The adinoles of Dinas Head, Cornwall.

(With Plate XI.)

By S. O. Agrell, B.A., F.G.S.

Department of Mineralogy and Petrology, University of Cambridge.

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Contents.

I. Introduction.

Dinas Head is a small promontory adjoining Trevose Head, some five miles west of Padstow on the north coast of Cornwall. Petrographical attention was first drawn to it by Howard Fox, who in 1894 [5], noted the development of albite-rich rocks between greenstone and slate, and he concluded that the rock was an adinole. He also noted the peculiar spherulitic development of albite giving some rocks an igneous appearance, but, on account of the fine banding preserved in these rocks, he concluded that they were metasomatized sediments. This conclusion was subsequently supported by McMahon and Hutchings [13]. The Memoir of the Geological Survey of the Padstow and Camelford district [17] agrees with Fox as to the origin of the adinole, and points out the exceptional thickness of its development when compared with other greenstone-slate contacts.

The latest publication is that of Dewey [4], who showed that the composition of the slate into which the greenstones are intruded affects in some measure the products of metamorphism. Namely, that purple and red slates develop spots, but are not adinolized; green slates develop spots and poor adinoles; grey and black slates do not develop spots, but are strongly adinolized. That is, those sediments poor in Fe_2O_3 are altered to adinoles, and those rich in Fe_2O_3 to spotted slates. He suggests that the material was added as albite-rich liquors carrying magnetite, and that these liquors were derived from the albite-dolerite intrusion; and further, that those intrusions which, in general, have $Fe_2O_3:FeO$ greater than three to one, give rise to adinoles at their contact with slates.

The present study was undertaken in order to investigate the chemistry of adinolization more closely and to discover the reason for the development of such an exceptional thickness of adinole at Dinas Head.

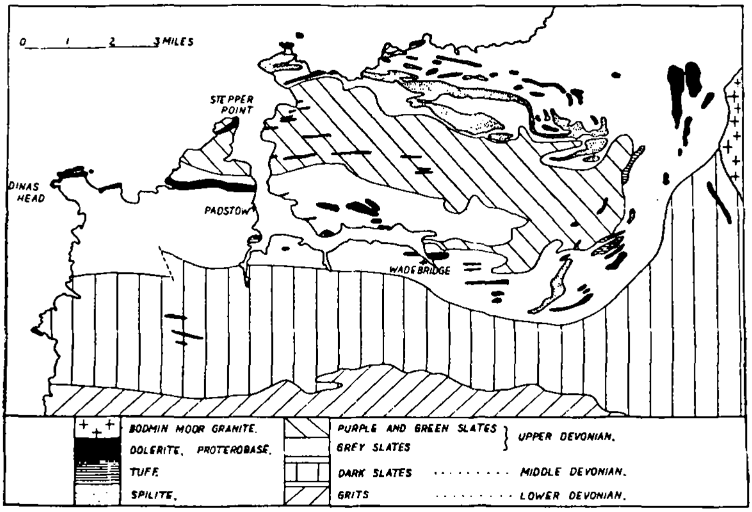


FIG. 1. Geological sketch-map of the St. Mabyn syncline, based on data taken from publications of H.M. Geological Survey.

II. General Geological Relations.

Dinas Head is situated at the seaward end of the south limb of the St. Mabyn syncline (fig. 1) and is composed of a series of dark slates, limestones, and cherts of Upper Devonian age into which, prior to the imposition of cleavage on the sediments, there has been intruded a sill of albite-dolerite. This intrusion is at about the same stratigraphical level as the spilites and tuffs on the north side of the syncline, and, chemically, is closely allied to them.

A series of albite-rich rocks interpreted as adinoles occurs between the dolerite and the unaltered sediments. Being on the line of movement which runs from Trevose Head to Tintagel [8], all the rocks have been strongly folded and faulted during the Armorican orogeny, and as a result the detailed relations are obscured by the folding of the adinole into the slates and by its being torn away from the contact with the igneous rock, and no one band of sediment can be traced with certainty into its metasomatized equivalent.

