, with some corrections necessitated by new data. For comparison, two variants are presented in Figure 1, where (a) is the preceding and (b) is the new one.

[1]Printsipy klassifikatsii granitnykh pegmatitov i ikh teksturno-parageneticheskiye tipy.



The following items increase from mother granite to more advanced pegmatite types: the degree of differentiation in pegmatite, the size of individual mineral grains (including type IV); the content of highly volatile compounds; the amount of albite and quartz; the content of rare elements and the amount and variety of rare-metal minerals (including type IV); the role of the hydrothermal stage in replacement processes, and the volume of replacement minerals.

The following items decrease: the comparative amount of pegmatite with a granitic and graphic texture; the content of microcline and orthoclase.

FIGURE 1. Diagram of textural-paragenetic pegmatite types.

a) preceding; b) new variant.

1 - granite; 2 - pegmatoid granite; 3 - microcline; 4 - quartz; 5 - contact fringes and zones of a muscovite-quartz-feldspar composition; 6 - graphic and granitic pegmatites; 7 - block zone; 8 - monomineral microcline zone; 9 - quartz-spodumene zone; 10 - blocks and zones of quartz; 11 - replacement zones and complexes: albite,[1] quartz, muscovite, microcline relicts, rare-metal minerals: lepidolite, beryl (commonly containing cesium), niobate-tantalates, polychrome tourmaline, spodumene, etc.; 12 - lepidolite zone; 13 - spodumene; 14 - beryl; 15 - pollucite; 16 - amblygonite; 17 - in cavities: minerals of kaolinite group, quartz crystals, lepidolite, kunzite, etc.; I-IV) textural-paragenetic types.

[1] Because of identification difficulties, the replacement complex combines albite of two generations: formed in the process of replacement and formed independently from pegmatite melts.

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PRINCIPLES OF PEGMATITE CLASSIFICATION

It is well known that the task of working out a scientific classification for natural bodies, within a class or a family — be they animal, vegetable, or mineral — is as difficult as it is important. This difficulty arises from the fact that bodies grouped in the same class are in fact stages of a single evolutionary process, with all shades of commonly imperceptible transition between them. Because of that, designation of types within a class or a family; e. g., a rock family, calls first of all for determining well-defined boundaries marking a sharp change in properties, as a result of which the bodies acquire essentially new features in the process of evolution. Identification of such criteria reflecting the basic features of natural bodies and setting one type apart from the other is the principal task in working out any classification. It should be kept in mind that in the progress from one link to another, (from type to type), the change affects a complex of criteria, including the secondary, rather than a single principal criterion. For this reason, the value of a classification depends on how typical its criteria are, and how accessible to observation. To be sure, classification criteria may change in time, with new methods of study, as witness crystallochemical structures which, along with chemical composition, have recently become one of the main classification criteria for minerals.

As of now, there are several classifications of pegmatites, based on various principles. Some students, both here and abroad, classify pegmatites by their mineral composition, into microclinic, microcline-albitic, albitic, albite-microclinic, and muscovitic; others classify them by chemical composition, into lithium, sodium-tantalum, beryllium, and other pegmatites. There are high- and low-temperature pegmatites; also simple and compound, according to their chemical and mineral composition; etc.

A detailed critical analysis of various pegmatite classifications [10, 15, 16] has been made before by the author [4]. We believe that they have the common fallacy of being, as a rule, one-sided and qualitative, without a quantitative evaluation of either the chemical or mineral aspect of the process; because of the lack of clean-cut criteria, the application of these classifications is quite difficult. This is readily understandable because pegmatites, being a product of granite magmas, are composed of the same elements and basically of the same minerals, but present commonly in quite different ratios. Consequently, without a definite reference to their quantitative chemical or mineral composition, it is in effect impossible do devise a scientific classification; this quantitative aspect, without taking into account the structure and texture, can be ascertained only after a volume testing or production. Moreover, such classifications do not consider the genetic features of pegmatites; they do not reflect the conditions of formation of individual pegmatite types, nor the differences in the properties and role of the same minerals in pegmatites of different types. It should be kept in mind, that even the percent composition alone, without taking into account the textural-structural and paragenetic features, will not reveal the genetic properties of pegmatites, as witness the designation of microclinic, microcline-albitic, and other pegmatites.

It appears then, that in these types, bodies sharply differing in properties and origin are grouped together. Suffice it to say that, in one example, microcline enters the composition of pegmatite with a granitic texture, with a grain size of 1 to 2 cm^3; in another example, microcline occurs in growths with quartz, and the pegmatite is graphic; in still another, microcline forms large crystals and blocks up to several cubic meters. In addition, microcline commonly forms monomineral zones, in places tens of meters thick, traceable for hundreds of meters along both the strike and dip. Quartz, too, may occur in huge blocks and belts.

Thus, the different bulk of minerals crystallized under different physicochemical conditions, even considered alone, determine the sequence of formation of various rock-forming minerals, which, in turn,, leads to the appearance of various associations of rare elements and rare-metal minerals.

A systematic classification of the immense amount of data on the numerous pegmatite fields of the world reveals an extreme variety and complexity in the chemical and mineral composition and textural-paragenetic features of granite pegmatites within individual well-developed fields, as well as the great difference between fields in different segments of the crust. This variety is expressed in different qualitative and quantitative relationships of rock-forming, secondary, and accessory rare-metal minerals, as well as in their different relationship in space and time. At the same time, there is an amazing similarity, repetition of composition and structure of pegmatites, with only a small number of kinds of composition and structure, despite the immense spatial and temporal break in the formation of pegmatite fields.

There seems to be a definite regularity in the chemical and mineral composition of pegmatites, expressed in a progressive complexity of mineral parageneses, from vein to vein, from field to field, and from simpler pegmatites to more complex ones. As a rule, the simplest pegmatites consist of two rock-forming minerals: K-feldspar and quartz. In other pegmatites, additional rock-forming minerals are represented by muscovite or plagioclase (mostly albite and oligoclase), lepidolite, spodumene, etc. This is also true for accessory rare-metal minerals; for example, the simplest pegmatites in structure and composition contain practically beryl alone, while others are characterized by a relative abundance of niobate-tantalates, cassiterite, pollucite, spodumene, lepidolite, petalite, etc. There are quite complex pegmatites which carry virtually all of these minerals.

