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LAYERED PEGMATITE-APLITE INTRUSIVES[1]

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ABSTRACT

Intrusive bodies of granitic pegmatite and aplite with simple or complex layering include those representing multiple injections of magma from external sources and those representing single injections of magma followed by segregation during crystallization. Those of the latter category can be subdivided into four classes, intergradations among which are not uncommon:

1. Bodies of aplite or fine-grained pegmatite with very large phenocrysts, or megacrysts. 2. Aplite bodies with marginal or interior pegmatite masses generally formed *in situ*. 3. Pegmatite bodies with marginal or interior aplite masses formed *in situ* or by autoinjection. 4. Highly asymmetric bodies whose upper parts consist mainly or wholly of pegmatite and whose lower parts consist mainly or wholly of aplite.

Zonal structure defines a gross layering within many pegmatite bodies, and a layer-like distribution of pegmatite and aplite also is common over a wide range of scales. Some of the aplites are faintly to distinctly flow layered, and others are featured by rhythmic layering in which adjacent thin and regular units differ from each other in composition. None of the observed types of layering is regarded as a result of crystal accumulation.

The bulk composition of the layered intrusive bodies falls in the thermal valley of petrogeny's residua system at an average composition corresponding to a parent magma saturated with water at high pressures (*e.g.* >2000 bars). This also is true of many individual pegmatite and aplite masses, in which the pegmatite is ascribed to crystallization of magma saturated with volatile constituents and the aplite to rapid crystallization of magma during escape of such constituents. In contrast, the aplite masses of most highly asymmetric bodies are markedly sodic and the associated pegmatite masses are correspondingly potassic in composition. This difference is attributed to segregation of major alkalies in the presence of silicate melt and coexisting aqueous vapor. Variations in distribution of the two fluid phases within a given intrusive, in distribution of alkalies between then, and in rates of diffusion of alkalies through the vapor could account for the known relationships between these complementary pegmatites and aplites.

All these types of bodies can be identified genetically with subsolvus granites and related rocks, and their common association is attributed to derivation from magmas with high water content. The amount of pegmatite and aplite associated with hypersolvus granites is trivial.

INTRODUCTION

Pegmatites and aplites have long been recognized as texturally contrasting rocks whose composition and features of occurrence bespeak close genetic affiliations. At thousands of localities throughout the world they are so intimately associated in both space and time that derivation from a common stem seems plainly indicated. Moreover, numerous individual bodies of rock comprise both pegmatite and aplite in various combinations, the paragenetic relationships of which suggest development within what may well have amounted to single systems.

In this paper attention is focused mainly upon pegmatite-aplite bodies in which layering either appears within masses of one or both rock types or is expressed by the gross arrangement of the masses themselves. The principal objectives are to summarize the observable physical relationships within these bodies, to report on certain contrasts in bulk composition of their constituent aplite and pegmatite masses, and to suggest mechanisms for explaining the origin of the rocks and their layering. The discussions are restricted to rocks of granitic composition, and to occurrences ascribed to initial emplacement of a magma. In an attempt to establish generalizations that are sound, the writers have drawn from their own observations of the past twenty years and also have made a careful search of the world literature for detailed descriptions of closely associated aplites and pegmatites.

Much of the background field work by Jahns was an outgrowth of earlier detailed studies of pegmatite districts under the aegis of the U. S. Geological Survey, and was supported during the period 1948–1962 by the California Institute of Technology, the American Research Institute and The Pennsylvania State University. Other field investigations, carried out independently by Tuttle during a period of several years, were supported by The Pennsylvania State University and the National Science Foundation. Funds for several chemical analyses also were suppled by the National Science Foundation. It is a

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pleasure to acknowledge the contributions of numerous colleagues with whom the writers have discussed the genesis of aplites and pegmatites; particularly helpful in this connection have been W. R. Griffitts, J. B. Hanley, J. J. Norton, and L. R. Page of the U. S. Geological Survey, E. Wm. Heinrich of the University of Michigan, and C. W. Burnham and L. A. Wright of The Pennsylvania State University.

Features of Occurrence

General relationships. Pegmatites and aplites occur predominantly in igneous and metamorphic terranes that encompass a very wide range of rock types. Metamorphic rocks are common hosts for bodies of pegmatites and for bodies comprising both pegmatite and aplite; remarkably rare in such environments, however, are bodies that consist solely of aplite. No such restriction appears to exist within igneous terranes, where both pegmatite and aplite are abundant, either in separate bodies or as component parts of single bodies. Many groups of such bodies are distributed systematically within or around much larger masses of intrusive igneous rock with which they may be genetically related.

Layered intrusive bodies composed of both pegmatite and aplite range from thin stringers and lenses to pods and tabular masses hundreds of feet thick and a mile or more long. They also vary considerably in attitude, form, and complexity of form, commonly in response to contrasting structural features in the host rocks (see summaries in Landes, 1942; Cameron *et al.*, 1949). Although it is not feasible to consider any average or typical shape, tabular and pod-like bodies probably are more abundant than all other kinds taken together.

The layered bodies herein discussed are referred to as intrusives because they seemingly were emplaced by magmatic injection, accompanied in some occurrences by stoping. The most common and most convincing evidence for such injection is provided by structural relationships that indicate dilation of the country rock, especially where these relationships can be fixed in three dimensions. That the injected material was magma is variously suggested by systematic variations in size, structure and composition of many bodies with respect to igneous plutons (Cameron *et al.*, 1946, pp. 5–8; Heinrich, 1953; Varlamoff, 1960), by the occurrence of some bodies as autoinjection products within such plutons, by the merging of other bodies into larger masses of normal plutonic rocks, and by numerous textural, structural, and compositional features within the layered bodies themselves. These and other criteria for magmatic injection, as outlined and discussed in the published record (*e.g.*, Jahns, 1955, pp. 1057–1067; Chadwick, 1958; *c.f.* King, 1948), have been applied in the present study to the selection of occurrences for critical analysis. Although the writers are convinced that the bodies under discussion are igneous intrusives, their primary intent here is not so much to defend this view as to determine whether it is compatible with all known features of these bodies and their contained rock types.

Pegmatite-aplite relationships. Layered pegmatite-aplite intrusives can be readily grouped into two major categories:

I. Composite bodies and complexes representing multiple injection of magma from external sources.
II. Bodies representing a single injection of magma, followed by segregation during crystallization and, in some occurrences, by autoinjection of residual fluid.

The second category can be subdivided into four classes as follows:

1. Bodies of aplite or fine-grained permatite with very large phenocrysts, or megacrysts.
2. Aplite bodies with marginal or interior pegmatite masses generally formed *in situ*.
3. Pegmatite bodies with marginal or interior aplite masses formed *in situ* or by autoinjection.
4. Highly asymmetric bodies whose upper parts consist mainly or wholly of pegmatite and whose lower parts consist mainly or wholly of aplite.

These classes can be readily identified, each in numerous and widely distributed occurrences, but various combinations and intergradations are by no means rare. Some aplite masses of Class 4, for example, contain abundant megacrysts and hence correspond to Class 1, and some bodies of Class 1 contain so many megacrysts or so many clusters of such large crystals that they could be identified with Class 2 or even with Class 3. The basic distinctions, however, are easily recognized among most of the pegmatite-aplite intrusives that have been observed by the writers.