III. The Igneous Rocks.

The intrusive rock is a typical 'greenstone' and the available exposures show that it has the form of the irregular upper surface of what is possibly a thick sill, or the upper surface of a plug-like mass from which sills develop, for it sends several distinct tongues into the sediments. These sediments and associated sills may be seen best on the south side of the headland and dip about 20° to north. They are upfaulted again on the north of the headland, and, although the relations here are more obscure, a tongue of igneous rock branching from the main mass can be observed. Where Dinas Head joins the main part of Trevose Head, the upper part of the igneous rock is at sea-level. Above Stinking Cove a wide dike commences striking across Trevose Head. The general relations of the igneous rock and the altered and unaltered sediments are shown on the map in fig. 2.

1. *Petrography of the albite-dolerite.*—The bulk of the intrusive rock at Dinas Head is albite-dolerite which appears as a coarsely mottled, dull, dark-green rock with paler patches, and which weathers with a rusty crust where out of the influence of the sea waves. The greater part of the rock is strongly carbonated and chloritized, and little of the original textures can be seen (fig. 4 c). In less altered specimens, pseudomorphs after ophitic pyroxene are preserved and correspond to the paler patches in the rock.

Albite of refractive index (γ 1·537–1·541 in different specimens), corresponding to a composition $Ab_{100}An_0$–$Ab_{92}An_8$, occurs as laths penetrating the pseudomorphs after ophitic pyroxene and as laths forming the groundmass of the rock. In all specimens zoning is absent and no traces of a more basic plagioclase are observable. The albite is usually twinned on the albite law and in the fresher rocks is of a limpid appearance and has, as inclusions, small linearly arranged granules of carbonate and flakes of white mica.

Pyroxene is not found in the typical dolerite, but pseudomorphs after ophitic plates occur of a fibrous mineral of the bowlingite group, whose optical properties are α 1·570 pale brown to nearly colourless, γ 1·605 dull brown, $\gamma - \alpha$ 0·035, 2V very small, sensibly uniaxial, negative.

Fibres of the mineral show positive elongation and straight extinction. Calcite may occur in a granular form associated with the bowlingite.

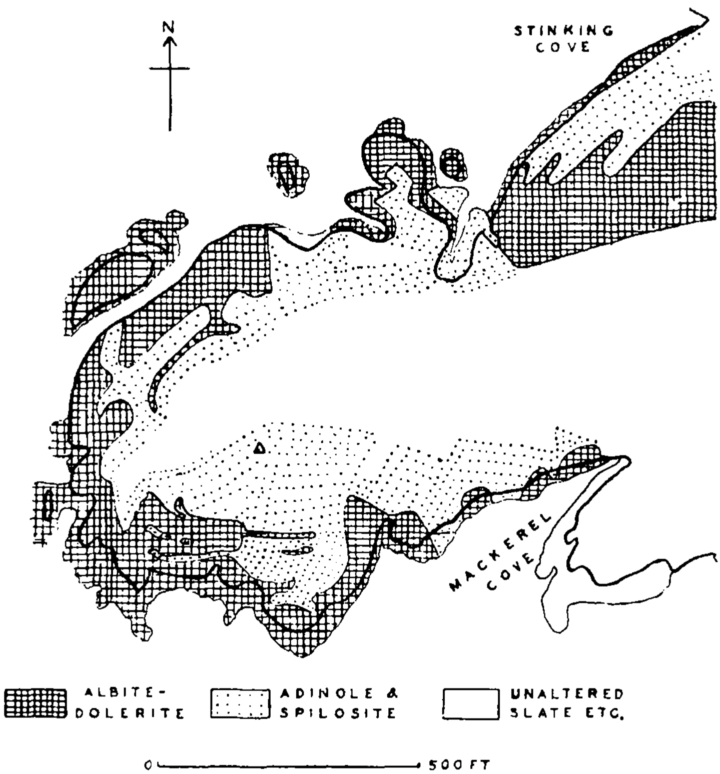


FIG. 2. Geological sketch-map of Dinas Head to show the distribution of the dolerite, slates, and adinoles.

Chlorite is usually very fine grained and belongs to the diabantite-aphrosiderite group [16, p. 280], being optically negative with β 1·625–1·643. It forms the matrix in which all the other minerals are set, and occasionally is seen as pseudomorphs after pyroxene and (?) biotite, in which case it contains small grains of sphene or anatase.

Serpentine in the form of small pools of a fine-mesh serpentine is common in most of these rocks, but in no case does it appear to be a pseudomorph. Prehnite occurs occasionally as sheaf-like aggregates of crystals. A ferriferous calcite sometimes occurs along with the bowlingite replacing the pyroxene, and a colourless granular calcite occurs abundantly throughout most of the rocks and in small stringers.

