THE AMERICAN MINERALOGIST
JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

Vol. 20 JANUARY, 1935 No. 1

THE PEGMATITES OF FITCHBURG, MASSACHUSETTS

C. STANFIELD HITCHEN,* *London, England.*

The pegmatites which form the subject of this paper are exposed in the McCauliff quarry at Rollstone Hill on the western outskirts of the town of Fitchburg, Massachusetts. They occur as vein-like masses within the Fitchburg granite which Emerson[1] regards as the typical rock of the core of the great central batholith of southern New England. The pegmatite bodies themselves are of an interesting and peculiar type and consist of a number of members which show some variation in size, emplacement, and mineral content. Graphic granite—so common in many of the New England pegmatites—is here entirely absent, and there is also little evidence of later hydrothermal activity. At the same time, a number of interesting auto-metamorphic effects are observed which might well be described as "deuteric," if that term may be used to imply late-stage magmatic effects within a closed system.

The granite of Rollstone Hill has been described by Emerson[2] and by Dale,[3] and consists of a fresh medium grained muscovite-biotite-microcline granite showing a gneissic structure due to a rude layering of the darker constituents. Isolated clots of mafic constituents largely consist of biotite, and represent xenoliths of schist in various stages of assimilation.

Microscopically, muscovite is seen in frequent association with biotite, the latter being particularly fresh and showing well-marked haloes around included zircons. Feldspars consist of early plagioclase of a composition varying between oligoclase and albiclase, a little orthoclase, and much microcline. Quartz is present in moderate quantity and encloses myriads of minute rutile needles. The accessory minerals consist of apatite and zircon together with

* A Commonwealth Fund fellow at Harvard University 1931–33.

[1] Emerson, B. K. Geology of Massachusetts and Rhode Island: *U.S.G.S., Bull.* **597,** p. 231.

[2] Emerson, B. K. *op. cit.*, p. 232.

[3] Dale, T. N. The Chief Commercial Granites of Massachusetts, New Hampshire, and Rhode Island: *U.S.G.S., Bull.* **354,** p. 46 (supplement).

small variable quantities of tourmaline and garnet. One of the most striking features is the abundance of myrmekitic intergrowths of quartz and albitic plagioclase which, together with small irregular masses of albite, encroach upon the borders of orthoclase and microcline, and also occur within them. Sederholm[4] has noted that myrmekite is commonest in those granites which have assimilated basic rocks, and in the present case there can be little doubt that the granite has assimilated large quantities of chloritic schist. In a recent discussion on the origin of myrmekite, Hills[5] lends support to the original hypothesis of Väyrynen,[6] namely that it results from the crystalloblastic development of biotite, in which change plagioclase and quartz are liberated.

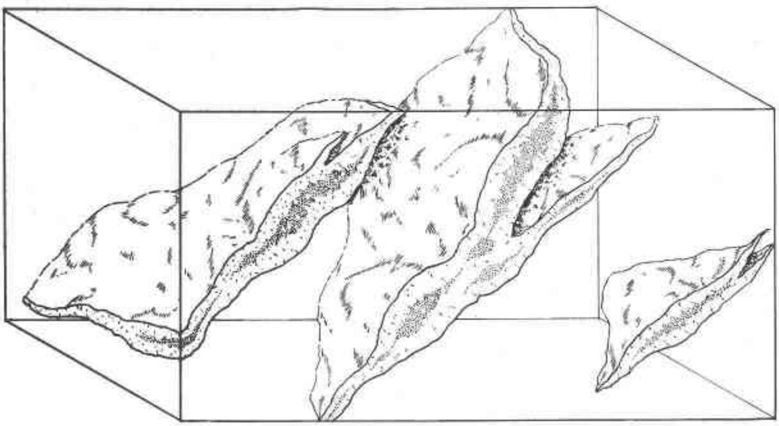

FIG. 1. Ideal sketch illustrating the occurrence of the principal tourmaline type pegmatites at Fitchburg.

The pegmatites occur within the granite, sometimes as well defined veins and veinlets, sometimes as small pipe-like bodies, and sometimes as masses of highly irregular shape. In all cases they show a frozen contact with the enclosing rock and never contain cavities. In general, field observations tend to show that the larger members form irregular lenses and dip northwards at angles vary-

[4] Sederholm, J. J. On Synantetic Minerals and Related Phenomena: *Bull. Comm. Géol. de Finlande*, no. **48,** 1916.

[5] Hills, E. S. An Unusual Occurrence of Myrmekite: *Geol. Mag.*, vol. **LXX,** p. 294, 1933.

[6] Väyrynen, H. Petrologische Untersuchungen der Granito-dioritischen Gesteine Süd-ostbothniens: *Bull. Comm. Géol. de Finlande,* no. **57,** 1923.

ing from 40 to 60 degrees (Fig. 1). This is in harmony with Andersen's[7] observations, for he states that, while pegmatites have fairly parallel sides, they taper off within a short distance and are actually more lens than dike-shaped.

All the pegmatites tend to die out as they reach the granite forming the top of the hill, and there is reason to believe that the upper surface of the present hill is not far below the original contact surface of the granite with the schists which formerly covered it. Pegmatites similar to those of Rollstone Hill are found at other places on the Fitchburg granite outcrop, and Emerson and others mention such pegmatites as passing out into the surrounding schists. This is not unlikely, but no case of extra-granitic occurrence was noted in the vicinity of the McCauliff quarry.

As already mentioned, the pegmatites of Fitchburg show some variation in size, texture and mineral content, and it has been found possible to classify them into several distinct types, as follows:

I. Biotite Type.
II. Tourmaline Type.
III. Beryl Type.
IV. Titanite Type.
V. Allanite Type.
Calcite Veins.

With the exception of one beryl-bearing member, all the larger pegmatites belong to the Tourmaline Type; the remainder being represented by insignificant veinlets and stringers. Actually, the calcite veins can hardly be classified as pegmatites, but they appear to represent a concluding term in the sequence of post-magmatic events. The various types are noted in detail below.

I. Biotite Type

This is a somewhat subordinate type occurring in the form of thin meandering stringers, which rarely exceed two inches in thickness, and which present an irregular contact with the enclosing granite. The principal minerals consist of biotite, microcline, muscovite, and quartz: tourmaline is entirely absent and no primary plagioclase was encountered in any of the specimens studied.