(a) Composite bodies and complexes

Many bodies of aplite are plainly intrusive into, across, or along earlier-formed bodies of pegmatite, and the reverse relationship is almost as common (*e. g.*, Cook, 1925; Derry, 1931; Heinrich, 1945; Jahns *et al.*, 1952, p. 30; Olson *et al.*, 1946, p. 10). Successive injection is most simply expressed where dikes of pegmatite and aplite occupy sets of primary fractures within cogenetic plutons of granitic rock,

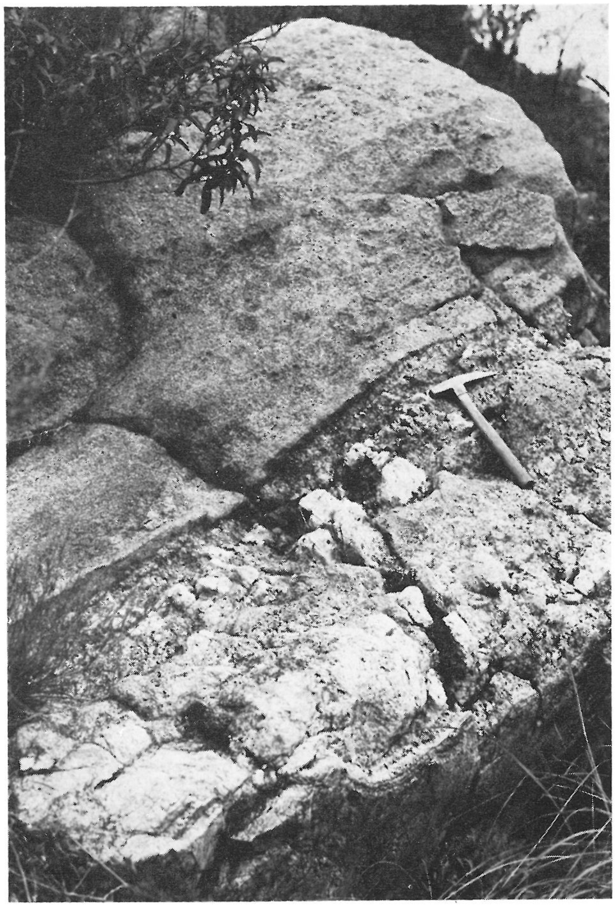

FIG. 1. Intrusive contact between pegmatite-aplite sill and overlying faintly layered fine-grained quartz-albite-muscovite pegmatite (or coarse-grained aplite). Upper part of sill is coarse grained and rich in graphic granite; lower part, here incompletely exposed, is much finer grained and distinctly layered. Rock bodies dip to left and away from observer. East slope of Hiriart Mountain, Pala district, California.

and where one set of dikes transects another. Evidences of transection are supplemented, in many of these and other occurrences, by the presence of aplite apophyses in pegmatite or pegmatite apophyses in aplite, and by the relationships between pegmatite-aplite contacts and the disposition of primary flow structure within either or both rock bodies.

A gross layering results from the presence of sill-like masses of aplite (identified in some published accounts as fine-grained granite) within tabular bodies of older pegmatite. Similar injected masses of pegmatite within host aplite also have been observed, but are not so abundant. The source of the younger magma may have been external with respect to many of these composite bodies, but the possibility of autoinjection cannot be dismissed for numerous occurrences where the younger aplite or pegmatite appears to lie wholly within the older rock body. Even where local cross-cutting relationships can be recognized, it rarely is clear whether the transecting mass is a feeder or an apophysis.

Gross multiple layering attributable to successive injections of magma appears within many swarms and complexes of closely spaced parallel sills or dikes, as in the Keystone district of South Dakota (Orville, 1960, pp. 1473–1475) and the Pala district of southern California (Jahns and Wright, 1951, pp. 16–18). These tabular bodies, which generally range in thickness from a few inches to 25 feet, are in direct contact with one another in some places (Fig. 1) and are separated by plates or screens of country rock in others (Fig. 2). Although many of them are very thin, these country-rock screens tend to be continuous for considerable distances and to thicken, thin, or pinch out gradually. Where they are absent, the juxtaposed bodies of pegmatite or aplite commonly retain their respective identities, and layering within such complexes is then defined by sharp, in many places almost planar, parting-like contacts between adjacent bodies.

Added elements of layering are provided by the contrasting lithologic units within individual "two-ply" bodies that comprise indigenous pegmatite and aplite. Bodies of this kind, described farther on, are well represented among intrusive complexes, and the continuity of their consistently disposed internal units further distinguishes each body from its neighbors. Where the contact between two juxtaposed

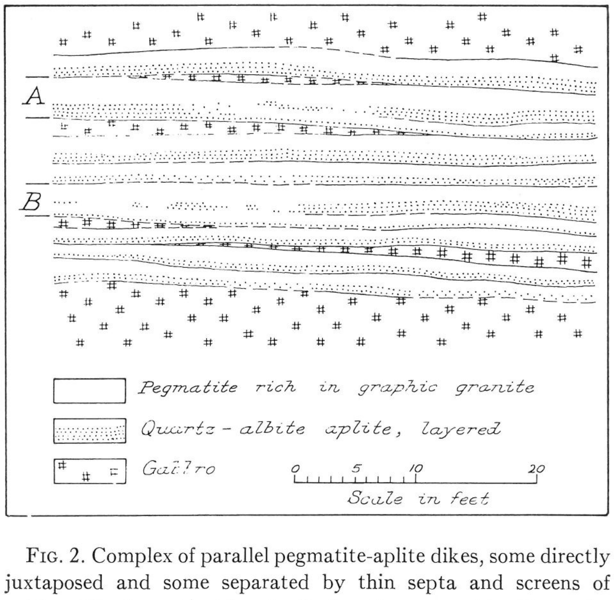

FIG. 2. Complex of parallel pegmatite-aplite dikes, some directly juxtaposed and some separated by thin septa and screens of gabbro. Nearly vertical longitudinal section normal to dike walls. Northwest of Alamo, Northern Baja California, Mexico.

pegmatite-aplite bodies gradually loses its definition and becomes unrecognizable, the units within these bodies commonly remain in their normal positions and thus attest to very limited mixing of the adjacent injected magmas (B, Fig. 2). In contrast, mixing and even homogenizing of such magmas is indicated where pairs of "two-ply" bodies can be traced into single bodies with a correspondingly simple "two-ply" internal structure (A, Fig. 2). The distribution of pegmatite and aplite in the transition zones generally reflects increasing degrees of mixing of the adjacent magmas, presumably in directions toward parts of the respective systems in which these magma pairs were almost wholly liquid at the same time.

(b) Individual pegmatite-aplite bodies

The following generalizations concerning individual pegmatite-aplite bodies have been drawn mainly from the writers' studies of occurrences in New England, the southern Appalachian region, Minnesota, Missouri, Texas, the Black Hills region, the Rocky Mountain region from Montana to New Mexico, southern Nevada and western Arizona, and southern California and adjacent parts of Mexico. Many of these occurrences also have been studied by other investigators, several of whom have given careful attention to relationships between pegmatites and aplites; references to their published views are made farther on. Most of the illustrations in the present paper show pertinent and well-exposed relationships in the pegmatite districts of southern California and Baja California, but they fairly represent features observed in numerous other districts as well.