No less diversified are the structural and textural features of pegmatites, closely related to their genesis. Some pegmatite bodies differ little from granites in structure and texture. Then there are graphic pegmatites, coarsely crystalline pegmatite bodies with an incipient zonation, and pegmatite veins with a well-defined zonation. In some of these bodies, rock-forming minerals are grouped in monomineral zones, with distinct replacement complexes commonly present along with the zones. Finally, there are bodies and entire fields of albite-spodumene pegmatites where the structural features and zonation are less conspicuous because of the sharply different chemical and mineral composition and the geologic conditions of their formation. It should be emphasized that gradual qualitative and quantitative transitions expressed in a regular change of structure, texture, and composition are present in these pegmatite groups. Similarities and differences between minerals of the same isomorphic series can be compared to some extent to relations between pegmatites.

All this makes for great difficulty in working out a classification and renders any classification one-sided, if it is based on a single criterion rather than on the entire gamut of criteria. It goes without saying that a differentiation of pegmatites by types is based on their variety, while pegmatite bodies within a type are grouped by the similarity of criteria on which the classification is based.

In assuming that granite pegmatites are a family of rocks, we cannot consider them apart from their mother intrusions. A view of pegmatites as links in a single evolutionary chain against a background of granite affords a better understanding of their origin and facilitates the task of classification.

Taken for the basis of a textural-paragenetic classification; i. e., the designation of types, are the different parageneses of minerals as well as structural and textural features of pegmatites. The totality of these criteria reflects the original chemical composition of pegmatite solutions, as well as the quantitative relationships of their principal minerals, and their conditions of formation. It should be kept in mind that even as a structure carries in it the implicit stages of its evolution, so does a texture show transitions from one type to another. It may be observed that a fine-grained granitic structure changes at a certain stage of its development to a block structure which in turn, as if by a concentration of microcline crystals, becomes monomineral while the quartz forms individual blocks and zones. These transitional stages are just as conspicuous in paragenetic associations.

At certain stages of development, paragenetic structural and textural features of pegmatites become so well expressed, qualitatively and quantitatively, that it becomes possible to draw boundaries between pegmatite types and to designate the place for each type in the general development of granite pegmatites.

Parageneses of rock-forming minerals, taken as a basis for designating the types, are supplemented by associated and accessory minerals, including the rare-metal ones. To be sure, the notion of rock-forming and associated minerals is a relative one; in the evolution of a pegmatite process and its types, some rare-metal accessory minerals become rock-forming, while some rock-forming minerals are reduced in rank.

TEXTURAL-PARAGENETIC TYPES OF PEGMATITES

In the following exposition, we take up the empirically established regularities in the structure of pegmatites and then we turn to a theoretical analysis of these regularities. In the description of types (Figure 1), we emphasize first the nature and relationship of principal rock-forming minerals: K-Na-feldspars (microcline-orthoclase), plagioclase (albite-oligoclase), quartz, spodumene (petalite), muscovite (lepidolite), and then the other minerals, including the rare-metal ones.

Each pegmatite type so defined and described can be illustrated by many examples from pegmatite fields of the U. S. S. R. No less abundant is illustrative material from other countries: the United States (South Dakota, North and South Carolina, California), Canada, Brazil, South Africa (Hamakvalend), Madagascar, India, Manchuria, etc.

Type I — even-grained to graphic. This type practically corresponds to granite in chemical and mineral composition. Principal rock-forming minerals are K Na-feldspars and quartz with small amounts of mica, black tourmaline (locally abundant), garnet, etc. Component minerals of this type are fine-grained, closely-knit and nearly contemporaneous. Rare-element minerals are virtually absent, and the replacement processes are poorly developed. The composition of these pegmatites suggests the slight importance of volatile compounds in their formation.

The relative importance of Type I pegmatite veins and zones is quite different in different fields. Locally, they make up the bulk of pegmatite rocks in a given field, while some other fields contain only isolated bodies or a few zones in structurally more complex pegmatites. The ratio of the volume of pegmatite with a graphic or granitic texture to that of pegmatites with other textures varies widely from vein to vein.

There are veins made up almost fully of graphic or granitic pegmatites; in others, this rock accounts for only 5 to 10% of the total volume (see Figure 1).

Pegmatites of Type I, showing different textures (granitic and graphic), represent in effect, different stages of a pegmatitic process, with the graphic texture corresponding to a more advanced pegmatite. This pegmatite is formed under the most favorable physicochemical conditions, as witness the massive growth of its feldspar: in the words of V. I. Vernadskiy [1] "like a sponge with its pores filled with quartz". However, considering the similarity in the time and conditions of their formation, as well as the lack of sizable accumulation of rare elements in these pegmatites, we group them in one type.

The occasional phenomenon of a graphic pegmatite located in small segments near the center of a granitic pegmatite is readily explained by thermal conditions in those parts of a forming body more favorable for the crystallization of graphic pegmatites.

There are transitions between pegmatites of types I and II (block), expressed in the presence of segments of block structure in even-grained and graphic bodies.

Thus, it appears that Type I has quite a simple mineral paragenesis corresponding to granite in composition.

Type II — block. This type is quite common among granite pegmatites and is characterized by the presence of two zones. The outer zone, or "ring" (in lenticular and columnar bodies) is represented by granitic and graphic pegmatite. The other zone, mostly the central one, consists of large but non-uniform crystals and blocks[2] (from a cubic decimeter to tens of cubic meters) of K-Na-feldspars and quartz blocks; as such, it is made up of a different mineral association. In a block zone, K-Na-feldspars were precipitated much earlier than quartz, although these minerals are still not quite well separated, and form a discrete complex or zone.

Rare-metal minerals (beryl, cassiterite, niobotantalate, rare-earth minerals, etc.) occur in fairly large crystals, although, as a rule, they are uncommon and scarce. Their composition depends on geochemical features of a given pegmatite field. Some block pegmatites contain beryl alone; in others, columbite and a number of other rare-metal minerals are present. Rare-metal minerals are localized in the central zone and usually occur in quartz, being older than it. In isolated examples, rare-metal minerals such as beryl are occluded by a portion of the crystal in microcline.

Replacement phenomena are inconspicuous in these pegmatites, being expressed in small segments of mica, albite, and younger quartz, all developed on microcline of the block zone as well as in the first zone. The replacement process grows in intensity with the growth of the importance of block pegmatite in the vein's make up.

It is quite interesting to trace the origin and development of Type II pegmatites. This type always develops on the background of Type I, as is excellently demonstrated in well-exposed pegmatite bodies. It can be seen that individual segments of pegmatite veins, usually those near to the middle, exhibit larger grains within the granitic or graphic textures; this appears to be followed by a sharp break in the conditions of formation, where graphic quartz ceases to crystallize and the microcline grows alone, for a long time, with its crystals growing progressively larger toward the middle of the vein. The formation of microcline is followed by mass crystallization of quartz; in this way a true block structure is developed (see Figure 1).

