Tourmalinization in the Dartmoor granite.

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Introduction.

ON the basis of field relationships, the main types of the Dartmoor granite can be referred to four stages of intrusion, the sequence being from relatively basic to thoroughly acid.[1]

To this sequence is closely related an increase in the content of tourmaline and in the extent to which autopneumatolysis (with tourmalinization) was effective before solidification of the rock was complete.

Autopneumatolysis is well displayed by many minor intrusions referred to the latest stage. Such an intrusive rock is reddened more or less uniformly throughout its entire mass, and volatile constituents exhaled from its margin have reddened a contact-zone of the grey granite into which it is intrusive. In rocks which, like the intrusive rock mentioned above, were pneumatolysed during the course of crystallization and by their own volatile constituents, neither brookite nor anatase has been observed; whereas both these minerals are usual in reddened granite which, like that of the contact-zone, was pneumatolysed after its solidification was complete. The probability that brookite and anatase develop during tourmalinization, and mainly at the expense of the titanium-content of the biotite, has already been discussed.[2]

After biotite, tourmaline is the most abundant and constant accessory mineral in all the normal granite types except those referred to the

[1] A. Brammall and H. F. Harwood, The Dartmoor granite: its mineralogy structure, and petrology. Min. Mag., 1923, vol. 20, p. 53.

[2] A. Brammall and H. F. Harwood, The occurrence of rutile, brookite, and anatase on Dartmoor. Min. Mag., 1923, vol. 20, pp. 23-24.

earliest stage of intrusion. In the latter, tourmaline is either scanty or wholly absent, unless the mass has been affected by post-solidification pneumatolysis. In types referred to the second and third stages of intrusion both tourmaline and biotite are abundant, these two minerals occurring in roughly reciprocal proportions. In many types referred to the closing stage, tourmaline is present to the almost complete exclusion of biotite (e.g. in the Jordan aplite); or, as in much of the Holne Moor microgranite, biotite may persist, though much altered.

In the present paper, the modes of occurrence of tourmaline in the granite are described, and probable modes of origin are discussed. As reference will be made in certain cases to the association of tourmaline with some of the minor accessories, a list of the mineral assemblages characteristic of the chief granite types is given in the following table.

List of Accessory Minerals in the normal Granite.

	Stage I.	Stage II.	Stage III.	Stage IV.
Biotite	VA	VA–A	VA–A	A–nil
Tourmaline	s–nil	A–VA	A–VA	VA
Apatite	va	va	va	va
*Andalusite	—	s	vr	—
Cordierite	—	a	s–a	—
*Corundum	—	vr	vr	—
*Fluor	—	—	r	r
Garnet	—	l	s	vr
Ilmenite	s	a	a	l
Magnetite	s	s	s	r
*Molybdenite	—	r	—	—
Monazite	—	s	s	r
Muscovite	s	s	s–a	s
Pyrites	r	s	s	vr
Pyrrhotine	r	r	r	r
*Rutile	r	r	r	r
*Sillimanite	—	r	—	—
Sphene	vr	s–a	s–r	—
*Spinel	—	s	vr	—
*Topaz	—	r	r	r
Zircon	s	l	l	s

Dominant accessories: VA = very abundant, A = abundant.

Minor accessories: va = very abundant, a = abundant, l = less abundant, s = scanty, r = rare, vr = very rare.

* An asterisk denotes inconstant occurrence.

Notes to the foregoing table:

1. This approximate quantitative estimate is the average of determinations made in the laboratory on samples of granite collected at numerous localities. The samples were first crushed, and the crushed material was then examined

for mineral constituents by the methods usually employed with sedimentary rocks.

2. Among the minor accessories, the most variable, quantitatively, are muscovite, sphene, garnet, rutile, andalusite, spinel, and cordierite (including its alteration products); and the 'average' given in the table above would be qualified, in some cases considerably, for specific localities.

In the following studies of the modes of occurrence of tourmaline, the main purpose is to show that very little of the tourmaline can be described with absolute certainty as primary (pyrogenic) and co-ordinate with such minerals as zircon and phenocrysts of felspar, the primary character of which cannot be doubted.

Tourmaline: modes of occurrence and probable modes of origin.