(i) Porphyritic aplites and pegmatites. Many aplites and very fine-grained pegmatites contain prominent anhedral to euhedral phenocrysts, or megacrysts, that range in maximum dimension from about an inch to nearly 5 feet (*e.g.*, Wheeler, 1935; Jahns, 1953; Varlamoff, 1954; Orville, 1960; Volborth, 1962). By far the most common megacryst constituent is perthite, with or without graphically intergrown quartz. Large individuals of quartz also are present at some localities, as are strips and plates of muscovite or biotite. Megacrysts of apatite, beryl, garnet, tourmaline, allanite, monazite, tantalite-columbite and other accessory minerals are by no means rare, but normally they are distinctly smaller than the perthite crystals.

The groundmass of these rocks consists typically of quartz and albite, along with lesser amounts of microcline and various combinations of micas and accessory minerals. It is hypautomorphic-granular with a sugary appearance, and the average grain size is in the range 0.2–5.0 mm for most occurrences. Where the groundmass is coarser than the limits usually set for aplites, the term pegmatite is applied to the rock mainly on the basis of the megacrysts, which are of giant size relative to the other constituents.

All gradations have been noted between rock in which the megacrysts are uniformly or irregularly scattered and rock in which such crystals are notably concentrated in the upper part of the intrusive body. The limiting case is an asymmetric "two-ply" body in which the upper part is coarse-grained perthite-rich pegmatite and the lower part is albite-rich aplite (Fig. 2). The entire range in distribution of megacrysts commonly is observable within a single body. All these kinds of prophyritic rock also grade into nonporphyritic aplite through progressive decreases in number of megacrysts and corresponding increases in the amount of groundmass microcline, and into medium- to coarse-grained pegmatite through progressive coarsening of the groundmass.

The groundmass of the porphyritic aplites and pegmatites ranges from essentially homogeneous and massive to sharply and strikingly layered. The layering is compositional, and is expressed mainly by thin, continuous laminations that are relatively rich in garnet, tourmaline, muscovite or combinations thereof. These parallel units are separated by somewhat thicker laminations in which such minerals are much less abundant or absent. Layers thinner than 3 mm in general are most sharply defined, but some as thick as 10 cm can be identified without difficulty. Layered groundmass rock commonly is traceable into homogeneous rock, either laterally through abrupt termination or gradual fading of the laminations, or in directions normal to the layering through sudden lack of additional laminations or through progressive thickening and fading of succeeding laminations.

The mineralogic layering tends to be parallel with the walls of the containing intrusive body, and to reflect irregularities in these walls. In detail, individual layers butt against the megacrysts, wrap partly around them, or pass through them as outlines of growth sufaces within the large crystals (Fig. 7; *c.f.* Jahns, 1953, pp. 584–585; Staatz and Trites, 1955, pp. 23–24; Orville, 1960, pp. 1471–1472). Orientation of the layering adjacent to some perthite megacrysts is highly variable and plainly reflects the influence of these crystals, as pointed out by Orville (1960, pp. 1471–1472, 1487), but his suggestions that the layers were distorted, contorted, and disrupted by subsequent growth of the megacrysts seem open to question. The observed relationships are equally well explained in terms of simultaneous crystallization of layered aplite and large perthite individuals, and it is difficult to account for the "phantom" layers within the perthite crystals in any other way. The writers are in full accord, however, with Orville's conclusion (p. 1472) that numerous irregular grains of plagioclase and quartz within the megacrysts are genetically related to both the "phantom" layers and the fine-grained groundmass outside.

Evidence of small-scale deformation is widespread in the layered groundmass of some intrusive bodies. Movement is indicated by flexures that suggest a uniform direction of dragging, by piercing folds, and by ruptures and very small faults that have been "healed" through subsequent crystallization. That most of the disturbance occurred during consolidation of the bodies also is indicated by protoclastic structure in the rocks thus affected, and by the presence of adjacent younger layers that are undeformed (Fig. 7B). Effects of deformation can be observed in all parts of the layered sequences, and normally can be distinguished from primary irregularities that are confined to the immediate neighborhood of megacrysts; in places they clearly have been superimposed upon such irregularities.

FIG. 3. Dike of essentially massive aplite fringed with large, inward-directed crystals of potash feldspar. Granite block in H. E. Fletcher quarry, Westford, Massachusetts.

(ii) Symmetrical pegmatite-aplite bodies. The intrusives herein referred to as symmetrical include aplite bodies with simple fringes of megacrysts (Fig. 3) or pegmatitic crystal aggregates, aplite bodies with interior masses of pegmatite that are irregularly or systematically disposed, and pegmatite bodies with marginal or interior masses of aplite (*e.g.*, Watson, 1902; Andersen, 1931, pp. 29–31; Emmons, 1940, p. 8; Varlamoff, 1954). The aplite bodies with coarse-grained margins appear either to have begun their crystallization as pegmatites and completed it as aplites, or to have crystallized both coarse- and fine-grained material simultaneously through some process of segregation. Layers, lenses, and patches of pegmatite entirely within bodies of aplite also appear to have been formed *in situ*. Some of them transect the host aplite on a small scale and evidently are very late products of crystallization. Others are traversed by layers that represent the adjacent aplite, the relationships suggesting essentially simultaneous development; these pegmatite masses can be viewed as analogues of the megacrysts described above.

Aplitic rock forms selvages along the margins of many pegmatite bodies, including some with pronounced internal zoning (Cameron *et al.*, 1949). Where present in the interiors of pegmatite bodies, it generally forms thicker masses of tabular to highly irregular shape. These masses commonly transect pegmatite in some places, butt against it in others, and are cut off by pegmatite in still others. Features indicating autoinjection from other parts of the host body are characteristic of many occurrences.

A simple or complex gross layering results from the distribution of pegmatite and aplite in most of the symmetrical bodies (Fig. 3), and an additional layering is contributed in numerous bodies by lithologically contrasting pegmatite zones. On a smaller scale, some of the aplite masses are flow layered; this structure typically is expressed by a very faint to distinct taffy-like streakiness that is quite different from the more regular mineralogic layering described earlier (Fig. 4). The mineralogic layering is present in a few of the aplites that do not exhibit flow structure, but it rarely is a conspicuous feature. Deformation of the layers, presumably by local movements during crystallization, is not uncommon.

(iii) Asymmetric pegmatite-aplite bodies. Highly asymmetric pegmatite-aplite bodies have been reported from many parts of the world (*e.g.*, Waring, 1905; Schaller, 1925; Derry, 1931; McLaughlin, 1940; Merriam, 1946; Heinrich, 1948; Hanley, 1951; Jahns and Wright, 1951; Gates, 1954; Varlamoff, 1954; Sheridan, 1955; Staatz and Trites, 1955; Thurston, 1955; Hutchinson and Claus, 1956; Simpson, 1960; Orville, 1960), and they are far more abundant than the published record would indicate. Their upper parts characteristically are dominated by medium- to coarse-grained perthite-rich pegmatite, and their lower parts by aplite or very fine-grained pegmatite that is rich in albite. This lithologic separation is essentially complete in some bodies, regardless of their shape or attitude; thus the aplitic rocks appear in the footwall parts of moderately dipping to horizontal tabular bodies (Figs. 1, 2, 4), and in the keelward parts of bodies that dip very steeply or are not tabular in form. The lithologic contrast is considerably less than complete in most occurrences, where the lower aplitic rock contains numerous perthite megacrysts or layers and pods of potassic pegmatite and the upper pegmatitic rock contains fine-grained albite-rich interstitial material or poorly-defined masses of sodic aplite.