Under the microscope, biotite is found to be particularly fresh and free from included zircon; it is associated with primary muscovite and a little magnetite. In hand specimens microcline presents a faint bluish translucent appearance, and microscopically

[7] Andersen, O. Discussions of certain phases of the genesis of pegmatites: *Norsk. Geol. Tidsskr.*, vol. **XII**, p. 6, 1931.

is seen to contain a smaller amount of perthitic albite than in the other types of pegmatites; it is also comparatively free from incipient kaolinization. The only deuteric effect consists of the development of small masses and isolated crystals of albite both around and within the microcline crystals. This effect, so noticeable in the case of the other types of pegmatite, is relatively insignificant in the biotite veinlets. Another late-stage effect consists of the development of sericite in fissures traversing the primary minerals. Accessory minerals are negligible and only rarely are small zircons imbedded in the microcline.

An examination of the biotite veinlets leads to the conclusion that they represent an early, highly potassic differentiate of the residual mother liquor (restmagma).

II. Tourmaline Type

This type includes the largest and most abundant pegmatites in the McCauliff quarry. They occur in the vein-like, though ac-

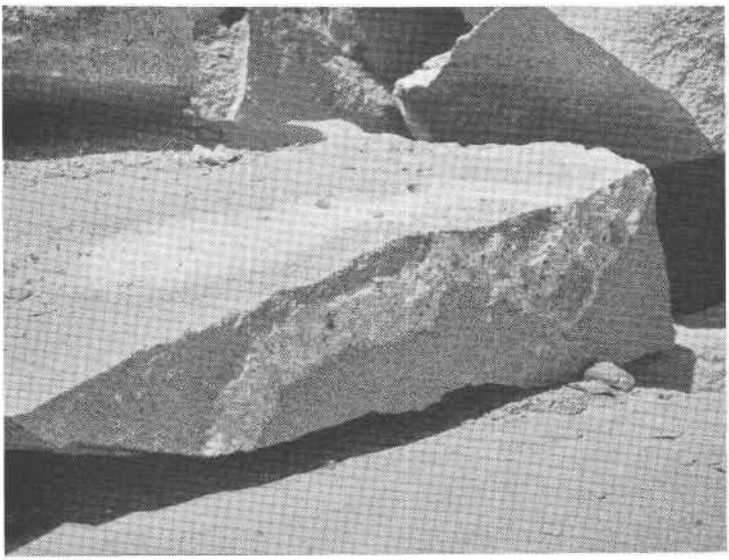

Fig. 2. Vein-like form assumed by a minor tourmaline type member, enclosed in granite.

tually lenticular masses already described, and present a striking contrast with the enclosing granite. The lenses of the larger members sometimes possess a maximum thickness of 3 to 4 feet, although a thickness of 1 to 2 feet is more normal.

White feldspar occurs coarsely crystallized upon the selvages and also as "phenocrysts" set in the purplish-brown quartz which usually fills the center of each lens (Fig. 3). Typical crystals of black tourmaline (schorlite) are embedded both in the feldspar and quartz, and are remarkable for the manner in which they have been fractured and off-set, and "healed" by later quartz and

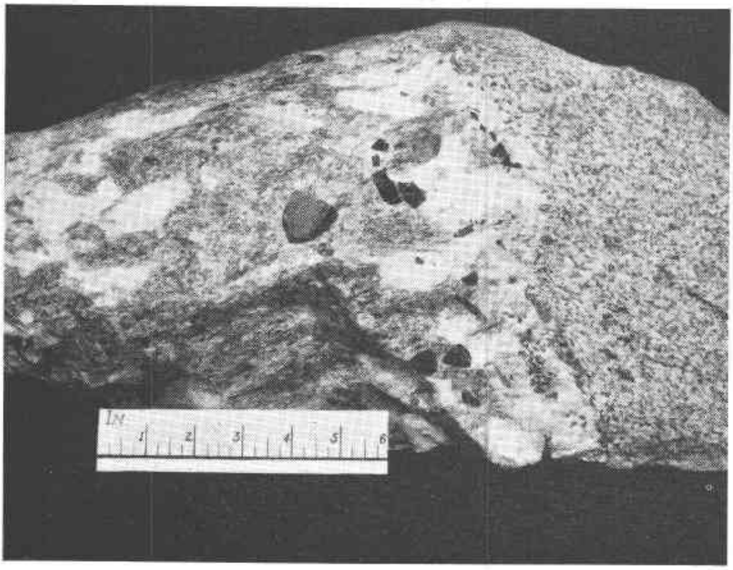

Fig. 3. Cross-section of a tourmaline type pegmatite showing white feldspar crystallized on the walls, and purplish-brown quartz occupying the center.

feldspar (Fig 4). Another interesting feature is the replacement of individual tourmaline crystals by quartz along a central core parallel to the vertical axis, the phenomenon being most noticeable in the case of fractured crystals. The proportions in which feldspar, tourmaline, and quartz are present vary considerably—even in different portions of the same lens. Especially is this true of tourmaline, which sometimes constitutes 8–10 per cent of the pegmatite, and at other times is entirely absent—at least locally. Megascopically, the texture is very variable but in general corresponds to the width of the lens at any given place. Occasional bunches of muscovite mica form the only important accessory mineral.

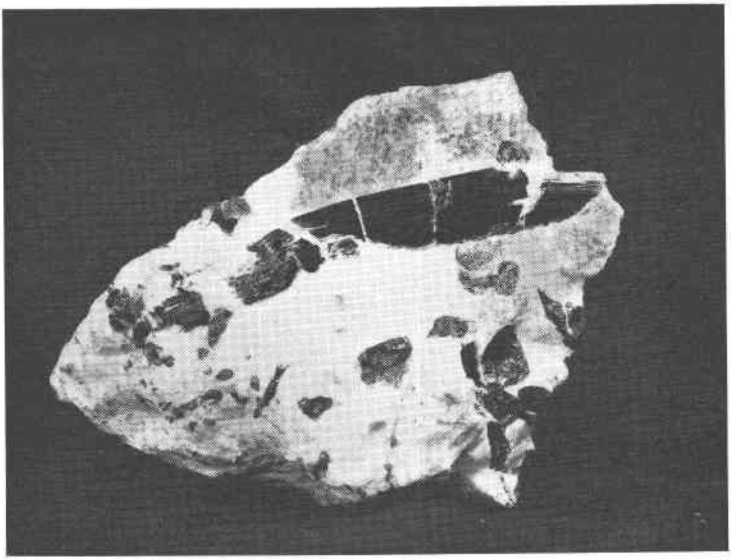

FIG. 4. Tourmaline crystal, fractured, off-set, and "healed" by later quartz and feldspar.