In the normal grey granites, the following modes of occurrence of tourmaline have been observed:

1. (*a*) Minute grains isolated from 'baueritized' biotite,[1] and occurring, like zircon and apatite, as inclusions in the biotite.
   (*b*) Minute euhedrons in a biotitic groundmass, and comparable in size to the crystals of zircon, apatite, and monazite with which they may be associated.

Such tourmaline is of pre-solidification date, and it is probably primary.

2. Large irregular crystals of brown or parti-coloured tourmaline embedded in normal biotitic groundmass:
   (*a*) Replacing mats of biotite flakes, and sometimes reproducing the micro-structures of the mica flakes with striking fidelity.
   (*b*) Enveloping zoned plagioclase (marginally albite); blue at contact with the plagioclase (fig. 6).
   (*c*) Showing finger-like projections of blue tourmaline along the albite channels in perthitic orthoclase, which is thus 'stoped' for its albite and is itself replaced by brown tourmaline (fig. 2). In this connexion it may be remarked that tourmaline usually contains soda in excess of potash, and this fact may to some extent explain the replacement of albite before orthoclase in such cases as the one described.
   (*d*) Showing a blotchy (parti-coloured, brown and blue) 'design' more or less closely resembling groundmass-texture. The blue portion of such a 'design' may reveal the original outline of a plagioclase crystal which has been partly tourmalinized (fig. 7), and the design as a whole probably indicates that the constituents of a groundmass

[1] A. Brammall and H. F. Harwood, loc. cit., pp. 22–23.

complex have been tourmalinized individually, and without the accompaniment of fluxing. Plates of parti-coloured tourmaline optically continuous throughout are common.

The groundmass in contact with such tourmaline often contains the normal amount of biotite and plagioclase, both unaltered. It seems clear, therefore, that such tourmaline, though of pre-solidification date, is secondary, and that by its development the concentration of boric acid in the environing fluid became so reduced that biotite and felspar crystallizing out later remained unaltered.

3. (*a*) Well-formed crystals lining miarolitic cavities. These tourmaline crystals are associated with euhedral felspar, and occasionally also with quartz, fluor, and apatite. Such cavities are rare, and have been observed only in granite of stage III type. For a good specimen showing tourmaline, felspar, and fluor, the authors are indebted to Mr. W. Miners, of Widecombe.

The primary character of this cavity-tourmaline is at least doubtful. It may conceivably have developed at the expense of biotite and felspar exposed to the vapours which distended the viscous mass and formed the cavity.

(*b*) Aggregates of parti-coloured tourmaline (both granular and prismatic) embedded in orthoclase phenocrysts and thus completely isolated from the groundmass. These cannot safely be regarded as primary; nor can similar aggregates enclosed in a mat of biotite flakes.

4. (*a*) Schorl-quartz pseudomorphs after orthoclase phenocrysts, embedded in normal grey groundmass. This tourmaline is of course secondary.

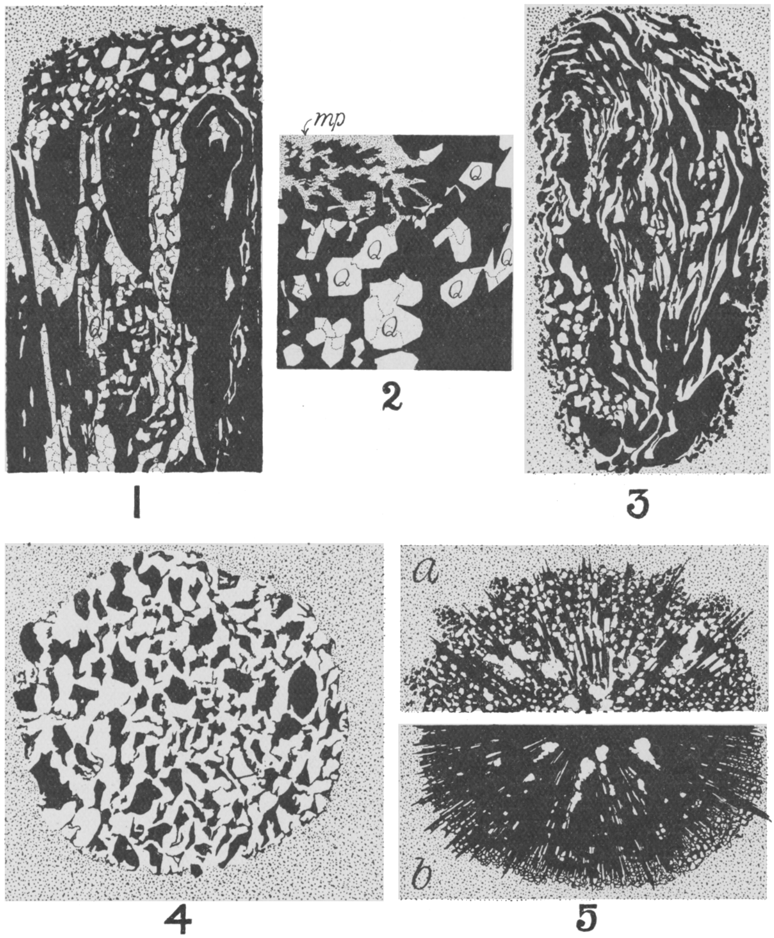
The same 'black' pseudomorphs have been observed also in rocks reddened by post-solidification pneumatolysis.

