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The occurrence of a gold-bearing pegmatite on Dartmoor.

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Introduction.

A REMARKABLE pegmatite occurring on Bittleford Down (Wind Tor), near Widecombe, is described in the Survey Memoir [1] as a vein-rock containing (*a*) abundant hornblende, a mineral not previously found in any of the post-Carboniferous granites of the west of England, (*b*) much sphene, (*c*) porphyritic crystals of oligoclase, and (*d*) quartz crowded with fluid inclusions.

This rock is of peculiar interest in other respects. Its complete freedom from biotite and its high content of felspar (oligoclase dominant over orthoclase) imply considerable deviation in bulk composition from the normal Dartmoor granite. Moreover, its accessory minerals include both gold and silver.

[1] The Geology of Dartmoor, Mem. Geol. Survey, 1912, p. 41.

Considered broadly as a coarse-grained felsic type, its position in the list of variants from the normal granite is shared by a still more felsic rock with which it is closely associated in the field. This rock is intrusive in the normal granite of the Bittleford locality ; but it was first observed as a broad dike-vein in the normal granite at Wittabarrow, which is regarded as the type locality.[1]

The two rocks present the most noteworthy contrast in mineral and chemical composition yet observed among the numerous coarse-grained modifications of the granite. This paper presents the results of a detailed petrological study of these rocks.

Occurrences.

The Bittleford Pegmatite.—This rock occurs as boulders, some half a ton or more in weight, lying loose on the surface of the moor or partly sunk in the turf. The boulders are strewn over a belt about 50 yards wide at its northern limit immediately below Wind Tor. The boulder-belt fans out somewhat as it extends south-west towards the bank of the West Webburn between Jordan and Ponsworthy, where it terminates abruptly. Boulders of the same rock-type have been found in the bed of the West Webburn near Ponsworthy and on the left bank of the East Webburn below Scobitor (Cockingford). A few small blocks have been observed at low levels between Jordan and Challacombe about 2½ miles to the north ; also between Jordan and Corndon, and at a few other localities.

The source of the boulders must have been a substantial body of rock ; but after an exhaustive search of the Bittleford locality the authors are convinced that the pegmatite is not here *in situ.* Nor is a concealed outcrop suspected ; for a trench opened up across the boulder-belt revealed at least 17 feet of 'head', only the upper layers of which contained blocks of the pegmatite.

Minor boulder-belts occur (1) on Dunstone Down, (2) on the west slope of Hamel Down, half-a-mile north of Wind Tor, and (3) at Ponsworthy, in the northern part of Cleave Wood.

The Wittabarrow Felsic Rock.—This rock is not restricted to the type locality. It occurs *in situ* as a sill-like sheet injected along the pseudo-bedding planes in the 'giant granite' (stage 2 type)[2] capping Wind Tor. Sheets and transgressive veins of the rock, intrusive in the same granite

[1] A. Brammall and H. F. Harwood, The Dartmoor granite : its mineralogy, structure, and petrology. Min. Mag., 1923 (June), vol. 20, pp. 41-42.

[2] Ibid., p. 53.

type, occur on Pudsham Down, at Hollow Tor (east of Widecombe), Bell Tor, and Sharp Tor; also in a small cliff on the left bank of the East Webburn below Cockingford; on the slope below the scarp-like face of Corndon Tor, and elsewhere.

The rock is clearly of post-stage 2 age. It may therefore belong to either the 'blue granite' (stage 3) epoch,[1] or to the later stage characterized by aplitic injections (e.g. the Jordan dike), quartz-tourmaline veins often bearing specular iron-ore and cassiterite, and by extensive pneumatolysis.

As the relative age of the Bittleford pegmatite is not determinable on the basis of direct field evidence, the results of detailed mineral and chemical analyses were examined for data bearing on the petrological relationship of the pegmatite to the Wittabarrow rock on the one hand, and to the two main granite types on the other.

Mineral and Chemical Composition.

