Dravite-bearing rocks from Dinas Head, Cornwall.

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IN a previous paper [1] describing the geological and petrographical details of the adinoles of Dinas Head, short references were made to the common occurrence among the adinoles and associated rock-types of the magnesia-rich tourmaline, dravite. It is proposed now to describe these tourmaline-rich rocks in more detail and to discuss the question of their origin.

Distribution of Dravite-bearing Rocks.

Adinoles with accessory tourmaline occur wherever true adinoles are developed at Dinas Head, although tourmaline is characteristically absent from types 2 *a*, *b*, *c*, and 3 [1, pp. 318–323]. Bands with up to 30 % tourmaline occur interbanded with normal adinoles of type 1 and with certain spilosites.

Rocks composed entirely of the tourmaline are confined to two localities: the first is at the top of the cliff on the north side of Dinas Head just below the faulted junction of the adinoles with the slates and limestones; the second is on a small shelf of folded adinoles just above high-water mark on the north side of the headland facing Stinking Cove.

Petrography.

1. *Dravite-bearing spilosites.*—Descriptions and figures of these rocks, and an account of how they grade into dravite-bearing adinoles have already been published [1, pp. 314–315].

2. *Dravite-bearing adinoles.*—A preliminary account of these rocks has already been given [1, pp. 318], but for convenience of reference the main types into which it is convenient to group them will be summarized here and the previous descriptions amplified only where rendered necessary by more recent work.

(*a*) Isolated rods or tufts of dravite needles of approximately the same size as the minerals in the groundmass of the adinole may be randomly distributed or concentrated in certain bands accentuating the original fine banding of the rock.

(*b*) The tourmaline crystals are similar to those in (*a*), but occur in small pools or as bands of inwardly directed needles enclosing adinole similar to, but coarser in grain-size than, that forming the main part of the rock.

(*c*) In the hand-specimen, some adinoles show a fine banding due to carbonate. In slice these rocks are seen to be composed of a base of a fine intergrowth of quartz and albite with evenly scattered granules of leucoxene and a little chlorite as in the normal adinoles. In this are narrower bands, often lenticular, composed of coarser crystals of albite enclosing crystals of dravite, either as radiating tufts or as little groups parallel to the albite twin-plane (fig. 1A). Marginally, these bands show concentrations of ankerite (dolomite 70, Fe-dolomite 30 %) as irregularly bounded crystals with a tendency to develop rhombohedral outlines. These are often associated with narrow cross-cutting veins of similar carbonate, but albite, when present in these veins, is never coarse-grained or with inclusions of acicular dravite. Occasionally small patches of zoisite occur. It is evident here that the introduction of carbonates was not responsible for the increase in grain-size of certain bands, but that they travelled along these already coarser bands as being the easier way. The increase in grain-size of the albite may be associated with an introduction of boron-rich solutions after the albitization, or to some effect of the initial composition of a banded sediment on simultaneously introduced sodium- and boron-rich solutions.

(*d*) Belts of dravite and patches of adinole show coarser areas which are mainly pools of quartz enclosing needles of dravite and rutile.

In all these types the dravite has the same optical properties: colourless to very pale green with average refractive index values of ω 1·631, ϵ 1·610.

3. *Dravite-sericite-rock.*—This is a pale greeny-white, somewhat fissile rock, weathering with many small excrescences, which occurs interbanded with normal, sheared, and spherulitic adinoles on the north side of Dinas Head. In slice, the base consists of poorly orientated sericite showing little tendency to envelop the tourmaline, together with evenly scattered granules of leucoxene. Set in this groundmass are rather irregular, though in general rounded, masses of dravite from one to two millimetres in diameter. Each of these is made up of a bundle of needles of dravite (ω 1·630, ϵ 1·611) in patchy parallel growth, and showing a zonary distribution of colour from a dark grey, rather opaque

border to a colourless inner zone with pale brown faintly dichroic patches (fig. 1B). Partial analysis of this rock gave SiO_2 57·80, B_2O_3 3·94 %.