(*b*) Coarse-grained 'black' tourmaline (parti-coloured or zoned) which, with quartz, has replaced the groundmass of granite in bulk, the orthoclase phenocrysts being replaced by granular quartz. Post-solidification pneumatolysis is clearly indicated.

The best examples so far observed of this type of tourmalinized granite occur in the form of huge boulders, four tons or more in weight, in a depression some 700 yards due south of Haytor Rocks.

Somewhat similar boulders on Hamel Down have yielded brookite, anatase, and cassiterite (assaying at 19 lb. to the ton), together with topaz, zircon, &c.

The characters of this boulder-stone merge into those of quartz-



Figs. 1–5.

Types of micro-structure displayed by the tourmaline-quartz nodules in the Dartmoor granite. (Tourmaline—black ; quartz—white.)

Fig. 1. Cross-fracture showing the 'coralloid' structure. ×5.

Fig. 2. Transverse section of nodule (fig. 1), showing polygonal areas of quartz mosaic, and a plate of microperthite (*mp*) partly 'stoped' of albite by blue tourmaline (brown at contact with orthoclase). ×9.

Fig. 3. Lamellar structure. ×5.

Fig. 4. Granular aggregate of tourmaline and quartz, showing sharp boundary against the groundmass ; the most common type. ×5.

Fig. 5. Radiate structure ; a type common in aplites. Granular tourmaline and quartz (with a little orthoclase usually) traversed by acicular crystals of tourmaline. (*a*) ×2/5 ; (*b*) ×2.

schorl vein-rock, which is specially abundant along the axes of minor valleys and depressions, although granite in the immediate neighbourhood may show few if any traces of pneumatolysis.

5. Granules, prisms, and plates in the tourmaline-rich nodules described below.

Tourmaline-rich nodules in the granite.

These nodules are abundant in most post-stage I types of the granite. They are more resistant than granite to weathering, and on the weathered surfaces of tor-rock they are often conspicuous as wart-like protuberances

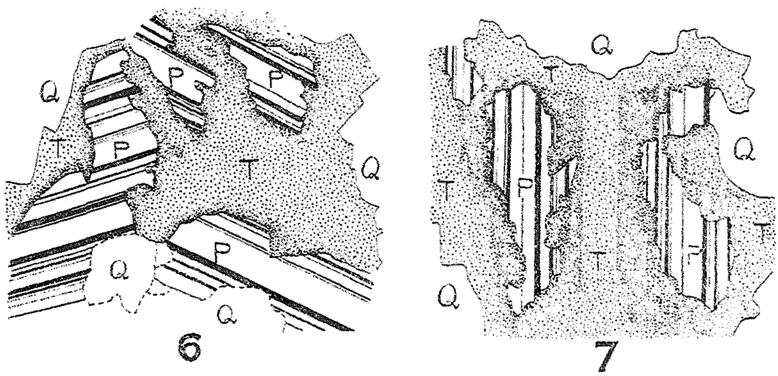


FIG. 6. Optically continuous plate of brown tourmaline replacing zoned plagioclase (marginal zone, albite); blue at contact with plagioclase. ×15.

FIG. 7. As for fig. 6. Illustrating a mode of origin of some parti-coloured tourmalines. The area occupied originally by plagioclase is now occupied by blue tourmaline. ×15. Q = quartz, T = tourmaline, P = plagioclase.

up to several inches in diameter. They tend to be rounded or ellipsoidal in shape, but jagged and very irregular masses are common.