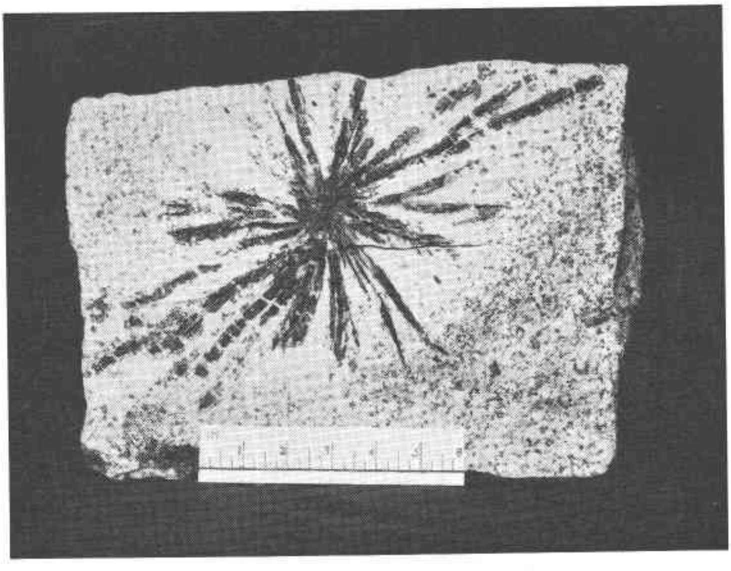

FIG. 5. Fine specimen of a "sunburst" of radiating tourmaline needles preserved in the Harvard Museum. The "sunburst" is associated with a white feldspathic matrix (just visible) similar to that forming the filling of the titanite veinlets.

Microscopically, the feldspar is found to consist of microcline and plagioclase, the former being greatly in excess. Various perthitic intergrowths are observed in the microcline which are fully described under "Mineralogical Notes." The plagioclase ranges in composition between albiclase and oligoclase and shows both albite twinning and a combination of albite and pericline twinning. Occasional anti-perthitic structures are sometimes observed in the plagioclase in the form of small irregular patches of microcline. During the early stages of formation, feldspar and tourmaline apparently crystallized together, but the former continued to crystallize long after the latter had completely separated. Quartz was the last mineral to crystallize and is found enclosing earlier minerals and filling fissures. Inclusions in the feldspar consist of occasional grains of apatite, zircon, tourmaline, muscovite, and chlorite.

Deuteric and related effects observed microscopically in the tourmaline type pegmatites consisted of:

(a) development of occasional patches of myrmekite,
(b) coarse vein perthite in microcline,
(c) veinlets of microcline traversing plagioclase,
(d) development of small albite crystals and quartz around the borders of, and within the microcline, the effect being of a similar character to that described by Colony.[8] In places where it has thus been attacked, the microcline tends to develop cloudiness,
(e) development of sericite along thin fissures traversing quartz and feldspar.

Biotite, despite its abundance in the Type I veinlets, is entirely absent from the tourmaline-bearing members, and these two minerals are never found to occur together in the same pegmatite. Similar observations have been recorded by Bastin[9] andMegathlin[10] in the case of the Maine and the New Hampshire pegmatites respectively. Some have suggested that tourmaline and biotite are mutually exclusive minerals, but a more satisfactory explanation appears to lie in the assumption that most pegmatite magmas yielding tourmaline were endowed with sufficient boron to convert all ferromagnesian constituents to that species. With insufficient

[8] Colony, R. J. The final consolidation phenomena in the crystallization of an igneous rock: *Jour. Geol.*, vol. **31**, p. 169, 1923.

[9] Bastin, E. S. Geology of the Pegmatites and Associated Rocks of Maine: *U.S.G.S.*, *Bull.* **445**, p. 16, 1911.

[10] Megathlin, G. R. The pegmatite dikes of the Gilsum area, New Hampshire: *Econ. Geol.*, vol. **24**, p. 174, 1929.

quantities of boron only a partial conversion ensues and biotite and tourmaline then occur side by side—as, indeed, actually happens in the case of some of the assimilated xenoliths of schist. The idea that tourmaline may be formed at the expense of biotite appears to have been first suggested by Patton in 1898.[11]

The fact that a large number of the tourmaline crystals are broken and off-set, while only relatively few of the feldspar crystals are thus affected, indicates that this protoclastic shattering took place at a stage when most of the tourmaline had separated, and a large amount of quartz and feldspar still remained uncrystallized. Megathlin[12] reports similar shattering of the tourmaline in the case of the Gilsum pegmatites and attributes it to "readjustment during crystallization"; he does not, however, state whether he believes such readjustment to be the result of internal or external forces. In the case of Fitchburg, the writer is inclined to the view that shattering was produced by external forces acting on the granite, which caused deformation of the enclosed pegmatites.

III. Beryl Type

As far as is known, this type is represented by only one member which occurs at the southern end of the quarry, others, however, may exist beneath the granite debris which covers the quarry floor and the adjacent hill slopes. While resembling the tourmaline type members described above, this beryl-bearing pegmatite is more definitely dike-like in character, and has a width of 1 to 1½ feet with fairly parallel walls.

As usual, white feldspar is clustered along the vein selvages and also occurs as "phenocrysts" towards the center of the vein. The filling consists of purplish-brown quartz and relatively large flakes of muscovite which are conspicuously grown on and around the feldspar phenocrysts. A small quantity of black tourmaline is present, most of it being embedded in the feldspar a short distance inwards from the granite contacts on either side. Almandine garnet and beryl are peculiar to this type of pegmatite and commonly occur associated with the quartz and muscovite. Individual beryl crystals are broken and off-set in a similar manner to the tourmaline of the Type II members. The structure of this pegmatite is illustrated in Fig. 6.

[11] Patton, H. B. *Bull. Geol. Soc. Amer.*, vol. 10, p. 21, 1898.

[12] Megathlin, G. R. *op. cit.*, p. 174.

