ZONING IN PEGMATITE DISTRICTS*

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Abstract

In numerous pegmatite districts the size, shape, external and internal structure, texture and mineral content of an individual pegmatite can be shown to be functions of the distance of the body from its batholith source. Not all of these characteristics are independent variables, for the host rock is an important factor in influencing shape and external structure and thus indirectly internal structure. It is suggested that mineralogically and structurally complex pegmatites owe their generally distant position from the batholith to a relatively late withdrawal from the pegmatitic hearth with resulting increased fluidity, greater rare-element content and greater penetrability of the surrounding rocks.

Introduction

Widespread and intensive field investigations of pegmatite mineral deposits during the last 15 years have yielded considerable information on their mineralogy, internal structure and genesis. More recently additional attention has been directed toward the study of pegmatite districts or provinces and toward relating the characteristics of individual pegmatites to their regional distribution and geology. Such studies, although yet few in number, already reveal some systematic variations within pegmatite provinces. This *regional zoning* of pegmatites apparently is comparable to zoning that has been recognized in various districts containing hydrothermal mineral deposits, typified, for example, by Butte, Montana (Sales and Meyer, 1949), Cornwall, England (Davidson, 1930), Leadville, Colorado (Laughlin and Behre, 1934) and the Cordillera Real, Bolivia (Turneaure and Welker, 1947). For a general discussion of zoning in hydrothermal districts, reference should be made to the work of W. H. Emmons (1937, 1940), one of the chief advocates of the zoning concept.

The purpose of this paper is to report some new examples of zoning in pegmatite districts, to examine critically others recorded in scattered references and to discuss the factors that influence such zoning.

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sity of Michigan, which enabled the writer to study pegmatites in European countries during the summer of 1950.

DEVELOPMENT OF THE ZONING CONCEPT

Recognition of the close spatial ties between pegmatite swarms and marginal parts of batholiths was employed as one of the original arguments for the magmatic origin of pegmatites. DeBeaumont (1847), for example, related the distribution of pegmatites to other characteristic peripheral phenomena ("granite aura") of granite masses. Subsequent writers on pegmatites have underlined the spatial and genetic relationships between offspring pegmatites and parent batholith. Landes (1933, p. 38) summarized viewpoints on this association thus: "Of greatest frequency is the occurrence of pegmatite in the laterally adjacent country rock. However, many pegmatite bodies occur entirely within what is probably the parent intrusive. In this case the contact between pegmatite and enclosing rock may be a gradational one." Emmons (1940, p. 25) also emphasized that, "Many pegmatites are found in the upper parts of granite batholiths and in their roof."

A few early observers presented more detailed information on systematic pegmatite variations within a district. Brögger, who generally was far in advance of his contemporaries in his understanding of pegmatites, described (1890) an excellent example of mineralogical zoning in the Langesundfjord district, Norway. Van Hise (1904, p. 724), pictured the arrangement of Black Hills pegmatites as follows: "From the central mass (of granite) great quartz-feldspar dikes radiate. In passing away from the core the dikes become smaller and have a less typical form; at the same time the material assumes the appearance which we ordinarily denominate pegmatitic. . . . Still farther away the pegmatitic masses begin to have vein-like characters—that is, there is a rough concentration of the material in different layers parallel to the walls. Still farther away a true banded-vein structure is found."

Except for casual and scattered observations, however, the phenomenon of district zoning was not studied further in a systematic way until Gevers (1936) supplied a classic description of the Namaqualand deposits, which he found were zonally arranged in three groups: interior, marginal and exterior. This classification correlated mineralogical and structural variations of the pegmatites with their positions relative to the source batholith. A similar type of zoning to which Gever's divisions were applicable was discovered by the writer (1948) in the Eight Mile Park district of Colorado. Emmons (1940, pp. 23–24) related the zoning to the vertical dimension: "Nearly all pegmatitites that carry metals, lithium minerals, and gems are found in the roof regions of batholiths above the lower limit, or dead line, . . . The quartz-feldspar-mica pegmatites, however, are found also deep within batholiths. They form at higher temperatures than do most of the metalliferous veins and are found lower in the parent masses and farther below the roof contacts than are mineral veins. The dead line for such pegmatites is much deeper that that for metalliferous veins, and in many large bodies of granite and of granite gneiss there seems to be no lower limit for quartz-feldspar-mica pegmatites."

The problem of district zoning has been discussed by Cameron *et al.* (1949, pp. 5–9), who cite a number of examples and conclude that "These examples are enough to indicate that such (district) variations offer a promising field for further and more systematic study."

Discussion of the interrelations of the factors involved is difficult, for we lack quantitative data on pegmatite composition and on changes in the vertical dimension. Nevertheless this review and summation will have achieved its purpose, if it succeeds in provoking its readers into further consideration of the problems advanced.

