5. PEGMATITES OF SOUTHERN CALIFORNIA*

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INTRODUCTION

For many years the southern California region has attracted the attention of geologists interested in pegmatites and pegmatite deposits, largely because of the well-known gem and lithium occurrences in San Diego and Riverside Counties. These world-famous pegmatites have been so often noted or described in the literature that they commonly are regarded as typical of the pegmatites in the region, even though this actually is far from the case. More than 90 percent of all published contributions on California pegmatites deal with the gem-bearing dikes of San Diego County alone!

It is the main purpose of this brief paper to summarize the distribution, occurrence, composition, and structure of all the known pegmatites in southern California, and to discuss several aspects of their geologic and economic significance. Much of the information has been obtained from the published record, a sampling of which is included in the list of references at the end of the paper. In larger part, however, the writer has found it necessary to draw from the results of his own observations, many of which were made in reconnaissance and hence are not wholly satisfactory as a background for generalizations. This qualification with respect to basic data plainly underlies the summary and discussions that follow.

The pegmatites of southern California can be divided into three major categories in terms of their general form and mode of occurrence:

1. Very small stringers, lenses, and pods of gabbroic and, in a few areas, more granitic composition, that generally appear to have been formed as segregations within masses of genetically related igneous rock.
2. Small, irregular masses, of tonalitic to granitic composition, that form layers, lenses, pods, branching swarms, and stockworks in *lit-par-lit* gneisses and other hybrid rocks, as well as in contact zones between masses of igneous rocks and older rocks that flank or surround them.
3. Small to very large individual masses, of tabular to pod-like form and tonalitic to granitic composition, that ordinarily occur in igneous and metamorphic rocks.

For the sake of brevity, the pegmatites of these three categories are hereinafter referred to as segregation masses, complexes, and discrete pegmatite bodies, respectively. These terms are of necessity much generalized, as each category includes pegmatite bodies of various forms. Further, the terms are intended to be mainly descriptive, and hence to involve a minimum of genetic implication. As might be expected, nearly all gradations can be observed among these three major types of pegmatites.

The distribution and occurence of pegmatites in southern California are summarized in table 1. Those masses that form the complexes are both widespread and locally abundant. They constitute by far the largest part of the pegmatite material in the region, but they have received little detailed attention from petrologists and other investigators. The segregation masses are considerably less abundant, although they are more widespread than published accounts of southern California geology might suggest.

By far the best known pegmatite bodies in the region represent the third category, which includes most of those with complex composition and spectacular mineralogy, and all of those that have yielded commercial quantities of economically desirable minerals. Some of the discrete bodies are very large, and many are structurally complex. These and other features of unusual interest are reflected in the attention given to the pegmatites of this category in the discussions that follow.

SEGREGATION MASSES OF PEGMATITE

Pegmatite masses of the segregation type are locally abundant in the Peninsular Range province (fig. 1), where they occur mainly in gabbroic rocks of the southern California batholith. They also are present in the western San Gabriel Mountains, in a few other, much smaller areas in the Transverse Range province, and in parts of the southern Sierra Nevada. Several scattered occurrences are known from the Mojave Desert and Basin-Range regions.

All of these pegmatites occur in igneous rocks to which they appear to be closely related in composition, age, and genesis. They appear as stringers (fig. 2), dikes, and pod-like masses (fig. 3) that are simple to highly complex in form. They rarely are more than 15 feet long, and most are less than 5 feet in maximum dimension. Contacts with the host rock are sharp to gradational, and the most blended contacts are typical of the most irregular masses of pegmatite.

Most of the segregation pegmatites are gabbroic in composition, and consist chiefly of hornblende and calcic to intermediate plagioclase in various proportions. Other mineral constituents include biotite, pyroxenes, apatite, magnetite, chlorite, epidote, and, rarely, quartz and alkali feldspars. Segregation masses of more granitic composition also have been observed, mainly in coarse-grained, felsic intrusives in parts of the Sierra Nevada and several mountain ranges of the eastern Mojave Desert. These pegmatites consist chiefly of perthite, quartz, and sodic plagioclase, with or without subordinate

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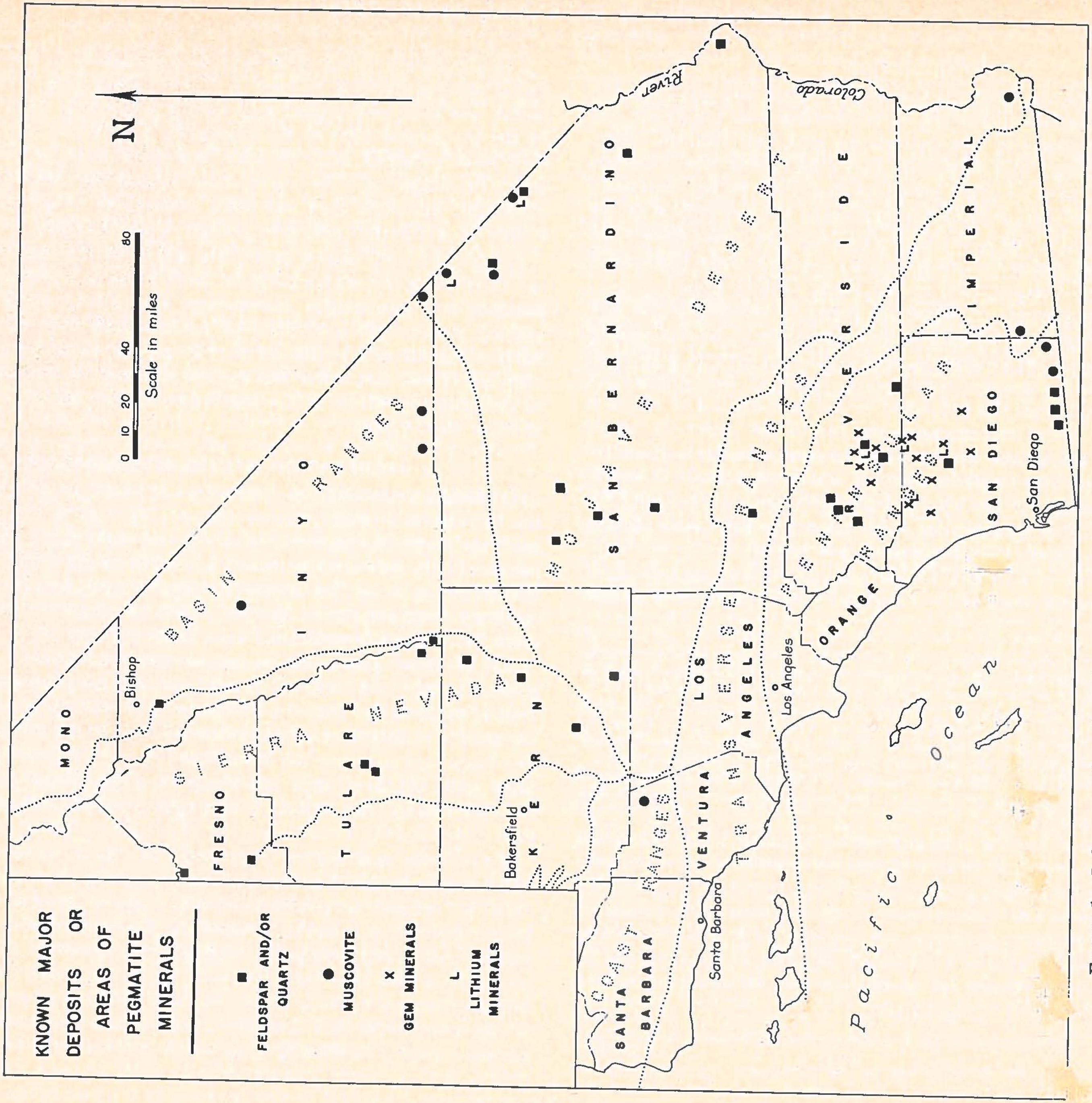

FIGURE 1. Index map of southern California, showing natural provinces and major pegmatite areas.