The masses of albite-rich aplite generally constitute from 10 to 45 per cent of the containing intrusive bodies. Their relative abundance is less than 10 per cent in many bodies, especially those that are not conspicuously asymmetric, but rarely is it greater than 45 per cent. Among all the intrusives that have been examined by the writers, the distinction between aplite and overlying pegmatite is most evident in horizontal to moderately inclined dikes and other tabular bodies. As in groundmass of the porphyritic aplites described earlier, some of these footwall aplites are essentially massive whereas others are mineralogically layered, and in places strikingly so (Figs. 5, 6). Various concentrations of garnet, tourmaline, and muscovite define the thinnest and sharpest laminations, which typically are 0.5 to 3 mm thick, whereas adjacent laminations that are poor in these minerals tend to be thicker. Fine-gained pegmatite commonly forms still thicker conformable layers within the aplitic sequences (Figs. 5, 6), some of which also are featured by concordant rows of perthite crystals (series of triangles in footwall aplite of Fig. 4; also Fig. 7E), tourmaline prisms, or muscovite plates.

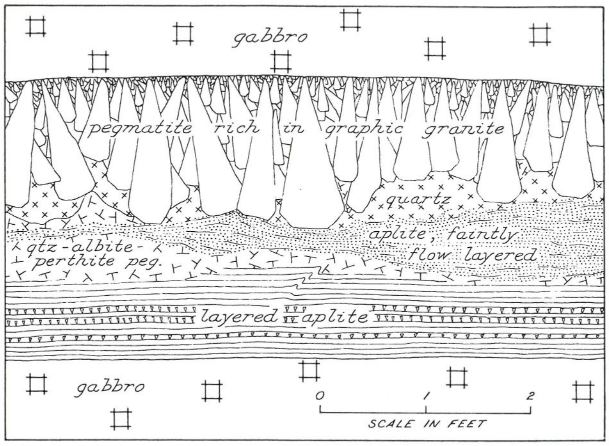

FIG. 4. Typical relationships between pegmatite and two contrasting varieties of aplite. Longitudinal section in asymmetric part of moderately-dipping Himalaya dike, Mesa Grande district, California. Composition of central aplite is near the granite minimum (large solid circle on MG curve, Fig. 10), whereas that of footwall aplite is markedly sodic (left-hand end of MG curve, Fig. 10).

Although properly referred to as megacrysts, the relatively large individuals of perthite, graphic granite, tourmaline, and muscovite within the aplitic rocks ordinarily are much smaller than crystals of the same minerals in the overlying pegmatitic rocks (Fig. 4). Where elongate, these megacrysts tend to be oriented normal to the aplite layering, which is grossly parallel with the adjacent walls of the containing intrusive bodies (*c.f.* Figs. 1, 2, 4, 7). As in the porphyritic aplites already described, the attitude of the layering is markedly influenced in detail by the large crystals.

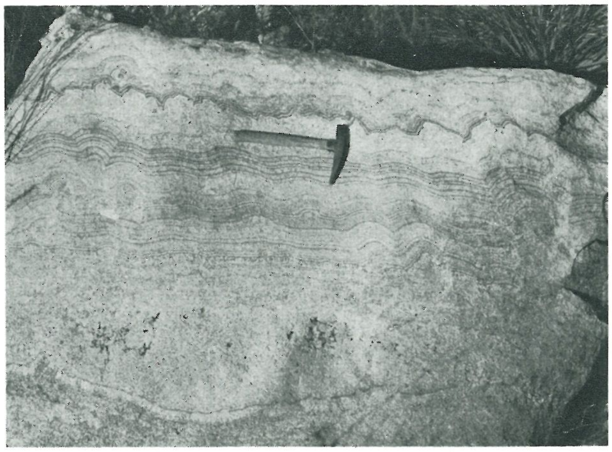

FIG. 5. Quartz-albite aplite with thin, sharply-defined garnet-rich layers and a few thicker layers of fine-grained pegmatite rich in perthite. Some of the nested loops in the layering lie above crystals or crystal aggregates of perthite with graphically intergrown quartz (*c.f.* Fig. 7, D). South slope of Hiriart Mountain, Pala district, California.

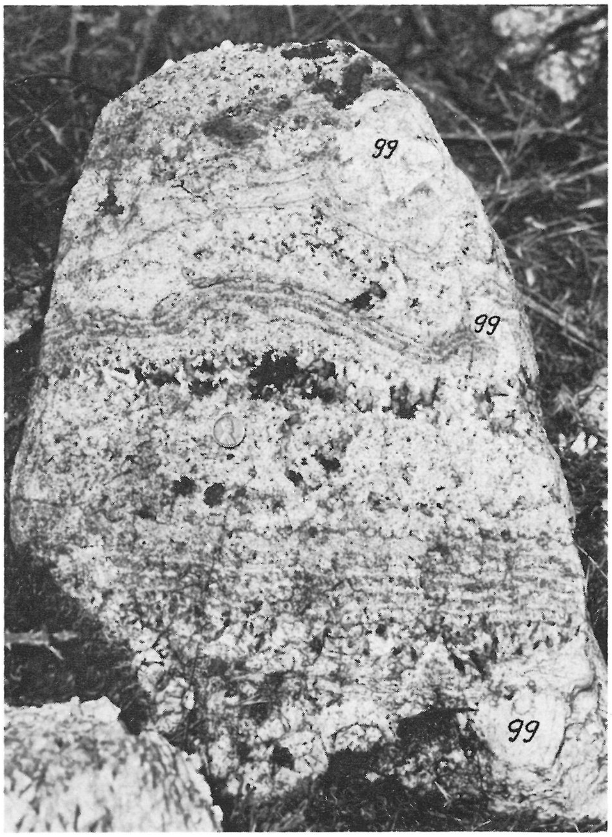

FIG. 6. Layered complex of fine- to medium-grained perthite-quartz-albite-schorl pegmatite and quartz-albite-schorl aplite, with scattered large crystals of perthite and graphically intergrown quartz (gg.)

In several districts the megacrysts of perthite, with or without graphically intergrown quartz, are distinctly elongate parallel to the *a*-axis. Some laminations in the adjacent aplite terminate abruptly against such crystals, but others pass through them along deflected paths that outline "phantom" surfaces (Fig. 7A, C, F; Figs. 8, 9). The distribution of included laminations clearly reveals that these megacrysts grew toward the center of the intrusive body, that some of them broadened markedly as they grew, and that most of them, during their growth, projected somewhat ahead of the aplite layers developing adjacent to them. Younger aplite layers curve around the ends of the megacrysts, forming loops that become successively broader and more subdued (Figs. 5, 7A, C, D). Some megacrysts are gradational into surrounding aplite, and Schaller (1925, 1953) has demonstrated extensive albitization of microcline in such situations. In places the relations are further complicated by stringers and patches of younger coarse-grained perthite and graphic granite (Fig. 9).