EXAMPLES

Africa

Namaqualand (Gevers, 1936; Gevers, Partridge and Joubert, 1936). The Namaqualand pegmatites fall into three groups: those in the central part of the granite batholith, the *interior* pegmatites; those within the batholith along its periphery, the *marginal* pegmatites; and those outside the batholith in the metamorphic rocks, the *exterior* pegmatites. Interior pegmatites are abundant, narrow and erratically distributed. They contain chiefly quartz, microcline and some muscovite, garnet, schorl and beryl. Pegmatites of the relatively narrow marginal zone are not as abundant but commonly are larger than the interior type. In their general mineralogy they resemble those of the interior, but some have been extensively altered by post-magmatic mineralization. The exterior pegmatites, which occur in a 10-mile wide zone beyond the batholith borders, characteristically display a well developed internal structure with cores of massive quartz. Many of them have been extensively modified by hydrothermal replacements, involving the formation of albite, muscovite, tourmalines, spodumene, lepidolite, columbite-tantalite, euxenite, polycrase, monazite, xenotime, lithiophilite, molybdenite, bismuth, scheelite and chalcopyrite. It is in these pegmatites that the bulk of the rare-element minerals is concentrated. Farthest from the batholith is the zone of hydrothermal quartz-tourmaline veins.

Erongo, Area, South-West Africa (Gevers and Frommurze, 1929; Gevers, 1942). Interior pegmatites are not reported. Marginal pegmatites that occur along joint planes in the granite and at its contacts usually strike parallel with the metamorphic foliation. They contain microcline, quartz, graphic granite, albite, schorl and rarely some cassiterite. A well developed internal structure occurs in many. The exterior-zone pegmatites, which are in schist, also show internal structural units and generally are tabular or lens-like sills. Schorl is characteristically rare, but many bodies are albitized and contain associated cassiterite, muscovite, lepidolite, alkali tourmaline, triplite, lazulite, molybdenite, arsenopyrite and bismuth minerals.

Kabba Province, Central Nigeria (Jacobson and Webb, 1946, 1947). Within the Old Granite occur interior-type pegmatites containing chiefly microcline and quartz. Those in the marginal zone are similar with some biotite as well. Some are albitized, but they contain only small amounts of columbite-tantalite or cassiterite. In the schists and gneisses, exterior pegmatites of microcline, quartz and muscovite are albitized with cassiterite and columbite-tantalite.

The zonal distribution of wolframite, cassiterite and columbite in Nigeria has been described by Haag (1943), who finds three zones:

(1) Outside the Younger Granite wolframite predominates; cassiterite is minor or absent; columbite is absent.

(2) Within the Younger Granite near its margins cassiterite predominates; wolframite may be abundant; columbite begins to appear.

(3) Deeper within the granite columbite predominates; cassiterite is abundant; wolframite decreases.

Asia

Kodarma, India (Biswas, 1929; Roy, Sharma and Chattopodhyay, 1939). Holland (1902) noted that Indian mica-bearing pegmatites occur mainly in mica schist, whereas pegmatites in granite do not contain mica. In Kodarma two groups of pegmatites have been recognized. Those in the parent granitic gneiss (Dome gneiss) and in closely adjacent schists and paragneisses are microcline-quartz-graphic granite pegmatites with subordinate plagioclase and muscovite, very minor tourmaline, garnet, beryl and apatite and no mineable concentrations of muscovite. These can be classed as marginal-zone pegmatites. Exterior deposits, which are confined to the schists and paragneisses, are typical plagioclase-muscovite pegmatites with microcline rare or absent. Conspicuous accessories are apatite, garnet, beryl and schorl or biotite. The individual exterior pegmatites are markedly differentiated with wall zones of schorl, muscovite, quartz, garnet and apatite, an intermediate feldspathic zone, a core-margin unit rich in muscovite and beryl and a quartz core.

Turkestan Range, U.S.S.R. (Shsherbakov, 1936; Strelkin, 1938). On the northern slope of the Turkestan Range a porphyritic granite of Variscan age has been intruded into middle Paleozoic gneisses, mica schists and andalusite schists. Pegmatites have formed in an aureole around the granite and are especially developed along the south or hanging-wall side of the pluton. Three well-defined zones are recognized: (1) Biotite-schorl pegmatites within the granite close to both the north and south contacts and in the metamorphic rocks as far as 100 meters from the margins. Microcline, quartz and oligoclase are the chief minerals. (2) Schorl-muscovite pegmatites with beryl that occurr in the schists and gneisses in a zone 300–800 meters from the granite. (3) Albitized pegmatites, 800–1500 meters from the granite, only along its hanging-wall side. These contain cleavelandite, spodumene, lepidolite, alkali tourmalines, beryl, amblygonite, lithium-manganese phosphates, columbite and economic concentrations of cassiterite.