Table 1. Distribution and occurrence of pegmatites in southern California.

Province	General nature of pegmatite bodies	General composition of pegmatite bodies	Age of pegmatite	General abundance of pegmatite bodies
Sierra Nevada	Small to large dikes, sills, and pod-like masses	Tonalitic to granitic	Jurassic?	Sparse; abundant in only a few areas
	Very small stringers and pod-like masses in igneous rocks	Gabbroic	Jurassic?	Rare
	Numerous small, irregular masses in *lit-par-lit* gneisses and other hybrid rocks	Tonalitic to granitic	Jurassic?	Abundant
Basin Ranges	Small to large dikes, sills, and pod-like masses	Mainly granitic	Pre-Cambrian	Sparse to locally abundant
	Small to moderately large dikes and pod-like masses	Mainly monzonitic to granitic	Mesozoic	Sparse to very rare
	Numerous small, irregular masses in *lit-par-lit* gneisses and other hybrid rocks	Tonalitic to granitic	Mainly pre-Cambrian	Sparse; abundant in only a few areas
Mojave Desert	Small to large dikes, sills, and pod-like masses	Mainly granitic*	Pre-Cambrian	Sparse to locally abundant
	Small to moderately large dikes and pod-like masses	Mainly monzonitic to granitic	Mesozoic	Sparse to very rare
	Numerous small, irregular segregations in igneous rocks	Mainly granitic; some gabbroic	Pre-Cambrian and Mesozoic	Abundant in a few areas; very rare elsewhere
	Numerous small, irregular masses in *lit-par-lit* gneisses and other hybrid rocks	Tonalitic to granitic	Mainly pre-Cambrian	Sparse; abundant in only a few cases
Transverse Ranges	Small dikes, sills, and pod-like masses	Tonalitic to granitic	Cretaceous or older	Sparse to moderately abundant
	Very small stringers and pod-like masses	Dioritic to gabbroic	Cretaceous or older	Abundant in a few areas; absent elsewhere
	Numerous small, irregular masses in *lit-par-lit* gneisses and other hybrid rocks	Dioritic to granitic	Cretaceous or older	Rare to locally abundant

Table 1. Distribution and occurrence of pegmatites in southern California—Continued.

Province	General nature of pegmatite bodies	General composition of pegmatite bodies	Age of pegmatite	General abundance of pegmatite bodies
Peninsular Ranges	Relatively continuous dikes and elongate pod-like masses	Mainly granitic†	Cretaceous	Very abundant as swarms in many well-defined areas; sparse elsewhere
	Small to moderately large dikes and pod-like masses	Tonalitic to quartz-monzonitic	Cretaceous and older	Sparse to very abundant
	Very small stringers and pod-like masses	Dioritic to gabbroic	Cretaceous	Locally abundant; absent elsewhere
	Numerous small, irregular masses, swarms, and stockworks in igneous, metamorphic, and hybrid rocks	Tonalitic to granitic	Cretaceous and older	Rare to locally abundant

* Includes a few bodies of lithium-bearing pegmatite.
† Includes numerous bodies of lithium-bearing pegmatite.

muscovite and biotite. Some of the potash feldspar contains graphic intergrowths of quartz. Minor amounts of garnet, tourmaline, magnetite, apatite, beryl, sphene, chlorite, epidote, and calcite are present locally.

The major minerals generally form anhedral to subhedral crystals that are ½ inch to 6 inches in maximum dimension. Most of the gabbroic pegmatites are uniform aggregates of such crystals, but in others the minerals show a distinct zonal distribution with respect to the walls of the containing body. This is in every way similar to the zoning described for granitic pegmatites by Cameron, et al. (1949). In general the pyroxene is near the walls, the hornblende is nearer the central part of the body, and the plagioclase is more widely distributed (fig. 3). Quartz and alkali feldspars, where present, are centrally disposed.

A similar zonal structure appears in most of the less basic segregation masses, and typical wall-to-center sequences include oligoclase—perthite—quartz, graphic granite—perthite—quartz (fig. 4), and oligoclase—graphic granite—perthite—muscovite and sodic albite—quartz.

Many of the segregation masses appear to have been formed in place, and they probably represent local concentrations of mineralizer-rich fluids that were developed during the end stages of crystallization of the enclosing igneous rock. Others evidently were injected

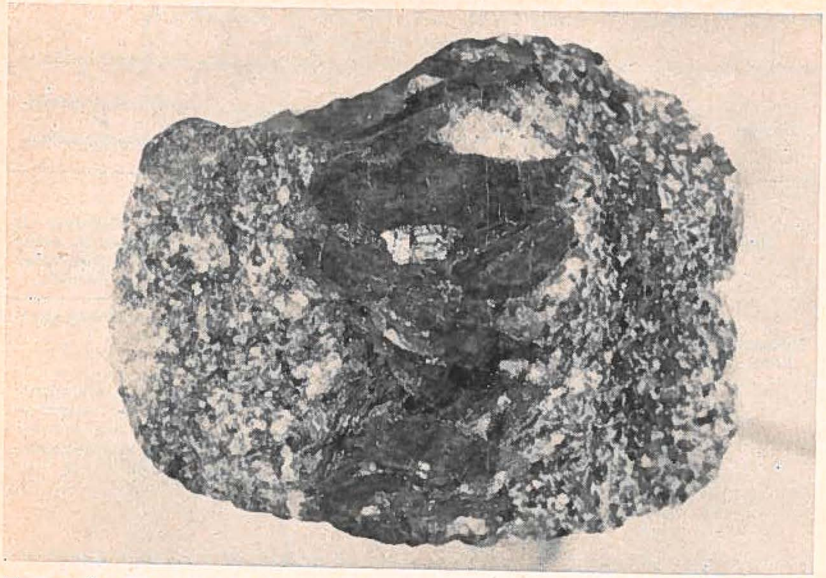

FIGURE 2. Three-inch stringer of hornblende-rich pegmatite in medium-grained gabbro, western San Gabriel Mountains.

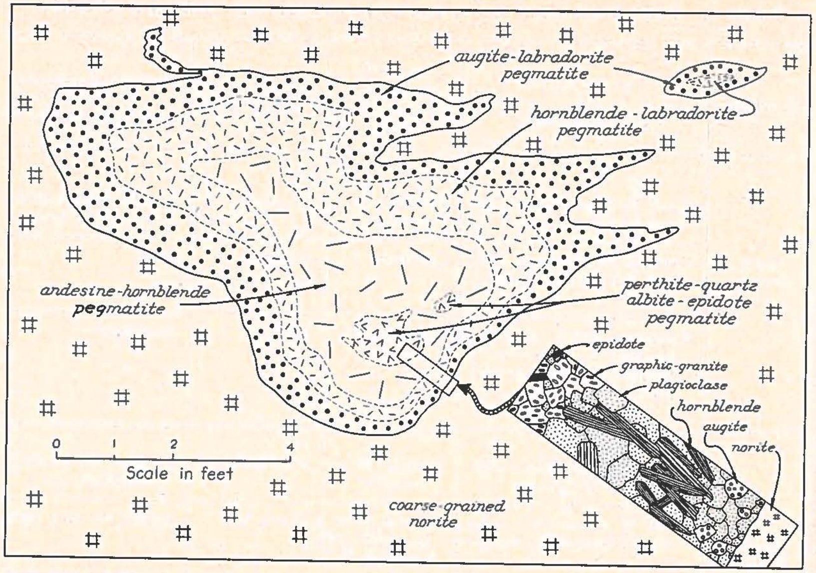

FIGURE 3. Pod-like mass of gabbroic pegmatite in coarse-grained norite, western San Gabriel Mountains.