(*a*) *Texture and micro-structure.*—The average texture of a nodule is usually coarse or fine according as the nodule occurs in coarse-grained granite or fine-grained aplite. The micro-structure often varies with the direction in which the nodule is sliced. The following varieties, based on texture and micro-structure, are noted as being representative:

1. *Coralloid.*—Irregular prisms of tourmaline in granular quartz. Two or more prisms may be in optical continuity via lateral processes extending across the channels of quartz (fig. 1). The tourmaline is usually brown or parti-coloured (blue and brown). Colour-zoning is uncommon, but may be pronounced.

2. *Lamellar.*—Layers of tourmaline alternating with layers of granular quartz. The tourmaline of several layers may be in optical continuity. Zoning is rare (fig. 3).
3. *Granular.*—Tourmaline-quartz mosaic (fig. 4) or tourmaline enclosing quartz poecilitic fashion (fig. 2). In thin slices, quartz enclosed in tourmaline often shows a polygonal outline suggestive of idiomorphism, but examination of the quartz between crossed nicols usually resolves the polygonal section into a mosaic (fig. 2).

   The micro-structures described under 1–3 above suggest that the tourmaline crystallized out from a system in a more or less perfect state of flux.[1] In some examples of the 'coralloid' and granular types, the tourmaline is strongly zoned; in others, parti-colouring in the larger plates of tourmaline recalls the micro-structure of groundmass (cf. figs. 7 and 9).
4. *Radiate.*—Acicular tourmaline developed radially and traversing a granular aggregate of tourmaline, quartz, and altered felspar, usually orthoclase (fig. 5 *a*). In rare instances, the tourmaline is wholly acicular, and radially arranged (fig. 5 *b*). This type of nodule is common in aplites.

(*b*) *Mineral Composition.*—Felspar is scanty or wholly wanting in most nodules, but felspathic tourmaline-quartz nodules are not uncommon. The content of minor accessories is on the whole consistent with the type of granite in which the nodule occurs. An examination of a suite of nodules from granite of stage II type on Hamel Down yielded the following interesting assemblages of minerals:

Apatite—as stout prisms; abundant.

Zircon—strongly zoned; subordinate in amount to apatite.

Andalusite—scanty, but markedly pleochroic (blood-red to green).

Garnet—red; scanty.

Monazite—scanty; partly rounded by corrosion.

Sphene—very abundant; as transparent colourless grains bounded, in part, by crystal faces, and showing strong dispersion.

Rutile and ilmenite—very scanty. (Anatase and brookite absent.)

Cassiterite—as rare grains. The occurrence of this mineral was regarded by the authors at first with some suspicion, but it was confirmed by examination of nodules collected later from the same locality.

[1] Compare the following blowpipe reactions. In the borax bead all silicates are fluxed. In microcosmic salt all silicates except the borosilicates (e. g. tourmaline and axinite) leave an infusible residue of silica.

Qualitatively, this assemblage (excluding cassiterite) is characteristic of high-level granites of this type. Quantitatively, however, sphene is much in excess of the average, while ilmenite is much below the average. Moreover, the sphene is unusually clear and transparent.

If, as seems probable, the tourmaline in these nodules is secondary and was formed at an early stage of crystallization in the magma, the abnormal abundance of sphene, the unusual scantiness of ilmenite, and the complete absence of brookite and anatase, may have a genetic significance: titanium dioxide liberated on the breakdown of original biotite and ilmenite may enter sphene at magma-temperature; whereas under conditions of post-solidification pneumatolysis it forms brookite and anatase.

Modes of origin.—It is conceivable that fluid patches specially rich in borosilicate flux may segregate from the fluid magma at an early stage and crystallize as an aggregate of tourmaline and quartz similar to nodules of types 1–3 described above. On the other hand, that such nodules do result from the pneumatolysis of already crystallized minerals of the groundmass is suggested not only by the phenomena described on pages 321–2, but also by a suite of tourmalinization phenomena observed in a reddened granite on Hamel Down. In the groundmass of this granite, small areas of felspar and biotite are attacked at several clustered spots, and zoned tourmaline has developed sporadically, especially in the felspar (fig. 10). Such clustered grains of zoned tourmaline appear to have developed progressively into larger masses of zoned tourmaline (figs. 8 and 9). In some sections of these nodules there occur small cavities containing tabular anatase in addition to rutile and quartz. In nodules of types 1–3 described above, such cavities have not been observed, nor has either anatase or brookite been detected, though sphene is often abnormally abundant and ilmenite unusually scarce.

