THE AMERICAN MINERALOGIST, VOL. 42, SEPTEMBER-OCTOBER 1957

ANDALUSITE- AND CORUNDUM-BEARING PEGMATITES IN YOSEMITE NATIONAL PARK, CALIFORNIA

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ABSTRACT

Five andalusite- and corundum-bearing pegmatites occupy the *ac* joints of interbedded pelitic hornfels and quartzite in the marginal portion of a roof pendant at May Lake, Yosemite National Park, California. The pegmatites are composed of quartz, orthoclase, biotite, muscovite, andalusite, corundum, etc. Andalusite ($N_x = 1.646$, $2V_x = 84°$) is concentrated in the margin zones and is partly replaced by muscovite. Small biaxial corundum crystals with margins of diaspore are enclosed in the muscovite in the interior of the altered andalusite crystals. The pegmatites are thought to have formed by magmatic injection and reaction of the magma with the wall rocks, with the formation of andalusite in the reaction zones. Later potash metasomatism partly converted the andalusite to a mixture of muscovite, corundum, and diaspore.

The age of biotite from one of the pegmatites (88.2 million years) indicates they are genetically related to the Sentinel granodiorite rather than the adjacent Mt. Hoffmann quartz monzonite.

INTRODUCTION

Andalusite has been reported in granitic pegmatites from many localities; indeed, the best specimens of andalusite have come from pegmatites and related andalusite-quartz veins (Lacroix, 1892, p. 32–33, Murdoch and Webb 1938, p. 47, Hintze 1897, p. 135–136). Although such pegmatites are not uncommon they are interesting from a genetic standpoint. Most andalusite pegmatites and veins are apparently located in aluminous metamorphic rocks near acid plutonic bodies. Consequently their genesis is usually interpreted as being related to their environment; e.g. magmatic reaction with aluminous xenoliths. A few andalusite pegmatites, however, are located in rocks that are not notably aluminous, and in such cases, because their genesis is not obvious, various hypotheses have been offered to account for their origin. Macdonald and Merriam (1938, p. 592–594) for example, suggested that the andalusite and corundum of a Fresno County pegmatite are of pneumatolytic origin, the aluminum having been introduced by "aluminous vapors" after crystallization of the surrounding minerals.

The purpose of this paper is to describe a group of andalusite- and corundum-bearing pegmatites in a Sierran roof pendant and to consider their origin.

LOCATION

Five small tabular andalusite- and corundum-bearing pegmatite dikes are exposed on the rocky north shore of May Lake in the central part of Yosemite National Park, California (Fig. 1). They are enclosed in thermally metamorphosed sedimentary rocks in the northwestern margin of a roof pendant. They are limited to a small area about 100 feet from the contact with the Mt. Hoffmann quartz monzonite although none of them adjoins the quartz monzonite at the surface.