COMPOSITION

Methods of determination. Data on composition have been obtained for pegmatite-aplite dikes in the Harding area and Petaca district of New Mexico and the Pala, Rincon, and Mesa Grande districts of southern California. Composite samples of both aplite and pegmatite in the Main Harding dike, New Mexico, were obtained from diamond-drill cores, from numerous outcrops, and from the walls of extensive mine workings. The average composition of each rock type was determined by chemical analysis, and the bulk composition of the entire dike was calculated by weighting the analyses according to the respective abundance of pegmatite and aplite. These abun-

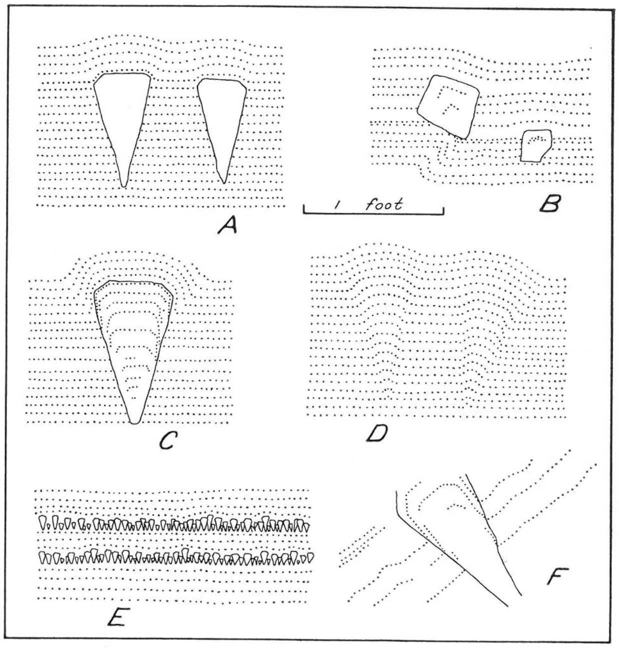

FIG. 7. Typical relationships between thinly layered quartz-albite aplite and relatively large individuals of perthite with graphically intergrown quartz. Vertical sections in footwall parts of pegmatite dikes, southern California. Aplite layering shown diagrammatically. A. Tapered crystals of perthite, El Molino dike, Pala district. B. Equant crystals of perthite with included aplite layers, Mack dike, Rincon district. C. Tapered perthite crystal with growth zones outlined by aplite layers, Himalaya dike, Mesa Grande district. D. Fan structure in aplite layering, with small patches of graphic granite (not shown) in lower part of each fan. Katerina dike, Pala district. E. Layers of small perthite crystals within aplite, Angel Field dike, Mesa Grande district. F. Tapered perthite crystal with growth zones outlined by widely-spaced aplite layers, Himalaya dike, Mesa Grande district.

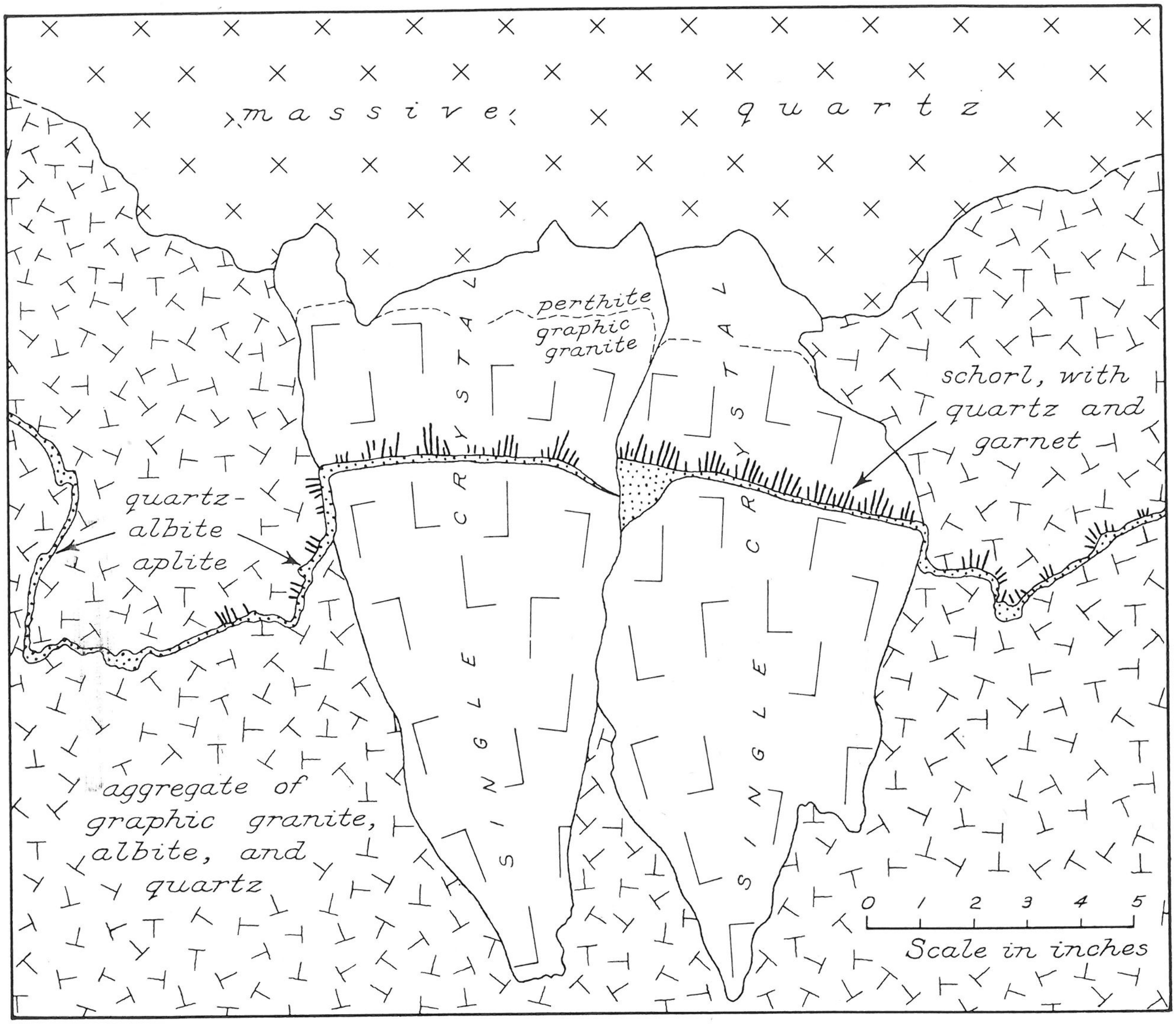

FIG. 8. Relationships among large crystals of perthite with graphically intergrown quartz, aggregate of large anhedral crystals of quartz, medium-grained graphic granite-quartz-albite pegmatite, and quartz-albite aplite. Vertical face of gently-dipping pegmatite dike, Los Gavilanes, Northern Baja California, Mexico.

dances were estimated directly from measurements in the field and indirectly from detailed plans and sections of the dike.

A similar approach was used for the Katerina dike in the Pala district and the Upper Mack dike in the Rincon district, except that sampling and measurements were confined to outcrops and mine workings. The relative amounts of aplite and pegmatite in the Katerina dike were determined megametrically by making measurements along a set of linear traverses oriented normal to the dike walls and spaced 2 feet apart. The relative amounts of megacrysts and aplitic groundmass in the Upper Mack dike were determined through measurements along traverses spaced 6 inches apart, and two sets of these traverses, at right angles to each other, covered each rock exposure.