4. *Dravite-rocks.*—These rocks are hard and dull or creamy grey in colour and are distinguishable from adinoles by their rather waxy lustre. They may be considered conveniently in three groups.

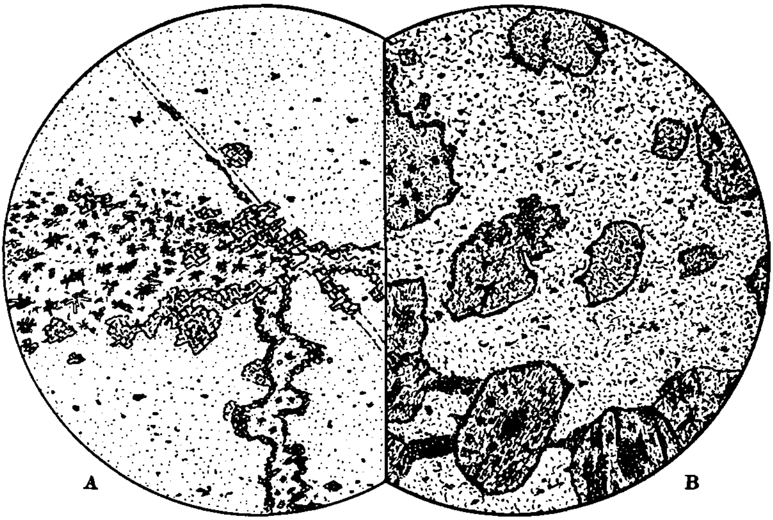

FIG. 1A. Adinole with band containing dravite needles and veined by ankerite. ×16.

FIG. 1B. Dravite-sericite-rock, showing parallel growths of dravite set in unorientated sericite. ×8.

(*a*) Hard, dull grey rocks of very fine grain with an irregular fracture and very fine clear banding. With increasing alteration these types show a slightly more flinty fracture, a less perfect banding, and the development on the weathered surfaces of small pinky-white spots about half a millimetre in diameter. The parent rock of these types is not known with certainty: that it was a sediment is suggested by the fine banding; in some cases it may have been a slaty type, for, although no two specimens are alike, it is possible under the microscope to select a series showing a transition from a sericite-rich rock to one composed essentially of dravite and illustrated by the following three stages:

(i) The least altered type (fig. 2) consists of a base of fine-grained sericite, in which patches of minutely fibrous, colourless tourmaline have developed. Leucoxene granules are evenly distributed throughout.

Qualitative chemical tests were necessary to prove the abundant boron in this rock as the grain-size does not permit accurate optical identification.

(ii) In the succeeding stage of alteration all the sericite is replaced by needles of dravite. The tourmaline is colourless or very pale brown, a slight mottling which appears in the slice being due probably to bundles of these very small needles (±0·01 mm. in length) in parallel orientation. The banding is marked by small granules of leucoxene which is insoluble in hydrofluoric acid and may therefore be anatase, and by films of carbonaceous material. Partial analysis of this rock gave SiO_2 45·59, B_2O_3 7·24 %.

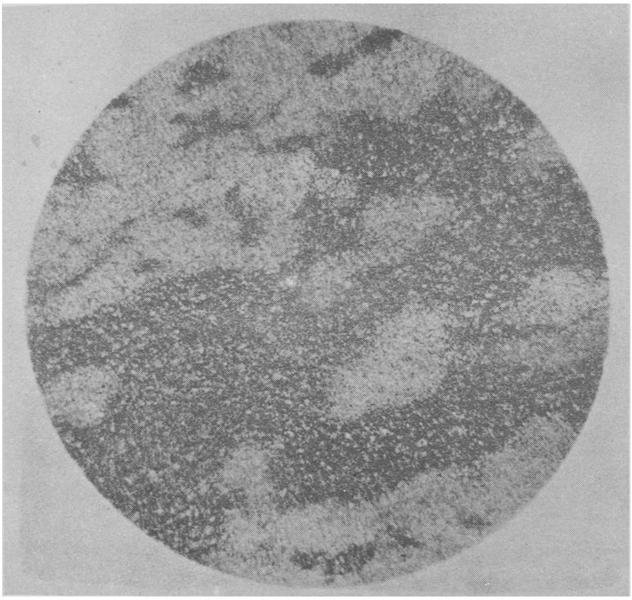

FIG. 2. Dravite-sericite-rock, showing sericite (light) partially replaced by dravite (dark). Crossed nicols, ×30.