Chemical Analyses.—Bulk-analyses of these four rocks (each from its type locality) are given below (the first two being repeated from this vol., p. 41), together with an analysis of the biotite in the stage 2 granite. An analysis of the biotite in the stage 3 granite has already been published.[2]

	I. 'Giant Granite' Saddle Tor (Stage 2).	II. 'Blue Granite' Haytor E. Q'y (Stage 3).	III. Witta-barrow Felsic Rock (Post-stage 2).	IV. Bittleford Pegmatite (Age ?).	— Biotite Saddle Tor Granite.
SiO_2	71·69	73·66	73·16	72·29	33·84
Al_2O_3	14·03	13·81	13·95	14·46	20·57
Fe_2O_3	0·57	0·21	0·03	0·19	3·90
FeO	1·93	1·51	0·47	0·44	18·74
MgO	0·66	0·45	trace	0·97	5·59
CaO	1·49	0·67	0·43	2·42	0·45
Na_2O	3·03	2·89	2·57	4·53	0·40
K_2O	4·59	5·02	8·16	2·43	9·03
$H_2O(+110°)$	1·29	1·25	0·31	0·76	3·39
$H_2O(-110°)$	0·47	0·41	0·33	0·66	1·41
CO_2	nil	nil	nil	nil	—
TiO_2	0·33	0·16	0·04	0·48	1·39
ZrO_2	nil	trace	nil	nil	nil
P_2O_5	0·23	0·24	0·16	0·21	—
Cl	trace	0·01	trace	trace	—
F	—	—	—	—	0·91

[1] A. Brammall and H. F. Harwood, loc. cit., 1923 (June), p. 53.
[2] Ibid., 1923 (March), p. 23.

	I. 'Giant Granite' Saddle Tor (Stage 2).	II. 'Blue 'Granite' Haytor E. Q'y (Stage 3).	III. Witta-barrow Felsic Rock (Post-stage 2).	IV. Bittleford Pegmatite (Age ?).	— Biotite Saddle Tor Granite.
S	nil	nil	trace	nil	—
C	—	—	—	—	—
MnO	0·06	0·06	0·01	0·02	0·48
BaO	trace	trace	trace	nil	0·02
SrO	nil	nil	nil	nil	—
Li_2O	trace	trace	trace	trace	0·19
Cr_2O_3	—	—	—	—	trace
V_2O_3	—	—	—	—	0·04
Total (less O for F)	100·37	100·35	99·62	99·86	99·92

Mineral Composition.—The composition of these rocks has been determined in terms of both actual and ' norm ' minerals, full advantage having been taken of the fact that the composition of the biotites, as well as that of the felspars and minor accessories, is known.

For the purpose of computing the actual mineral composition, a careful estimate of the percentage amounts of biotite and tourmaline was essential. The percentages given for these two minerals in the following tables were decided upon after consideration of estimates obtained by several methods of computation.

A theoretical *maximum* percentage for biotite is determinable directly from the bulk-analysis in each case, but this maximum must be corrected to allow for tourmaline (present in all the rocks), amphibole (present only in the pegmatite), and for some of the minor accessories. Partial analyses of tourmalines and of the amphibole provided a guide to the allotment of iron, magnesia, and lime.

Percentages regarded as certainly approaching the *minimum* for both biotite and tourmaline were computed from the results of fractional separation carried out on crushed rock material (freed from rock-flour) by means of heavy liquids, the electromagnet, and several tedious subordinate devices. The latter included abstraction of mineral grains by means of the camel-hair brush, elimination of apatite by digestion with cold nitric acid, and ' baueritization ' of biotite, followed by elimination of the ' bauerite ' by heavy liquids.[1]

Micrometric estimations of the percentage amount of biotite were found to approach more nearly to the theoretical maximum than to the minimum.

[1] A. Brammall and H. F. Harwood, loc. cit., 1923 (March), p. 22.

The authors are satisfied that the figures given approximate closely to fact, so far as the more important minerals are concerned. For tourmaline, however, the figures are certainly a little too high: the rock samples actually analysed were free from the conspicuous nodes of tourmaline common in all the types.

Approximate Mineral Composition.