The fine-grained portions of the White dike in the Petaca district and the Himalaya dike in the Mesa Grande district were sampled and analyzed chemically. The coarse-grained portions were analyzed modally by the technique applied to the Upper Mack dike, except that the lines of traverse were 1 foot apart. Data on average composition of all minerals

FIG. 9. Large crystal of perthite with graphically intergrown quartz, flanked and capped by much finer-grained layered aplite-pegmatite. Some schorl-rich layers form angular, upward-extending loops that outline growth zones in the perthite crystal (*c.f.* Fig. 5 and Fig. 7, C, F). Several layers are interrupted by an irregular and apparently younger clot of perthite and quartz (pq). Himalaya dike, Mesa Grande district, California.

amounting to more than 1 per cent of the pegmatitic rocks were obtained by chemical analysis of a composite sample of each mineral. The modal and chemical data then were combined to yield an average composition for the coarse-grained rocks in each dike.

All rock compositions, as expressed in chemical terms, were converted to normative compositions, and these were then recast on the basis of normative albite+orthoclase+quartz=100. The results are plotted in Fig. 10 for direct comparison with the trend of the isobaric minimum in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O under water-vapor pressures ranging from 0.5 to 4 kilobars. Data from the excellent quantitative analyses by Orville (1960) for pegmatites in the Keystone district of South Dakota and by Simpson (1960) for pegmatites in the Ramona district of California have been recalculated on the same basis, and the results also are plotted in Fig. 10.

Composition of pegmatite-aplite bodies. As represented by the right end of the Ram curve and by the interior points (small solid circles) on the other curves in Figure 10, most of the analyzed pegmatite-aplite bodies have bulk compositions that lie near the thermal minimum in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O. Moreover, all of the compositions lie on the silica side of the isobaric minimum, and on the average, they fall at positions corresponding to elevated water-vapor pressures (2000 to 4000 bars) along the minimum.

The compositions of the central masses of flow-layered aplite (large solid circles in Fig. 10) within the Katerina and Himalaya dikes also are near the "granite minimum," and correspond very closely to the bulk compositions of the respective containing dikes. Numerous published analyses suggest that the compositions of simple aplites that are not intimately associated with pegmatite are strongly clustered in the same general area of the diagram.

Figure 10 emphasizes the great compositional contrasts between footwall or keelward masses of aplitic rock and overlying masses of coarse-grained rock in highly asymmetric intrusive bodies (BR, BA, Hard, Pe, Pa, and MG curves). In terms of their respective compositions, as represented by the open circles at opposite ends of the curves, these masses appear as complementary parts of intrusive bodies whose bulk compositions tend to lie near the "granite minimum." The length of each curve reflects the difference between the ratios of major alkalies in the aplitic and pegmatitic portions of the containing body. Further, it corresponds satisfactorily with the respective lithologies of these aplitic and pegmatitic portions, in effect indicating the extent to which these rocks are modally as well as spatially distinct from each other.

Maximum compositional contrasts are shown by the CJ and Rin curves in Figure 10, which relate the megacrysts and groundmass of porphyritic aplitic rocks. The megacrysts consist of perthite and graphically intergrown quartz, and they contain more of the $KAlSi_3O_8$ component than any of the other analyzed materials. If viewed as products of segregation, they reflect major abstraction of $KAlSi_3O_8$ without any significant change in the ratio of $NaAlSi_3O_8$ to SiO_2 in the remainder of the system. It is interesting to note that the same general trend is shown by most of the other curves.

ORIGIN

Layering. The gross layering produced by multiple injection of magma to form tabular bodies of pegmatite and aplite generally can be identified with little difficulty. Apophyses and cross-cutting relationships confirm the age differences within such complexes, and individuality of the intrusives is variously revealed by screens of country rock, by well-defined partings between directly juxtaposed bodies, and by the continuity of lithologic units within the respective bodies. Most layers and lenses of aplite formed within pegmatite bodies, either by autoinjection or by injection from external sources, also are easily recognized through their contact relationships and the attitude of flowage structure within them. The remainder of the observed gross layering is attributable to masses of pegmatite and aplite that evidently were formed *in situ* and that appear to reflect processes of fractional crystallization and segregation that are discussed farther on.

Layering on much smaller scales distinguishes many aplites and some rather fine-grained pegmatites that have undergone flowage during their consolidation. Such flow structure generally appears as a streakiness resulting from thin, discontinuous, and faintly defined layers of slightly contrasting grain size. Some also differ slightly in composition. Many of the crystals in these layers are broken or granulated, and evidences of rolling and attenuation are fairly widespread. Flow layers in marginal parts of the rock masses commonly tail away from adjacent buttresses and projections of older rock in a manner indicating unidirectional movement.

Much less obvious is the origin of the mineralogic layering in the groundmass of porphyritic aplites and pegmatites and in the fine-grained parts of highly asymmetric pegmatite-aplite bodies. Formation of the layered sequences has been contrastingly ascribed, for example, to simple crystallization from a "hydrous magma" (Waring, 1905, p. 366); to rhythmic crystallization from pegmatitic liquids locally impoverished in volatile constituents (Jahns, 1955, p. 1103); to rhythmic primary crystallization, accompanied in some instances by streaming of liquid (Staatz and Trites, 1955, pp. 23–24; Thurston, 1955, pp. 30–31, 65); to rhythmic replacement in an early, probably primary aplite (Merriam, 1946, pp. 242–243); to later-stage replacement of pre-existing graphic granite by soda-rich solutions (Schaller, 1925, pp. 274–277); and to channel-controlled hydrothermal replacement of earlier pegmatite minerals (McLaughlin, 1940, pp. 62–63). Evidence for replacement of perthite by albite of the layered sequences is undeniable in many occurrences, as is evidence for replacement of the layered sequences by coarse-grained perthite; it seems appropriate, however, to regard these relationships as second-order features of not more than local significance, as the great bulk of the layered rock shows no evidence of having been formed at the expense of earlier solid material. Moreover, the widespread relationships between albite-rich layered rock and perthite megacrysts strongly indicate that these texturally and compositionally contrasting materials formed at essentially the same time.

If primary crystallization from a magma is accepted as the dominant process in development of the layered sequences, as argued by several investigators (*e.g.*, Orville, 1960, p. 1486; also see above), it remains to account for the origin of the remarkably uniform laminations. It is tempting to regard them as products of gravitational crystal settling. They show some of the characteristics of igneous cumulates described from numerous basic and ultrabasic complexes (*e.g.*, Wager, 1953; Wager *et al.*, 1960), and the garnet and tourmaline that distinguish so many of them are relatively heavy minerals. On the other hand, they do not exhibit the graded bedding, cut-and-fill structure, cross-bedding, and other sedimentational features that are common in igneous cumulates. Instead, some of their features are all but impossible to reconcile with a mechanism of crystal settling; these include veneers of garnet, tourmaline, and other minerals of the aplite layers attached to what must have been overhanging surfaces (Fig. 7C, F), as well as fringes of tourmaline prisms and muscovite plates oriented normal or nearly normal to the layering (Fig. 8).

Rhythmic primary crystallization, with development of successive laminations *in situ*, seems in best accord with all known features of the mineralogically layered rocks. Episodic development of crops of garnet, tourmaline, or muscovite crystals may well have resulted from alternating periods of undersaturation and supersaturation with respect to these minerals, perhaps in response only to a very slowly dropping temperature gradient, but perhaps also in response to slight fluctuations in confining pressure on a magma saturated with volatile constituents.