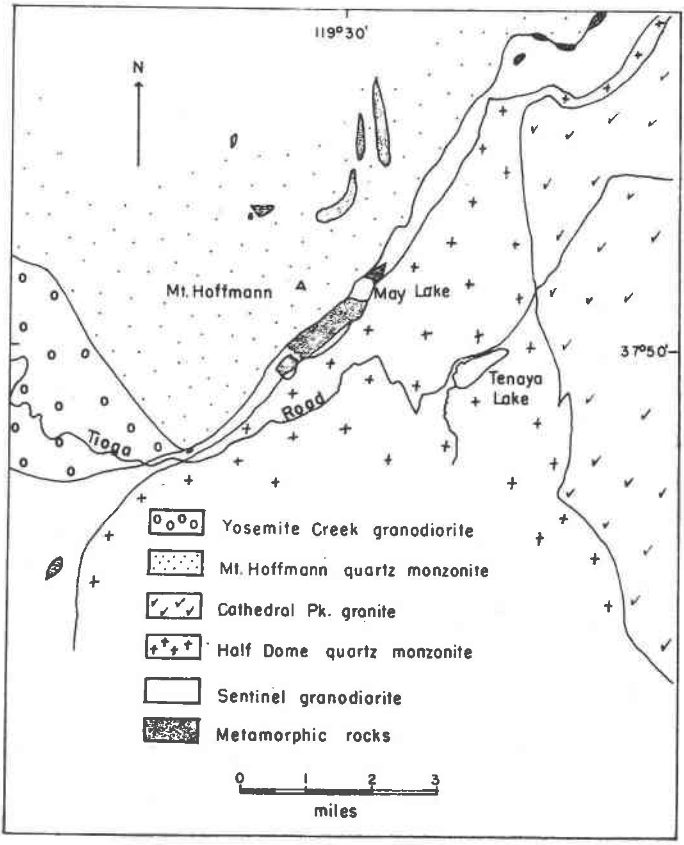

FIG. 1. Geological sketch map showing portion of Yosemite National Park.

General Geological Setting

The pendant of metamorphic rock, a northeast-trending mass about 2 miles long and $\frac{1}{2}$ to $\frac{3}{4}$ of a mile wide, is the largest of a group of pendants near May Lake. It is partly enclosed by the Sentinel granodiorite and its northwestern boundary is in contact with the Mt. Hoffmann quartz monzonite. The southeastern border of the pendant is locally in contact with the Half Dome quartz monzonite but a thin band of Sentinel granodiorite usually separates them. The oldest of these granitic rocks is the

Sentinel granodiorite and the youngest is the Mt. Hoffmann quartz monzonite. The sketch map (Fig. 1) shows the general relationships.

Small, fine- and medium-grained pegmatite dikes are common in the marginal portions of the granitic masses and in the adjacent metamorphic rocks. They are mineralogically simple and most of them consist of quartz, perthitic potash feldspar, oligoclase, and biotite with the usual accessories. Allanite and monazite in megascopically conspicuous crystals are not uncommon in the pegmatites associated with the Sentinel granodiorite. Muscovite is common in pegmatites cutting meta-pelitic rocks, and hornblende is a conspicuous constituent of those cutting diopside hornfels. In general the mineral composition of each pegmatite seems to be genetically related to its wall rock.

The metamorphic rocks that make up the May Lake pendant are mainly quartzite and pelitic hornfelses with minor amounts of marble, calc-silicate hornfels, and amphibolite. About 2500 feet of strata are present and although no fossils have been found within them they are thought to be of late Paleozoic Age.

The pendant itself trends northeast but the structural trend of the metamorphic rocks is to the northwest, the rocks having been folded into a series of anticlines and synclines that plunge N. 40°–80° W. at 50°–70°. The rocks are lineated and show prominent *b* lineations and conspicuous *ac* joints. Locally they show schistosity parallel to the bedding. In general their fabric is highly discordant with that of the adjacent granitic rocks, contacts are sharp, and all field and laboratory evidence indicate that the granites were magmatically emplaced.

Pegmatites

The pegmatites range from 10 to 47 feet in length and from 0 to 18 inches in thickness. The two best exposed ones are only 2 to 4 feet apart and appear to be connected by thin quartz-feldspar veins between half an inch and an inch in thickness. All five are in a zone about 110 feet wide and are essentially parallel, striking N. 15°–20° E. and dipping 50°–55° S.E. They gradually thin toward their ends and *ac* joints with the same attitude extend away from them. In general the pegmatites seem to be fillings of *ac* joints.

The sides of the dikes are nearly parallel so that major irregularities in opposite walls seem to match. In detail, however, the walls are minutely irregular and not strictly parallel, suggesting the pegmatites have partially replaced their walls.

Mineralogy of the Pegmatites

The pegmatites are vaguely zoned with marginal, fine-grained andalusite-bearing zones, a poorly defined medium-grained core composed mainly of quartz and feldspar, and intermediate zones. The central of the five pegmatites is the thickest and best zoned, but all of them show the same general characteristics. Their mineral composition is difficult to estimate because of variation in grain size and the tendency of minerals to occur in clusters. Table 1 is an estimate of the modal composition of the central pegmatite; the others are essentially similar but may contain less andalusite and more tourmaline.