Ilmenite occurs as skeletal plates altered to leucoxene, which may generally be recognized as sphene, although anatase is developed occasionally. Pyrite and needles of apatite are found in very small amounts.

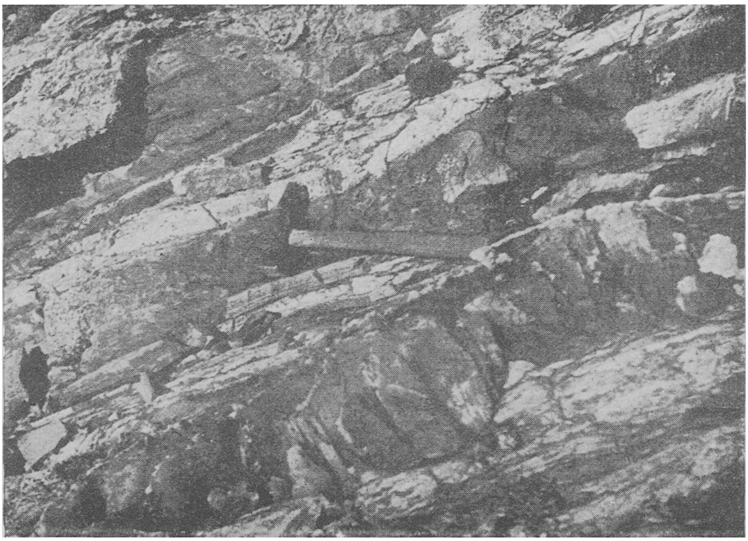
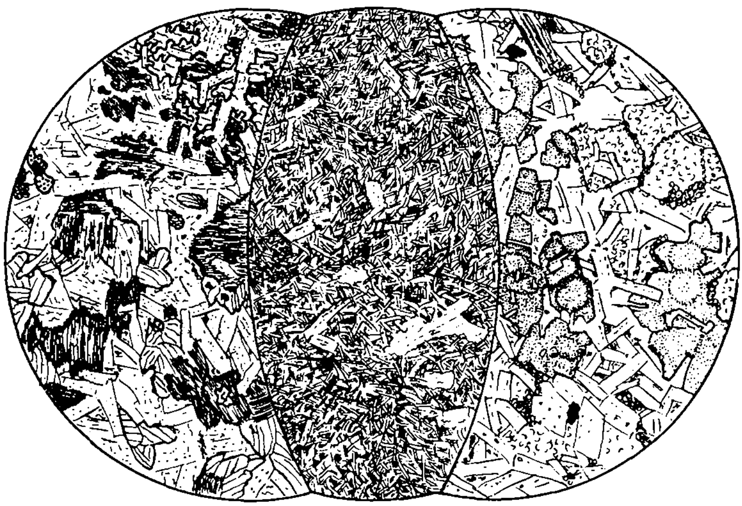


Fig. 3. Interbanded spilosite and adinole from the west side of Dinas Head, Cornwall.

No pegmatitic facies of this dolerite has been observed, nor have xenoliths of albitized sediment been found. The varieties of dolerite near the contact are usually so chloritized that the original minerals cannot be identified, but occasionally on the south side of Dinas Head a thin band of chilled margin can be seen. In thin sections this is seen to be made up of over 90 % of albite which occurs as thin laths about 1 mm. in length arranged in a criss-cross manner, giving the rock a woven appearance when seen between crossed nicols (fig. 4 B). Chlorite fills the interstices, and accessory minerals are carbonate, sphene, anatase, apatite, and ilmenite.

2. *Petrography of the pyroxene-bearing albite-dolerite.*—This rock occurs only in one rocky knob on the south side of Dinas Head. On the fresh surface it has a dark greeny-black lustrous appearance. Pyroxene is a colourless pigeonite and occurs as relicts of ophitic plates (fig. 4 A).

Hornblende is a fibrous, pale-green actinolite with γ 1·65 and $\gamma{:}c = 16°$. It replaces the pyroxene and is itself replaced in part by a pale biotite with γ 1·62, $\alpha = \beta$ pale straw, γ pale foxy-red. These replaced ophitic plates are penetrated by the laths of albite, which, together with much granular calcite, form the groundmass. Ilmenite occurs as grains and skeletal plates surrounded by a broad rim of sphene.