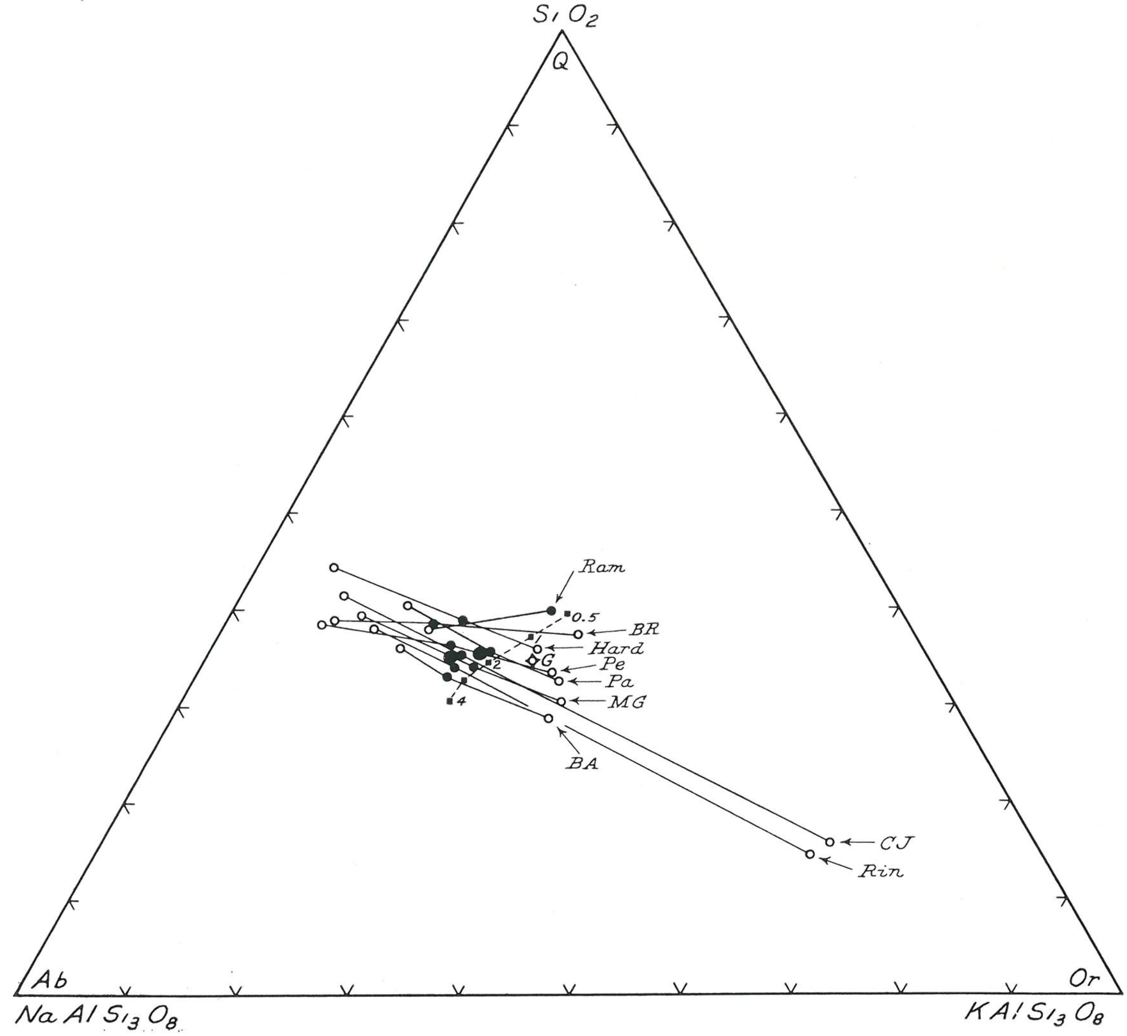

FIG. 10. Distribution of normative albite, orthoclase, and quartz in pegmatite-aplite intrusives, related to trend of the isobaric minimum (dashed line) in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O under water-vapor pressures ranging from 0.5 to 4 kilobars. G—normative plot for average of 571 analyzed granitic rocks (Tuttle and Bowen, 1958, pp. 75, 79). Other points as follows:

Curve	*Rock body*	*Point (with respect to curve)*	*Analyzed material*	*Method of analysis*	*Source of data*
BR	Layered member, Buell Ranch pegmatite complex, Keystone district, South Dakota	Left end	Aplitic footwall unit, locally layered	Chemical	Orville (1960)
		Right end	Porphyritic hanging-wall unit	Chemical	
		Interior	Total layered member	Chemical & modal	
CJ	Camp Judson pegmatite, Keystone district, South Dakota	Left end	Aplitic groundmass, layered	Chemical	Orville (1960)
		Right end	Average perthite megacryst	Chemical[1]	
		Interior	Total rock	Chemical & modal	
BA	Burnt Area pegmatite, Keystone district, South Dakota	Left end	Porphyritic footwall unit	Chemical & modal	Orville (1960)
		Right end	Porphyritic hanging wall unit	Chemical & modal	
		Interior	Total pegmatite	Chemical & modal	
Ram	Pegmatite dikes, Ramona district, California	Left end	Footwall aplite, layered	Chemical	Simpson (1960)
		Right end	Total pegmatite & aplite	Chemical & modal	

(Continued on facing page)

[1] Determinations of Na_2O and K_2O; Al_2O_3 and SiO_2 calculated on basis of assumption that only alkali feldspars and quartz are present in the mode.

Pegmatites and aplites. A very close genetic relationship between pegmatites and aplites has been advocated and documented by many investigators, from Andersen (1931) to Zavaritsky (1950), and views in this area have been summarized most recently by Schneiderhöhn (1961, pp. 493–503). Magmatic pegmatite and pegmatite-aplite bodies have been increasingly regarded as products of crystallization in closed or "restricted" systems, chiefly on the basis of structural, textural, compositional, and paragenetic relationships (for a summary of arguments, see Jahns, 1955, pp. 1058–1097), and most of the contrasting lithologic units within such bodies have been ascribed to fractional crystallization and crystal segregation. Aplites generally have been viewed as products of volatile-poor magmas that otherwise resembled pegmatite-forming magmas, but there has been much disagreement as to how these melts were formed, as to whether they incurred a loss of volatile constituents before or after emplacement, and as to whether they crystallized in open or closed systems (*c.f.* Andersen, 1931; Derry, 1931; Emmons, 1940). Increases in viscosity due to escape of volatiles have been most commonly referred to in explaining the grain size of aplites (*e.g.*, Vogt, 1923; Andersen, 1931).

The present writers regard all the aplitic rocks discussed in this paper as derivatives of magmas that were pegmatitic, *i.e.*, that contained substantial amounts of dissolved water or other volatile constituents. However, quite different processes are thought to account for two contrasting types among these aplites:

1. Normal aplites, with compositions near the "granite minimum," that occur as separate bodies containing little or no pegmatite and that also form distinct masses within some bodies of pegmatite.
2. Sodic aplites that form separate bodies containing abundant megacrysts or pegmatite and that also occur as segregated masses within many bodies of pegmatite.

Gradations between these types of aplite and among these modes of occurrence are common, and they probably reflect combinations of the processes outlined below.