Europe

Iddefjord, Norway. Vogt (1931), noted that within the granite "great" pegmatites are rare but small and very small ones are common. Within the surrounding gneisses, "great" pegmatites with internal zones, are common.

Halden (Fredrichshald), Norway (Brögger, 1906). The pegmatites of the eastern zone, closest to the granite, contain chiefly quartz, microcline and micas, whereas those in the northern part of the district are richer in rare minerals.

Langesundfjord, Norway (Brögger, 1890). The feldspathoidal syenite pegmatites of this district lie mainly within the parent augite syenite and nepheline syenite bodies. The rare mineral content of the pegmatites increases markedly toward the nepheline syenite contacts: The zone 5–3 kilometers from the contact is distinguished by pegmatites bearing anorthoclase, albite, nepheline, sodalite, barkevikite, lepidomelane, magnetite and traces of zircon, apatite and pyrochlore. Those bodies from 3–0 kilometers from the contact contain most of the rare mineral concentrations including moreover, such rare species as eudidymite, hiortdahlite, cappelenite, gibbsite, leucophane, nordenskioldine, meliphane, melanocerite, rosenbuschite, wöhlerite, johnstrupite, hambergite and eudialite. Moreover, most rare species are represented strongly only in pegmatites within 1.5 kilometers from the nearest contact. Brögger's map (1890) outlines the zone of meliphane-bearing pegmatites and is thus the first map showing mineralogical zoning in a pegmatite district.

South America

Bolivia (Ahlfeld, 1936). Pegmatites of the Bolivian tin belt, which contain biotite, muscovite, molybdenite, cassiterite and some wolframite occur within the "roof-zone" of the batholith. Hypothermal types of veins are further out, "within the inner zone of contact" (Ahlfeld, 1936, p. 61).

Eastern Minas Gerais, Brazil. Regional variations have been recorded by Pecora *et al.* (1950, p. 248) as follows: "In general, simple pegmatites characterize the mica districts south of the Rio Doce, whereas complex pegmatites are characteristic of the region north of the river. Certain accessory minerals occur more commonly in specific districts or in geographic groups of pegmatites; for example, phosphate minerals are most abundant in the area north of Conselheiro Pena, tantalite and columbite in the district near Governador Valadares and Poaia, and beryl in the districts near Conselheiro Pena and Governador Valadares." According to Pecora (priv. comm.) the areal geology is too imperfectly known to permit a correlation between these variations and position of the parent batholith, at the present time.

Canada

Yellowknife-Beaulieu Area, Northwest Territory (Jolliffe, 1944; Rowe, 1952). Jolliffe (1944, p. 2) states, "Pegmatites carrying rare-element minerals are most common in the "hot" (i.e. contact-metamorphosed) sediments around bodies of younger granite. Some occur within the border phases of such bodies. . . . So far as is known they do not occur within the "cool" (i.e. unmetamorphosed) sediments." The district zoning has been delineated by Rowe (1952, pp. 10–11), who states, "This (regional) zonation . . . features five zones. The first zone, the zone closest to the granite, contains large, irregularly shaped pegmatites that have poorly developed internal structure, and that contain graphic granite. The second zone is composed of pegmatites containing graphic granite and beryl. In this zone the pegmatites tend to be lenticular and have a somewhat better developed internal structure. The third zone contains many pegmatites that have beryl as a component, but have no graphic granite. These pegmatites are regular in shape, and much smaller, and display a readily recognizable internal structure. The pegmatites of the fourth zone are structurally similar to those of the third but many contain columbite-tantalite as well as beryl. The fifth zone, the one farthest from the granite, features pegmatites that are spodumene-bearing." These zones are outlined in Rowe's figure 1B.

Southeastern Manitoba (DeLury, 1929; DeLury and Ellsworth, 1931). Pegmatites occur both in the granite and in metamorphic roof pendants. The former type contains few rare minerals and no economic mineral concentrations. In the roof-pendant pegmatites, however, rare-element minerals are much more common, including spodumene, lepidolite, amblygonite, topaz, beryl, apatite, monazite, lithium phosphates, columbite-tantalite, uraninite, bismuth, bismuthinite, molybdenite, arsenopyrite and sphalerite. These dikes also are markedly zoned. At West Hawk Lake (Stockwell, 1933) microcline pegmatites are common in volcanic and sedimentary rocks near the granodiorite contact, albite pegmatites predominate farther away and lithium pegmatites lie at a still greater distance from the contact.

Preissac-LaCorne Area, Quebec (Norman, 1945; Tremblay, 1947; Derry, 1950). Pegmatites in the central part of the granite bodies are of the common quartz-microcline-muscovite type with a little garnet. They are in part irregular in shape with weak control by the granite on their emplacement. Those with rarer minerals occur near the margins of the intrusives and commonly show orderly internal structure. The sequence of mineralogical zones outward from the batholith is: (1) Beryl pegmatites with columbite-tantalite. (2) Spodumene-muscovite pegmatites. (3) Molybdenite pegmatites with bismuthinite and pyrite. The zones were mapped by Tremblay (1947, figure 7).