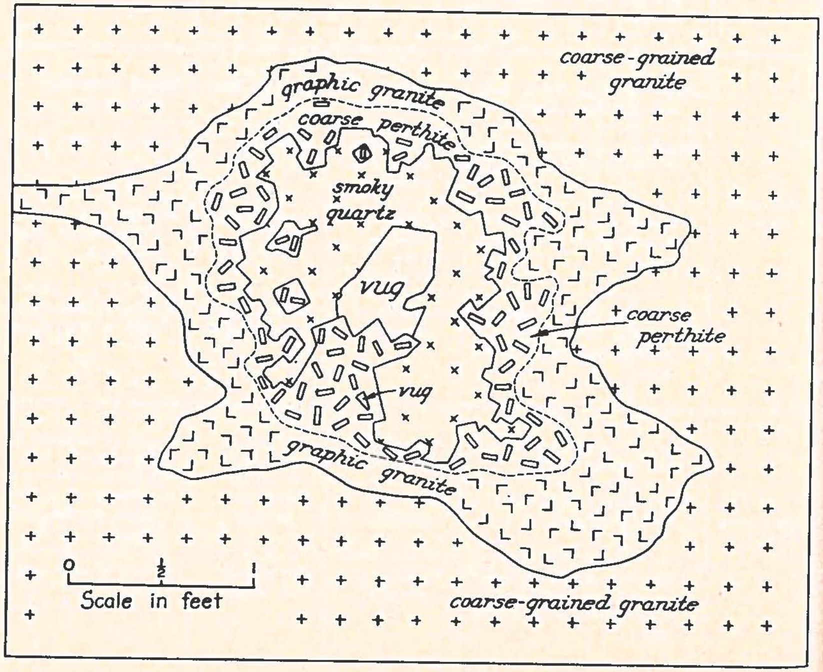

FIGURE 4. Pod-like mass of granitic pegmatite in coarse-grained granite, Whipple Mountains.

into solid or nearly solid rock, and perhaps were derived from pockets of fluid that had formed elsewhere in the crystallizing intrusive mass. A variety of these auto-injection features has been described by F. S. Miller (1938, pp. 1220-1222, 1230) from gabbroic rocks of the Peninsular Range province. In no occurrences do the pegmatitic fluids appear to have moved for great distances from their sources.

In the gabbroic complex of the western San Gabriel Mountains, both anorthosite and norite are extremely coarse grained (see Higgs, Contribution 8, this chapter), and hence might be regarded as special varieties of pegmatite. These rocks form gigantic segregation masses, but no complete gradations in size are known between these masses and the small ones described above.

Most of the segregation masses of pegmatite in southern California appear to be genetic associates of Mesozoic igneous rocks, especially in the western parts of the region. Farther east, in the Mojave Desert and Basin-Range provinces, many of the pegmatite-bearing intrusives are pre-Cambrian in age.

PEGMATITE COMPLEXES AND HYBRID ROCKS

Pegmatite complexes, consisting in general of numerous small, irregular masses (fig. 5), are significant parts of the older crystalline rocks that form the so-called "basement complex" of many areas in southern California. They occur, for example, in the pre-

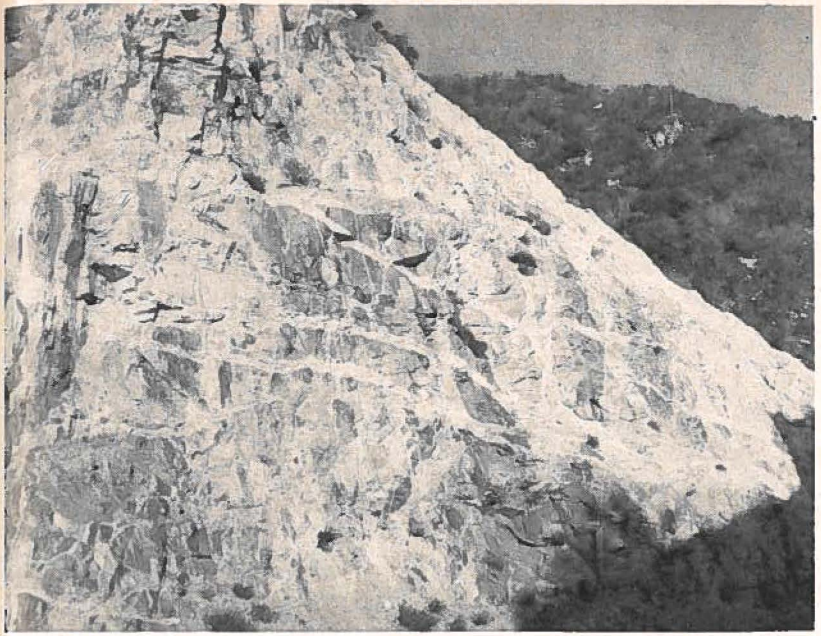

FIGURE 5. Typical complex of granodiorite pegmatite in hybrid gneiss, western San Gabriel Mountains.

batholithic rocks of the Peninsular Ranges and the Sierra Nevada, in the metamorphic rocks of the San Gabriel and San Bernardino Mountains, and in the early pre-Cambrian rocks of several desert ranges in the southeastern part of the State. In addition, they appear as parts of hybrid rocks and pegmatitized zones at and near the margins of many bodies of intrusive rocks. These contact complexes are chiefly of Mesozoic age in southwestern California, but both pre-Cambrian and Mesozoic ages are represented in areas farther east and northeast.

Though mentioned repeatedly in descriptions of crystalline rocks in southern California (for example, W. J. Miller, 1946), the pegmatite complexes have not been described in detail. They generally are referred to as groups of subparallel, anastomosing, or scattered small pegmatites, and all too often are dismissed as complicating elements in rocks that already seem too complex for interpretation by ordinary methods of study. The few detailed observations thus far made suggest that different pegmatites in some of these complexes were injected into, or were formed within, the host rocks at different times, and that the age differences commonly are reflected by differences in composition (fig. 6). The pegmatites also show significant relations to episodes of deformation, recrystallization, and reconstitution of the host rock, and further detailed study of such occurrences might well provide valuable information concerning the development of the rock as a whole.

Most of the pegmatite complexes are mineralogically simple, and consist of quartz, plagioclase, and potash feldspar, with or without micas and accessory constituents. In gross composition they range from tonalitic to granitic, and most are in the general granodioritic field. Many individual pegmatites in the complexes appear to be internally homogeneous, whereas others, especially the largest and most bulbous ones, show well-developed zonal structure like that described for the discrete pegmatites farther on.

Many of the pegmatite complexes are demonstrably intrusive into the containing rocks, whereas others just as clearly were developed in place by replacement of the host rock. Most appear to have been formed by some combination of the two general processes, but the quantitative relations are not easily determined, especially where the pegmatites form parts of lit-par-lit gneisses and other hybrid rocks. Further, it is evident that various complexes differ from one another in age, in conditions of emplacement, and in source of the pegmatite material. Much more study is needed before the problems can be properly defined, let alone solved!

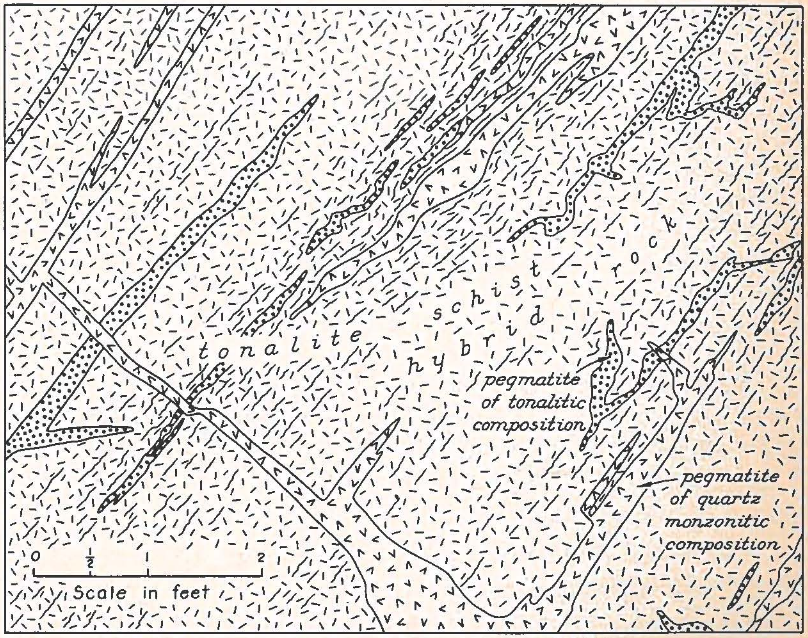

FIGURE 6. Pegmatite complex in tonalite-schist hybrid rock, near Escondido. Pegmatites of two different ages are represented.