Examined microscopically sections of the beryl-bearing pegmatite are found to exhibit similar features to those encountered in sections of members belonging to the tourmaline type. Feldspar mainly consists of coarsely crystallized microcline-microperthite

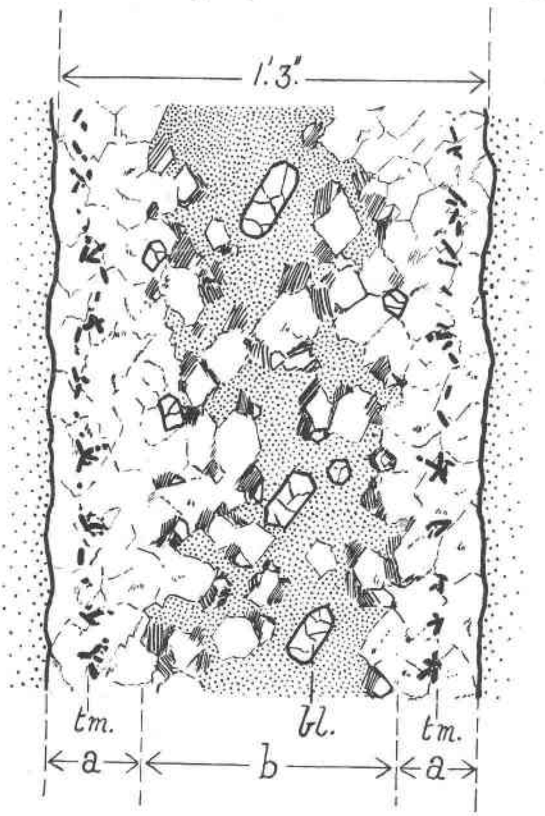

FIG. 6. Cross-section of the beryl vein: (a) outer zones consisting of feldspar and small amounts of tourmaline (tm.), (b) center zone of feldspar, muscovite, and beryl (bl) embedded in quartz.

with a little plagioclase showing anti-perthitic structures. Late-stage magmatic effects, etc., are identical with those described under Type II, except for the fact that minute pink crystals of almandite accompany sericite in fissures traversing quartz and feldspar.

IV. Titanite Type

Members of this somewhat rare type occur as meandering veinlets only a few inches in width, and might well escape casual observation owing to their similarity to the enclosing granite, and their gradational contact with it. Their filling consists of white feldspathic material of a texture only a little coarser than that of the granite. Muscovite mica is fairly abundant in individual crystals, but quartz is very subordinate. Embedded in the feldspathic matrix, titanite and ilmenite occur both as individual crystals and as crystalline aggregates. Small quantites of allanite and calcite are occasionally present.

The most striking feature microscopically, is the advanced albitization of the microcline, consisting of the development of small crystals and masses of albite both around and within the potash feldspar (Pl. A, 1). This effect, already noted in connection with the other types of pegmatites, reaches its maximum development in these titanite veinlets. A partial analysis of the white feldspathic matric by F. A. Gonyer yielded: $K_2O=9.87$ per cent, $Na_2O=3.38$ per cent, $CaO=0.52$ per cent. The grating structure of the microcline is intermediate in coarseness between that of the granite and that of the tourmaline pegmatites. Both apatite and garnet are present as accessories and small zircons embedded in the feldspar are particularly numerous. Tourmaline is absent, but occasional flakes of chloritized biotite occur, which have probably been derived from the adjacent granite.

Titanite and ilmenite occur in intimate association and their microscopic relations suggest that the former has resulted by replacement of the latter (Pl. A, 2). The fact that calcite occurs in contact with these two minerals not only lends support to such a view, but also seems to indicate the chemical mechanism involved.

$$3(FeO,\ TiO_2)+\underbrace{3Ca(HCO_3)_2+3SiO_2}_{\text{in solution}}=$$

ilmenite

$$\underbrace{3(CaO,TiO_2,SiO_2)}_{\text{titanite}}+\underbrace{3Fe(HCO_3)_2}_{\text{removed in solution}}$$

There is reason to believe that calcium bicarbonate may be stable in hydrothermal solutions, provided the amount of carbon dioxide and the pressure are sufficiently great.

Observations on these stringers suggest that they were derived from a more sodic differentiate, which was capable of a greater degree of auto-metamorphism, than the more potassic fractions represented by pegmatites of types I, II, and III. The titanite and ilmenite, and the greater abundance of small zircon crystals are, of course, consistent with a more sodic environment. The gradational contact of these stringers with the granite would seem to point to the more aqueous, and penetrating character of this sodic differentiate—especially during auto-metamorphism when albite and quartz replaced the potash feldspar. The residual liquors active at that stage succeeded in passing beyond the confines of the pegmatite, and have produced albitization of the microcline, and chloritization of the biotite in the adjacent granite.

v. Allanite Type

The allanite at Fitchburg is mostly confined to extremely thin, though well-defined quartz stringers, which pass through the granite independently and rarely attain a greater width than half an inch. At certain points these allanite veinlets intercept the tourmaline (type II) pegmatites, and they are consequently younger than the latter.

Blocks containing these allanite veinlets have a tendency to split along the plane of the vein, and thus to reveal the greenish-black allanite in the form of flattened, prismatic crystals which are grouped, sometimes into stringy fibrous patches, and sometimes into stellate aggregates. With the exception of uraninite, which has recently been noted by Prof. A. C. Lane,[13] and which appears to have been found in association with allanite the stringers contain no other minerals in addition to quartz, allanite, and metamict products of the latter.

Calcite Veins

In one or two places, small calcite-filled fissures occur, which, although not of pegmatitic origin, appear to complete the sequence of igneous events. The vein selvages are marked by an abundance of minute albite crystals, small quantities of purple fluorite, and larger and more perfect plates of ilmenite and muscovite which protrude into the brownish calcite filling the center of each vein. The structure and mineral assemblage are seen to advantage when the calcite has been removed by acid.

Mineralogical Notes

In his appendix to his "Catalogue of American Minerals," published in 1825, Robinson mentions quartz, mica, schorl, beryl, and

[13] Lane, A. C. Age of Fitchburg Granite: *Science*, vol. **78**, p. 435, 1933.

sulphuret of molbydena, as occurring at Pearl Hill, five miles north-east of the "village" of Fitchburg. This, persumably, is the first reference to Fitchburg minerals. A similar suite was discovered when the McCauliff quarry was opened in 1865.

TOURMALINE. As schorlite this mineral occurs abundantly in the type II pegmatites. Crystals are simple and of the usual prismatic habit with striated prism faces. In size they normally range from 0.5 cm. to 10 cms. in length, and from 0.1 cm. to 2.5 cms. in cross section; exceptionally large individuals measuring over 30×5 cms. have, however, been reported. The forms commonly present are $m(10\bar{1}0)$, $a(11\bar{2}0)$, and $r(10\bar{1}1)$; more rarely $o(02\bar{2}1)$ is observed. In complete specimens hemimorphism is expressed by termination at one end by $r(10\bar{1}1)$, and at the other by $r(10\bar{1}\bar{1})$ and $o(02\bar{2}\bar{1})$. Ward[14] gives the refractive indices as $\epsilon=1.638$ and $\omega=1.664$.

The crystals are remarkable for two structures:

(a) they have frequently been transversely fractured, the cracks having been "healed" by later quartz and feldspar (Fig. 4).
(b) they often show quartz cores which appear to be the result of a replacement that most readily took place along a direction parallel with the vertical axis.