(iii) Without any increase in grain-size, type (ii) passes into types which show large patches of minute needles in parallel orientation, generally with the *c*-axes lying in the plane of the banding. Often the slice has a woven appearance between crossed nicols owing to two sets of interlacing needles. Very occasionally a single idiomorphic tourmaline may be observed with ω colourless, ϵ pale olive-green. These may represent, in part, detrital tourmaline in the original sediment, but this cannot be proved. Fine granular calcite occurs commonly, either as bands in the groundmass or more or less evenly distributed. Isolated crystals of quartz and albite enclosing long needles of dravite occur: these crystals are irregular in outline and around them the felt of dravites is extra dense. Randomly distributed throughout the rock are small grains of a mineral not yet identified, but whose properties are recorded as colourless, two cleavages, straight extinction, and refractive index approximately 1·62, double refraction about 0·010. Partial analyses of this rock gave SiO_2 44·32 and 43·01, B_2O_3 7·01 and 7·12 %. The values for B_2O_3 are only 2 % lower than those for average dravites, so that if the rock is largely tourmaline, a supposition supported by X-ray powder photographs, there is present 70–80 % of dravite. The analyses also show that the change from the fine-grained 4 *a* (ii) to the coarser 4 *a* (iii) must be a physical one.

(*b*) Pale, milky-grey, fine-grained rocks breaking with a dull, waxy fracture. They all show some banding, but generally as coarser structures than in the types just described. Macroscopically, the three main types show the following features:

(i) Fine banding without change in grain-size.

(ii) Banded lenticles elongated in the 'bedding' planes, the lenticles appearing harder and glassier than the rest of the rock and somewhat like chalcedony.

(iii) Fine parallel bands of a white powdery material in the usual fine-grained base.

Microscopically, the corresponding slices show:

(i) Needles of colourless dravite about 0·01 to 0·10 mm. in length, but otherwise showing all the characters of the tourmaline described in the most highly altered types of 4 *a* (iii). The banding is seen to be due to fine granular calcite and to the better parallel-growth development of the tourmaline fibres.

(ii) A base similar to (i) but with even better alignment of the needles in the bedding planes. The glassy bands and beads are revealed as well orientated, coarse parallel growths of dravite, usually with a marginal concentration of granular calcite and relatively free from leucoxene (fig. 3). Sometimes broad bands suggesting a vague sector twinning may be seen in these areas. Narrow veins with quartz, sericite, calcite, and a little pyrite cut sharply across the rock. Partial analysis gave SiO_2 39·41, B_2O_3 8·04 %. These figures approximate to the values for actual dravites more closely than do those for 4 *a* (ii) and 4 *a* (iii), and suggest that this rock has been more completely replaced.

(iii) The groundmass consists of a fine-grained interlocking mass of colourless or very faintly green needles of dravite, each about 0·05 to 0·10 mm. long and arranged in a random manner with accompanying granules of leucoxene and carbonates. In this are seen patches and bands corresponding to the white powdery material of the hand-specimen, and in which the needles may be up to 0·25 mm. in length. These have the same optical properties as those of the groundmass, ω 1·631, ε 1·610, and are arranged in a criss-cross manner with no interstitial material. There also occur occasional pools of quartz with inclusions of dravite needles. Partial analysis of this rock gave SiO_2 46·10, B_2O_3 7·75 %. The unidentified mineral already referred to has been recognized in these three types.