United States

Maine. Bastin (1910) observed that the pegmatites with unusual minerals were concentrated in the border zones of granite batholiths and recognized two mineralogical types: a sodium-lithium group and a fluorine group. In the Poland quadrangle Hanley (1939) found that pegmatites with lithium minerals are farther from the granite contact than the potash feldspar-beryl pegmatites.

West-central New Hampshire (Chapman, 1941; Olson, 1942). Pegmatites within the Mount Clough pluton of the Bethlehem gneiss are segregation, shear zone and filled fissure types. They are normally small and consist dominantly of quartz, microcline, plagioclase and subordinate muscovite, biotite, schorl, garnet and beryl. Pegmatites in schist (Littleton formation) outside the pluton contain, in addition to the above constituents, cleavelandite, triphylite, graftonite, apatite, uraninite, autunite and columbite as well as other accessory species.

Middleton District, Connecticut (Foye, 1922; Cameron and Shainin, 1948). In this district Foye (1922) noted that pegmatites with rarer minerals are confined almost exclusively to the Bolton schist or to the Middleton series around the Monson (Glastonbury) granite gneiss, and contain such species as cleavelandite, beryl, muscovite, lepidolite, cookeite, spodumene, garnet, alkali tourmaline, chrysoberyl, triplite, triphylite, lithiophilite, monazite, zircon, columbite, samarskite, microlite, uraninite, autunite, molybdenite and sphalerite. Subsequent studies by Cameron and Shainin (1948) on the beryl deposits of the district confirm the earlier observations. Their map (p. 355) shows that 10 of the 12 main beryl-bearing pegmatites are either in the Bolton schist or in the Monson gneiss very close to its contacts with the schist.

Spruce Pine District, North Carolina (Maurice, 1940; Olson, 1944). The pegmatites are genetically related to bodies of alaskite. The pegmatites are larger and more abundant near the margins of the alaskite masses than in their interiors, and most pegmatites occur in migmatite, gneiss and schist around the alaskite. In the interior pegmatites biotite is almost absent. Very thick pegmatites are most common near the alaskite border, either in the alaskite or in the adjacent country rock. In these marginal-zone bodies the ratio of microcline to plagioclase probably is higher than in pegmatites farther out. These also contain more green muscovite, much of it with A-structure. Rum and ruby muscovites appear mainly in exterior pegmatites, with the rum type generally closer to the intrusive masses and the ruby type farther out to the west and northwest. The more calcic plagioclase is reported from exterior pegmatites, and the most sodic plagioclase apparently occurs chiefly in marginal-zone bodies.

Franklin-Sylva District, North Carolina (Olson and others, 1946; Heinrich, in press, *A*). Pegmatites within the Whiteside tonalite—granodiorite batholith are small and simple in their mineralogy, containing mainly quartz, oligoclase and muscovite. A zone of pegmatites in gneisses closely adjacent to the batholith on its northwest side and in roof pendants of gneiss is characterized by the presence of deep green to dark brown muscovite, commonly heavily stained by magnetite, and by the absence of much microcline. Accessory minerals, which are rare, include beryl, samarskite, alkali tourmaline, gahnite, zircon, autunite, torbernite, uranophane and fine-grained almandite. Farther out to the northwest the muscovite is mainly red-brown and ruby in color, and the accessory assemblage consists of allanite, pyrite, pyrrhotite, chalcopyrite, bornite, schorl, kyanite and large single crystals of spessartite. Some pegmatites of this zone also contain units in which microcline is a major constituent, and others carry abundant coarse biotite.

Jahns and Lancaster (1950) also have recorded for the Hartwell district of Georgia and South Carolina and the Ridgeway-Sandy Ridge district of Virginia regional color variations in muscovite, in which pegmatites in and near the intrusives contain green mica, whereas in those farther away the mica is rum colored.

Alabama (Hunter, 1944, Heinrich, in press, *B*). Cassiterite-bearing pegmatites occur in feldspathized schist near the margins of the Pinckneyville tonalite. The tonalite plutons are elongated northeast-southwest, and many of the tin deposits occur along their northwestern flanks.

At greater distances from the contacts muscovite pegmatites are strongly developed, containing schorl, garnet, biotite and rare apatite, beryl, tantalite, kyanite, pyrite and graphite. As in the Erongo district of South-West Africa schorl and cassiterite are generally mutually exclusive.