A B C

FIG. 4 A. Pyroxene-albite-dolerite. $\times 27$.
FIG. 4 B. Marginal modification of dolerite. $\times 27$.
FIG. 4 C. Normal albite-dolerite. $\times 27$.

It is possible that this rock has been less subject to autolytic alteration than has the preponderant type. Along joints the ferromagnesian minerals are usually prehnitized and much carbonate and sphene have developed. It is in these types that the albite sometimes shows the fine pepper-and-salt texture of interlocking granules that is so characteristic of the adinoles.

3. *Petrography of the segregation veins.*—These veins are often present cutting the dolerite close to the contact with adinole, but can seldom be traced any distance into the latter. They are sharp walled, about 10 cm. thick, and distinctly banded. Albite as grains 4 mm. in diameter makes up the bulk of the rock and is marginally intergrown with dolomite and ankerite. Chlorite is usually also present. The ankerite has

ω 1·705, corresponding to the composition $CaMg(CO_3)_2$ 70 %, $CaFe(CO_3)_2$ 30 %.

4. *Chemical composition of the albite-dolerites.*—Analyses of the normal albite-dolerite (1) and of the pyroxene-bearing type (2) are given in table I and agree fairly closely, especially when account is taken of the strong autolytic modification to which both rocks have been subjected. Norms calculated on a CO_2-free basis show that in the case of the normal albite-dolerite there would not be enough lime to form normative calcite. In the mode, FeO replaces CaO in the carbonate associated with bowlingite.

TABLE I. Chemical analyses of albite-dolerites and slates.

	1.	2.	A.	3.	4.	5.
SiO_2	46·90	45·10	46·73	56·97	60·36	64·70
TiO_2	1·58	1·26	2·74	0·62	0·56	0·58
Al_2O_3	14·92	16·04	18·73	22·36	18·25	20·77
Fe_2O_3	1·63	1·67	0·00	0·63	0·60	0·89
FeO	9·72	8·26	10·14	5·16	6·94	1·86
MnO	0·16	0·17	0·37	0·00	0·04	trace
MgO	6·58	7·96	3·56	2·84	3·24	1·52
CaO	4·15	7·60	8·62	0·60	1·12	trace
Na_2O	3·79	3·61	3·54	0·51	0·12	0·31
K_2O	0·46	0·48	0·88	4·57	3·14	4·81
H_2O+	4·92	4·68	3·31	4·32	4·26	3·42
H_2O-	0·70	0·80	0·35	0·60	0·70	0·65
P_2O_5	0·13	0·10	0·37	0·09	0·09	0·12
CO_2	4·38	2·22	0·58	0·00	0·48	trace
C	—	—	—	0·88	0·00	0·34
Total	100·02	99·95	99·97	100·15	99·90	99·97
Sp. gr.	—	—	—	2·81	2·66	2·73

1. Albite-dolerite, Dinas Head. Analyst, W. H. Herdsman.
2. Pyroxene-albite-dolerite, Dinas Head. Analyst, W. H. Herdsman.

A. Albite-diabase, Trusham station quarry, Devonshire. Analyst, E. G. Radley [17]. Also FeS_2 0·05.

3. Black carbonaceous slate with small chlorite-rich spots, Dinas Head. Analyst, W. H. Herdsman. B_2O_3 0·00.
4. Dull grey-green spotted slate, Dinas Head. Analyst, W. H. Herdsman. B_2O_3 0·00.
5. Black fissile spilosite, Dinas Head. Analyst, W. H. Herdsman. B_2O_3 0·00.

IV. THE SEDIMENTARY ROCKS.

The unaltered sediments are predominantly dark slates and call for little description. Bands of crinoidal and unfossiliferous sheared limestone, sometimes associated with chert, occur as a horizon in brown-black calcareous shales. At the end of the headland these are replaced by green-black slates showing minute puckering.

A band of coarse schalstein occurs just above high-water mark on the north side of the headland. It is two or three feet thick and can be traced only for a few yards. It is very probably a continuation of a similar band occurring between tide marks below the lighthouse on Trevose Head. This is the only rock which has been recognized as definitely showing primary pyroclastic features on Dinas Head. No recognizable tuffs, keratophyric, and hence like adinoles, in composition, have been found to explain the great thickness of the adinole.