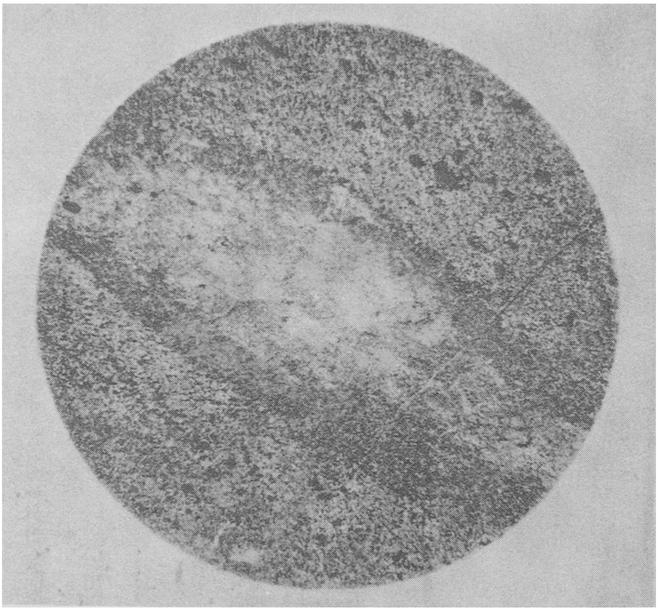

FIG. 3. Dravite-rock, showing large parallel growth of dravite needles set in a fine-grained groundmass. Crossed nicols, × 20.

(*c*) Spherulitic dravite-rock. This is a fine-grained, waxy, green-grey rock showing some banding accentuated by bands rich in calcite. Microscopically, it is seen to consist of a mass of small spherulites of colourless dravite ranging from 0·02 to 0·06 mm. in diameter, with ω 1·632, ε 1·610. Leucoxene and calcite occur in granular form through-

TABLE I. Chemical analyses of dravite.

	1.	1A.	B.	C.	D.	E.	F.	G.
SiO_2	38·84	39·73	38·30	36·57	36·80	36·52	35·96	36·41
TiO_2	1·01	nil	0·15	0·36	0·18	0·17	0·14	1·61
Al_2O_3	36·48	37·32	36·99	35·01	37·14	33·41	30·85	31·27
B_2O_3	8·64	8·84	10·38	9·78	9·63	10·32	10·73	9·65
Fe_2O_3	0·26	0·26	trace	trace	0·18	n.d.	n.d.	nil
FeO	0·60	0·61	0·22	1·12	1·80	0·30	0·76	3·80
MnO	nil	nil	0·01	0·01	trace	0·57	—	trace
MgO	6·96	7·12	8·90	11·40	8·33	11·25	13·67	9·47
CaO	0·52	0·53	nil	0·37	0·11	0·42	2·41	0·98
Na_2O	1·21	1·24	1·88	1·39	1·60	2·34	1·63	2·68
K_2O	0·64	0·65	nil	0·25	0·08	0·57	0·09	0·21
Li_2O	nil	nil	0·16	nil	nil	—	—	nil
H_2O+	3·62	3·70	3·55	4·46	4·48	3·76	4·16	3·79
H_2O-	0·88	nil	nil	nil	0·10			
F	trace	trace	0·07	n.d.	n.d.	0·12	n.d.	nil
Total	99·73	100·00	100·61	100·72	100·43	99·75	100·40	99·87
Sp. gr.	—	—	3·03	3·03	3·03	3·038	3·05	—
ω	—	1·631	1·634	1·635	1·636	1·6355	1·637	—
ϵ	—	1·610	1·612	1·612	1·614	1·6130	1·616	—
$\omega-\epsilon$	—	0·021	0·022	0·023	0·022	0·0225	0·021	—

1. Spherulitic dravite-rock associated with adinole, Dinas Head, Cornwall. Analyst, W. H. Herdsman. Also Cr_2O_3 0·07.

1A. The same recalculated to 100 % less TiO_2 and H_2O-.