DISCRETE PEGMATITE BODIES

Distribution and Occurrence. The discrete pegmatite bodies in southern California appear as dikes, sills, lenses, and masses of bulbous or highly irregular form. They are widely distributed in the Sierra Nevada, in the Basin-Range province to the east, in the Mojave Desert region, and in the Transverse Ranges and Peninsular Ranges in the southwestern part of the State (fig. 1).

As noted in table 1, these individual masses are particularly abundant in the Peninsular Range province, where most of them are genetically related to rocks of the great composite batholith of southern California (see Larsen, Contribution 3, this chapter). Pegmatites of tonalitic, granodioritic, and quartz-monzonitic composition are closely associated with stocks and other large plutons of similar respective compositions, and also appear in septa, screens, and larger masses of pre-batholithic metamorphic rocks. Somewhat younger pegmatites of granitic composition also are genetically related to the batholith, and occur mainly as subparallel dikes in certain of the gabbroic and tonalitic plutons. These include numerous gem- and lithium-bearing dikes. A few other pegmatites, mostly of granodioritic and quartz monzonitic composition, appear to antedate rocks of the batholith.

On the basis of their geologic relations, the pegmatites of the southern California batholith probably are middle or late Cretaceous in age (Jahns and Wright, 1951, pp. 18, 44). Isotopic analyses of lepidolite from the Stewart dike, at Pala, suggest ages ranging from about 110 million years (Ahrens, 1949, p. 250) to 147 ± 5 million years (Davis and Aldrich, 1953, p. 380), which would indicate a range from middle Cretaceous to middle Jurassic. An age of 100 million years, based on analyses of clean zircon concentrates, has been calculated for a tonalite (Larsen, et al., 1952) that represents the batholith. This tonalite is older than most of the pegmatites.

Individual masses of pegmatite also are abundant in parts of the southern Sierra Nevada, where they appear in plutons of the Sierra Nevada batholith and in older masses of schist, quartzite, and other metamorphic rocks. The batholith rocks are commonly regarded as Jurassic in age, and these pegmatites are therefore tentatively assigned to this period (see table 1).

Dikes, sills, and other bodies of pegmatite also are present in the Transverse Ranges, and are locally abundant in the San Gabriel, San Bernardino, and Little San Bernardino Mountains. Few of them are as large as many of the pegmatites in the region to the south and east, but they show the same general ranges in composition. Some of them may be as young as Cretaceous, but it is quite possible that many of them are Jurassic or older.

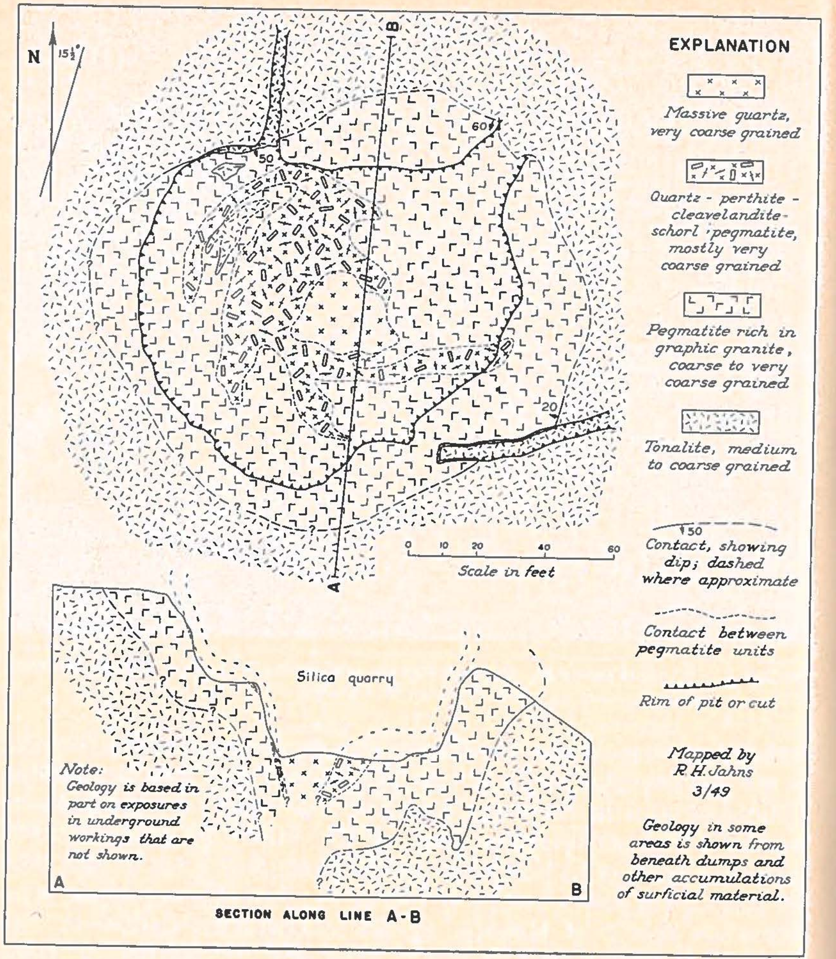

FIGURE 7. Geologic sketch map and cross section of the Southern Pacific pegmatite, near Nuevo in western Riverside County.

Although crystalline rocks are well represented in the Basin-Range and Mojave Desert provinces of southeastern California, remarkably few pegmatites are present in these large areas (fig. 1). Scattered occurrences are known from the Inyo Mountains, the Panamint Range, the Amargosa Range, the New York Mountains, the Whipple Mountains, the Granite Mountains, and many other ranges and buttes in the region, but still other broad terranes of igneous and metamorphic rocks appear to be virtually barren of pegmatites. Among the bodies of pegmatite that have been observed, many are probably of Mesozoic age, especially in the western parts of the

FIGURE 8. Aerial view north-northwest over a part of the Pala district, San Diego County. Subparallel dikes of gem-bearing pegmatite form rib-like outcrops on Hiriart Mountain, in foreground, and on Little Chief Mountain, immediately beyond wash in foreground at left. Gem mines in the view include the Katerina (K), Vanderburg (V), El Molino (EM), Fargo (F), and Pala Chief (PC). Elsinore fault zone at upper right. *Pacific Air Industries photo.*

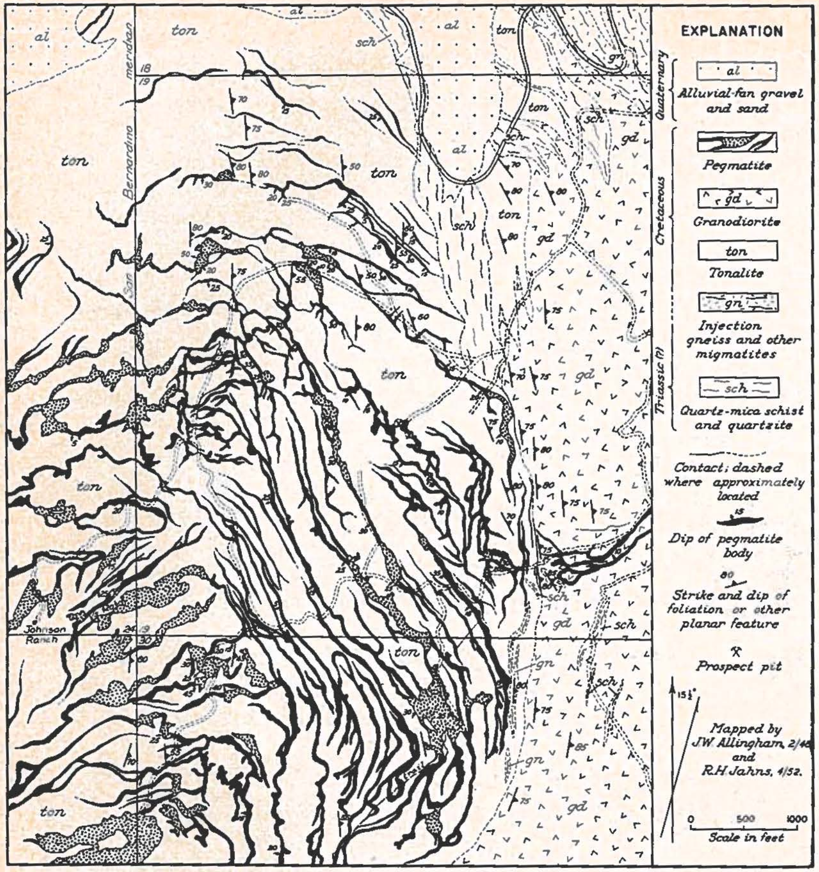

FIGURE 9. Swarm of pegmatite dikes on Rincon Mountain, San Diego County.