Under the microscope, thin sections of the large tourmalines show normal characters and are, with the exception of occasional small zircons, free from inclusions. A study of the quartz cores (Pl. A, 3, 4) suggests that the mechanism of replacement consisted, first of a partial re-solution of the early formed crystals, the cavities so formed being then filled by quartz. Thousands of minute needles of tourmaline are seen in the quartz of the cores. The replacement is of a magmatic type and may have been effected by late-stage liquors. There is no evidence to suggest that it may have been due to the action of hydrothermal solutions.

In addition to the crystals described above, tourmaline occurs in several other ways, namely:

(a) as black "sooty" masses representing aggregates of innumerable microscopic crystals of schorlite;
(b) in a form constituting a crude graphic intergrowth with quartz, similar to the quartz-tourmaline intergrowths found in the Gilsum (N. H.) and certain of the Maine pegmatites;
(c) very rarely as clusters of radiating needles ("sunbursts") as illustrated in Fig. 5.

[14] Ward, G. W. *Amer. Min.*, vol. **16**, p. 162, 1931.

The sooty variety (a) appears to be secondary, and may possibly represent a deposition of the material that was taken into solution during the replacement of the early formed crystals. The clusters of radiating needles (c) are associated with a relatively fine feldspathic matrix identical with that of the titanite veinlets. The individuals forming a cluster show transverse fracturing similar to that described above, but in the present case, the tourmaline has undergone considerable replacement by the white albitic matrix in which it is embedded. In places the tips of the crystals appear to penetrate the granite on either side of the vein. The origin of these peculiar "sunbursts" presents a difficult problem, but it is possible that they represent an early separation of tourmaline from the restmagma which gave rise to the titanite veinlets.

MICROCLINE (MICROPERTHITE). This mineral commonly occurs coarsely crystallized upon the walls of the Type II pegmatites, but a number of more perfect crystals are found embedded in the quartz occupying the center. These latter are best suited for purposes of study and normally measure 5 to 8 cms. along the *c*-axis. The forms present include,—

$c(001)$, $b(010)$, $m(110)$, $M(1\bar{1}0)$, $f(130)$, $z(1\bar{3}0)$, $x(\bar{1}01)$, $y(\bar{2}01)$, $p(\bar{1}11)$, $o(\bar{1}\bar{1}1)$.

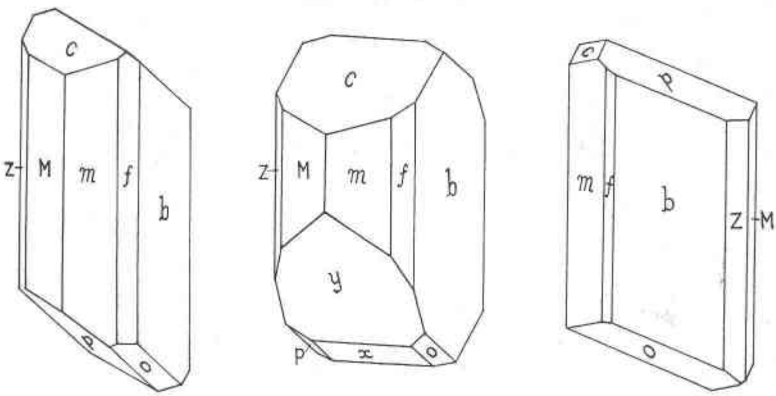

FIG. 7. Crystals of microcline.

Crystals are tabular with $p(\bar{1}11)$ sometimes prominent; in other cases only simple prisms and pinacoids are present (Fig. 7). Most crystals are twinned on the Carlsbad law and show a well marked murchisonite parting. Refractive index determinations gave: $\alpha=1.518$, $\beta=1.522$, $\gamma=1.527$. An analysis by F. A. Gonyer yielded:

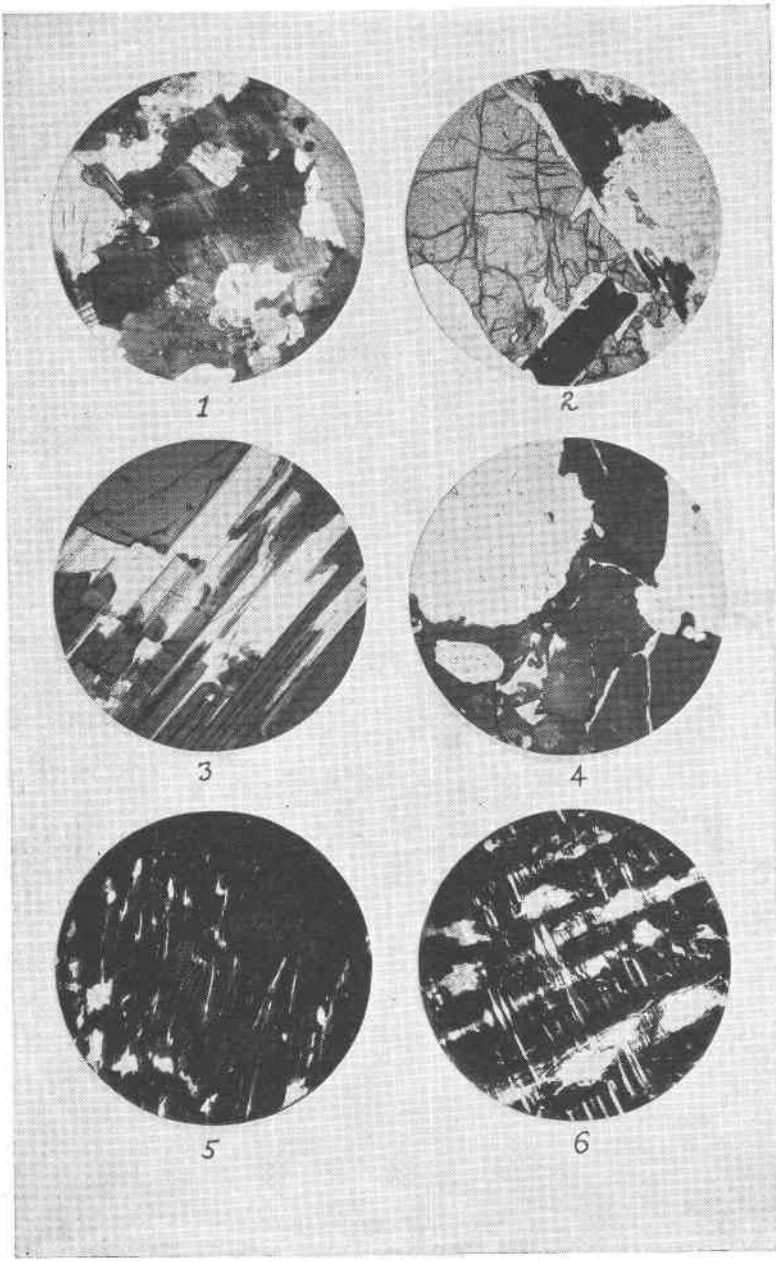

PLATE A

(1) Deuteric replacement of microcline by small masses of albite and myrmekitic intergrowths, in the feldspathic matrix of the titanite (type IV) veinlets. Crossed nicols.
(2) Titanite and ilmenite with intervening calcite. The titanite veinlets, ordinary light.
(3) Longitudinal section of tourmaline crystal, showing replacement by quartz along a direction parallel with the vertical crystallographic axis. Ordinary light.
(4) Similar to Fig. 3, but a transverse section. Ordinary light.
(5) Section of microcline cut parallel to (010), showing film perthite (fine striations). Crossed nicols.
(6) Section of microcline cut parallel to (001), showing cross-twinning and coarse vein perthite. Albite twinning of the latter just visible. Crossed nicols.