V. Rocks showing Effects due to Pure Thermal Metamorphism.

In a general way these rocks always lie between the unaltered sediments and the spilosites and adinoles. The first change visible is always a development of spots which may be one of the three following types:

(*a*) In black slates, small chlorite-rich spots, lenticular in shape and about 0·5 mm. long, occur in a groundmass of fine sericite with a little chlorite, in which clastic grains are still visible. Films of carbonaceous material are abundant in the sericite, and around the chlorite spots they have been pushed apart like the eyelids around an eye. Fig. 5 A shows this blepharitic structure which is a common feature in spotted slates [18, pp. 64–66]. The chlorite has γ 1·623, $\gamma-\alpha$ 0·002 approx., is optically negative, olive in colour, and hence a diabantite. It is thought that these spots are due merely to a local rearrangement of material, the bulk composition of the rock being unchanged. The chemical composition is given under (3) in table I and shows no unusual features.

(*b*) In black slates there are sometimes developed much larger spots up to 3 mm. in diameter and elongated in the fissility planes. They are marked by a concentration of chlorite similar to the above and are fringed with carbonate, now represented by limonite which sends rays into the cores of the spots. The groundmass is made up of fine sericitic white mica, some chlorite, and disperse carbonaceous films. Minute granules of leucoxene occur throughout. Clastic quartz occurs both in the groundmass and in the spots.

(*c*) In dull green-black slates occur compound spots, possibly allied to those described in (*b*). These are 2–3 mm. long and are elongated in the fissility planes (fig. 5 B). They show a chevron structure. A thin outer zone of chlorite delineates the spot, and from this irregular rays of chlorite, with or without fine granular calcite, branch towards the centre of the spot. The chlorite has γ 1·612, $\gamma-\alpha$ 0·001 approx., and is optically positive or negative, thus corresponding to a magnesium-rich diabantite.

Between these rays, and making the core of the spot, there occurs unoriented white mica (γ 1·588). A considerable amount of quartz may be present in the spot, generally associated with the chlorite rays, but sometimes with the sericite, and occurs as fine interlocking grains compared with the angular grains associated with the sericite of the groundmass. The groundmass is sericite with a little chlorite and ores, and its analysis (4, table I) shows the characters typical of an argillaceous rock. The colour change from black to green is accompanied by an increase in the ratio of FeO to Fe_2O_3.

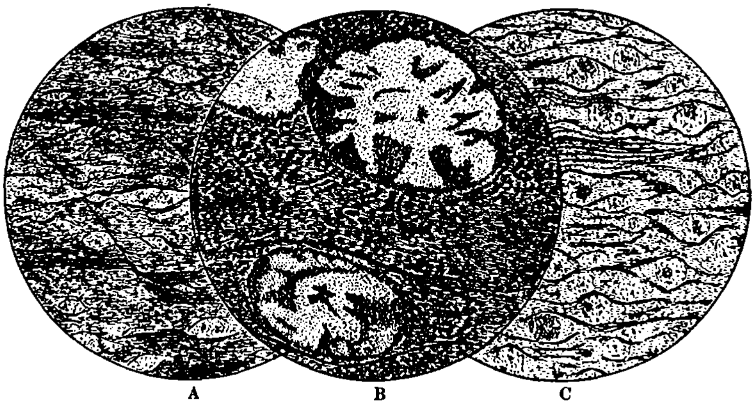


FIG. 5A. Black carbonaceous slate. A sericitic groundmass with carbonaceous films showing blepharitic structure around chloritic spots. $\times 20$.

FIG. 5B. Dull green spotted slate. A sericite-chlorite groundmass with spots composed of a margin of chlorite with a little calcite, sending rays into a sericitic core. $\times 8$.

FIG. 5C. Black slaty spilosite. A sericitic groundmass with films of carbonaceous material showing blepharitic structure around round spots composed mainly of quartz and a little chlorite. $\times 20$.

These spots have not the simple structures of spots due to localized concentration of material, and it is evident that very definite reactions must have taken place to produce, for example, the quartz that is present. Possibly they represent incipient cordierite, just as those with regular chevrons have, at many localities, including Stepper Point [17, p. 49] and Trusham [18, p. 65], been taken to represent incipient chiastolite. The chemical composition agrees closely with that of the hornfelses of group I of Goldschmidt, so that it is not unreasonable to expect some such reaction to have taken place in the early stages of metamorphism.