region. Most of the remainder are pre-Cambrian in age, and some of those in the extreme northeastern part of San Bernardino County and the southeastern part of Inyo County may represent the northwestern edge of the so-called Arizona pegmatite belt, which embraces a large number of pre-Cambrian pegmatites in west-central Arizona.

Structural Features. The discrete pegmatites in southern California are highly variable in general form, attitude, and size, and do not differ markedly in these features from pegmatite bodies in many other parts of the world. Most are a few feet to about 500 feet in maximum dimension, and are moderately thick with respect to their length and width (fig. 7). Discordant bodies are predominant, and even the few that are concordant transect the country-rock structure in detail. The pegmatite-wallrock contacts generally are sharp, but in several occurrences they are gradational over distances of a few inches.

Noteworthy exceptions to some of the above generalizations are provided by most of the granitic pegmatites of the Peninsular Range province, and by a few of those in the southern Sierra Nevada. These are dikes with unusually large along-strike and down-dip dimensions relative to their thickness. They range in length from a few feet to nearly a mile, and are slightly less than 10 feet in average thickness. In most districts they are very uniform in attitude, and have moderate to gentle dips. They commonly appear as swarms, in which the individual dikes are essentially parallel to one another but tend to branch and join in detail (figs. 8, 9).

These thin and remarkably continuous dikes evidently were emplaced along subparallel fractures that are best developed in plutons of gabbroic and tonalitic rocks. The fractures are independent of schistosity, foliation, lineation, and primary flow layering in these rocks, and are not related systematically to the walls of individual plutons. They are thought to have been formed as tensional features during the end stages of cooling in the southern California and Sierra Nevada batholiths (Jahns and Wright, 1951, p. 18).

Many of the discrete pegmatites, regardless of their general form, appear to be essentially homogeneous internally, in that they are simple aggregates of quartz and feldspars, with or without micas and accessory minerals. Many others, in contrast, show a systematic internal arrangement of their constituent minerals, which ordinarily appears as a well-defined zonal structure (Cameron, et al., 1949; Jahns and Wright, 1951; Hanley, 1951). The pattern of zoning is remarkably consistent from one pegmatite body to another, and even from one pegmatite district to another. Each zone, which can be distinguished from the immediately adjacent zone on the basis of differences in mineralogy or texture, reflects to some degree the shape and size of the containing pegmatite body. The zonal structure in some pegmatite bodies is complicated by younger fracture fillings and replacement masses of closely related pegmatite, and locally by younger pegmatite dikes and sills that commonly are also zoned (fig. 10).

Composition and Texture. The gross composition of the discrete pegmatites in southern California ranges from tonalitic to granitic. Gabbroic pegmatites are by no means rare, but most of these seem best classified as segregation masses.

Quartz, perthite (generally microcline with lenticular lamellae of albite), and sodic plagioclase are the dominant minerals, and commonly are accompanied by muscovite, biotite, apatite, beryl, garnet, sulfide minerals, and tourmaline, either singly or in some combination. Rarer accessory constituents include bismuth minerals, cas-

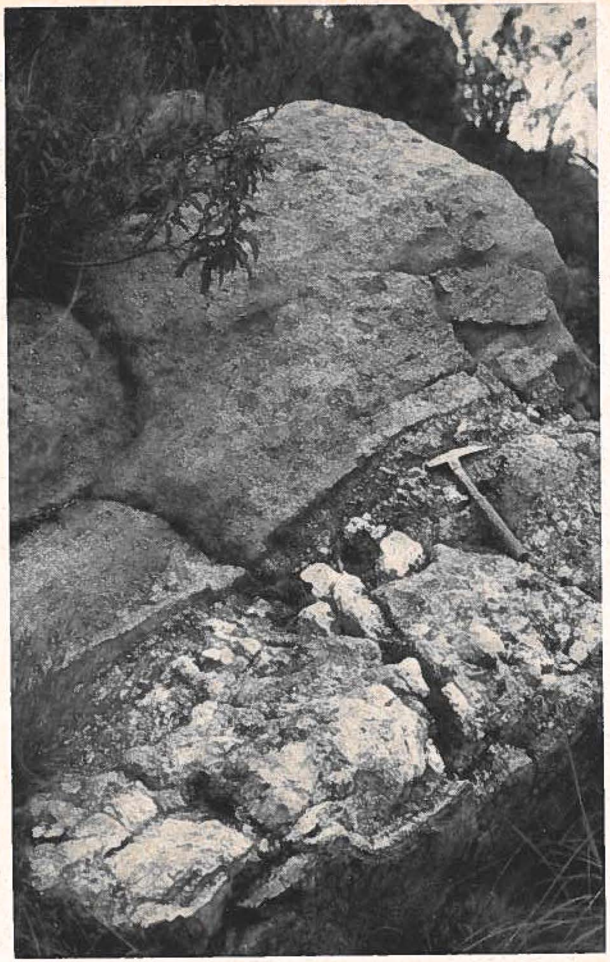

FIGURE 10. Composite pegmatite mass, Pala district, San Diego County. Three-foot sill of coarse-grained pegmatite is flanked by older, much finer-grained pegmatite. Note the sharp contact above hammer head. The margins of the sill are fine-grained quartz-albite-perthite pegmatite with muscovite, garnet, and schorl, and the inner parts consist mainly of coarse-grained graphic granite and quartz.

siterite, columbite-tantalite, epidote, microlite, monazite, spinel, topaz, and triplite (Murdoch and Webb, 1948, 1952; Jahns and Wright, 1951). Zeolites and clay minerals are widespread, but rarely are abundant. Lithium minerals are locally abundant in granitic pegmatites of the Peninsular Range province, and are present in a few pegmatites in the eastern Mojave Desert region.

The pegmatites that show no pronounced zonal structure generally are medium to coarse grained, and contain no marked concentrations of the less common minerals. Minor amounts of apatite, beryl, garnet, and other accessory minerals are disseminated through some of these rocks.

The outer parts of the zoned pegmatites generally are granitoid in texture, and are fine- to coarse-grained aggregates of feldspars and quartz, with or without other minerals. The inner zones, in contrast, are essentially monomineralic or consist of two or more minerals in coarse- to giant-textured aggregates (figs. 10, 11). Some of the crystals are truly enormous, and have dimensions measured in feet or even in tens of feet.

Perthite, much of it graphically intergrown with quartz, is abundant near the walls of many pegmatites, but where both plagioclase and potash feldspar are present in a given body, the plagioclase ordinarily lies nearer the walls. A noteworthy exception is the cleavelandite variety of albite, which has a wider distribution and is a common constituent of fracture fillings and replacement bodies. Quartz and potash feldspar are the most abundant minerals of the inner zones (figs. 7, 10), and the quartz is accompanied by spodumene and lepidolite in most of the lithium-rich pegmatites.

FIGURE 11. Very coarse-grained perthite and quartz, with large prisms of schorl. Perthite crystals are fringed with aggregates of muscovite and albite. Stewart mine, San Diego County.