Pikes Peak-Florissant District, Colorado. The Pikes Peak granite in parts of Douglas, El Paso, Teller and Park counties contains groups of small pegmatites in which an outer layer of graphic granite frames a central vug partly filled with microcline and amazonite crystals, clear and smoky quartz crystals, topaz, phenacite, fluorite, zircon, biotite, muscovite, cleavelandite, siderite, cassiterite and additional rarer species. In outer parts of the batholith and in the metamorphic rocks around its periphery the pegmatites contain a markedly different accessory suite: muscovite, biotite, apatite, triplite, beryl, columbite, garnet, magnetite and pyrite and are of larger size and entirely different internal structure.

Eight Mile Park, Colorado (Heinrich, 1948). In the central parts of the Pikes Peak granite body occur swarms of tabular, well-zoned pegmatite dikes that average 1–2 feet in thickness and consist of microcline, quartz, oligoclase, muscovite, biotite and schorl. These interior pegmatites have not been hydrothermally altered. Within the granite along its borders are relatively large, horizontal or gently dipping sheet or discoidal pegmatites that crosscut the primary granitic foliation. They possess a rude internal structure with small core pods and are made up chiefly of microcline, quartz, muscovite, biotite and graphic granite. In a few of these marginal pegmatites post-magmatic mineralization has produced small replacement units of albite, muscovite, beryl, tourmaline, garnet and triplite along the footwall core contacts. The exterior-zone deposits, which are large sills in the Idaho Springs schist, are well-zoned and in many cases have been extensively altered by hydrothermal replacement, with the formation of albite (including cleavelandite), muscovite, garnet, schorl, apatite, beryl, triplite, columbite, lepidolite, alkali tourmaline, natromontebrasite and chalcocite. Nearly all of the commercial feldspar, mica and beryl has been mined from exterior pegmatites.

Micanite District, Colorado (Hanley, Heinrich and Page, 1950; Bever, 1952). Pegmatites of economic significance or of complex mineralogy in the Micanite district are clustered close to the sides of an elongated granodiorite body, which appears to be a large projection from the roof of an underlying Pikes Peak granite batholith. These marginal pegmatites, which occur mainly in the flanking sillimanite and biotite schists and to a much lesser extent in the granodiorite itself, have been mined for feldspar and mica and contain the assemblage: muscovite, biotite, beryl, garnet, apatite, schorl, Fe-Mn phosphates, magnetite, Bi minerals, euxenite, cordierite and sillimanite. Pegmatites at greater distances from the granodiorite are not zoned and lack the accessory mineral suite.

Quartz Creek District, Colorado (Hanley, Heinrich and Page, 1950). Pegmatites in the marginal parts of the granite body and in the hornblende gneiss close to the granite contacts are characterized by a strong lithium replacement phase in which cleavelandite, lepidolite, zinnwaldite, pink muscovite, alkali tourmaline, alkali beryl, topaz, microlite, columbite, monazite, gahnite, fluorite and rarely spodumene and amblygonite were formed. Pegmatites at greater distances from the contacts contain muscovite, beryl, schorl and minor columbite, monazite and samarskite.

Other Colorado Districts. In the Climax area of northeastern Lake County, Butler and Vanderwilt (1933) have noted the marked concentration of pegmatitic material in country rock schist and in granite close to their contact and the dearth of pegmatites in the interior parts of the granite mass. The bodies contain accessory muscovite, biotite, magnetite and garnet, but pegmatites in the granite lack biotite. Crawford (1913) has reported similar relationships in the Monarch district of Chaffee and Gunnison Counties. District zoning of pegmatites in the northern part of the Front Range has been recognized by Boos (1947).

Petaca District, New Mexico (Jahns, 1946). Pegmatites in the granite of this district are of small size, irregular shape, simple mineralogy and homogeneous structure. Those in the metamorphic rocks marginal to the batholith are structurally of two types: (*a*) Sills and dikes parallel with the foliation in strike but crosscutting in dip, and (*b*) other types of dikes. Most of the mica deposits and concentrations of rarer minerals such as fluorite, columbite, monazite, beryl and samarskite occur in the last type.

Boulder Batholith, Montana (Heinrich, 1949). Within the batholith pegmatites are associated with aplitic dikes in which they may occur as pods or tabular masses. These segregation-type pegmatites are commonly zoned inward as follows: aplite, fine-grained graphic granite, medium-grained granitic quartz-microcline pegmatite, vugs with crystals of microcline, quartz (usually smoky), albite and sphene. Other marginal pegmatites have small quartz cores and contain accessory amethyst, allanite, schorl, biotite, garnet, apatite, magnetite and pyrite. The exterior type of pegmatite is normally a sill with variable zonal development. Muscovite and garnet are common in some; others contain rose quartz, schorl, epidote, graphite, apatite, fluorite and zircon.

Discussion

Zone variables

The differences between groups of pegmatites in a single district are due to variations in the following characteristics: size, shape, structural relationship to wall rocks (external structure), internal structure (zoning, etc.), texture and mineral content. Not all of these characteristics are independent variables, nor does their systematic variation in all cases depend exclusively on the relative distances of the pegmatites from their parent batholith.