	I. 'Giant Granite' (Stage 2).	II. 'Blue Granite' (Stage 3).	III. Wittabarrow (Post-stage 2).	IV. Bittleford Pegmatite.
Quartz	34·0	36·8	25·9	31·2
Orthoclase	22·3	26·2	48·1	14·5
Plagioclase *Ab*	25·4	24·4	21·7	37·7
Plagioclase *An*	5·7	1·7	1·1	6·8
Biotite	9·6	7·9	0·5	nil
Tourmaline	0·8	0·3	1·3	1·2
Amphibole	nil	nil	nil	5·2
Sphene	trace	nil	nil	1·1
Apatite	0·54	0·52	0·38	0·51
Ilmenite	0·4	0·04	0·06	0·06
Haematite	nil	nil	nil	0·07
Minor Accessories (See Note 2)	0·6	0·4	0·3	0·12
Deficiency % (See Note 3)	0·66	1·74	0·66	1·54
	100·00	100·00	100·00	100·00

NOTES.—(1) The plagioclase in rocks I and IV is an oligoclase, whilst in II and III it is an albite.

(2) *Minor Accessories:*

I. '*Giant Granite*' (Saddle Tor). Zircon,[1] garnet, pyrites, pyrrhotite, cordierite (with pinite), andalusite, sillimanite, spinel, corundum, monazite, muscovite, molybdenite, topaz, barytes, rutile.

II. '*Blue Granite*' (Haytor East quarry). Zircon, pyrites, pyrrhotite, topaz, fluor, muscovite, monazite, garnet, ? pinite.

III. *Wittabarrow Felsic Rock.* Pyrites, pyrrhotite, zircon, fluor, muscovite, monazite, topaz.

IV. *Bittleford Pegmatite.* Pyrites, pyrrhotite, zircon, molybdenite, gold, and silver.

Pneumatolysed varieties of these rocks yield very different assemblages of accessory minerals.[2] Anatase and brookite are characteristic; specular iron-ore is common; topaz, fluor, apatite, monazite, and chalcedony are less common; cassiterite is rare.

[1] A. Brammall and H. F. Harwood, loc. cit., 1923 (March), pp. 27–31.

[2] Ibid., pp. 20–26.

(3) *Percentage Deficiency.*—Quantitative estimation of mineral species present in a solid rock must necessarily be an approximation only, even when a useful check in the form of bulk analysis is available. This is particularly true as regards minor constituents.

The deficiencies given above could probably be disposed of by purely arbitrary allotment of water and alumina to sericite or kaolin, or to both; by trivial provision for chlorite, limonite and (in the case of the pegmatite especially) for fluid inclusions in quartz. Moreover, the percentages given for the minor accessories express little more than the order of magnitude of the actual percentages. In the four cases dealt with, discrepancy takes the form of 'deficiency': were other rocks similarly analysed, 'excess' is equally likely.

The relative age of the Bittleford Pegmatite.

The variation in mineral composition shown by the four rocks is displayed graphically in fig. 1. This variation-diagram indicates that:

(*a*) The rocks constitute a suite, within which variation is progressive.

(*b*) The Wittabarrow rock is essentially an orthoclase-quartz-albite rock, allied by specific plagioclase content to the stage 3 granite.

(*c*) The Bittleford pegmatite is an oligoclase-quartz-orthoclase rock, allied by its plagioclase to the stage 2 granite.

In the Dartmoor intrusion-sequence, a definite break between the epochs represented by the two main granites is demonstrable.[1] Moreover, the field evidence indicates very definitely a post-stage 2 age for the ittabarrow rock. As the variation-diagram links the latter closely with the stage 3 granite, it is reasonable to infer that the Wittabarrow rock is a leucocratic (felsic) variant of that granite. It is difficult to avoid the conclusion that the Bittleford pegmatite stands in analogous relationship to the stage 2 granite.

The correlation thus inferred is in harmony with the grouping of the four rocks according to the Cross-Iddings-Pirsson-Washington system of classification, thus:

III.	Wittabarrow Rock	1.4.1.2. (Omeose)
II.	'Blue Granite' (Stage 3) ...	1.4.1.3. (Liparose)
I.	'Giant Granite' (Stage 2) ...	1.4.2.3. (Toscanose)
IV.	Bittleford Pegmatite	1.4.2.4. (Lassenose)

This correlation may possibly explain the restricted occurrence of some at least of the minor accessories, e.g. fluor and molybdenite.

The derivation of the Wittabarrow rock from the magma which yielded the main stage 3 granite implies differentiation

(*a*) in favour of felsic minerals at the expense of biotite,

[1] A. Brammall and H. F. Harwood, loc. cit., 1923 (June), pp. 40–42

(b) in favour of orthoclase at the expense of plagioclase, i.e. in favour of potash at the expense of soda and lime.