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	H_2O+	Total
Per cent	64.26	18.55	0.62	0.13	0.29	1.91	13.78	0.32	99.86

—from which the following mineral composition is computed:—

Orthoclase = 82.16%, Albite = 16.44%, Anorthite = 1.40%. According to Warren[15] microcline is only able to hold about 8% of albite in solid solution, any excess being represented by perthitic intergrowths as in the present case.

Microscopic Features—Sections parallel to (010). The fine microperthite associated with the murchisonite parting is clearly seen under crossed nicols, individual fibres or lamellae measuring from 1 to 2.5 mm. in length (Pl. A, 5). This microperthite although much coarser, is of a similar character to that described by Spencer,[16] and corresponds to the "film perthite" of Andersen,[17] which the latter regards as due to ex-solution, but probably at a lower temperature than his "string perthite." In this orientation (010) the angle between the fine lamellae of perthite and the basal cleavage is 73°

Coarse microperthite occurs fairly abundantly as stringy veins and lenticular patches occupying no special orientation: cut in this position, no twin lamellae are visible. This coarse perthite corresponds to the "vein perthite" of Andersen,[18] which he regards as due to solutions from the pegmatitic magma filling contraction cracks. Alling[19] suggests that in origin, such a form of perthite marks the boundary line between the deuteric and hydrothermal phases. Alteration products form cloudy patches on the peripheries of the blebs of coarse "vein perthite."

Sections parallel to (001). In this orientation both the characteristic cross twinning of the microcline and the lamellar twinning of the albite, forming the coarse "vein perthite," are observed under crossed nicols (Pl. A, Fig. 6). The finer "film perthite," however, is only barely visible and forms faint "striations" at right angles to

[15] Warren, C. H. A quantitative study of certain perthitic feldspars: *Proc. Amer. Acad. Arts & Sci.*, vol. **51**, p. 127, 1915.

[16] Spencer, E. A contribution to the study of moonstone from Ceylon and other areas and the stability-relations of the alkali feldspars: *Min. Mag.*, vol. **XXII**, pp. 291–365, 1930.

[17] Andersen, O. The genesis of some types of feldspar from granite pegmatites: *Norsk. Geol. tidsskrift*, B. X, h. 1–2, p. 149, 1928.

[18] Andersen, O. *op. cit.*, p. 150.

[19] Alling, H. L. Perthites: *Amer. Min.*, vol. **17**, p. 61, 1932.

the (010) cleavage. The whisps and lenses of "vein perthite" show a rude orientation parallel to the (100) edge.

OLIGOCLASE (ANTI-PERTHITE). Primary oligoclase occurs along with microcline as phenocrysts in the Type II pegmatites. Crystals are usually poorly developed, but contact measurements revealed the presence of the following forms:—

c(001), *b*(010), *m*(110), *M*($1\bar{1}0$), *y*($\bar{2}01$), *r*(403), *f*(130), *e*(021).

In habit the crystals tend to be somewhat tabular parallal to *c*(001) and resemble those from Fine, St. Lawrence Co., N. Y., described by Penfield.[20] Determinations of refractive indices yielded, $\alpha=1.538$, $\beta=1.542$, $\gamma=1.545$. An analysis of the alkalies by F. A. Gonyer gave, $Na_2O=7.72$ per cent, $K_2O=2.06$ per cent—from which is calculated the following mineral composition: Orthoclase $=12.58$, Albite$=65.24$, Anorthite$=22.58$ per cent (by diff.). The plagioclase is therefore oligoclase (Ab. 74.29, An. 25.71), the 12.58 per cent of potash feldspar being present, partly in solid solution, and partly as anti-perthitic blebs. Most authorities concede that, at ordinary temperatures, the solubility of the orthoclase molecule in albite is small, amounting to about 4–6 per cent. A higher figure of 8 per cent is given by Spencer.[21] In the present instance, the amount of potash feldspar occurring as anti-perthite is estimated at about 2–3 per cent, leaving some 9–10 per cent in solid solution in oligoclase.

Microscopic characters. Sections parallel to (001) show fine lamellar twinning possessing an extinction angle of 2°–3°. Irregular patches of anti-perthitic microcline are present, and thin "rafts" of secondary calcite traverse the section, inclined at an angle of about 85° to the direction of the lamellae. Sections parallel to (100) show the principal cleavage parallel to (001), which is rendered conspicuous by calcite filling—as are other fissures. The angle between the principal cleavage and the twin lamellae measures 93°.

BERYL. Beryls of gem quality are said to have been obtained at Fitchburg, but most of the material is of the ordinary translucent variety, ranging in colour from deep golden yellow to pale green. Individual crystals measure 0.3 to 2.0 cms. in diameter and consist of simple combinations of *c*(0001), and *m*($10\bar{1}0$). They are frequently broken and off-set in a similar manner to the tourmalines.

[20] See Dana, E. S., A System of Mineralogy, 6th Ed., p. 332.

[21] Spencer, E. *op. cit.*

The indices of refraction are, $\epsilon = 1.578$, $\omega = 1.585$, which, according to Winchell,[22] indicates an alkali content of about 2 per cent. There is a tendency for the smaller beryl crystals—especially those of a golden colour—to be clearer and more perfectly formed, and they may represent a somewhat later deposition.

ALLANITE. At Fitchburg, allanite is largely confined to thin quartz stringers which pass independently through the granite. The mineral usually occurs in them as fibrous-looking bunches of flattened, prismatic crystals, which possess a resinous lustre and range in colour from dark green to black. In places a superficial reddish-brown decomposition product has been formed by weathering. Individual crystals are invariably curved, and are usually too poor for accurate measurement, the following simple forms have, however, been identified:—

$$c(001),\ a(100),\ e(101),\ r(\bar{1}01),\ o(011).$$

The habit is similar to that of epidote, with $e(101)$ prominent. Grains show an extremely weak birefringence and possess an average refractive index of 1.69.