The discussion is handicapped, of course, by the fact that, in some districts of low relief and where the attitudes of the batholithic contacts are not known, we cannot readily relate pegmatite variation to any factor save *horizontal* distance from an *outcrop* of batholithic rock.

Relation of size and shape to type of host rock

The shape of an intrusive* pegmatite body may be controlled to a very large extent by the structure of the rock into which the pegmatitic magma was intruded. Injections of pegmatitic magma will tend to follow preexisting channelways or potential channelways, namely, fractures, faults, crests, or troughs of folds, foliation planes and contacts between different rock units. In competent or massive rocks, such as granite, granodiorite, quartzite, marble and poorly foliated gneisses, fractures and faults play a major role in localizing pegmatitic intrusion and molding the resulting form of the crystallized body. Thus these pegmatites are commonly discordant and have tabular, anastomosing or entirely irregular outlines. Pegmatites in incompetent rocks, for example the micaceous schists, tend to be at least partly concordant, and are shaped as lenses, tabular sills, inclined tubes, phacoliths, troughs and hoods. These relations have been discussed by Landes (1942), by Cameron *et al.* (1949), and by Staatz and Trites (1950), who also note that, "With the intrusion of large amounts of pegmatitic material, the effect of the country rock on the shape of the pegmatite is usually obscured, and the body assumes an irregular stock like shape. The type of country rock thus appears to have the greatest control over the final shape of the smaller pegmatite bodies."

The average size of pegmatites in a single district seems to be largest in the marginal group. Interior pegmatites usually are small.

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* In the following discussion it is understood that pegmatites are, in the main, of intrusive nature and that wholesale replacement of country rock or segregation and crystallization in situ within batholiths are minor genetic processes.

Relation of size and shape to internal structure

Vlassov (1943) has attempted to define the relationship between (1) internal structure and rare mineral concentration and (2) shape and size. He concludes:

(*a*) That the highest concentrations of rare elements (Li, Cs, Be, Rb, Cb, Ta, Bi, Sn, etc.) are to be found in the largest pegmatite bodies and particularly in those with an oval shape, i.e., lenses and stocks.
(*b*) That zoning is better developed in pegmatites of oval shape than in those of tabular shape.
(*c*) That replacement units are best developed in large oval pegmatites.

These conclusions, although perhaps applicable to certain districts, are untenable for pegmatites of many other regions.

No general relationships between pegmatite size and degree of zonal development have been established. Within a single province some very large pegmatite bodies may be very poorly zoned or unzoned, whereas pegmatites of moderate or even small size display marked internal differentiation. However, in an individual body that pinches and swells, zones normally are more numerous in the thicker parts of the pegmatite, and it is in such bulges that cores or core pods have been developed. As noted by Cameron *et al.* (1949, p. 21), "The core segments generally correspond to these bulges in shape and attitude, and their size commonly is a reflection of the dimensions of the bulge as well." In general in very thin pegmatites, those two feet or less in thickness, zonal structure is rarely developed. This size range of pegmatites has probably the highest percentage of unzoned representatives. But it cannot be asserted, on the other hand, that a large size guarantees a large number of zones.

Similarly it cannot be maintained for pegmatites in general, that those of oval outline (lenses or stocks) show better developed zoning or more strongly developed replacement features than do tabular pegmatites. Among the many outstanding United States examples of tabular pegmatites in which both zoning and replacement units are markedly developed are the Harding pegmatite of Taos County, New Mexico, the Brown Derby pegmatites of Gunnison County, Colorado, and a number of gem and lithium pegmatites of the Pala district, San Diego County, California (Jahns, 1951).

Thus as has been noted in several examples, within a pegmatite district there may be systematic variations in the degree or perfection of internal structural development. These variations may accompany regular differences in shape, but in general, pegmatite shape and degree of development of internal structure appear to be independent features.

Relation of internal structure to mineral content

Unzoned pegmatites normally are mineralogically simple, and those of granitic composition contain microcline, quartz, oligoclase-albite, muscovite, biotite, schorl, spessartite, zircon, apatite and magnetite. Pegmatites that contain zones without secondary petrologic units (replacements or fracture fillings) may have, in addition, such species as low alkali beryl, spodumene, columbite, amblygonite and Fe-Mn phosphates. Pegmatites in which both zones and secondary units occur are mineralogically most complex, and contain cleavelandite, sodic "sugary" albite, lepidolite, zinnwaldite, cookeite, alkali tourmaline, alkali beryl, petalite, pollucite, topaz, tantalite, microlite and sulfides in replacements or fractures fillings. Increasing mineralogical complexity commonly is a function of increasing structural complexity. Large and well-developed replacement units are to be found only in pegmatites in which a magmatic zonal structure was first developed. But of course, the zones may be obscured or partly destroyed by the replacement effects. The formation of zones apparently is prerequisite to the generation of fluids that form the secondary units through reaction and replacement. This relationship weighs heavily in favor of closed system conditions for structurally complex pegmatites.