B. Dravite replacing granite, Karragullen, Western Australia. Analyst, D. G. Murray in E. S. Simpson, 1931.

C. Dravite from quartz-dravite vein in granite, Swan View, Western Australia. Analyst, E. S. Simpson, 1931.

D. Dravite from spherulitic quartz-dravite vein in granite, Jarrahdale, Western Australia. Analyst, H. P. Rowledge in E. S. Simpson, 1931.

E. Dravite from talc-schist, Dobrova, Carinthia. Analyst, W. Kunitz, 1929.

F. Dravite from Gouverneur, New York, U.S.A. Analyst, W. Kunitz, 1929.

G. Dravite in marble, Monroe, Connecticut, U.S.A. Analyst, R. B. Riggs, 1888.

out the rock and by being concentrated in certain layers accentuate the banding. An occasional grain may be seen of a mineral agreeing fairly closely with apophyllite. The chemical composition of this rock, determined after removing all the calcite with dilute hydrochloric acid is given in table I, column 1. Column 1A is the same analysis recalculated to 100 % after the removal of the values for H_2O (—105° C.) and for TiO_2, on the assumption that all the latter is present as leucoxene. Calculating on a basis of O_{93}, these analyses correspond respectively to

1. $H_{11\cdot71}(K_{0\cdot40}Na_{1\cdot14}Ca_{0\cdot27})(Mg_{5\cdot04}Fe^{++}_{0\cdot24}Fe^{+++}_{0\cdot09}Al_{20\cdot89}Ti_{0\cdot37})B_{7\cdot24}Si_{18\cdot87}O_{93}$

1A. $H_{11\cdot80}(K_{0\cdot40}Na_{1\cdot15}Ca_{0\cdot27})(Mg_{5\cdot08}Fe^{++}_{0\cdot24}Fe^{+++}_{0\cdot10}Al_{21\cdot06})B_{7\cdot30}Si_{19\cdot01}O_{93}$,

that is approximately to $H_{12}Na_2(Mg_6Al_{21})B_7Si_{19}O_{93}$. If the structural formula of tourmaline is assumed to be $X_3Y_{27}B_9Si_{18}H_xO_{93}$, and it is borne in mind that these figures are based on the analysis of a rock as distinct from that of a mineral, the agreement must be considered as very close, and would be closer still, and correct, to some extent, the low value of the X group, if the calculation was based on B_9 instead of on O_{93}.

Detection of Tourmaline.

In most of these rocks, the dravite is either too fine-grained or else present in amounts too small to permit the certain identification of the mineral in thin section. For separating the actual mineral, the insolubility of tourmaline in cold hydrofluoric acid was relied upon, and the refractive indices recorded were always obtained on material treated in this manner.

In some other cases, the detection of boron was effected by chemical means, using the methyl borate method. As this proved only that boron was present and not necessarily that the mineral was tourmaline, X-ray powder photographs were taken of those rocks in which the chemical analysis showed large amounts of B_2O_3 approximating the theoretical amount in tourmaline, and the spacings calculated and compared with the results obtained from a crystal of undoubted tourmaline. Although, in most of the specimens, comparatively few lines could be measured, the results which were obtained are consistent with the rock being composed mainly of tourmaline.

The Origin of the Dravite-bearing Rocks.

The occurrence of dravite in adinoles as described from Dinas Head is unique, but in order to elucidate the relation of the boron to the albite-dolerite, it is necessary to consider the recorded occurrences of similar magnesia-rich tourmalines.