It is suggested that the normal aplites were formed from magmas, including rest-magmas in pegmatite systems, that incurred substantial losses of dissolved volatiles through reduction in confining pressure. This is thought to have occurred either during or after emplacement, as argued by Emmons (1940, pp. 5–8). Prior to any loss of volatiles, the liquidus temperatures of such pegmatitic magmas would be relatively low, say in the range 600°–680° C., at moderate to high confining pressures. If a magma in this temperature range were to lose volatiles through a drop in confining pressure, its liquidus temperature

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Curve	*Rock body*	*Point (with respect to curve)*	*Analyzed material*	*Method of analysis*	*Source of data*
Hard	Main Harding dike, Taos County, New Mexico	Left end	Footwall aplite	Chemical	This paper
		Right end	Pegmatite, remainder of dike	Chemical	
		Interior	Total rock in dike	Chemical & modal	
Pe	White dike, Petaca district, New Mexico	Left end	Fine-grained pegmatite, keel of dike	Chemical	This paper
		Right end	Pegmatite, remainder of dike	Chemical & modal	
		Interior	Total rock in dike	Chemical & modal	
Pa	Katerina dike, Pala district, California	Left end	Footwall aplite, layered	Chemical	This paper
		Right end	Pegmatite, remainder of dike	Chemical	
		Interior	Total rock in dike	Chemical & modal	
		Interior (large dot slightly below curve)	Aplite in small central mass, slightly flow layered	Chemical	
MG	Himalaya dike, Mesa Grande district, California	Left end	Footwall aplite, layered (Fig. 4)	Chemical	This paper
		Right end	Pegmatite, remainder of dike	Chemical & modal	
		Interior	Total rock in dike	Chemical & modal	
		Interior (large dot)	Central aplite, faintly flow layered (Fig. 4)	Chemical	
Rin	Upper Mack dike, Rincon district, California	Left end	Aplitic groundmass, in part layered	Chemical	This paper
		Right end	Average perthite megacryst	Chemical[1]	
		Interior	Total rock in dike	Chemical & modal	

would rise in quick response and crystallization in flood necessarily would follow, regardless of any change in viscosity. The aplite thus formed would be a quenched rock, but in this instance the result of a "pressure quench."

The sodic aplites, together with their complementary pegmatites or perthite megacrysts, constitute bodies whose bulk composition trends toward correspondence with the thermal valley of petrogeny's residua system. These rocks evidently were developed by processes of segregation, and their genesis can be explained in terms of the model proposed by Jahns and Burnham (1963) for the crystallization of granitic pegmatites. According to this model, segregation of major alkalies can occur in significant degree if a pegmatitic magma becomes saturated with volatile constituents, *i.e.*, if both silicate melt and vapor are present in the system. Experimental evidence indicates that potassium is extracted from the liquid by a vapor in preference to to sodium, and that potassium and other constituents can travel rapidly through the vapor in response to a temperature gradient. If the composition of the magma were at or near the thermal minimum for the confining pressure imposed upon it, preferential loss of the potassium feldspar component would promote crystallization of albite-rich rock from the melt, probably in the form of an aplite. Potash feldspar could crystallize from the vapor, either in the immediate vicinity or elsewhere in the system.

Experimental studies have shown that in general, the phases crystallized from the vapor are much coarser than those crystallized directly from the melt, and that the degree of segregation of alkali feldspars and other minerals is in part a function of gravitational rising of the vapor phase within the system. It seems probable that variations in distribution of the two fluid phases within a given intrusive, in distribution of alkalies between them, and in rates of diffusion of alkalies through the vapor could well account for the known relationships between the complementary pegmatitic and aplitic rocks that have been described.

Relations with granites. Pegmatites and aplites are found almost exclusively in the subsolvus granites. The subsolvus granites indicate a hydrous environment (Tuttle and Bowen, 1958, p. 139), and it is not surprising to find that the pegmatites are characteristically associated with them. On the other hand, the hypersolvus granites carry little, if any, pegmatitic and aplitic material. Pegmatites have been described in association with granites which are hypersolvus, but they are usually present in very small amounts.

Laboratory studies (Tuttle and Bowen, 1958, p. 74) have shown that granites crystallized at low water vapor pressure will carry a single alkali feldspar and quartz as the principal constituents (in nature, the alkali feldspar unmixes to perthite giving a perthite-quartz, hypersolvus, granite). If the confining pressure and the water content are high, two feldspars will crystallize side by side giving a subsolvus granite. In other words, water dissolves in the melt at high pressure and lowers the liquidus below the feldspar solvus, thereby permitting two feldspars, a plagioclase and potash feldspar, to crystallize together under equilibrium conditions. Normally, the potash feldspar contains appreciable soda feldspar in solid solution at the temperature of final magmatic crystallization, and it is necessary to unmix large quantities of soda feldspar to obtain a relatively pure potash feldspar which is characteristic of the subsolvus granites. This is accomplished by the vapor phase, which is a potent flux at the high pressures. These subsolvus granites and gneisses, commonly carrying a potash feldspar which contains less than 10 per cent albite, are the home of pegmatites and aplites. It is these granites that generate relatively large quantities of pegmatite and aplite material.

In contrast, the hypersolvus granites commonly contain no pegmatitic and aplitic material at all, and if present, it is usually in vanishingly small amounts. Warren and Palache wrote (1911, p. 126) "Pegmatite development, so common in many granites, were almost unknown in the Quincy granites until some few years ago, a pegmatite was discovered in one of the quarries and later two other pegmatites were exposed in another quarry." A careful search of twelve quarries during the present study did not turn up a single pegmatite or aplite. Where present, the pegmatites of the hypersolvus granites are themselves hypersolvus, indicating high temperatures of crystallization and presumably low initial contents of water in the magmas. Furthermore, the small amounts of water vapor present during the end stages of magmatic crystallization probably escaped before cooling to the temperatures of the solvus, because the perthite has not been recrystallized to separate grains of plagioclase and microcline. No examples of hypersolvus aplites have been found.

There are all gradations between these two extreme granite types, and it is suggested that the amount of pegmatitic material and the type of granite will depend to a large extent on the water content of the magma. The hypersolvus granites represent magmas initially low in water or magmas that lost much of their water before consolidation as a result of near-surface crystallization where the overburden is not great enough to permit large amounts of water to remain in solution. The subsolvus granites, on the other hand, may carry large amounts of pegmatitic and aplitic material or none at all, depending on the cooling history of the intrusive.

Role of water vapor. Water vapor is essential for the formation of granite pegmatites and aplites, and perhaps the most important function is to provide a low-viscosity fluid for the growth of large crystals. It is also important in lowering the liquidus temperature of the magma, thereby permitting two alkali feldspars to crystallize side by side. Liquidus lowering also permits certain hydrous phases which are unknown as phenocrysts of rhyolites (such as muscovite) to appear at liquidus temperatures. Water vapor serves to recrystallize early-formed minerals and act as an agent for metasomatic reactions. An essential function of water vapor in the genesis of aplites is to provide a mechanism for quenching by relief of pressure. This is probably the only way that rapid quenching can be induced in deepseated rocks.

Thus we have four important functions of the water vapor in the genesis of pegmatites and aplites: 1) lowering of the liquidus temperature by solution in the liquid, 2) providing a low viscosity medium for transport of material, 3) promoting recrystallization and metasomatic replacement of early-formed crystals, and 4) affording a mechanism for quenching by relief of pressure.

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