VI. Rocks showing Localized Metasomatism—Spilosites.

These occur between the slates and the adinoles and are somewhat sporadic in development. Spilosite and adinole may even be seen banded together.

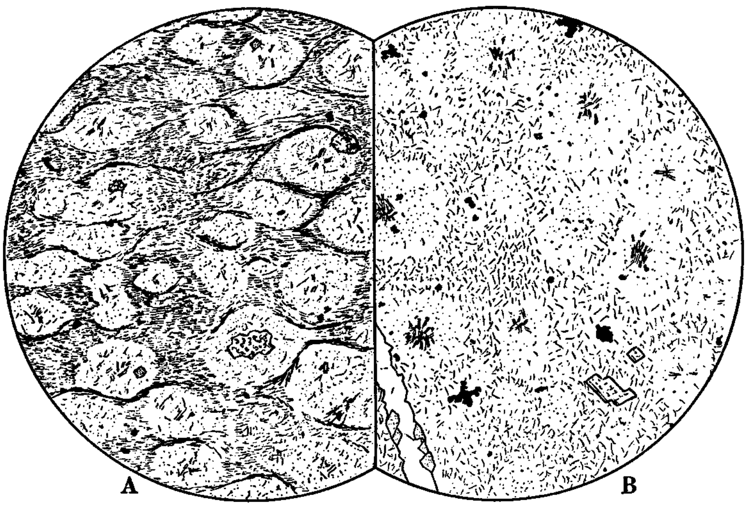

A B

Fig. 6 A. Spilosite. Spots of fine-grained albite with a little chlorite, colourless tourmaline, and anatase are set in a groundmass of sericite with thin carbonaceous films. ×27.

Fig. 6 B. Spilositic adinole. Coarser areas of albite with colourless tourmaline are set in a very fine-grained groundmass of the same mineralogical composition with mossy aggregates of leucoxene and occasional small rhombs of ankerite, and cut by a quartz vein showing marginal recrystallization of albite. ×27.

An example analysed (5, table I) is, in hand-specimen, a black slaty spilosite with spots of pin-point size. These spots are composed of quartz with a little chlorite and leucoxene and are set in a groundmass of fine white sericitic mica with thin carbonaceous films forming typical blepharitic structures around the quartz spots. Leucoxene occurs as very fine granules in the groundmass (fig. 5 c). The analysis of the rock shows that it could be equally well regarded as a normal spotted slate, for there is nothing, except the high silica percentage, which might be attributed to the metasomatism.

Coarser types occur in which the material in the spots can be definitely recognized as albite. These rocks have small spots about 1 mm. in diameter, and are composed of interlocking crystals of albite with which are associated tabular crystals of anatase or granular leucoxene and needles of a colourless tourmaline of the dravite-uvite series (average ω 1·635) [11, p. 221]. The groundmass is composed of sericitic white mica without any tourmaline (fig. 6 A). It is of interest to note here that Fox [5, pp. 705, 715] recorded the presence of minute crystals of hexagonal outline, which he tentatively referred to wollastonite in some cases, to tridymite in others. It is possible that these are small needles of tourmaline comparable with those just described. This rock forms the dark bands in fig. 3 and has been analysed (6, table II), and may be compared with B, a spilosite from the Harz analysed by Kayser [10, p. 139].

This coarser type can be seen to pass into what may be termed a spilositic adinole, by replacement of the groundmass sericite by very fine-grained albite and quartz accompanied by minute tourmaline needles, granules of leucoxene, and small rhombs of ankerite. The initially metasomatized spots are seen as coarser areas about 1 mm. in diameter evenly scattered through the rock and composed of the same minerals as the later-formed fine-grained base (fig. 6 B). The analysis is given under (7) in table II. This type of adinole forms the white bands in fig. 3, and the change from spilosite to spilositic adinole corresponds to the original banding of the rock. As these two rocks, so closely interbanded, must have been subject to the same metasomatic fluids, it follows that the composition of the original sediment had a very strong control over the ease with which it could be adinolized.