In thin sections, allanite itself—as distinct from its peripheral (metamict) alteration products—appears to consist of two substances, which are easily distinguished when a longitudinal section is viewed in polarized light. Both varieties are of a dull greyish green colour, but one is slightly darker and possesses well marked pleochroism (blue-green to red-brown). This pleochroic variety is anisotropic and polarizes in greys of a high order. The lighter variety is isotropic and non-pleochroic, and comprises the bulk of the material: in it are set lenses and "rafts" of the pleochroic variety. An orange coloured alteration product fringes the allanite and there are also small masses of associated opaque material.

These observations are in agreement with those of Watson[23] who has studied allanite from a number of localities in the eastern United States. He distinguishes a pleochroic and a non-pleochroic variety, and finds that the pleochroism and refractive indices of the former vary with different localities. He further finds that the orange alteration product possesses indefinite optical properties, and is of no fixed composition. It essentially consists of H_2O, Fe_2O_3, Al_2O_3, Ce_2O_3, and SiO_2, in varying proportions.

[22] Winchell, A. N. Elements of Optical Mineralogy, *New York*, **1928**, Part II, p. 272.

[23] Watson, T. L. The weathering of allanite: *Bull. Geol. Soc. America*, vol. **28**, pp. 463–500, 1917.

GARNET (SPESSARTITIC ALMANDITE). Garnets at Fitchburg are confined to veins in the south end of the quarry, and are fairly plentiful in the beryl vein. Individuals sometimes measure over 2 cms. in diameter, and show the trapezohedron *n* (211) and the dodecahedron *d* (110) in combination, the former being usually dominant. The smaller crystals are transparent and of a fine ruby red colour; more rarely yellowish-red and pink tints are seen.

An analysis (by F. A. Gonyer) of carefully picked material yielded:—

	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MnO	MgO	TiO_2	Total
Per cent	36.07	21.10	7.05	17.38	1.18	17.88	0.28	none=	100.94

from which the following mineral composition is calculated—

Almandite	52.49 per cent.
Spessartite	41.53 " "
Pyrope	0.92 " "
Andradite	3.55 " "
	98.49

By orthodox calculation, amounts of silica, alumina, and ferric oxide remain over, which cannot be allocated to garnet species. The above composition is obtained by converting the balance of Fe_2O_3 to FeO and calculating as almandite. The remaining balances of SiO_2 and Al_2O_3 are thereby satisfied.

In addition to the larger crystals, garnet occurs in minute crystals in late sericite fissures and is there frequently associated with arsenopyrite. There are also masses of microscopic garnets which fill spaces between quartz and feldspar. Both occurrences suggest hydrothermal origin.

Williams[24] has recently suggested that the appearance of manganiferous garnet (spessartitic almandite) in the final magmatic extract is an expression of the fact that progressive differentiation increases the MnO/FeO ratio in magmas. This becomes apparent after differentiation has reduced the MgO/FeO ratio almost to the elimination of MgO.

The remaining Fitchburg minerals are noted briefly below.

QUARTZ. Occurs abundantly in the larger pegmatites moulding earlier minerals. It is invariably massive and of a purplish-brown

[24] Williams, G. T. A granite-schist contact in Stuart Island, New Zealand: Title of paper read before the Geological Society of London, December 6th, 1933. Not yet published.

colour, which Holden[25] attributes to silicon, set free by the disintegration of silica under the influence of radioactive substances. Although fairly clear and free from inclusions, it is internally much shattered.

BIOTITE. Confined to the "Type I" veinlets where it occurs in plates 1–2 cms. across. The refractive indices are: $\alpha=1.640$ β and $\gamma=1.645$, and suggest siderophyllite.

MUSCOVITE. Found most abundantly in the beryl pegmatite where it is grown upon, and may possibly replace, feldspar. It occurs in pinkish bronze plates up to 4 cms. across. Refractive indices: $\alpha=1.562$ $\beta=1.591$, $\gamma=1.595$.

ILMENITE. This mineral occurs occasionally as large platy crystals in the quartz of the "Type II" pegmatites. In addition, corroded ilmenite is found in association with titanite and calcite in the "Type IV" veinlets, while yet a third occurrence is noted in the calcite veins, where the mineral forms delicate hexagonal plates. In the latter, the crystals are somewhat distorted, but measurement shows them to be combinations of $c(0001)$, $r(10\bar{1}1)$, $n(22\bar{4}3)$, and, more rarely $\pi(\bar{1}2\bar{1}3)$.

TITANITE. Appears to be wholly confined to the "Type IV" veins, where it occurs massive and in individual crystals up to 2 cms. across. The crystals are simple, tabular, and cinnamon brown in colour. The only forms present are $c(001)$, $n(111)$, and $l(\bar{1}12)$.

APATITE. Very rare, but occasionally occurs embedded in feldspar and associated with almandite in the beryl pegmatite. The mineral occurs in rude hexagonal prisms, 1 to 2.5 cms. in length, and is pale grey to greenish-white in colour. Refractive indices: $\epsilon=1.632$, $\omega=1.634$.

FLUORITE. Small light purple to colourless cubes, 0.3 cm. along an edge, occur on the selvages of the calcite veins.

SULPHIDES. Very small quantities of arsenopyrite, pyrrhotite, chalcopyrite, and molybdenite occur in the tourmaline and beryl-bearing pegmatites, and are there usually associated with the quartz forming the core. A similar occurrence of sulphides in quartz was reported by Warren and Palache[26] in the case of the Quincy pegmatites.

[25] Holden, E. F., The cause of color in smoky quartz and amethyst: *Amer. Min.*, vol. **10**, p. 224, 1925.

[26] Warren, C. H. and Palache, C. The pegmatites of the riebeckite-aegerite granite of Quincy, Mass., U. S. A.; their structure, minerals, and origin: *Proc. Amer. Acad. Arts & Sci.*, vol. **XLVII**, p. 125, 1911

Arsenopyrite is the most abundant sulphide and occurs both massive and as crystals commonly showing the forms:—

$$m(110),\ q(011),\ e(101),\ k(021),\ t(013).$$

Certain crystals of this mineral from Fitchburg, recently acquired by the Harvard Museum,[27] are somewhat complex and show, in addition to the above, the forms:

$$g(111), o(112), i(312), n(012), \phi(023), \tau(031), x(321), B(514).$$

These crystals form a parallel group about 1 cm. in diameter, and are in contact with beryl and quartz in which they leave sharp moulds. The forms $o(112)$, and $B(514)$ were both first found on crystals from Franklin, N. J., and later on crystals from a pegmatite in Newry, Maine.