The nodules containing zoned tourmaline (with anatase) may conceivably have arisen at a *late* stage in the crystallization of the groundmass, and as a result of autopneumatolysis. Tourmaline veins are numerous, however, at this locality, and autopneumatolysis of a stage II granite type is at least doubtful. But whether the nodules of zoned tourmaline (with anatase) arose before or after the completion of crystallization in the groundmass, the anatase has merely the status of a secondary mineral.

Among the nodular inclusions common in the granite, those composed of fine-grained 'basic' granite comparable to the granite of stage I type rarely contain tourmaline except in their marginal zones. Killas inclusions, usually altered to hornfels, are similarly free from tourmaline.

On the other hand, small basic segregations composed essentially of biotite and plagioclase, with very little quartz, are of common occurrence; so also are patches similar to these clots but containing also tourmaline.

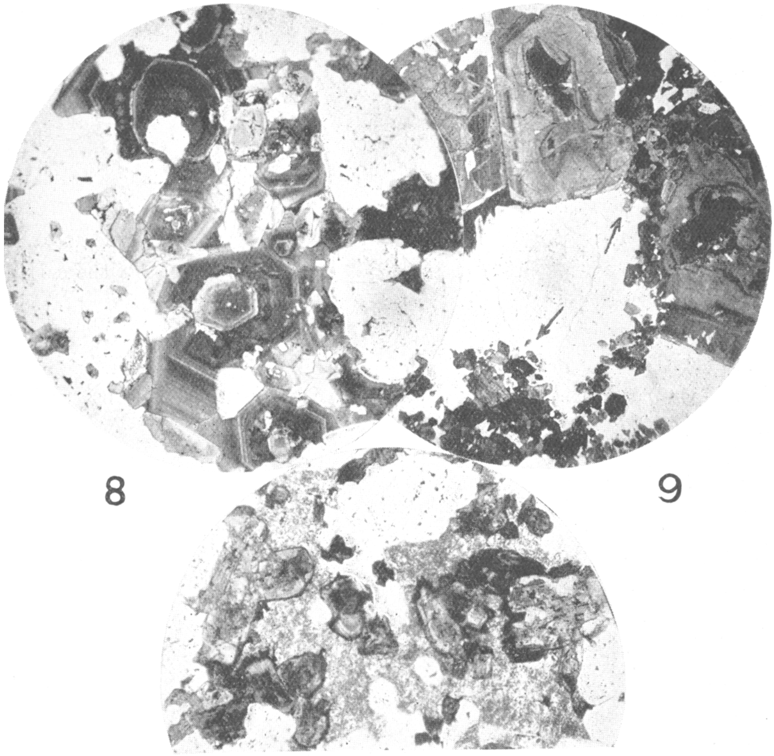


FIG. 8. Zoned tourmaline (secondary), and quartz enclosing grains of tourmaline. Minute cavities in the tourmaline are infilled with quartz enclosing rutile and anatase. ×20.

FIG. 9. Secondary tourmaline; parti-coloured cores and colour-banded marginal zones, with marginal outgrowths of schorl embedded in quartz. The cores show tourmaline pseudomorphs after biotite and plagioclase. ×20.

FIG. 10. Zoned brown tourmaline (secondary), developing at several centres in orthoclase. ×20. Compare the cluster of similar tourmaline crystals indicated by the arrows in fig. 9.

(Photomicrographs figs. 8–10 represent parts of one and the same nodule.)

The authors are of opinion that some at least of such basic segregations were completely tourmalinized at an early stage in the crystallization of the magma, and became the nuclei of tourmaline-rich nodules.

The radiate tourmaline-quartz nodules common in aplite are fairly uniformly distributed throughout the aplite mass. Growth appears to have been rapid. In some 'grey' vein-types containing biotite, the groundmass around a nodule is free from biotite.

Mineral changes involved in the conversion of a basic segregation to the nucleus of a tourmaline-quartz nodule.

In the following section an attempt is made to present some idea as to the nature of the reactions involved in the conversion of basic segregations to tourmaline-quartz nodules by the mechanism presumed above.