VII. Completely Metasomatized Rocks—Adinoles.

The adinoles are of a simple mineralogical composition being essentially albite and quartz. Associated with these, there commonly occur chlorite, calcite, ankerite, leucoxene, and a colourless tourmaline of the dravite-uvite series. Zoisite, rutile, graphite, and prehnite occur in very small amounts.

In the field, adinoles are characteristically banded like a normal series of sediments. They exhibit a variety of textures and structures, some of which can be seen developing, others of which present no clue as to their origin. According to these, the rocks may be divided into the following groups:

1. *Normal adinoles*—very fine-grained with albite, quartz, and calcite. They may be rich in carbonate.

2. *Pseudomorph-bearing adinoles*—in which the pseudomorphs are of three types:
   (*a*) quartz-chlorite pseudomorphs after andalusite;
   (*b*) carbonate-chlorite pseudomorphs after andalusite;
   (*c*) chlorite-rich types with occasional pseudomorphs after andalusite and many replacements of initial spotting or of incipient andalusite or cordierite.
3. *Carbonate-rich adinoles*—characterized by globular masses of ankerite, up to 2 cm. in diameter.
4. *Spherulitic adinoles*—characterized by spherulitic groups of albite.
5. *Sheared adinoles.*

It has been possible to trace the changes from slate into adinole only in the normal adinoles. There are, however, features in the adinoles of the other groups which provide clues as to the stages of their development.

1. *Normal adinoles.*

These are built up essentially of albite and quartz and appear as hard, white-weathering rocks with a grey-white cherty appearance on the fresh surface. They are distinctly bedded and may be interbanded with other types of adinole. A very fine banding may also run through them, and is best seen on weathered surfaces or in thin sections [7, fig. 57 A]. Jointing is prominent and is accentuated by very thin quartz veins which may fill the joints, giving a somewhat brecciated appearance to the rock.

The albite and quartz occur as minute, sutured, interlocking grains too fine to allow detailed optical tests. The average refractive index is $1{\cdot}537\pm$, so that the greater part is albite. Analysis also shows that albite makes from 65 to 85% of the rock, and that it never has more than 5% of anorthite. Set in this groundmass coarser patches of albite of one of two types may occur. (*a*) The patches are rounded or irregular areas about 0·25 mm. in diameter. They are made up of coarse albite and chlorite and merge rapidly into the groundmass. These are relicts of the first-albitized spots. (*b*) Rounded pools about 0·2 mm. in diameter are made up of one or two crystals of albite with a faint brown turbidity, and have a sharp though crenulate contact with the groundmass. Quartz may also occur in the same manner. These may also represent the first-albitized spots or may be a later recrystallization phenomenon.

Chlorite occurs as minute flakes throughout the rock; as it increases in amount the rocks pass into adinoles of group 2 *c*. Carbonaceous films occur in some specimens and serve to accentuate the original banding

[7, fig. 57 A]. Leucoxene may occur as small mossy aggregates evenly scattered through the rock and sometimes banded. In places they have been concentrated into larger aggregates leaving an impoverished zone around them. This seems commonest near a contact with the dolerite (fig. 7 A). Minute needles of colourless dravite occur in small amount in many of the adinoles. Zoisite may occur as isolated granules.

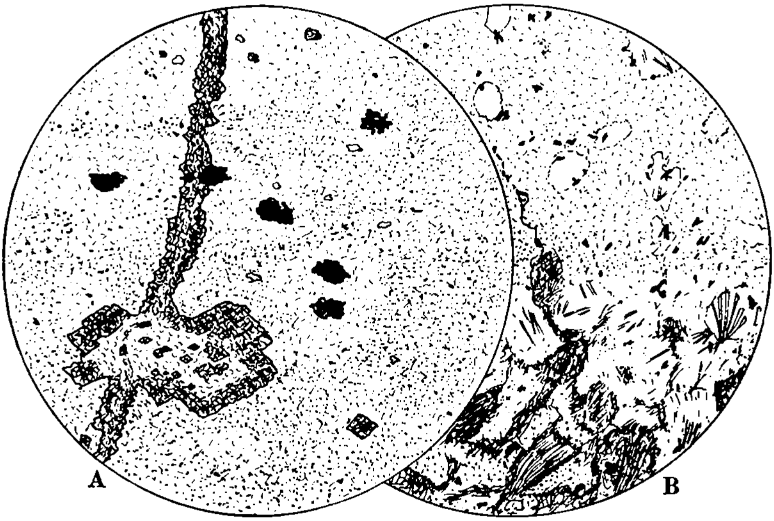


FIG. 7 A. Normal adinole. A very finely crystalline base of albite and quartz with flakes of chlorite and granules of leucoxene, the latter sometimes segregated, is cut and replaced by an ankerite vein. × 27.