In individual pegmatite veins, segments of block structure occupy an area of about 1 m^2 and even less; in better developed Type II bodies, this area is measured in tens and hundreds of square meters. Block pegmatites often form entire zones; which indicates the full development of this type.

It has often been observed in the field that block structure is often present in central parts of pegmatite veins. Conditions particularly favorable for this have been noted in bulges of medium-sized veins, in oval bodies, in bends of veins, in domes, etc., which suggest a thermal regimen favorable for a slower crystallization and a more complete differentiation.

Naturally, with an increase in the volume of segment or zones of block structure, and with

[2] Small-size block structure, with feldspar crystals and quartz bodies up to 30 x 30 x 30 cm; medium-size block, up to 1 m^3; large-size block, 1 to 3 m^3; and giant-size, over 3 m^3.

a concentration of microcline crystals, Type II progresses to Type III.

Type III — fully differentiated. Type III is the next step in the process of formation of pegmatite bodies. The latter have as many as three independent zones. The outer one, similar to that in the preceding types, consists of graphic and granitic textures, although its part in the constitution of the vein is much smaller, compared with the preceding type (see Figure 1). The middle zone is almost all K-Na-feldspar, usually microcline, locally orthoclase. The central zone is represented by massive quartz bodies of various forms, most often oval. The quartz is generally pink, because of the presence of manganese compounds, which suggests concentration of this element following an advanced and thorough crystallization. Incidentally, this suggests that other rare and dispersed elements besides manganese may have become concentrated in this process; like manganese, they virtually do not participate in the rock-forming minerals.

Rare-metal minerals are associated with the contact zone of K-Na-feldspar and quartz; as a rule, they are younger than the quartz. Some of these minerals (spodumene, beryl, tantalite, etc.) occur as crystals in the feldspar near the central quartz zone; in that event, they are older than the young varieties of microcline.

The content of rare-metal minerals in Type III pegmatites is commonly high; for each pegmatite field it is, as a rule, higher than in the preceding types. A number of veins of Type III, in some pegmatite fields, are a commercial source of beryl and spodumene (Brazilian pegmatites, etc.).

Replacement processes are better developed here than in the preceding type. The assemblage of replacement minerals occupies larger areas but does not form individual zones, unlike Type IV. These areas are made up of albite, younger quartz, and muscovite, with rare-metal minerals, garnet, etc., among them. As a rule, the replacement proceeds along the interior part of the microcline zone and in individual microcline crystals in quartz; it also affects the periphery of that zone, helped by faults along which the replacing solutions penetrate various segments of the pegmatite body.

Thus Type III is represented by different paragenetic groups of rock-forming and accessory rare-metal minerals; i. e., by a different paragenesis.

Veins of Type III are considerably less common in pegmatite fields than veins of Types I and II. As a rule, Type III is developed in larger, chiefly oval pegmatite bodies or in large bulges of thick veins. Every gradation from Type II to III has been observed. Some features of Type III appear in those pegmatite bodies of Type II where microcline crystals begin to concentrate and quartz blocks begin to differentiate, but a monomineral microcline zone is not yet formed. In this case, segments of pure quartz occur along a zone of large-size block pegmatite, usually near the middle.

Type IV — rare-metal replacement. Type IV is represented as a rule by large oval to columnar bodies, from a few to 150 m thick. Such bodies exhibit a different combination of paragenetic mineral associations, expressed in four basic individual zones (Figure 2). Three of these zones are similar to those of Type III pegmatites while the fourth is made up of replacement minerals and of relicts of earlier minerals. Type IV is represented by the best differentiated veins. In best developed bodies of this type, often in individual fields of rare-metal pegmatites with a considerable lithium content, an independent quartz-spodumene zone appears along with the above-named principal zone; it follows the monomineral microcline zone and gradually changes to a quartz core. Present in this zone, in many pegmatite fields, are amblygonite, lithiophyllite, and other lithium minerals. In its turn, the replacement zone can be differentiated into several subzones, on the basis of mineral composition and texture: quartz-muscovite-beryl, lepidolite-albite, quartz-albite, clevelandite, sugary albite, etc.

A replacement zone is developed as a rule at the contact of the monomineral microcline zone and the quartz core, with the K-Na-feldspar zone the principal object of replacement. In the presence of an independent quartz-spodumene zone, replacement processes are developed along the monomineral microcline and quartz-spodumene zones (see Figure 2). In such a case, minerals of the replacement zone carry relicts of block quartz, along with the spodumene. At times, the replacement takes place along the contact of the graphic pegmatite zone and the outer side of the monomineral microcline zone.

The replacement zone is made up of albite — usually clevelandite, muscovite, younger quartz and garnet; present among the rare-metal minerals are beryl (lithium of cesium types), often pink; niobo-tantalates (columbite, tantalite, ugandite, microlite), cassiterite, pollucite (in bodies of over 1 m^3, and in tens and hundreds of tons per vein), lepidolite, petalite, phosphates of lithium and manganese, bismuth minerals, and relicts of the early-stage minerals (such as spodumene).

The bulk of rare-metal minerals in Type IV occur at the periphery of quartz bodies and replacement zones. In veins of this type, in the