The quartz of the pegmatites is anhedral and colorless and in thin section shows numerous minute irregular cavities containing both a liquid phase and a bubble of gas. Individual grains are usually about 1 to 3 inches in greatest dimension but range up to 8 inches. The potash feldspar is orthoclase micro-perthite. It appears to be optically monoclinic ($\perp$X, Z$\wedge a=5°$; $\perp$Z, X$\wedge b=0°$), with an optic axial angle of about 55°(−). This corresponds to about 75% Or and 25% (Ab-An) (MacKenzie and Smith 1956, p. 406). The feldspar is pale pink and occurs as anhedral to subhedral crystals ranging in size up to 10 inches in greatest dimension. Locally it contains irregular patches and streaks of muscovite concentrated along grain boundaries, fractures, and cleavage planes; apparently the mica has replaced the orthoclase. The plagioclase is oligoclase (An_{25}) and occurs as subhedral white crystals seldom more than two inches in greatest dimension. The margins of many grains are partly replaced by muscovite and in places the plagioclase is cloudy and partially argillized.

TABLE 1. ESTIMATED MINERAL COMPOSITION OF THE CENTRAL PEGMATITE (volume per cent)

Quartz	37
Potash Feldspar	35
Plagioclase (An_{25})	15
Andalusite	5
Biotite	3
Muscovite	2
Titaniferous Hematite plus Corundum	1
Tourmaline	1
Other accessories	1

Tourmaline is found principally in clusters of subradiating black prisms one quarter to three eighths inch in diameter and several inches in length but isolated crystals are enclosed in most of the principal minerals. Many individual crystals of tourmaline pass uninterruptedly through several mineral grains, seemingly replacing everything in their way. Small granular patches of tourmaline occur chiefly in the margins of the pegmatite bodies, apparently replacing feldspar. In general the

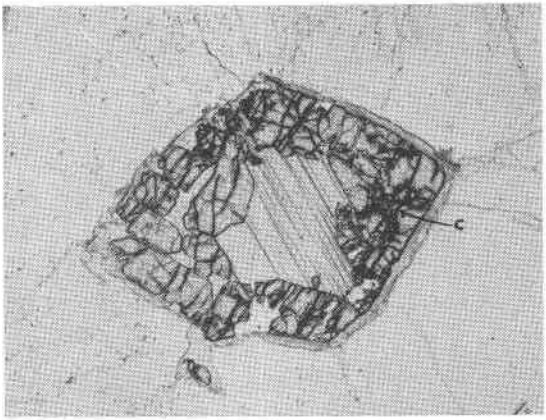

PLATE 1. Andalusite crystal enclosed in quartz and largely replaced by muscovite. Arrow points to small isolated crystal of corundum which is actually separated from andalusite by a sheath of muscovite. Lack of corundum elsewhere is possibly due to adequate supply of silica at time of introduction of potash. Radial cracks in quartz may have been permeability channels for potash introduction. Plain light, ×18.

tourmaline is erratically distributed and individual crystals show no obvious preferred orientation. The mineral is pleochroic from dark green to pinkish-brown in thick sections, ϵ is about 1.65, corresponding to intermediate schorlite.

Biotite is present as subhedral, platy crystals that range from 1 to 4 inches in greatest width. Individual crystals show no preferred orientation and many plates stand at high angles to the walls of the pegmatite. Muscovite (2V about 40°) is generally subhedral and occurs in clusters erratically distributed throughout the pegmatite. Fine-grained muscovite is also present in or marginal to orthoclase and plagioclase, apparently replacing both.

Small tabular crystals of titaniferous hematite are scattered throughout but seem to be more abundant in the marginal zones with the andalusite. The crystals are euhedral to subhedral with prominent development of the basal pinacoid, but the faces are generally rough and imperfect. The crystals are one tenth to one half inch wide and up to one tenth of an inch in thickness and many of them contain small inclusions of rutile and quartz. A positive qualitative reaction for titanium was obtained by boiling a hydrochloric acid solution of the fused mineral with tin. The specific gravity was determined on a Berman microbalance to be 5.13 ± 0.01 (average of three determinations) which corresponds to a mixture of 74.2% hematite and 25.8% ilmenite by weight or 72.3% and 27.7% by volume respectively.