Confining ourselves to occurrences in granite of stage III type, we will assume that the plagioclase approximates to albite and that the early-formed biotite has approximately the composition of the mica analysed from this type.[1]

A partial analysis of the parti-coloured tourmaline in a typical nodule showed that, as in the majority of tourmaline analyses, soda is considerably in excess of potash, the results obtained being $Na_2O = 1{\cdot}50\,\%$, $K_2O = 0{\cdot}06\,\%$.

Taking the ratio FeO : MgO in the biotite as a further convenient basis for the selection of a possible tourmaline as the end-product, we find that this ratio is closely approached in five analyses of tourmaline cited by Dana.[2] Rejecting two of these on the ground of colour alone, and another on account of its relatively high content of manganous oxide, there remain two analyses (nos. 15 and 16) which are comparable with the biotite, no. 16 showing the closest agreement.

On the basis of the biotite and tourmaline thus selected, the following calculations are made:

Available in the basic segregation:	Grams.	*Products:*	Grams.
Biotite (titaniferous):		Tourmaline	147·25
Analysis total, less $H_2O(-)$ . . .	99·36	Sphene	4·32
Plagioclase:		(No free silica)	
Albite, for balance of soda required . . .	20·95		
Anorthite, for balance of lime required . .	2·41		

[1] A. Brammall and H. F. Harwood, loc. cit., 1923, p. 23.

[2] Dana's 'System of Mineralogy', 6th ed., 1892, pp. 554–5, analyses nos. 15, 16, 17, 27, and 33.

Additional requirements:	Grams.		*Losses*:	Grams.	
Boric acid . .	14·28		Excess potash .	7·86	
Alumina . .	21·59		Fe_2O_3 unallotted .	3·49	
Silica . . .	5·83		Li_2O, F, V_2O_3, &c.	1·50	
	——	41·70		——	12·85
	Total	164·42		Total	164·42

The deficiency of alumina and silica noted in the left-hand column, considered in relation to the large amount of free silica present in the nodules, may be explained in two ways:

1. The magma may supply not only the required boric acid, but also other constituents, including alumina and silica.
2. The original basic segregation may contain felspar in excess of the minimum (plagioclase) assumed. If such felspar be drawn upon to supply the deficit of alumina and silica, the quartz present in the nodule could be reasonably explained as residual silica. Of the two alternatives, this seems to be the more probable.

Calculations based on other tourmaline analyses indicate a similar deficiency of alumina and excess of alkali (chiefly potash) in the original basic segregation. If this be assumed as the general case, it follows that the formation of tourmaline on the scale observed in granites of post-stage I type must have appreciably disturbed the balance between potash and alumina in the magma. Thus potash may have been made available to promote the formation of mica from killas material caught up, and to an appreciable extent assimilated, by the magma.

Summary and Conclusions.

The magma-fraction represented by the earliest and most 'basic' type of Dartmoor granite was essentially free from those volatile constituents which promote the genesis of tourmaline.

The magma-fractions which yielded the later and progressively more acid types contained these volatile constituents in increasing concentration. In the products of the latest stage of intrusion, the concentration was such that the intrusive bodies were more or less severely pneumatolysed before crystallization was complete.

During the closing phase, the granite of east Dartmoor was affected by severe tensions. Numerous fissures opened, and afforded passage-way for fluids and gases from depth. These cracks and fissures were infilled with schorlaceous vein-stuff, quartz-schorl-rock, vein-quartz, or ore-bodies carrying specular iron-ore, or cassiterite, or both these minerals. The closing phase was marked by local tourmalinization of granite in place.

The tourmaline in the granite may be classified according to mode of origin as follows:

Pre-solidification: (*a*) Primary, pyrogenic.
(*b*) Secondary, directly replacing or pseudomorphing felspar and biotite; or developing from a borosilicate flux of felspar, biotite, &c.

Post-solidification: Secondary, as for (*b*) above.

The greater part of the tourmaline is secondary.

It is probable that the titanium-content of biotite and ilmenite which become contributory to tourmaline enters sphene and rutile when tourmalinization takes place at magma-temperatures, and that it forms anatase, brookite, or rutile under conditions of post-solidification pneumatolysis.

The authors consider it probable that basic clots formed in the fluid magma were tourmalinized at an early stage and became the nuclei of some at least of the tourmaline-rich nodules which are common in the coarse-grained granites.

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