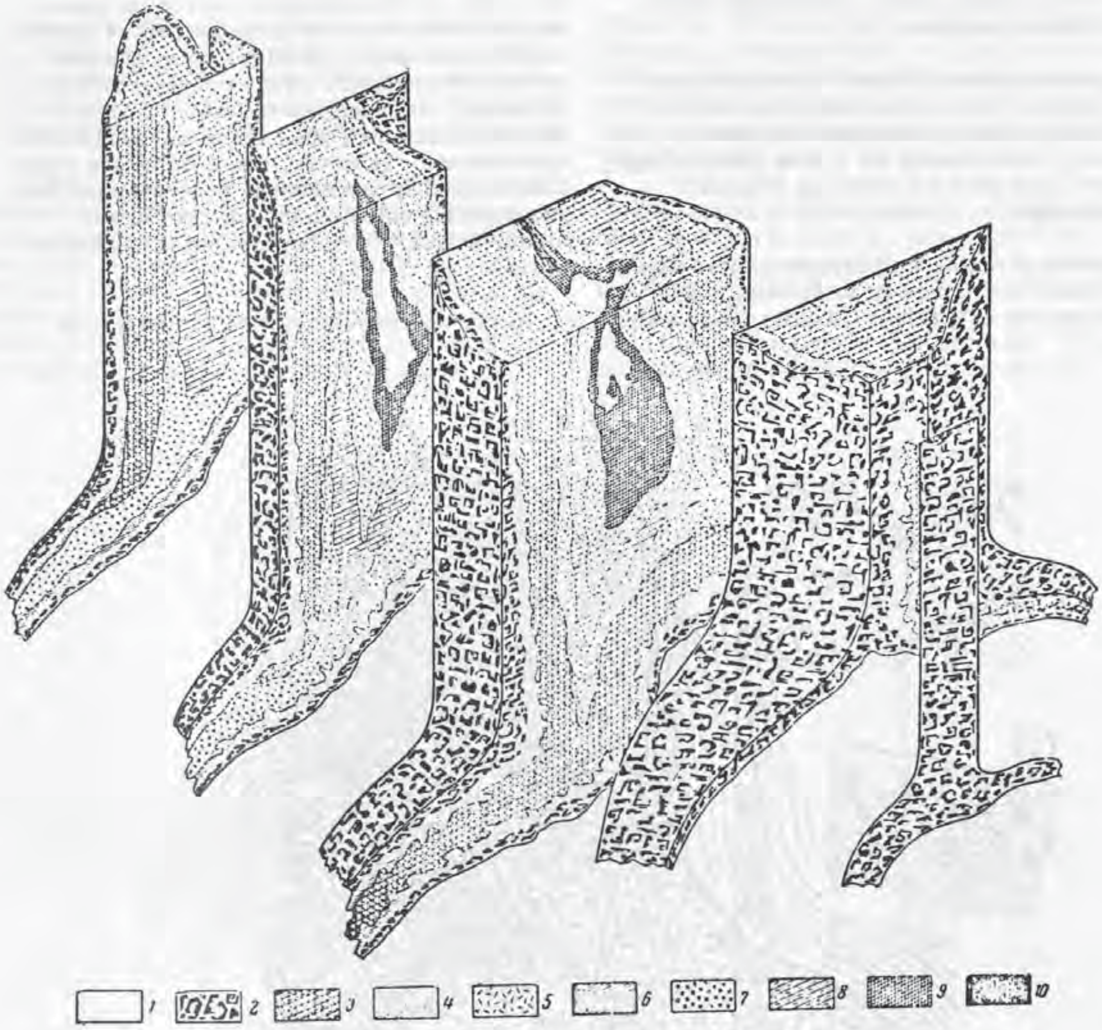

FIGURE 2. Pegmatite vein of Type IV.

1 - gabbro; 2 - zone of graphic pegmatite; 3 - monomineral and block microcline zone; 4 - block quartz zone; 5 - quartz-spodumene zone; 6 - fine-grained albite complex; 7 - quartz-muscovite complex; 8 - clevelandite-spodumene complex; 9 - thin-tabular albite; 10 - lepidolite-albite complex.

same field, more rare-metal minerals are formed at the replacement stage than is the case for Type III.

Cavities of various sizes, common in bodies of Type IV and occupied by crystals of quartz, polychrome tourmaline, lepidolite, kunzite, clevelandite, and muscovite, in an argillaceous matrix, indicate a comparatively high content of highly volatile compounds in original pegmatite solutions, as well as the presence of a high concentration of these compounds during the process of differentiation. These features also suggest the importance of later replacement solutions, partly condensed out of the volatiles, in the formation of these pegmatites.

This type is characterized by the most complex mineral composition of all pegmatites. Veins of this type carry concentrations of all rare elements and virtually all rare-metal minerals in all veins of a given field. Specifically, occurrences of precious stones in uncontaminated pegmatites, such as rose spodumene, polychrome tourmaline, rose and transparent beryl are largely associated with this type. The presence of a large number of rare-metal minerals is explained by two factors: the complexity of chemical composition of the original solutions; and by a completed differentiation process. This promotes a concentration of rare elements up to the point of their forming individual minerals in large accumulations.

Type V — albite-spodumene. This type is represented by leucocratic rocks consisting chiefly of albite, spodumene, and quartz;

unlike the preceding types, microcline occurs in subordinate amounts.

Pegmatite bodies of Type V are most commonly tabular, from a fraction of a meter to tens of meters thick, traceable for about a kilometer, occasionally for 1.5 or 2 km, along the trend, and often for over one kilometer along the dip.

Zonation is not as well expressed here as in other types (see Figure 1, 3, 4); the graphic pegmatite zone is virtually missing, and so are, as a rule, the monomineral microcline zones and individual zones or large kernels of quartz. In some examples, the initial stage of albite-spodumene pegmatite (transitional from Type IV) shows thin monomineral microcline or bimineral microcline-spodumene and spodumene-quartz zones. However, these zones are often camouflaged by replacement processes and are recognizable only by microcline relicts in albite, in interstices between large spodumene grains.

Albite-spodumene pegmatites are just as

FIGURE 3. Vein of albite-spodumene pegmatite. (Drawn by I.B. Nedumov)

1 - tabular spodumene with quartz and some unevenly distributed albite; 2 - muscovite; 3 - fine-grained quartz-muscovite fringe; 4 - tourmaline; 5 - albite; 6 - quartz; 7 - coarse- to fine-grained quartz-feldspathic pegmatite with muscovite; 8 - microcline blocks. Arabic numerals in circles mark segments drawn in detail.

complex in chemical composition as the Type IV pegmatites but with considerably fewer mineral species; this is due to different conditions of formation and especially to the fact that their differentiation is not as complete as in Type IV.

Albite is represented by two generations: independently precipitated out of original solutions rich in albite components; and formed at the replacement stage, in a decomposition of K-Na-feldspars. The quantitative relationship of these two albite types in the fields investigated is obscure, as yet, pending further study. An indirect evidence of primary albite is the relatively low muscovite content in fields of this type, compared with the large amount of albite. Had the albite been formed at the expense of K-Na-feldspars only, there would have been considerably more muscovite present, but this is not the case.