PLATE 2. Zoned andalusite showing {110} cleavage and parting parallel to {001}. Section ⊥ *a* with X approximately N.S. Note minor development of fine-grained muscovite (bright material) along cleavage and parting cracks, but absence of corundum. Crossed nicols with analyzer 45° from X, ×27.

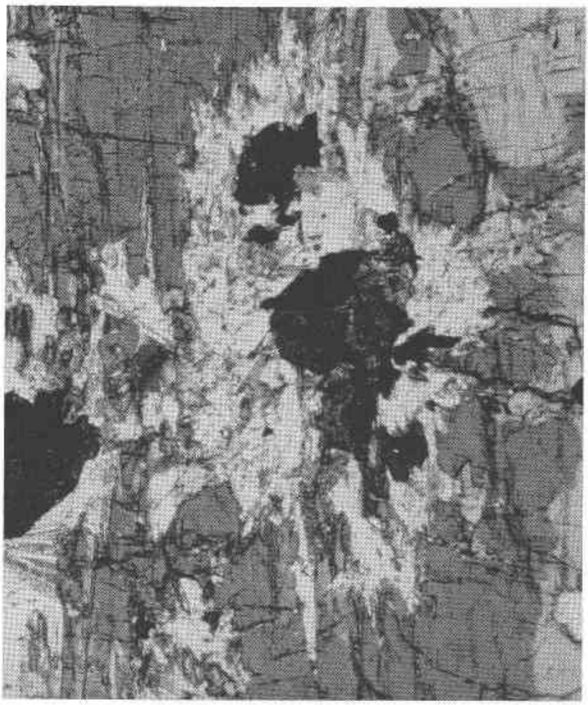

PLATE 3. Part of crystal shown in Plate 2. Black grains are dark blue corundum, surrounding white is muscovite, and light and medium gray is andalusite. Note irregular zoning of andalusite. Slide is about 0.04 mm. thick so zoning is more pronounced than in sections of standard thickness. Crossed nicols with analyzer about 45° to cleavage, ×27.

Andalusite occurs as striated brown, prismatic, tapering crystals with a silvery white coating of muscovite. Individual crystals range up to 4 inches in length and three quarters of an inch in diameter. They are concentrated in the marginal zones but in some cases occur well within the pegmatites. The crystals show a preferred orientation, the *c* axis of most individuals lying at high angles to the walls of the pegmatite. In thin section the andalusite is weakly pleochroic with X, pale pink, Y and Z pale greenish to colorless and $X>Y=Z$, $\alpha=1.646$, and $\gamma=1.656$, the 2V is 84°, negative and the dispersion about X is strong with $r<v$. The specific gravity of andalusite free from inclusions is 3.14 ± 0.01 (average of three determinations on a Berman microbalance); this along with the optical properties indicates that the andalusite contains about 5% of the Fe_2SiO_5 molecule (Tröger 1952, p. 44). Some crystals are zoned with irregular bands that have slightly lower birefringence and stronger pleochroism than most of the andalusite. These portions probably contain slightly more than 5% of the iron molecule. The andalusite apparently shows all stages of replacement by muscovite, the margins of the crystals being replaced by coarse mica, and veinlets and irregular patches of coarse- and fine-grained colorless mica are present in all of the crystals. Embedded in the muscovite in the interior of the andalusite crystals are small crystals of corundum and diaspore, the corundum constituting 10 to 15% of most crystals and diaspore less than 1%. Neither of these minerals was observed in the marginal portions of the altered andalusite crystals.

Corundum is present as small equant six-sided euhedral to subhedral crystals ½ to 2 mm. in diameter scattered throughout the andalusite-muscovite mixture but apparently always embedded in the muscovite. The crystals are pleochroic, biaxial, and generally zoned in shades of blue, but some zones are colorless and in some cases the Y and Z directions are bright yellow. A few grains were observed to have one end with Y = yellow and the other end Y = blue. Bluish grains have the following optical properties:

$\alpha=1.761$	bluish-green to nearly colorless
$\beta=$about 1.768	deep to pale blue
$\gamma=1.769$	deep to pale blue
$X<Y=Z$	
$2V_x=17°$	(average of 3 measurements)
$X=c$	

Yellow grains seem to have a smaller 2V and slightly higher indices of refraction but these properties were not accurately measured. Although the corundum crystals are enclosed in muscovite they show no obvious evidence of being replaced by the mica; instead small colorless subhedral crystals of diaspore are occasionally attached to their margins and locally the diaspore replaces the margins of the corundum grains.