The derivation of the Bittleford pegmatite from the stage 2 magma would thus involve differentiation (as regards the felsic constituents) in an opposite and reciprocal sense.

In typical specimens of the fresh rock, the felspars are dense with minute flakes of secondary white mica (sericite or paragonite) to an extent unusual in Dartmoor types. This fact, considered in conjunction with the presence of amphibole and haematite, and with the abundance of fluid inclusions in the quartz, suggests that the magma-fraction of which the pegmatite is the product was highly aqueous. The Wittabarrow

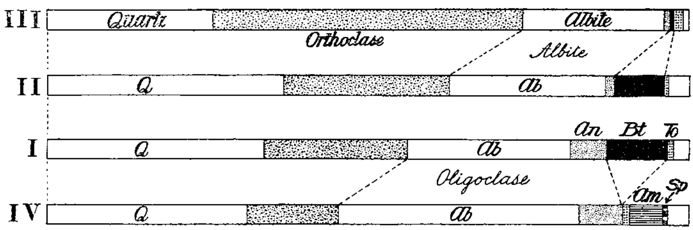

FIG. 1. Diagram representing the mineral composition of the four rocks.

rock, on the other hand, appears to be the product of a relatively dry magma-fraction.

In this connexion may be mentioned the fact that a 'melanocratic' vein-rock containing 20 % or more of biotite, together with porphyritic orthoclase, has been observed in the Widecombe district.

A brief petrological description of the pegmatite.

The Bittleford pegmatite is a tough, compact, coarse-grained rock, greenish-grey when fresh, weathering pinkish to dead white. Porphyritic crystals of oligoclase and of orthoclase are embedded in a matrix composed of oligoclase, quartz, orthoclase, pale-green amphibole, brown sphene, apatite, and haematite. A polished surface of the fresh rock is delicately colour-mottled—red, pink, green, grey, and white. Micrographic intergrowths of quartz and felspar are common (fig. 2, b). Similar intergrowths of amphibole and oligoclase also occur (fig. 2, c).

The amphibole is a pale-green, fibrous variety. In thin section, it resembles tremolite very closely. Occasionally it plays the part of a porphyritic constituent; most usually, however, it occurs as irregular masses enclosed in felspar. It is an aluminous silicate of magnesia, lime, and iron, and contains also a trace of manganese. Its birefringence is about 0·022. In longitudinal sections, the extinction-trace makes a maximum angle of 28° with the cleavage-traces, the character of the extinction-direction being positive. It recalls edenite, a variety characteristic of altered limestones rather than of igneous rocks. It weathers from pale-green to rose-pink, this colour change being due doubtless to the oxidation of ferrous iron. Neither field evidence nor the results of laboratory work on this rock warrant assumption that the amphibole is attributable to assimilation of greenstone or other country-rock. The same view is expressed in the Survey Memoir in reference to this rock.

Brown sphene showing remarkable pleochroism and dispersion is a conspicuous accessory. It occurs both as eumorphic crystals of the familiar type, and as irregular grains, often arranged as lines of inclusions in felspars (fig. 2, *a*). Crystals occasionally form fan-like and spiral aggregates, due probably to repeated contact-twinning (fig. 2, *b* and *d*).

Tourmaline tends to form conspicuous nodes, though such aggregates are far less common in this rock than in either of the two main granites. Amphibole, sphene, apatite, and ilmenite are often very abundant around the margins of a tourmaline aggregate (fig. 2, *c*).

Apatite is usually a conspicuous accessory.

The Gold and Silver.

Gold occurs as minute specks or gold-leaf spangles up to 1 mm. across, embedded in felspar and quartz. The largest particle observed occurs on the fracture-surface of a sample of the grey variety of the pegmatite. Microscopic specks, one or two to the square inch, have been observed in an exceptional specimen of the pinkish variety, the felspars of which are not less fresh than those of the grey rock. Some of these specks were isolated by the use of a needle and a strong pocket-lens.

Eleven representative samples of the pegmatite have been assayed by Assistant-Professor B. W. Holman, of the Royal School of Mines, whose kindness in this matter the authors gratefully acknowledge. He reports as follows:

'Although I found visible gold in several of the specimens examined, the specks were particularly small, and not such as to cause serious discrepancies in the assays.