Spodumene in albite-spodumene pegmatite often is an early mineral, having been precipitated with microcline, and locally earlier, in which situation it crystallizes normal to the vein walls, in tabular crystals thickening toward the central part of the vein body. Microcline in veinlets of this type is, as a rule,

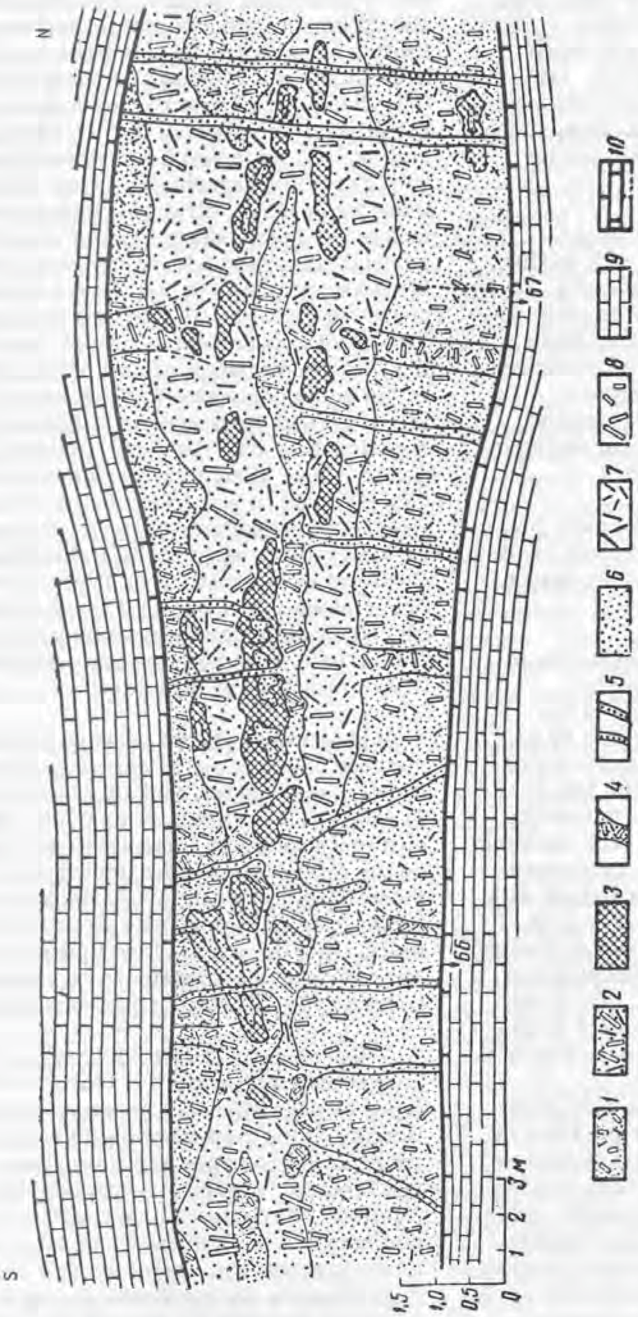

FIGURE 4. Diagrammatic sketch of an albite-spodumene pegmatite vein (Compiled by N.N. Mart'yanov).

1 - fine- to medium-grained quartz-albite-spodumene complex; 2 - coarse-grained complex of the same composition; 3 - block pegmatite (quartz, microcline); 4 - transverse veinlets of medium-grained quartz-albite-spodumene complex; 5 - quartz veinlets; 6 - quartz; 7 - albite; 8 - spodumene; 9 - marble-like limestone; 10 - marble.

grayish with blue cast and is represented by small-, medium-, and large-size blocks (up to 1 m^3). Its crystals are not as isometric as those of the preceding type, which also suggests different crystallization conditions. Quartz occurs in fine-grained and small-size block inclusions in the pegmatite groundmass; locally it also forms isolated bodies up to several cubic meters, in well developed thick bodies of Type V. Unlike the preceding types, this one carries no pink quartz, as a rule.

Albite-spodumene pegmatites have a rare-metal paragensis of their own. They are characterized by a high spodumene content, by a comparatively high and consistent beryl content, and by the presence of cassiterite, amblygonite, etc; niobotantalates are represented largely by the columbite group. On the other hand, lepidolite, pollucite, and vorob'yevite are virtually missing; this indicates, along with other factors, a relatively poor and incomplete differentiation.

Pegmatite bodies of Type V are finer-grained than the preceding types, with spodumene crystals measured in fractions of a centimeter or centimeters, rarely as large as one meter. Beryl occurs in crystals, often barely discernible by the naked eye, measured in millimeters and even in fractions of a millimeter. At the same time these pegmatites show a general and uniform coarsening of grain toward the middle of the vein.

Replacement processes are extremely important in Type V pegmatites. Minerals of the replacement complex are common throughout the pegmatite bodies.

All those features peculiar to pegmatite of Type V are determined on the whole by differences in chemical composition of the original pegmatite solution, especially by its lower potassium content and by a much higher content of Na and Li. Because of the law of active masses, this is reflected in the nature and sequence of crystallization in rock-forming minerals; graphic pegmatites are not formed, and neither is the thick monomineral zone with well expressed zones and kernels of quartz. In other words, the effect of the crystallization factor in the distribution of rock-forming and rare-metal minerals is dampened, and other conditions arise to control the behavior of individual elements, including the rare elements.

Of substantial importance in the formation of albite-spodumene pegmatites is the form of hollows which receive the pegmatite solutions; the composition of the enclosing rocks is also important. When lithium-rich pegmatite solutions penetrate mica schists, a considerable amount of lithium escapes to the lateral rocks; this is not true for marbles. As already noted, these pegmatites ordinarily show a well-expressed tabular form and are comparatively thick. In such hollows, pegmatite molten solutions cool off faster, with a correspondingly more rapid crystallization, which is not conducive to a differentiation of pegmatite bodies thus formed. It appears that when pegmatite solutions of a composition corresponding to albite-spodumene pegmatites fill up hollows of different forms, they form better-differentiated bodies approaching Type IV in structure and texture. Some veins in the Black Hills belong to such bodies (Etta-Main, Bob Ingersol).

These features of the composition of albite-spodumene pegmatites, along with their structure and texture, suggest that these pegmatites should be regarded as special bodies representing an independent line parallel to pegmatites in general. Indeed, in their extreme form, they are quite different from common non-rare-metal pegmatites which are 99.9% feldspar, quartz, and mica and are represented by rock with granitic to graphic textures. However, these two sharply different pegmatites are connected by intermediate links of all possible gradual transitions. For instance, some Brazilian pegmatites, being typical representatives of Type III, carry a considerable amount of spodumene, a typical Type V mineral. Type IV which occurs along with Type III in the same pegmatite fields (Mongolian Altai etc.), so that their genetic relations are unquestionable, carries much albite of two generations, along with spodumene (up to 150,000 tons in some veins) and other rare-metal minerals characteristic of Type V. In typically albite-spodumene fields (Southern California), pegmatites of Types III and IV occur along with those of Type V. Thus, a close genetic relationship exists for all these types, indicating both the unity and diversity of their conditions of formation.

In describing the zonation of pegmatites, no mention has been made of contact fringes locally attaining the rank of zones (see Figure 1) and at times rich in mica (up to 70% muscovite in a zone). In some veins and fields (such as the famous muscovite deposits in India), these fringes present fairly thick zones (up to 1.5 to 2 m) of high quality muscovite, commercially developed. Development of thick muscovite zones appears to be related to a certain type of rocks (micaceous shale).