Minor accessories rutile, zircon, and apatite are distributed throughout the pegmatites in small euhedral crystals but only the rutile is megascopically apparent.

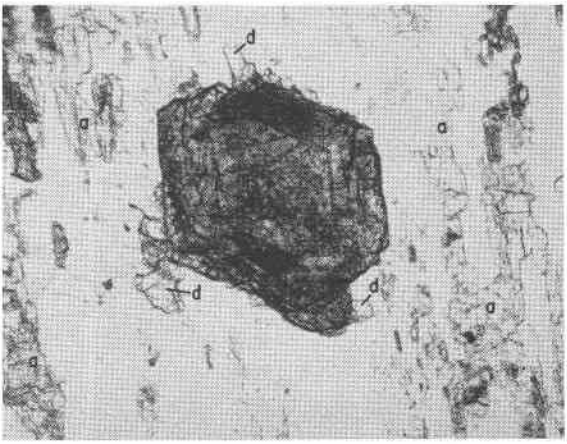

PLATE 4. Zoned corundum in muscovite that has replaced andalusite. Light colored marginal portions of crystals and adjacent colorless grains with high relief are diaspore (d). Grains with high relief near margins of picture are andalusite (a). Plain light, ×27.

METAMORPHIC ROCKS

The rocks enclosing the pegmatites are dominantly pelitic hornfels with minor interbedded quartzite. The hornfels is medium to dark gray, and banded with a vague schistosity parallel to the bedding, apparently because of the subparallel orientation of biotite crystals. Microscopically the hornfels is typically porphyroblastic with small (1 to 3 mm.) poikilitic andalusite crystals embedded in a fine-grained hornfelsic ground-mass that consists mainly of cordierite, andalusite, potash feldspar, and biotite with minor amounts of muscovite, quartz, magnetite, rutile, sillimanite, tourmaline, and monazite(?). Table 2 gives the estimated mode of a typical hornfels. The most variable constituent is apparently muscovite which occurs principally as fine-grained material replacing the marginal portions of andalusite grains and potash feldspar. Some of the muscovite is intergrown with biotite and this may be primary, although a replacement origin is suggested by some fabric relationships. In general the muscovite is thought to be mainly a secondary mineral and a retrograde product.

The quartzite is typically light gray, well-bedded to cross-bedded, and medium- to coarse-grained with a granoblastic texture. It shows welldeveloped mosaic structure with interlocking anhedral grains of quartz, interstitital potash feldspar and small grains of biotite, magnetite, and zircon. Locally small crystals of plagioclase, cordierite, and andalusite are conspicuous constituents. Muscovite is present in small amounts in most specimens, apparently replacing feldspar. In general quartz consti-