The questions arise: (1) Are pegmatites with rare element minerals in secondary units of a notably different bulk composition from pegmatites that carry only zones and consist chiefly of the more common minerals? (2) Are unzoned pegmatites of a different bulk composition from zoned deposits of a similar mineral content? The quantitative data available now are inadequate to provide a clear answer. Despite the mineralogical conspicuousness of most replacement units, their total volume is usually small as compared to that of the entire pegmatite body. In an entire district the amount of such hydrothermal material may represent but a minute fraction of all pegmatitic rock. For example, for the Eight Mile Park district of Colorado the volume of secondary pegmatitic material is estimated to be 1% or less of the total pegmatite present. Jahns in describing pegmatites of the Pala district likewise notes (1951, p. 28), "In few of the dikes, for example, do the coarse-grained replacement units appear to constitute more than 1 percent of the total pegmatite material present." Moreover as Gevers (1936, p. 360) has carefully pointed out, replacement does not necessarily require a wholesale transfer of all elements involved but may result from the exchange of only a few ions or radicals. Rare-element replacement minerals are formed if and when these uncommon elements become locally concentrated. In many pegmatites the mechanism for their concentration apparently never began operation, and these constituents are concealed as typical dispersed elements in the more ordinary pegmatite minerals. Examples are Li in muscovite and biotite, Rb and Cs in microcline, muscovite and biotite, rare-earths in apatite, zircon and garnet and Cb and Ta in sphene and zircon. Thus it may be possible that the differences in composition between some complex and simple pegmatites are more mineralogical than chemical and more apparent than real. According to Vlassov (1943) pegmatite shape is an important factor in determining whether the rare elements are accumulated or remain dispersed.

Despite the lack of quantitative compositional data, it is clear that in some pegmatite districts there exist real mineralogical differences among interior, marginal and exterior pegmatites and that these mineralogical variations may also correspond with variations in the internal structure. The causes of differentiation in individual pegmatites are still unknown. Why in a single district some pegmatites develop zones and others of the same general shape and apparent same mineral composition do not, remains to be answered.

Relation of mineral content to type of host rock

The idea that a general relationship exists between wall rock composition and pegmatite composition is an old wives' tale that, despite numerous decapitations, continues to sprout in hydra fashion under succeeding generations of pegmatite investigators. Recent contributors to this notion have been Biswas (1935), Zavaritsky and Kryjanovsky (1937) and Scholz (1950). Exomorphic and endomorphic effects between pegmatites and their wall rocks are exceedingly widespread. However such effects are almost invariably of very limited extent and have not influenced significantly the bulk composition of the pegmatite. It has been suggested that in some cases pegmatite magmas may become rather markedly contaminated through assimilation, e.g., the Quebec type phlogopite deposits (Landes, 1938). If such a process does take place, it is more likely to proceed at depth rather than at the level at which the pegmatite finally crystallizes and where wall rocks may differ from the rocks below. The bulk composition of pegmatites is independent, in general, of the composition of the host rock. In some districts in which pegmatites apparently occur preferentially in one wall rock type, the localization can be ascribed to structural rather than compositional features, e.g., see Jahns (1951, p. 15).

ORIGIN OF DISTRICT ZONING

As stated by Cameron *et al.* (1949, p. 8), "The concept of zonal distribution is appealing in its simplicity, but it may be that factors other than distance are of equal or greater importance in controlling the distribution of types of pegmatite." As noted previously, the pegmatite characteristics that vary within a district and whose systematic variation represent district zoning are size, shape (and external structure), internal structure and mineral composition.

Does the restriction in some districts of small pegmatites to the interior of batholiths mean that at the time of their intrusion only a minor quantity of pegmatite magma was available? Thus interior pegmatites could be interpreted either as coming early in the pegmatite stage when the generation of pegmatite magma had just been begun or late in the stage when the generative process was tapering off. The absence of rare-element minerals in interior pegmatites, however, appears to argue against their late formation and may indicate that this is a pegmatitic fraction that was expelled early, at a time when the rarer constituents had not yet achieved concentration in the batholithic hearth.

The shape of a pegmatite body is largely a function of the structural feature in which it was localized and crystallized, and this feature, in turn, depends considerably on the physical characteristics and tectonic history of the host rock. Wherever the quantity of magma intruded was unusually large, it may have overcome the controlling influence of the guiding structures. Thus shape may or may not be related to distance from the parent batholith.

Internal structure apparently is influenced only to a minor extent by shape and to an even lesser extent by size. The main factor or factors controlling the formation of zones and secondary structural units remain unknown, but in some districts variations in the development of internal units can be systematically correlated with distance from the batholith.