Polished sections of arsenopyrite show that it is particularly pure and free from intergrowths and inclusions.

Rarely small masses of pyrrhotite occur which, in polished section, furnish excellent examples of supergene alteration to concretionary marcasite. Grains of chalcopyrite are frequently grown upon the pyrrhotite.

Molybdenite is extremely rare but occasionally occurs in fissures in the beryl vein, associated with late sericite and small garnets.

Conclusion

The general tenor of accumulated evidence suggests that pegmatites are by-products of the crystallization of intrusive magmas, and have been derived from the consolidation of the residual, more mobile mother liquor. Such a fundamental premise is entirely acceptable in the case of the Fitchburg pegmatites, for not only do the pegmatitic bodies lie wholly in granite, but the quartz and feldspar which form the bulk of their filling, though much coarser in texture, are similar in character to the quartz and feldspar of the granite itself. Moreover, certain accessory species occurring in the granite, occur also in the pegmatites.

Enquiry into the exact nature of the processes whereby the residual liquors (restmagma) became separated and emplaced presents more difficult problems. In the present instance, the pegmatites occur as apparently isolated lenses and discontinuous stringers, without any obvious connecting channel-ways. Observa-

[27] I am indebted to Professor Palache for crystallographic data concerning these crystals.

tions on the pipe-like pegmatites associated with the riebeckite-aegerite granite of Quincy, Mass., led Warren and Palache[28] to regard them as "closed-system" pegmatites, which had resulted from the imprisonment, and crystallization in situ, of large bubble-like accumulations of mother-liquor within the granite. In view of the apparent isolation of the lenses, such a theory might prove applicable to the Fitchburg pegmatites. Andersen[29], however, observes that large, apparently isolated, lenses of pegmatite lie outside the granite in certain localities, and he is therefore forced to the conclusion that the material has been introduced through cracks of a capillary fineness which ordinarily escape detection in the field. Another point worthy of consideration is that, at any given time, we only see a very small fraction of a pegmatitic lens, and although it may appear isolated, we cannot be certain that hidden "feeders" do not exist. Observations on the larger (tourmaline type) pegmatites at Fitchburg certainly suggest that they are of the "closed system" type, though in view of Andersen's observation, a definite conclusion is impossible. Their present shape may, at least in part, be due to deformation by external forces acting upon the somewhat mushy, newly consolidated granite. If this were actually the case, it is easy to understand why some of the early-formed crystals are fractured and off-set in the manner described.

Possibly the most striking feature of the Fitchburg pegmatites is that their textural features and accessory minerals enable them to be classified into the five very definite and distinct types, which have been described in detail in preceding pages. Evidence regarding the sequence in which the various types were formed is incomplete, but it is known that the biotite veinlets preceded the tourmaline-bearing pegmatites, and that these latter are intersected by the allanite veinlets. These facts, taken in conjunction with mineralogical characters and occurrences at other localities, suggest that the sequence of formation was: (a) the biotite type, (b) the tourmaline type, (c) the beryl type, (d) the titanite type, and (e) the allanite type.

In seeking an explanation of the origin of these contrasted types, it seems impossible to escape the conclusion that they represent

[28] Warren, C. H. and Palache, C. *op. cit.*

[29] Andersen, O. Discussions of certain phases of the genesis of pegmatites: *Norske Geol. Tidsskr.*, vol. **XII**, p. 14, 1931.

successive fractions arising from the progressive crystallization of the mother liquor. Continued crystallization of a magma containing volatile substances normally results in the progressive formation, first of pegmatitic residues, and later, of hydrothermal solutions. With the exception of the allanite stringers, the residues which gave rise to the Fitchburg types, do not appear to have evolved beyond the pegmatitic stage, and evidence of hydrothermal activity, though not entirely wanting, is very meagre.

The various materials constituting the pegmatites are tightly crystallized and present a frozen contact with the enclosing granite. Cavities are absent and there are no signs of extensive hydrothermal replacement. The replacement of tourmaline crystals by quartz appears to be of a magmatic type, and possibly resulted either from the action of "late-stage" magmatic liquors, or from changes of solubility brought about by fluctuations of temperature and pressure. A special feature of the Fitchburg pegmatites is the deuteric replacement of microcline by small masses of albite and albitic plagioclase. This effect is barely noticeable in the biotite veinlets, is moderately developed in the tourmaline type pegmatites, and reaches maximum development in the titanite veinlets. If the various types represent successively derived fractions, as suggested, then the later the fraction, the greater the tendency for this form of deuteric replacement to ensue. Albitization resulting in the production of cleavelandite—though absent at Fitchburg—possibly represents the continued trend of the process at a lower temperature, and on a more extensive scale.

At Fitchburg, only the allanite stringers and calcite veins appear to be of true hydrothermal origin. In places where the former intersect the tourmaline pegmatites, microcline has frequently been replaced by allanite. Sparsely distributed sulphides, and small garnets associated with arsenopyrite in sericite-filled fissures in the beryl-vein, represent minor expressions of hydrothermal activity.

Regarded separately, members of the biotite, tourmaline, and beryl types have resulted from one initial crystallization and, except to the very minor extent cited above have remained unmodified by later hydrothermal agencies. Adopting the classification recently proposed by Landes,[30] the principal tourmaline-bearing members correspond to simple normal granite pegmatites. Graphic

[30] Landes, K. K. Origin and classification of pegmatites: *Amer. Min.*, vol. **18**, p. 96, 1933.

granite does not occur at Fitchburg. Andersen,[31] who has studied zoned pegmatites, states that plagioclase-graphic-granite is first deposited, and is followed by microcline-graphic-granite and finally, by quartz and feldspar not intergrown in graphic fashion. Judged by this observation, the Fitchburg pegmatites formed at a somewhat lower temperature than those New England pegmatites showing graphic inter-growths.

Finally, the pegmatites described in this paper appear to be chiefly of interest in that they tend to reveal the changes occurring in the pegmatitic residues before they assumed the characters of high-temperature hydrothermal solutions. They still remained richly feldspathic, but contained progressively increasing amounts of soda which, prior to complete consolidation, reacted with and replaced the already crystallized microcline.

The author gratefully acknowledges his indebtedness to Professor Palache, whose teaching inspired this present study. He also records his deep gratitude to the Commonwealth Fund of New York City, under whose auspices he was privileged to study in the United States.

[31] Andersen, O. Discussions of certain phases of the genesis of pegmatites: *Norske Geol. Tidsskr.*, vol. **XII,** p. 27, 1931.