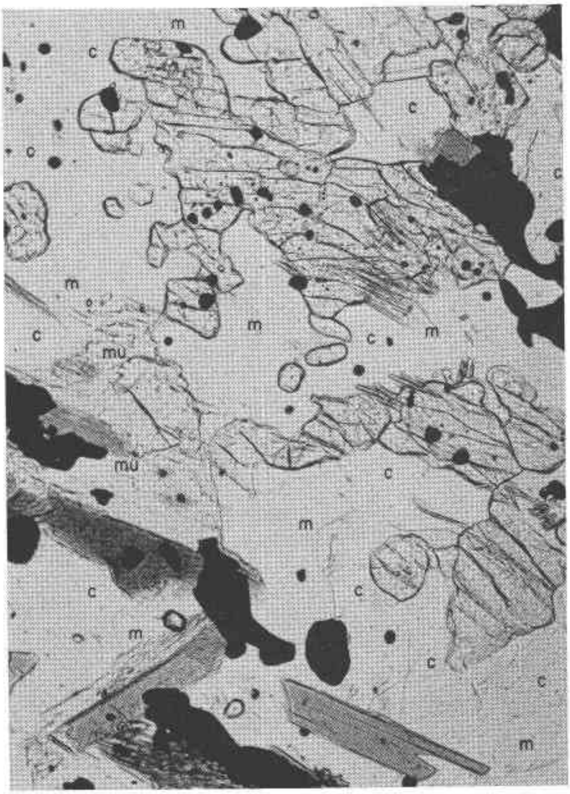

PLATE 5. Pelitic hornfels from wall of middle pegmatite. Composed mainly of andalusite (gray grains, high relief), opaque ore (black grains), biotite (dark gray), cordierite (c), microcline (m), sillimanite (acicular crystals), and muscovite (mu). Muscovite and biotite intergrowth in left central part of picture probably replaces microcline, andalusite and cordierite. Plain light, ×80.

tutes 85 to 95% of the bulk and potash feldspar 3 to 12%, with the accessories and biotite varying from 3 to 10%.

PETROGENESIS

Pegmatites are commonly thought to have originated either by (a) magmatic injection, (b) partial fusion of the host rock and migration of pegmatitic fluid into fractures or other suitable locis, or (c) metasomatic replacement of the host rock (Turner and Verhoogen 1951, p. 328). It is difficult however to account for the May Lake pegmatites by any one of the above mechanisms; apparently they were formed by a combination of processes.

The mineralogy of the pegmatites and adjacent rocks suggests that the mineral composition of the pegmatites was influenced by that of the

TABLE 2. ESTIMATED MINERAL COMPOSITION OF A TYPICAL PELITIC HORNFELS (volume per cent)

Potash feldspar	40
Andalusite	25
Cordierite	15
Biotite	6
Quartz	5
Opaque ore	4
Muscovite	2
Sillimanite	2
Accessories (rutile, monazite, apatite)	1

wall rocks. Spatial relationships, however, indicate that the pegmatites are essentially joint fillings with only limited replacement of the adjacent meta-sediments. Lack of preferred orientation of the micaceous minerals and the tendency for the andalusite prisms to stand at high angles to the walls indicate that the pegmatite did not flow into place as a mixture of crystals and liquid unless it has been recrystallized. Can the pegmatite have crystallized in situ from a magma that was injected in a completely molten state? If so how can one account for the presence of corundum in the crystalline product of such a silica-rich melt?

If it is assumed that the corundum and andalusite were both present before the muscovite crystallized then the corundum-andalusite assemblage has several features suggestive of an exsolution origin (Schwartz 1942, p. 363–364):

a. The corundum occurs as small individual crystals scattered throughout the andalusite.

b. It is restricted to the andalusite, and all andalusite crystals contain corundum.

c. The amount of corundum is small, only varying within narrow limits.

d. The chemical composition of the host is similar to that of its inclusions; the two are not incompatible.

But the corundum crystals show no preferred orientation and they are not equally distributed. Only where the muscovite replacement of the andalusite is uniform is the corundum uniformly distributed. Furthermore the corundum is always separated from the andalusite by muscovite; the corundum crystals, in other words, are actually enclosed in muscovite that replaces the andalusite. However, the corundum shows no signs of replacement by muscovite, instead it is partly replaced by diaspore. An exsolution origin for the corundum and andalusite therefore seems improbable. More likely the corundum was formed contemporaneously with the muscovite.

Andalusite has a very low silica content (36.8%) even though it can exist in equilibrium with quartz. Consequently, conversion of andalusite to muscovite (silica 45.6%) requires not only addition of potash and water but also silica. Complete conversion to muscovite is possible only if considerable silica is available:

$$3Al_2SiO_5 + 2H_2O + K_2O + 3SiO_2 \rightarrow 2KAl_3Si_3O_{10}(OH)_2$$
$$\text{andalusite} + \text{water} + \text{potash} + \text{silica} \rightarrow \text{muscovite}$$

If andalusite reacts with water and potash to form muscovite without introduction of silica, then considerable alumina will be left over which may crystallize as corundum or, if it reacts with water, as diaspore.

$$6(Al_2SiO_5) + 2H_2O + K_2O \rightarrow 2KAl_3Si_3O_{10}(OH)_2 + 3Al_2O_3$$
$$\text{andalusite} + \text{water} + \text{potash} \rightarrow \text{muscovite} + \text{alumina}$$

It seems probable, therefore, that the corundum and diaspore formed as by-products of the conversion of andalusite to muscovite in a silica-deficient environment. These reactions must have occurred after the initial crystallization of the pegmatite and under conditions such that silica from the pegmatite was unable to migrate to the interior of the andalusite crystals to participate in the process.