Rare-element mineralogy is controlled to a large extent by the type and quality of internal units. Thus regional variations in structural units are likely to be accentuated by conspicuous mineralogical changes. Yet in some districts there appear to be significant differences in the bulk compositions of the pegmatites of the various zones. In the Spruce Pine and Franklin-Sylva Districts of North Carolina and the Kodarma district of India the amount of microcline varies, so that the pegmatites range in composition from tonalitic through granodioritic to granitic.

Several general hypotheses may be considered in attempting to explain the origin of zoning in pegmatite districts:

(1) It can be postulated that zoning is not directly related to distance from the batholith, but rather that the variable pegmatite compositions are functions of size, shape, and type of wall rock or result from the confusion of two different pegmatite age groups within the same district. The examples cited and the discussion suffice to indicate that this idea is untenable.

(2) Roy, Sharma and Chattopodhyay (1939) believe that the granitic residuum of a batholith splits into K-rich and Na-rich immiscible fractions. The K-rich portion was ejected first while the granite was not completely consolidated. Following complete crystallization of the batholith the increased pressure resulted in expulsion of the Na-rich fraction to a greater distance from the granite. Because the Na-rich pegmatites also contain most of the important mica concentrations, it is suggested that the K for the muscovite is obtained by the Na-rich fluids through attack of the older, potash feldspar pegmatites at lower levels. The happy coincidences required by this hypothesis are sufficient to emasculate it. No microcline pegmatites were found in which the depotassification postulated could be demonstrated. It is reasonable to suppose that, if they existed, at least some would appear near or in the dome gneiss, since that part of the district represented a higher intensity environment, or a deeper or lower "level" in the sense of the authors. Zones cannot be considered in two dimensions alone but must be envisioned as three-dimensional shells. Furthermore the chances are most doubtful that in each case an expulsion of Na-rich fluid would always encounter a previously formed potash feldspar pegmatite, react with it and then be capable of further migration.

(3) Undoubtedly the period of collection and expulsion of pegmatitic rest-magma from a crystallizing batholith is a long one, during which pegmatitic material is released at various intervals depending upon the rate of accumulation and the magmatic pressure. During this lengthy pegmatitic period the batholith is continuing to crystallize and the composition of the residual magma is progressively changed. Thus fluids generated during the latter part of the pegmatitic stage might differ considerably from those formed and released earlier, both in general composition and in the content of rarer elements. This idea also has been advanced by Bateman (1942, p. 53), who stated: "Withdrawals of the early liquid yield simple pegmatite dikes that are varieties of igneous rocks; later withdrawals of a more aqueous stage yield pegmatites, commonly characterized by druses, compounds of tungsten, tin, uranium, titanium, beryllium, phosphorus, chlorine, fluorine, and other elements, . . ." Later Bateman expanded this concept somewhat (1951, pp. 86–87) to say: "The composition of the pegmatites depends in part on the original composition of the magma from which they spring, but also in larger part upon the stage of crystallization at the time they are withdrawn from the magma chamber. . . . If the residual fluid of a granitic magma is tapped off well before the completion of crystallization, it will consist largely of the ingredients of the minerals that are later to crystallize. . . . Such relatively early withdrawals will yield simple pegmatite dikes. . . . If the withdrawal of residual liquid takes place during a more advanced

stage of magma crystallization much of the feldspar will already have crystallized, but particularly there will be a greater concentration of mineralizers, and rare and uncommon constituents."

Vogt (1930, p. 115) thought that the various pegmatites at Langesundsfjord represent various stages of residual magmas "and this may probably be one of the different reasons on which the varying occurrence of the rare (pneumatolytic) minerals, described by Brögger, depends." Raguin (1946) also mentioned this idea of progressive changes in pegmatitic magmas by referring to the simple pegmatites as the "avant-coureurs" of magma and the complex pegmatites as the ultimate residua or quintessence of granitic substance. McLaughlin (1940) also has observed that in the Bridger Mountains of Wyoming complex pegmatites are younger than simple ones.

This hypothesis is an attractive one. If later pegmatitic fractions had higher contents of volatiles as well as rare-elements, their resulting lower viscosities should permit their extrusion to greater distances from the batholith. It might also be maintained that country rocks had by this time been heated to greater distances from the batholith and that the pressure in the magma had been further increased due to complete batholitic crystallization (Morey, 1922). External pegmatites, by this concept, are richer in rarer constituents because their magma was tapped off at the time of maximum maturity of the pegmatitic stage and are further from the batholith because of their lower viscosity, greater pressure and perhaps the extended thermal aureole of the batholith.

Thus the location and composition of a pegmatite depend upon: (*a*) The chemical character of the source batholith; (*b*) The stage of crystallization of the batholith at the time of withdrawal of the pegmatitic material; and (*c*) The penetrability of the rock around the pegmatite hearth.

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