The samples gave bullion-values, per long ton (2,240 lb.), ranging from 24·1 dwt. (0·0040 %), i.e. 9·1 dwt. (0·0014 %) gold and 15 dwt.

FIG. 2. Photomicrographs of the Bittleford Pegmatite.

(*a*) Irregular granules of sphene arranged as lines of inclusions in oligoclase; together with amphibole, apatite, and a little quartz. × 25.

(*b*) A fan-like aggregate of sphene crystals in a groundmass composed partly of a quartz-felspar eutectic and partly of an intricate intergrowth of felspar, quartz, and amphibole. × 30.

(*c*) A micrographic intergrowth of amphibole and felspar adjacent to an aggregate of tourmaline, amphibole, and ore-particles. × 21.

(*d*) Apatite in a spiral aggregate of sphene crystals. Growth-extension of the sphene has been hindered by a well-formed crystal of amphibole (upper part of the field). The rest of the field consists mainly of felspar enclosing ragged patches of amphibole. × 21.

(0·0023 %) silver, to 1·5 dwt. (0·0003 %), i.e. 0·4 dwt. (0·0001 %) gold and 1·1 dwts. (0·0002 %) silver. No sample was barren of either metal. Five samples gave values above 7 dwts. (0·0011 %); low values predominate. In all the samples except two, silver is in excess of gold; for one sample, the total of 8·4 dwt. (0·0013 %) included 7·8 dwt. (0·0012 %) silver. The occurrence of such an excess of silver in this association is unusual.'

Silver in the free state has not been isolated directly from the rock. It is uncertain how this metal occurs. Among the metallic specks have been observed some which are somewhat silvery, and it is probable that the metal occurs, in part at least, alloyed with the gold. Silver was looked for in the sulphidic accessories, essentially pyrrhotite. The electromagnetic concentrate obtained from about 250 grams of the crushed rock by means of the Ullrich separator was assayed and found to contain both gold and silver, in amount equivalent to 3·1 dwt. (0·0005 %) per ton of rock. Of this amount, only 0·5 dwt. was silver.

Gold is known from three other localities in Devon: North Molton,[1] where it occurs in slate; Torquay, where it occurs in limestone,[2] and Sheepstor,[1] a locality in west Dartmoor and within the granite area. Of these occurrences, the first two certainly present no analogy with that at Bittleford. The Sheepstor occurrence may, however, be comparable, though the record given by Greg and Lettsom for this locality is vague, and gives no hint as to mode of occurrence.

According to Dartmoor tradition, particles of gold were occasionally found by the tin-miners of olden days, but whether in the lode-rock or in alluvium tradition does not say.

A. Lacroix records the occurrence of gold in pegmatite.[3] The same author quotes C. F. Lincoln (1911) in respect of fifteen occurrences of the metal in granite. References to other occurrences are cited in the foot-note.[4]

Summary.

The gold-bearing Bittleford rock does not occur *in situ* at the type locality. It is a true igneous rock, and a product of a somewhat aqueous

[1] R. P. Greg and W. G. Lettsom, Mineralogy of Great Britain and Ireland, 1858, p. 237.

[2] W. T. Gordon, Nature, London, 1922, vol. 109, p. 583.

[3] A. Lacroix, Minéralogie de Madagascar, 1922, vol. 1, p. 163; vol. 2, p. 26.

[4] G. P. Merrill, Amer. Journ. Sci., 1896, ser. 4, vol. 1, p. 309 (Abstr. Min. Mag., vol. 11, p. 227). W. P. Blake, Trans. Amer. Inst. Min. Eng., 1897, vol. 26, p. 292.

fraction of the magma represented by the older of the two main granite types. Its affinities are with the pegmatites, and its position in the Dartmoor suite is among the minor intrusions. The gold and silver which it contains appear to be no less primary than the rest of the minerals with which these metals are associated.

The laboratory work necessary in connexion with the investigation of these rocks was carried out in the Departments of Geology and Chemistry, Imperial College. The authors express their thanks to Professor W. W. Watts and Professor H. B. Baker for laboratory facilities kindly placed at their disposal.