The distribution of the less abundant minerals is highly irregular in detail, but does follow broadly consistent patterns. A given mineral, for example, commonly is restricted to a zone or other lithologic unit that is quite distinct from adjacent units in the containing pegmatite body. Where the mineral occurs in more than one unit in the body, it generally shows consistent differences in composition and physical properties from one unit to the next. These features have been discussed in detail elsewhere (for example, Cameron, et al., 1949), and need no further review here.

Masses of fine-grained rock that is essentially quartz-albite-microcline aplite occur in some of the pegmatite bodies, and are by far most abundant in the dikes of granitic composition in the Peninsular Range province. They are most prominent in the footwall parts of these dikes, but also occur elsewhere. Some varieties of the aplite are distinctly layered, and the planar structure is accentuated in many occurrences by thin, subparallel layers that are rich in tiny crystals of garnet and/or schorl. This variety of aplite is known in several districts as "line rock" (fig. 12).

Origin. The discrete pegmatites appear to have been formed by injection of liquid material along fractures or other planes of weakness in the host rocks, in some occurrences accompanied by minor digestion of the older rocks. This is in sharp contrast to many of the pegmatite complexes already described, in which much of the pegmatite clearly was developed by replacement of the older rock. The intrusive origin of the discrete pegmatites is evidenced mainly by combinations of the following features:

1. The borders of most masses are sharp, and commonly can be traced across contacts between different types of country rock without change in attitude.
2. The pegmatite bodies themselves show no changes in composition or internal structure that can be correlated with differences in country-rock lithology, nor does the internal structure of these bodies reflect the detailed structure of the country rock.
3. Schist and other thinly foliated types of country rock commonly are crumpled or otherwise disturbed immediately adjacent to many pegmatite contacts.
4. The structure, mineralogy, and age relations of the units within the zoned pegmatites are not compatible with a process of development through replacement of country rock (Cameron, et al., 1949, pp. 97-106).

Following their emplacement, the discrete pegmatites appear to have crystallized from their walls inward, with much the same mineral sequence as in any ordinary plutonic or hypabyssal rock. The structure of the zoned pegmatites seems best attributed to fractional crystallization and incomplete reaction between successive crops of crystals and rest-liquid (Cameron, et al., 1949, pp. 97-106; Jahns, 1953, pp. 580-595), chiefly because of the remarkable consistencies in age relations and textural and compositional trends from one zone to another.

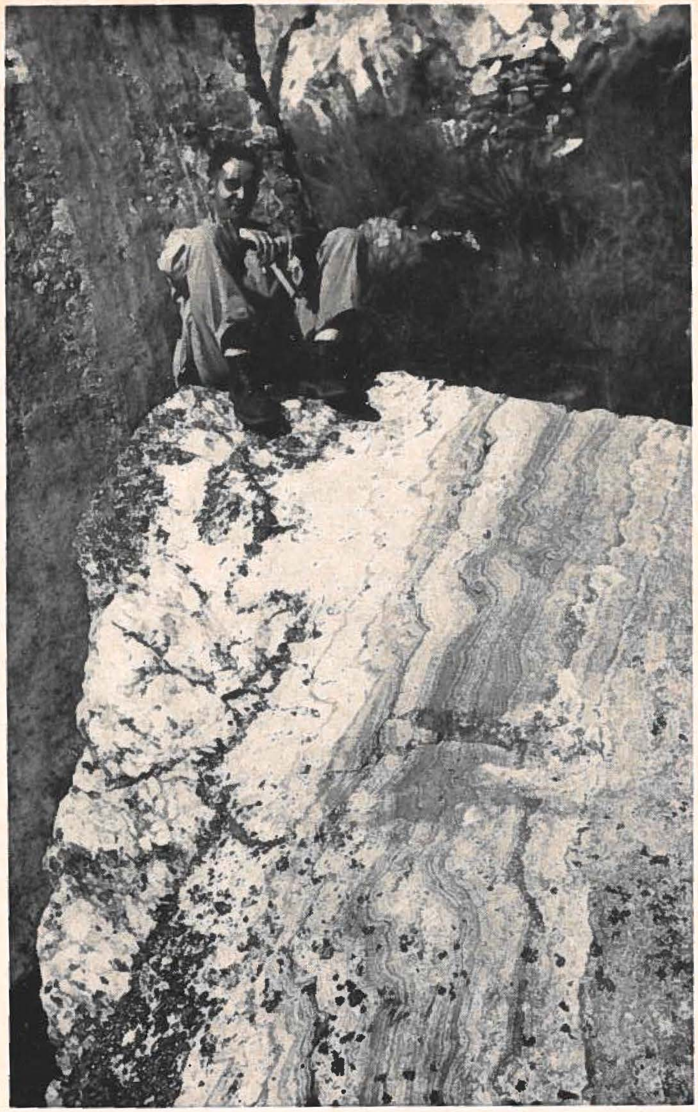

FIGURE 12. Sharply layered quartz-albite-garnet-microcline aplite (line rock) in contact with very coarse-grained quartz-rich pegmatite, near Pala, San Diego County.

Complications in the development of many of the pegmatites, especially during the end stages, are evidenced by widespread replacement features. In particular, much albite, muscovite, lepidolite, and quartz appears to have been formed in part by replacement of other pegmatite minerals, and evidences of corrosion and replacement are especially striking in the inner, pocket-bearing parts of many of the gem-bearing pegmatites. The total amount of replacement material rarely is large relative to the pegmatite body as a whole, but it may be moderately large in a few of the mineralogically complex bodies. Much of the replacement can be explained in terms of deuteric action during the intermediate and end stages of crystallization with a given mass of pegmatite.

The origin of the aplitic rocks within many of the pegmatite bodies is less clear. This fine-grained material has been variously interpreted as an early product of simple crystallization from a hydrous magma (Waring, 1905, p. 366), as an early, probably primary aplite, in some of which a rhythmic replacement yielded line rock and other layered varieties (Merriam, 1946, pp. 242-243), and as a much later result of replacement of pre-existing graphic granite by soda-rich solutions (Schaller, 1925, pp. 274-277). Evidence now at hand does not warrant a single definite conclusion, although it is clear that the aplitic rocks are integral parts of the pegmatite bodies in which they occur, and that some of these rocks show impressive evidence of mineral replacements.

GEOCHEMICAL FEATURES OF THE PEGMATITES

In general, the segregation pegmatites and the discrete pegmatites were formed from fluids that traveled varying distances from their sources, and can be regarded as late-stage products of magmatic differentiation. As such, they not only reflect the gross composition of larger igneous masses with which they are genetically associated, but also contain concentrations of rare elements that were present in the original magmas. Thus they provide samples of various magmas in the region—samples in which both major and minor constituents are relatively easy to recognize and study. Unfortunately, some of the pegmatite fluids seem to have moved such great distances from their sources that no genetically related rocks are exposed nearby. Certainly this appears to be the case with the granitic pegmatites of the Peninsular Range province.

Nearly all of the pegmatite bodies, including those of great mineralogic and structural complexity, are astonishingly similar to ordinary igneous rocks in gross composition. Even those with prominent masses of quartz rarely contain unusually high percentages of SiO_2, in terms of their entire bulk. Similarly, the percentages of alumina, lime, and the alkalies are in the normal ranges, and only iron is present in consistently low concentrations.

The minor constituents show some interesting trends. On the basis of mineralogic and chemical studies thus far made on the pegmatites of the Peninsular Range province, the magmas of the southern California batholith appear to have contained notable concentrations of boron, relative to magmas in other parts of the southwestern United States. Tourmaline is both widespread and abundant, and axinite is an accessory constituent of numerous pegmatites that are flanked or surrounded by limestone. Barium and strontium also are unusually abundant, and are concentrated mainly in the alkali feldspars. Lithium, phosphorous, and rare-earth elements are prominent minor constituents of many dikes, and thorium is well represented in several of them. Beryllium, bismuth, cesium, fluorine, manganese, columbium (niobium), rubidium, tantalum, titanium, and tin also are present, but not in unusual concentrations. Conspicuously rare are uranium, vanadium, and zirconium.