At Renfrew, Canada, dravite-uvite occurs in the Grenville limestone at its contact with a pyroxene-bearing granite-gneiss (Bruce, 4). In Madagascar, dravites occur associated with phlogopite-bearing granite-pegmatites where these cut pyroxenites, talc-schists, and crystalline limestones (Lacroix, 12). At Monroe, Connecticut, and Pierrepont, New York, U.S.A., dravite-uvites occur in chlorite-schists cut by granite-pegmatites (Riggs, 18). At Dobrova, Carinthia, and Gouverneur, New York, U.S.A., dravite occurs in talc-schists and dolomitic limestones cut by granite-pegmatites (Kunitz, 10). At Muruhatten, Sweden, ferriferous dravite occurs in migmatized serpentines and amphibolites (Du Rietz, 16, 17). In the Darling Range, Western Australia, dravite both replaces the granite and is found in it, accompanied by quartz, as joint infillings. It is described as being, in some cases, finely spherulitic, in others as so finely fibrous as to be obscure even under the microscope except between crossed nicols (Simpson, 23). In the Urals, ferriferous dravite is found in a serpentine near its contact with a Devonian limestone. The whole district is cut by granite-pegmatites (Duparc and Sigg, 6). In the Pyrenees, dravite occurs in metamorphosed marls and limestones, and schorl is found in shales at the contacts of many lherzolite masses. Here the tourmaline is everywhere associated with scapolite. It also occurs in the gypsum-anhydrite-albite-scapolite-leuchtenbergite-rocks at the contact of ophite intrusions, where it is considered to be a product of the metasomatism of gypsum deposits by the ophites (Lacroix, 11).

There has been a tendency to regard tourmalines of the dravite-uvite series as being the tourmalines characteristically associated with basic igneous rocks, but a critical examination of the available evidence suggests that this conclusion is not justified. In all but the last of the occurrences cited above a granitic source of the boron is available, and even in the case of the Pyrenean occurrences, more recent workers differ from Lacroix in their interpretation. Bertrand [3] considers that the metamorphism of the Mesozoic sediments is of a regional type, due to the burial of these sediments in the north Pyrenean Cretaceous geosyncline, and that the boron and chlorine were derived from the granite masses at depth in the region of injection. Longchambon [13] agrees with Bertrand on the grounds that not only may the tourmalinized and scapolitized rocks be found away from any lherzolite or ophite contact, but that they also occur at a constant tectonic horizon, that which had been buried deepest in the geosyncline. The boron is regarded as having been derived from a granitic magma at depth and the scapolitization produced by the action of this magma in distilling chlorine out of the saliferous horizons of the Trias, to be fixed in rocks of suitable composition (marls) in the overlying Jurassic and Cretaceous strata.

In the case of the dravite-scapolite-anhydrite-rocks associated with the ophites, it must be borne in mind that the boron here may be derived from borates in the original gypsiferous deposits.

In the example studied by Duparc and Sigg [6], the authors suggest that it is possible that a nearby granite may be the source of the boron, but in addition they point out that there is no reason why the basic igneous rocks should not contain the same volatiles as acid ones.

Support is lent to this idea by records of two other boron and basic rock associations, although in neither case is boron present in any large amount. Andreae and Osann [2] note the presence of tourmaline, a schorl, in a quartz-rich hornfels at the contact of the Palisade diabase, U.S.A. Walker [25] found 0·18 % B_2O_3 in a Scottish tholeiite, and came to the conclusion that this could be present only in the interstitial glass.

A more obvious association of boron and basic igneous rocks is shown by the development of datolite, such as has been described from the basalts and dolerites intrusive into the Trias of the Atlantic States of America by Cook and Kraus [5], Hawkins [8], Manchester [14], and Shannon [19–22]. Here datolite is associated with an end-stage assemblage of zeolites, calcite, and chlorite, either as veins cutting the dolerites, basalts, and contact-rocks or as vesicle infillings; in the latter case the source of the boron from the basic igneous rock seems certain. Many other occurrences of allied mineral associations are known, but except for a few occurrences, e.g. Monte Campotréra, Italy, described by Ferrari [7], these have not been fully investigated.

In the above cases there are no immediately associated granitic types, which, as in the case of the dravites previously described, could have been an alternative source of the boron.

The occurrence, described by Slavík and Fišer [24], of a shale at the contact of a diabase being converted into a fine-grained porcellanous datolite rock is the best example of the production of datolite as the result of boron metasomatism, associated with a basic igneous rock. It may be that at low temperatures in a lime-rich environment datolite is formed and at a higher temperature a tourmaline of the dravite-uvite series; there is, however, no decisive evidence on this point.