Thus we have identified, from an analysis of voluminous material, five textural-paragenetic types of pegmatites. The basis of this classification is the rock-forming minerals and their relationship in space and time, i.e., structure and texture. Used for a supplementary classification criterion were rare-metal minerals common and often abundant in all pegmatites. In working-out the early variants of this classification the emphasis was on rare-metal minerals suitable for manual ore sorting, since that was the method of exploitation of pegmatites prevailing then. In ablite-spodumene varieties, rare-metal minerals (beryl, columbite) are fine-grained; however, they must be accounted for in a classification, because of the development of beneficiation methods.

Rare-metal minerals complement the characterization of parageneses and provide means for a better understanding of the properties and formation condition of pegmatites. Thus, depending on the content of this or that rare-metal mineral, several sub-types can be identified among pegmatites of block Type II, such as beryl, beryl-columbite, monazite-orthite, pyrochlore-betafite, etc. In the same way, sub-types beryl-spodumene, beryl-columbite, monazite-euxenite can be identified in Type III; spodumene-lepidolite, petalite, lepidolite-pollucite, etc., in Type IV; spodumene-columbite, spodumene cassiterite, spodumene-beryl, in Type V; etc. The presence of a given rare-metal mineral depends on chemical composition of the original solution and on the formation conditions for pegmatites which, in turn, are naturally determined by geochemical features and physico-chemical conditions of the mother granite intrusions.

Theoretically, it seems reasonable to assume that each of these five types has a corresponding compound practically free of rare-metal minerals.

GENERAL REGULARITIES COMMON TO TEXTURAL-PARAGENETIC TYPES

A systematic classification of extensive material allows a formulation of a number of emphirical regularities pertaining to pegmatites and to the process of their formation.

1. Pegmatites, being derivatives of granite, constitute with them a discrete chain of rock evolution, where a gradual accumulation of certain properties brings it up to a breaking point; i. e., to the appearance of individual links corresponding in nature to certain types of pegmatites (see Figure 1). It may be assumed arbitrarily that the degree of development in a pegmatite corresponds to the magnitude of its difference from mother granites. It is also true, generally speaking that the more advanced the pegmatite type, the more it differs from granite, in its composition.

2. Each preceding type carries in its final development the features of the following type; i. e., each type has its inception in the preceding type, as illustrated in Figure 1, by gradual transition between the types.

Insofar as these pegmatite types are links of a discrete evolutionary process, it is natural that present among them are all of the intermediate forms. Thus, appearing at certain stages of graphic pegmatites are features of block pegmatite, in segments having a block structure. This is particularly well illustrated in the gradual transitions from Type II to Type III; features of the latter are present in some Type II pegmatites; e. g., concentrations of microcline crystals and quartz blocks. Appearing in Type III are accumulations of albite and replacement segments; in Type IV, they merge into an independent zone; and in Type V they are developed throughout the pegmatite body.

3. The internal structure and differentiation of pegmatites becomes more definite from Type I through Type IV, following the course of their evolution. The most complex are pegmatites of Type IV where the differentiation is at its maximum. Closely related to the crystallization differentiation are the development and intensity of replacement processes which lead, in pegmatites of Type IV, to the formation of an independent mineral complex and consequently further complicate their structure. The consecutive development of pegmatite types is expressed not in the appearance of new zones, alone, but also in the great development of zones existing in the preceding types.

As the structure of pegmatites (through Type IV) becomes more complex, the size of their component minerals, rock-forming as well as rare-metal, increases. Thus, spodumene occurs in comparatively small grains and crystals, in pegmatites of the first two types, while it reaches a giant size in Type III and especially in Type IV, where it may reach a few meters and locally as much as 10 m in length. This, however, does not preclude the presence of small crystals of rare-metal minerals, especially in replacement segments and zones. It should be noted in passing that, generally speaking, replacement processes lead to the formation of mineral complexes finer-grained than those on which they are developed.

The distribution of rock-forming and rare-metal minerals in Type V pegmatites is subject to regularities of their own, because of the above-mentioned specific features of their formation. Generally speaking, the concentration of those minerals is not as well developed in their zones and blocks.

4. The relative importance of granitic and graphic pegmatites decreases going from mother granite to Type V by way of the intermediate types, with a parallel decrease in the content of microcline and orthoclase, and an increase in albite and spodumene (see Figure 1). Thus, the microcline content in graphic pegmatite is about 75%, with about 50% in Type IV and about 10% in Type V. The amount of albite grows with each consecutive type, until albite becomes one

of the principal rock-forming minerals in Types IV and V. The spodumene content ranges from practically zero in Types I and II to rock-forming proportions in Type IV and especially V.

5. Parallel to the compositional change in the rock-forming minerals, the amount and variety of rare elements and highly volatile components increases from Type I on; at the same time, the volume and number of rare-metal minerals (through Type IV) increase while their chemical composition and crystallographic aspect change [4]. Of course, the nature of rare-metal minerals as well as their amount in individual types depend on geochemical properties of each pegmatite field, although they have certain features in common.

Rare-metal minerals are virtually absent in Type I.

Type II, being less developed, exhibits the smallest number and the smallest amount of rare-metal minerals in a given field; most common here is beryl with small amounts of niobo-tantalates and rare-earth minerals. Beryl is represented by fairly large, well-formed, long, columnar crystals generally occurring in quartz. A small portion of rare-metal minerals is associated with small segments of the replacement complex.

In Type III, considerable amounts of spodumene and amblygonite appear in places along with the above-named minerals; what is more significant, a comparatively larger amount of rare-metal minerals is present in the replacement complex.

Type IV is richer in mineral species and in accumulations of rare-metal minerals. This is explained by a more complete differentiation in this type, resulting in high concentrations of rare elements in individual zones, which is what determines the formation of a large number of mineral species. Present in Type IV, in addition to the above-named elements, and locally in large amounts, are lepidolite, pollucite, petalite, microlite, columbite, tantalite, ugandite, bismuth minerals, etc. Beryl and spodumene are associated as a rule with definite zones and segments. Spodumene and quartz form locally independent zones. Most rare-metal minerals are formed in the formation of the replacement complex.

Beryl of Type IV carries considerable amounts of Cs and Li and occurs in short columns and tablets. The beryl is commonly pink because of its considerable manganese content. Pollucite, present to a considerable extent in Type IV veins, occupies a strictly defined position at the contact of the replacement zone and quartz kernel. This type is characterized by an independent finely crystalline albite-lepidolite zone located near and above the quartz kernels.