These observations are in good agreement with the results of trace-element studies that have been made on the various non-pegmatitic rocks of the batholith (see Larsen, Contribution 3, this chapter), except for the case of lithium, which has a low concentration in these rocks relative to the average igneous rock. Perhaps the concentrations of this element in the Peninsular Range pegmatites, relative to the average pegmatite, in part reflect the great difficulty with which it can be fixed in the earlier crystallizing minerals of the non-pegmatitic rocks, thus resulting in a high partition factor for lithium in favor of pegmatite fluids that separated from crystallizing masses of these rocks.

The trends in minor-element distribution are less well known for pegmatites in other parts of southern California, but a few generalizations can be made. Many of the Mesozoic pegmatites contain notable concentrations of boron, phosphorous, rare-earth elements, and titanium, and some of them are relatively rich in thorium-bearing minerals, as well. Although uranium-bearing minerals are known from a few of the pegmatites (for example, Hewett and Glass, 1953; Neuerburg, 1954), this element appears to be present in concentrations far below the average for pegmatites in general.

The pre-Cambrian pegmatites, and especially those in the eastern parts of the Basin-Range and Mojave Desert regions, evidently represent an entirely different geochemical province. They are relatively poor in boron, but are remarkably rich in fluorine. Many also contain moderate concentrations of rare-earth elements and tungsten.

The distribution of quantitatively minor elements within the southern California pegmatites is typical of that for pegmatites in general. Some of these elements form minerals of their own, and others appear as guests in minerals that generally were developed at a late stage during crystallization of the containing pegmatite body. Thus beryllium forms beryl, bavenite, bertrandite, gadolinite, phenakite, and helvite; bismuth occurs as a sulfide, oxide, vanadate, and in several carbonate minerals; tantalum and columbium (niobium) form tantalite-columbite, microlite, pyrochlore, hatchettolite, and several other complex minerals; and the rare-earths appear in

*Table 2. Occurrence of commercially desirable minerals in the pegmatites of southern California.**

Mineral or commodity	Province or region				
	Sierra Nevada	Basin Ranges	Mojave Desert	Transverse Ranges	Peninsular Ranges
Coarse potash feldspar	Common	Common	Common	Rare	Common
Mixed soda and potash feldspars, coarse†	Common	Common	Common	Sparse	Sparse
Sheet muscovite	Rare	Sparse	Very rare	Very rare	None known
Scrap muscovite	Rare	Common	Sparse	Rare	Sparse
Commercial quartz†	Common	Common	Common	Rare	Common
Commercial beryl	Sparse	Sparse	Rare	Very rare	Rare
Commercial spodumene	None known	None known	Very rare	None known	Sparse
Lepidolite	Very rare	Very rare	Very rare	None known	Common
Tantalum-columbium minerals	Very rare	Rare	Very rare	None known	Rare
Rare-earth minerals	Very rare	Rare	Sparse	Very rare	Sparse
Gem minerals	Very rare	Very rare	Very rare	None known	Common

* The terms used in this table apply to the individual pegmatite bodies within a given province or region; for an appraisal of the general abundance of each mineral or commodity within such a province or region, the terms should be combined with the data in the right-hand column of table 1. The terms are intended to have commercial application as follows:
Common—major or widespread constituent of several pegmatites, or lesser constituent of many; commercially significant.
Sparse—major or widespread constituent of only one or two pegmatites, or moderately abundant in a few, or a minor constituent of many; of limited commercial significance.
Rare—minor constituent of a few pegmatites; of little commercial significance.
Very rare—known constituent of one or more pegmatites, but of mineralogic interest only.
† Rarely or never marketed because of geographic occurrence and/or low commercial demand.

monazite, allanite, euxenite, gadolinite, pyrochlore, samarskite, and xenotime. Cesium forms very rare pollucite, and is present as a guest element in much of the beryl. Fluorine forms fluorite in many of the pegmatites, and also is a widespread minor constituent of apatite, topaz, amblygonite, micas, and other minerals. Rubidium is a guest constituent of lepidolite and potash feldspar, and both strontium and barium appear in the alkali feldspars. Boron is mainly an essential constituent of the tourmaline and axinite.

ECONOMIC FEATURES OF THE PEGMATITES

Commercial operations in the pegmatites of southern California have yielded substantial amounts of quartz, feldspars, mica, lithium minerals, gem minerals, and other commodities, the total value of which probably exceeds 4 million dollars. Slightly more than half of this value is represented by the output of gem materials, consisting mainly of tourmaline, spodumene, beryl, topaz, garnet, and quartz. The geographic occurrence of these and other commercially desirable minerals in southern California is indicated in table 2.

The gem-bearing pegmatites of the Peninsular Range province have been mined intermittently since about 1890, but much of the easily recoverable material appears to have been worked out. Additional masses of gem-bearing ground are present in several districts, and detailed geologic studies have disclosed numerous structural and mineralogic features that should aid further prospecting and exploration; nevertheless, new concentrations of gem minerals undoubtedly will be more difficult and expensive to find than those already known and worked.

Feldspar has been mined from at least 40 large bodies of pegmatite in the eastern and southern parts of the Peninsular Range province, and from a few scattered occurrences in the Mojave Desert and Basin-Range regions. Production has amounted to about 150,000 tons, nearly all of which has consisted of very coarse-grained potash feldspar obtained from the inner parts of zoned pegmatite bodies (figs. 7, 13). Additional reserves of high-grade material are present, but commercial operations have been seriously limited by the distances of most deposits from centers of demand, as well as by keen competition from talc and other minerals, especially in the ceramic industry.

Small tonnages of pegmatite quartz have been obtained, chiefly for special ceramic uses, from several deposits in the Peninsular Range, Sierra Nevada, Basin-Range, and Mojave Desert provinces. The quartz ordinarily mined is very coarse grained and relatively pure, and commonly is associated with coarse potash feldspar in the central parts of large pegmatite bodies (figs. 7, 13). Demands for this material rarely are large.

No deposits of sheet muscovite are known from most pegmatite areas in southern California, and only a few small lots of this material have been obtained from the deposits that are sparsely scattered through the southeastern part of the State, and through parts of the Sierra Nevada and Transverse Range provinces. Mining for scrap mica has been more widespread, especially in the southeastern part of the Peninsular Range province, but production never has been large.

The Stewart mine, in San Diego County, yielded large tonnages of lepidolite, as well as some amblygonite and spodumene, during the period 1895-1928, and at one time was the largest domestic producer of lithium minerals. The two main ore bodies have been worked out, but additional concentrations of lepidolite and spodumene may be present elsewhere in this large pegmatite body. Small quantities of lithium minerals are known to occur in several other pegmatites

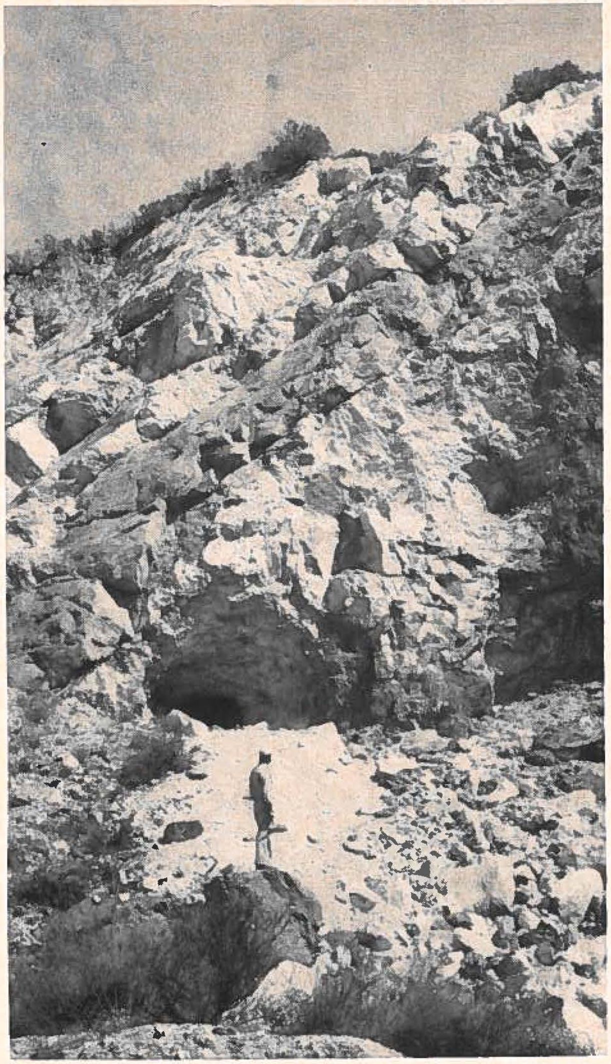

FIGURE 13. Very coarse-grained pegmatite, rich in quartz and perthite. Dark-colored rock is a septum of quartz-biotite schist. Houser Canyon feldspar quarry, San Diego County.