From a consideration of the evidence supplied by the descriptions of the known occurrences of magnesia-rich tourmalines, the following conclusions are drawn:

1. Like all other types of tourmaline, the source of the boron or of the tourmaline as such is a granitic magma.
2. In all cases, except that of the Darling Range granite, the presence of Ca and Mg in the Y group of the tourmaline is controlled by the composition of the mineral or rock with which the tourmaline is developed.

The ubiquity of the granite-tourmaline association would suggest that at Dinas Head also, the tourmaline is of granitic origin, but before a conclusion based on such general probabilities only can be accepted, the more particular data which suggest that the albite-dolerite may be the source of the boron must be examined.

Dravite has not been found away from the adinoles and their related rocks and the constant association of the albite and dravite suggest a common and contemporaneous origin of the boron and sodium. In the development of spilosites and spilositic adinoles, dravite is found associated with the albite in the initially formed spots of the spilosites, and also, as a second generation, in the coarser patches corresponding to these spots in the groundmass of the spilositic adinoles. When first described [1, p. 333], these features were regarded as signs of the simultaneous addition of boron and sodium. It is now recognized that this same arrangement is that which would be expected had the dravite formed later, having been able to grow as larger crystals in the coarser spots than in the finer groundmass. Certain other adinoles, in which dravite is found only in the coarser bands, support this argument, but without indicating whether the boron was introduced at the same time as the sodium or later.

The dolerite shows little axinitization and very little, if any, of the effects of the thermal metamorphism which has altered the rocks with which it is so intimately connected in the field, whereas at granite contacts at other localities, rocks similar to this albite-dolerite have been observed to be very susceptible to these effects. Thus it may be argued that the albite-dolerite must be the cause of any such changes in its neighbours.

Against the acceptance of this view in its entirety are the facts that the albite-dolerite, unlike the Cornish granites characterized by boron-bearing aureoles, contains no boron-bearing accessory minerals, whereas it is rich in a soda mineral, albite, and has undoubtedly caused much soda-metasomatism. The axinite described from a gash vein is better interpreted as having been formed after the consolidation of the basic rock.

From this evidence, weighted by the conditions of other dravite occurrences, it must at present be concluded that the albite-dolerite was the cause of the thermal metamorphism of the bedded rocks and of their subsequent adinolization; and, more tentatively, that the tourmalinization is due to a hypothetical granite emplaced under conditions such that only boron-bearing fluids were able to affect the rocks now exposed at Dinas Head, and that the albite-dolerite was either physically impermeable to, or chemically stable in the presence of these fluids. Perhaps the elevation in temperature associated with this was responsible for the development of the spherulitic adinoles by recrystallization, for it has been shown that this texture is of a later date than the adinolization [1, pp. 323–6]. Whether the boron was derived from a granitic source, as is favoured here, or was directly associated with the adinolization and derived from the albite-dolerite, it has 'reacted' with some mineral and we must investigate what this may have been.

In the adinole, the chemical composition would suggest a chlorite rich in the amesite molecule, but in the adinoles without dravite, the chlorite that occurs is a diabantite and so removal of iron should have taken place. In other cases, the dravite may replace albite itself, thus necessitating the introduction of magnesia, as would also be the case if the tourmaline molecule had been introduced as such, a possibility which must be borne in mind.

In the dravite-rocks, replacement of a different rock type is probable. The magnesium may represent some dolomitic constituent of a limestone corresponding to the calcareous bands which are found among the sediments at Dinas Head (1, p. 311), in which case, aluminium must have been introduced in large quantities. On the other hand, the sericite so abundant in the rocks which are regarded as representing the initial stages of the alteration to the almost monomineralic dravite rocks, as well as the very fine grain-size and chemical considerations, increase the likelihood that the original rock was an argillaceous sediment poor in iron and rich in magnesia. An argillaceous rock with such a high content of magnesium is admittedly an uncommon type, but there is no evidence for the alternative hypothesis, an introduction of magnesium such as has occurred in the Darling Range granite.

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