Type V carries a great volume of a limited number of species of rare-metal minerals, mostly spodumene and beryl with a small amount of columbite. As noted before, they are more evenly distributed through the pegmatite body (not counting the vertical zonation); an individual spodumene-microcline zone is present only locally at initial stages, in the transition from Type IV to Type V.

It appears that all these regularities are determined by the degree of differentiation in pegmatites as well as by other factors, active prior to crystallization.

6. Part of the pneumatolytic-hydrothermal stage grows more important in the formation of pegmatites, going from type to type, and with it grows the content of minerals (lepidolite, muscovite, pollucite) carrying water, fluorine, and other elements missing in minerals of early complexes.

One of the features which set pegmatites apart from one another is the degree of development in them of replacement processes the role of which, on the whole, also increases up to the highest type. Bodies of Type I, in their classic form, do not contain segments of replacement complexes. In Type II, replacement processes are still quite weak so that replacement complexes are unimportant in their constitution. They are associated here, as a rule, with the block microcline zone. In Type III, replacement processes are quite important, and replacement complexes gravitate toward the contact of the central quartz and the microcline zones. However, these complexes form broken-up segments of various sizes, rather than a single zone. Type IV is characterized by the presence of a thick and well defined replacement zone at the contact between the microcline and quartz monomineral zones. Locally, the replacement process penetrates other zones, as far as the periphery, by way of fractures.

In Type V, replacement processes are quite intensive, being expressed in the decomposition and replacement of K-Na-feldspars, spodumene, etc. As of now, it is hard to say in which one of these types IV and V the replacement processes are stronger, because it is hard to determine what proportion of albite, the main component of Type V, was formed at the replacement stage.

Without an understanding of these regularities common to all pegmatites, it is in fact impossible to grasp regularities in the structure of any given pegmatite body and to determine the causes of a particular paragenesis and association at any point of a vein; nor is it possible to determine the stage of development of a pegmatite body or its genesis. It is the underestimation, by many students, of these regularities peculiar to the pegmatite family that has led to the appearance of specific qualitative and mostly local classifications (by rock-forming minerals, chemical composition, rare elements); it also has led to the failure to recognize regularities in the distribution of rare elements and to a number of erroneous genetic conclusions.

It should be kept in mind that all these clean-cut regularities in the internal structure of pegmatites and the distribution in them of rock-forming and rare-metal minerals are at times strongly distorted and camouflaged because of the elements of occurrence of veins, intra-ore tectonics, superimposed replacement processes, etc. For example, veins may be asymmetric when a single monomineral microcline zone is developed instead of the two, with the other half of the vein made up of quartz. In that event, the replacement zone naturally develops at the periphery of a vein rather than in the middle of it. In some veins, block quartz is separated from the microcline zones. The vein structure is often strongly modified by replacement processes. All this is because pegmatite solutions are a complex physico-chemical system quite sensitive to the smallest change in factors affecting the formation of pegmatites (volume, form, elements of occurrence of veins, etc.). Consequently, the field student trying to determine the structure and process of formation of a pegmatite body should be guided by regularities common to the entire pegmatite family.

BASIC FACTORS IN THE FORMATION OF VARIOUS PEGMATITE TYPES

In determining the factors affecting the formation conditions for any natural objects, including pegmatite bodies, it should be kept in mind that the formation of all bodies is determined by a combination of factors acting together rather than separately, and that this combination varies in both space and time. For this reason it is difficult to ascertain the role of any single factor because it may be weakened or strengthened by the action of the others.

The activity period for factors affecting the appearance of this or that pegmatite type may be tentatively divided into two intervals, before and after the intrusions of pegmatite solutions into the rocks. Similar parageneses may originate as a result of either type of factors; in the first instance, this is due to the degree of "carving-out" the pegmatite solution hearths at depth; in the second, to the secondary distillation of highly volatile components, including the rare-metal accumulating in the upper parts of veins; also to a favorable differentiation process.

Factors leading to the formation of pegmatite types become operative as early as the intrusion time. The original chemical composition of pegmatite solutions is dependent to a great extent on the chemical and mineral composition of the mother granite. Granite intrusions are fairly different among themselves in composition, especially in the content of rare elements and volatile compounds; this determines to some extent the chemical composition of their derivatives, as well, including the pegmatite solution. This is one of the reasons for differences in pegmatite fields formed in different segments of the crust.

At the same time, it may be assumed that granite intrusions different in their over-all chemical composition may form pegmatite fields similar in composition, under propitious thermodynamic conditions. Thus fields with rare-metal pegmatites are formed under certain conditions, in connection with intrusions rich in the corresponding rare elements (lithium, cesium, beryllium, tantalum). On the other hand, intrusions poorer in these rare elements and formed during a longer time and at proper pressures — which promotes the change of rare element compounds to the volatile state and their concentration in the hearths of pegmatite solutions — are also accompanied by pegmatites rich in rare-element minerals.

It is also quite obvious from thermodynamic and physico-chemical considerations that granite intrusions, even most alike in composition, will yield different volatile fractions under different conditions of formation (pressure, for instance). Thus only water will become volatile at a certain pressure in an intrusion; aqueous compounds of beryllium at a different pressure in the same intrusion; tin and tungsten at other pressures; and sodium, lithium, cesium, and rubidium at still others; with a combination of all in some instances. Where water alone is concentrated at the top of a granite intrusion, the subsequently formed pegmatites are marked by a simple composition and carry no rare-metal minerals. In another situation, such rare elements as Li, Be, Nb, Ta, etc., pass to the volatile phase along with water vapor, which creates conditions favorable for a subsequent formation of compound rare-metal pegmatites.

Field observations indicating the immense importance of volatile compounds in the formation of pegmatite solutions are corroborated by theoretical considerations as well as by experimental physico-chemical study. In recent years, it has been shown experimentally that rare elements concentrating in pegmatites form various simple and compound volatiles. The American students L. Grossweiner and R. Seifert [11] have determined experimentally the feasibility of transporting beryllium, as hydroxide, in water vapor. It has been shown that the volatility of beryllium rises sharply with the vapor pressure, due to the formation of gaseous beryllium hydroxide. The same has been found true for Sn, Mo, and W; which is quite important because water is a common compound in igneous processes and an important factor in the formation of pegmatites.

Obviously, concentration conditions for highly volatile compounds in certain parts of intrusions depend on tectonic processes which take place in the formation period of intrusions and pegmatites. Tectonics determines the nature of development of pegmatites as physicochemical systems. Of great importance is the time of tectonic disturbance and the entry of pegmatite solutions into the hollows formed.