in the Peninsular Range province, as well as in the easternmost parts of the Mojave Desert and Basin-Range regions in the State.

The known pegmatitic occurrences of bismuth minerals, cassiterite, non-gem beryl, rare-earth minerals, tantalum-columbium minerals, and thorium minerals in southern California thus far have been of mineralogic interest only.

REFERENCES

Ahrens, Louis, 1949, Measuring geologic time by the strontium method: Geol. Soc. America Bull., vol. 60, pp. 217-266.

Cameron, E. N., Jahns, R. H., McNair, A. H., and Page, L. R., 1949, Internal structure of granitic pegmatites: Econ. Geology, Mon. 2, 115 pp.

Davis, G. L., and Aldrich, L. T., 1953, Determination of the age of lepidolites by the method of isotope dilution: Geol. Soc. America Bull., vol. 64, pp. 379-380.

Donnelly, M. G., 1936, Notes on the lithium pegmatites of Pala, California: Pacific Mineralogist, vol. 3, pp. 8-12.

Hanley, J. B., 1951, Economic geology of the Rincon pegmatites, San Diego County, California: California Div. Mines Special Rept. 7-B, 24 pp.

Hewett, D. F., and Glass, J. J., 1953, Two uranium-bearing pegmatite bodies in San Bernardino County, California: Am. Mineralogist, vol. 38, pp. 1040-1050.

Jahns, R. H., 1948, The gem deposits of southern California: Eng. and Sci. Monthly, vol. 11, no. 2, pp. 6-9.

Jahns, R. H., and Wright, L. A., 1951, Gem- and lithium-bearing pegmatites of the Pala district, San Diego County, California: California Div. Mines Special Rept. 7-A, 72 pp.

Jahns, R. H., 1953, The genesis of pegmatites. I. Occurrence and origin of giant crystals: Am. Mineralogist, vol. 38, pp. 563-598.

Kunz, G. F., 1903, On a new lilac colored spodumene, San Diego County, California: Science, new ser., vol. 18, p. 280.

Kunz, G. F., 1905, Gems, jewelers' materials, and ornamental stones of California: California Min. Bur. Bull. 37, 155 pp.

Larsen, E. S., Jr., 1948, Batholith and associated rocks of Corona, Elsinore, and San Luis Rey quadrangles, southern California: Geol. Soc. America Mem. 29, 182 pp.

Larsen, E. S., Jr., Keevil, N. B., and Harrison, H. C., 1952, Method for determining the age of igneous rocks using the accessory minerals: Geol. Soc. America Bull., vol. 63, pp. 1045-1052.

Macdonald, G. A., and Merriam, Richard, 1938, Andalusite in pegmatite from Fresno County, California: Am. Mineralogist, vol. 23, pp. 588-594.

Mackevett, E. M., 1951, Geology of the Jurupa Mountains, San Bernardino and Riverside Counties, California: California Div. Mines Special Rept. 5, 14 pp.

Merriam, Richard, 1946, Igneous and metamorphic rocks of the southwestern part of the Ramona quadrangle, San Diego County, California: Geol. Soc. America Bull., vol. 57, pp. 223-260.

Merrill, F. J. H., 1914, Mines and mineral resources of San Diego County, California: California Min. Bur. Rept. XIV, pp. 691-700, 706-708.

Miller, F. S., 1938, Hornblendes and primary structures of the San Marcos gabbro: Geol. Soc. America Bull., vol. 49, pp. 1213-1232.

Miller, W. J., 1946, Crystalline rocks of southern California: Geol. Soc. America Bull., vol. 57, pp. 457-542.

Murdoch, Joseph, 1936, Andalusite in pegmatite: Am. Mineralogist, vol. 21, pp. 68-69.

Murdoch, Joseph, and Webb, R. W., 1948, Minerals of California; 1952, Supplement: California Div. Mines Bull. 136 (and 1952 Supplement), 448 pp.

Murdoch, Joseph, 1951, Notes on California minerals: neuvite=samarskite; trona, and hanksite; gaylussite: Am. Mineralogist, vol. 36, pp. 358-361.

Neuerberg, G. J., 1954, Allanite pegmatite, San Gabriel Mountains, Los Angeles County, California: Am. Mineralogist, vol. 39, in press.

Norman, L. A., Jr., and Stewart, R. M., 1951, Mines and mineral resources of Inyo County: California Jour. Mines and Geology, vol. 47, pp. 99-100, 103, 127.

Rogers, A. F., 1910, Minerals from the pegmatite veins of Rincon, San Diego County, California: Columbia Univ., School of Mines Quart., vol. 31, pp. 208-218.

Schaller, W. T., 1903, Spodumene from San Diego County, California: Univ. California, Dept. Geol. Bull., vol. 3, pp. 265-275.

Schaller, W. T., 1904, The tourmaline localities of southern California: Science, new ser., vol. 19, pp. 266-268.

Schaller, W. T., 1912, New manganese phosphates from the gem tourmaline field of southern California: Washington Acad. Sci. Jour., vol. 2, pp. 143-145.

Schaller, W. T., 1922, The Mesa Grande, California, pegmatites, in Merrill, G. P., Handbook and descriptive catalogue of the collections of gems and precious stones in the U. S. National Museum: Smithsonian Inst., Bull. 118, pp. 138-139.

Schaller, W. T., 1925, The genesis of lithium pegmatites: Am. Jour. Sci., 5th ser., vol. 10, pp. 269-279.

Schaller, W. T., 1927, Mineral replacements in pegmatites: Am. Mineralogist, vol. 12, pp. 59-63.

Schaller, W. T., and Fairchild, J. G., 1932, Bavenite, a beryllium mineral, pseudomorphous after beryl, from California: Am. Mineralogist, vol. 17, pp. 409-422.

Schaller, W. T., 1933, Pegmatites, in Ore deposits of the Western States, pp. 144-151, Amer. Inst. Min. Met. Eng., New York.

Sperisen, F. J., 1938, Gem minerals of California: California Jour. Mines and Geology, vol. 34, pp. 34-78.

Sterrett, D. B., 1904, Tourmaline from San Diego County, California: Am. Jour. Sci., 4th ser., vol. 17, pp. 459-465.

Waring, G. A., 1905, The pegmatyte veins of Pala, San Diego County: Am. Geologist, vol. 35, pp. 356-369.

Webb, R. W., 1943, Two andalusite pegmatites from Riverside County, California: Am. Mineralogist, vol. 28, pp. 581-593.

Wright, L. A., 1950, Beryllium, feldspar, gem stones, mica, quartz crystal, in Mineral commodities of California: California Div. Mines, Bull. 156, pp. 132-133, 158-161, 164-168, 184-186, 206-208.

Wright, L. A., Stewart, R. M., Gay, T. E., Jr., and Hazenbush, G. C., 1953, Mines and mineral deposits of San Bernardino County, California: California Jour. Mines and Geology, vol. 49, pp. 163-165.