The occurrence and distribution of the tourmaline are rather difficult to explain. The manner in which isolated crystals penetrate all of the other major minerals—individual tourmaline prisms often extending through two or more other mineral grains—suggests that they are of replacement origin. Moreover, the erratic concentration of the tourmaline suggests that the requisite boron was introduced along structurally controlled permeability channels. If so, then tourmalinization must have occurred after the pegmatites had largely or completely crystallized.

The fabric of the pegmatites indicates that the andalusite crystals formed in place and did not flow into position as crystals suspended in a fluid medium. Their concentration in the marginal zones and the way they tend to stand at high angles to the pegmatite walls is reminiscent of reaction structures often seen in volcanic rocks, e.g. rims of fibrous pyroxene on the margins of quartzite xenoliths in olivine basalt. Although the compositional difference between a typical pelitic hornfels and a granite is not as striking as that between quartzite and olivine basalt, the contrast is enough to cause significant concentration and temperature gradients to form between the hornfels and a granitic magma. The melting point of a pelitic hornfels is probably considerably higher than that of granite, as the composition of the average pelitic rock is similar to that of quartz diorite (Nockolds 1954, p. 1019; Shaw 1956, p. 928). Consequently if a granitic magma is injected into pelitic hornfels the two will tend to react without appreciable melting of the hornfels, unless of course, the magma is superheated, which is improbable. If melting did occur it would probably be restricted to differential melting along quartz-potash feldspar boundaries immediately adjacent to the granite contact where the temperature of the hornfels was a maximum. Thus, the composition, fabric, and geometry of the pegmatites and their wall rocks all seem to indicate that the pegmatites were formed both by injection of granitic magma and by reaction with and partial replacement of the wall rocks.

Age of Pegmatites

Biotite collected from the central pegmatite was determined to be 88.2 million years old by the potash-argon method by J. Lipson, J. E. Evernden, and G. Curtis.* This value is only slightly less than that obtained for biotite from the Sentinel granodiorite but considerably greater than the value for the Mt. Hoffmann quartz monzonite and other nearby granitic rocks. Therefore the andalusite pegmatites are genetically related to the Sentinel granodiorite rather than to the nearby Mt. Hoffmann quartz monzonite. The effect of the latter and other nearby granitic rocks on the minerals of the pegmatite is apparently negligible as the potash-argon balance of the biotite was apparently not disturbed after emplacement of the Sentinel granodiorite.

Conclusions

A pegmatitic magma was injected into the *ac* joints of pelitic hornfelses, partially replacing them by reaction. Large andalusite crystals that formed in the reaction zone were partially replaced by mixtures of muscovite, corundum, and diaspore, the corundum and diaspore forming only in the interior of the andalusite crystals where the supply of silica was insufficient to convert all of the alumina to a silicate. Late in the history of the pegmatites, the feldspars were partly replaced by muscovite and many minerals were locally replaced by tourmaline.

Potash-argon dating of the pegmatitic biotite indicates that the andalusite pegmatites were emplaced about the same time as the Sentinel granodiorite.

* Personal communication, J. E. Evernden.

Acknowledgments

The present study was carried out at the University of California, Berkeley, as part of an investigation of the igneous and metamorphic rocks of the May Lake area. The writer wishes to express his appreciation to the University for financial assistance during the field work, and to Dr. F. J. Turner, Dr. Adolf Pabst, and Dr. C. M. Gilbert for assistance in the field and laboratory work. The writer is also grateful to Dr. Howel Williams and Dr. A. Pabst for critical reading of the manuscript.

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Manuscript received December 11, 1956.