It is quite obvious that when the hearths of these solutions — formed as the result of an emanation process — remain intact (not opening up) because of the lack of tectonic disturbances, they produce the widely distributed pegmatoid facies of granite. Because of the fine-grain of this facies, a considerable portion of their rare elements is dispersed to form scattered accumulations of rare-metal minerals. There are more and more data to the effect that pegmatoid granite facies accompanying rare-metal pegmatites in some fields carry such minerals as beryl, spodumens, and columbite, thus suggesting that there are ways of forming pegmatites, other than those thought of before.

When the hearths of pegmatite molten solutions open up at an early stage, namely before the accumulation of a large amount of highly volatile compounds, they produce simpler pegmatites with a poorly developed hydrothermal phase and replacement processes. In another extreme instance, a typical greisen process takes place with the formation of later contraction fractures. All other pegmatites are intermediate between these two extremes.

The second period of pegmatite formation, beginning with the appearance of fractures and with their intrusion by pegmatite molten solutions, is no less important in the development of various pegmatite types. Of great importance here, along with the original chemical composition of pegmatite molten solutions, is the nature and interaction of other factors: emanation and crystallization. Once within a fracture, the pegmatite solutions are under lower pressure and temperature conditions. Highly volatile compounds left behind in the hollows, too, seek the segments of lower pressures and temperatures; this leads to a new vertical differentiation and creates conditions for a corresponding paragenesis — and consequently for a pegmatite type — up and down the intruded hollow.

Field observations as well as experimental and theoretical study show that crystallization is one of the most important factors in the distribution of minerals and elements in pegmatite veins, and the paramount factor in the formation of various genetic types. In a number of occasions, a well-developed differentiation process leads to accumulations of residual solutions, similar to those in well-seasoned pegmatite hearths which give birth to albite-spodumene pegmatites. The progress of the crystallization factor depends a great deal on the volume and form of the hollows where pegmatite bodies are formed [6].

Small bodies cool off faster and crystallize in a fine-grained undifferentiated rock. Under those conditions, highly volatile compounds and the replacement processes are affected in different ways than those prevailing in larger bodies, and rare elements are dispersed throughout the crystallizing rocks. There are none of those rare-metal associations (cesium-beryl, pollucite, bismuth minerals, etc.) which originate out of similar molten solutions in larger and well-differentiated bodies. In isolated examples, the formation of pegmatite types is substantially affected by the composition and nature of lateral host rocks, their reaction with the pegmatite solution, and their capacity to produce hollows of various forms to be filled up by the pegmatites.

Thus with small fractures in rocks, even those pegmatite molten solutions rich in volatile and rare-metal compounds produce only minor veins of rare-metal pegmatites, without any commercial value. An example is albite-spodumene pegmatites in the area of the famous Kolor auriferous ore deposit of India, represented by thin, extremely small veins in metamorphic schist.

The escape of sizable amounts of K, Al, Si, and other elements to the lateral rocks effects a change in the composition of pegmatites. In some instances, such as with ultrabasic rocks, the reaction of pegmatite molten solutions goes so far as to form the so-called desiliconized pegmatites, quite different in their composition from "pure" pegmatites; this strongly affects the situation of both rock-forming and rare elements [6a]. When the intruded rocks are rich in calcium, crystals and blocks of a more basic plagioclase (oligoclase) are formed in peripheral parts of pegmatite veins, as a result of assimilation. The reaction of pegmatite molten solutions with metamorphic schists leads to the formation of thick contact deposits of muscovite (India).

Described here are only the main factors in the formation of pegmatites and in the development of their types. These factors are considerably more numerous. Thus, temperature is of importance as is the nature of its decrease, the role of volatile and endothermal compounds, the heat conductance of lateral rocks, etc. A powerful factor is time; i. e., the duration of a process. We emphasize once more that all these factors operative in the formation of pegmatites, as of all natural bodies, act in conjunction with one another and, what is quite important, may be mutually compensating. Thus, the duration of processes of emanation concentrations for highly volatile compounds, including the rare-metal compounds, in the formation of hearths of pegmatite solutions may be compensated for, in other granite intrusions, by an abundance of these compounds.

The formation of various pegmatite types is closely related to the origin of pegmatites, in general. The theories extant on the origin of pegmatites have been discussed in our other papers [3-5]. There are two main hypotheses of the origin of compound rare-metal pegmatites. The gist of one of them is that these pegmatites are formed out of independent pegmatite molten solutions originating in granite intrusions. Other students regard these pegmatites as the result of replacement and recrystallization of granite veins and fine-grained pegmatites in a reaction with younger hydrothermal solutions.

These hypotheses are dealt with in a voluminous literature and we are not going to pause for them here [7, 10, 15]. We only note that an overwhelming majority of working geologists accept the independent pegmatite solutions as the most satisfactory explanation for the totality of facts and problems related to regularities in the origin and development of pegmatites. More specifically, this view clarifies the clean-cut regularity in the distribution of rare elements and rare-metal minerals, in both space and time, which is unexplainable by the other theory. The opinions differ, however, on how these solutions are formed.

Some students (P. Niggli, A. Ya. Fersman, and others) believe that these compounds are formed in the crystallization of mother granite intrusions, as an intergranular residue whose intrusion initiates the formation of pegmatite veins; in other words, pegmatite solutions are regarded as a product of cooling-off and crystallization of granite intrusions. To illustrate this thesis, a number of students draw various physico-chemical diagrams. However, an analysis of field material on granite and pegmatites leads to the conclusion that the concepts illustrated by these diagrams have no direct bearing on the origin of pegmatite solutions.

The vast amount of field data accumulated in recent decades suggests a different origin of such compounds, and consequently of the pegmatites themselves. The presence of pegmatoid facies in granite intrusions, locally with such rare-metal minerals as beryl, spodumene, and columbite, as well as the gradual transition in time and space from pegmatoid intrusive facies and pegmatite veins, and the occurrence of the most complex pegmatites at the top of granite intrusions, all suggests that pegmatites are facies or phases of the granite intrusions themselves, being a product of accumulation of highly volatile compounds, including the endothermal rare-metal ones, through emanation in isolated, chiefly uppermost, parts of granite intrusions.

According to our data, the main trend of the process of initiation and development of pegmatite molten solutions is related to the concentration of volatile compounds in the intrusion of granites or other igneous bodies, rather than to crystallization of mother granite intrusions. Thus, pegmatites are facies or phases of the corresponding intrusions. We believe that these concepts afford the best explanation of the origin of pegmatites in general, as well as of their textural-paragenetic types and their regularities.

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