FIG. 7 B. Tourmaline-bearing adinole. Pools of quartz with needles of rutile and tourmaline, set in fine-grained albite, and merging into a felted mass of tourmaline needles set in albite. × 27.

Of carbonates, both calcite and ankerite occur. The latter has 70% dolomite and tends to be idiomorphic. These carbonates may form isolated crystals, patches, or larger nodules and bands showing intermediate stages to group 3 adinoles. The ankerite is usually connected with the quartz-ankerite veins and can be seen replacing the adinole (fig. 7 A). The calcite seems to be more in the bands and nodules, and it is possible that it has been derived from the original sediment. Some veins, which are generally earlier than those with ankerite, carry quartz alone, and the albite from the adinole forming the margin has recrystallized as little idiomorphic crystals directed towards the centre of the vein.

An analysis of a normal adinole with no dravite and a little ankerite, such as is shown in fig. 7 A, is given under (8) in table II, and agrees closely with the spilositic adinole (7) and the one (C) quoted by Fox [5].

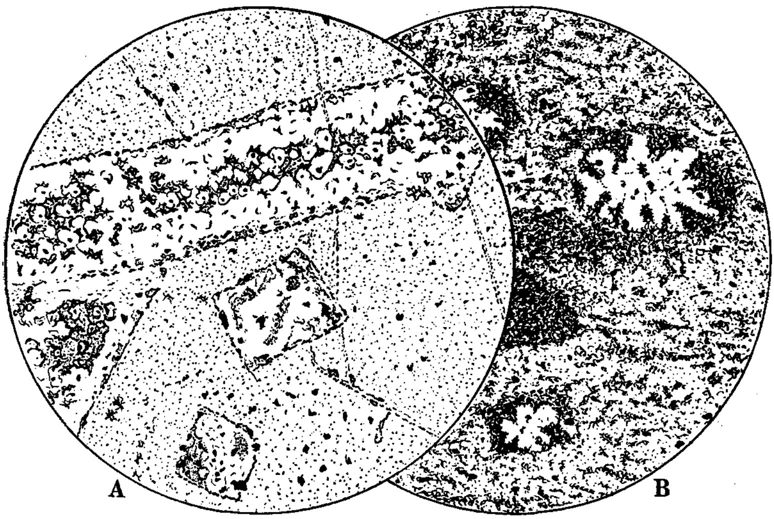
In adinoles carrying a large amount of colourless tourmaline, usually an intermediate member of the dravite-uvite series with ω 1·635 and ϵ 1·615 on the average, the tourmaline occurs in several distinct ways. (*a*) As tufts of needles concentrated in certain bands of an otherwise very fine-grained and even-textured adinole. (*b*) As tufts radiating from small elongated pools of coarser albite and quartz into a normal fine-grained adinole in which occasionally a little zoisite is present. (*c*) As needles in albite forming coarser bands 2 mm. wide with carbonate of a later stage of metasomatism, alternating with fine-grained adinole. (*d*) In a peculiar adinole showing rounded and elongated patches from 1¼ inch in length, composed of normal albite and quartz as fine-sutured grains with pools of coarser albite or quartz, several often in optical continuity. At the margins of these, needles of sagenitic rutile occur, and penetrating the pools are needles of tourmaline. This composite core is surrounded by a zone of coarser-grained material in which quartz predominates over albite and which contains many bunches of tourmaline needles. The space between the above patches is filled with very fine-grained albite full of felted bunches of tourmaline needles and granular leucoxene (fig. 7 B).

2. *Pseudomorph-bearing adinoles.*

These are found only on the south side of Dinas Head at distances less than twenty feet from any contact with the albite-dolerite. They have a white-weathering base like a normal adinole, but set in this, and generally weathering out from it, are pseudomorphs of a mineral which has the habit of andalusite (fig. 13, pl. XI). In different bands of adinole these pseudomorphs vary from ¼ to 1½ inches in length, and may be so abundant that a weathered surface is covered by an intergrown mat of them. In the actual outcrop they are a means of indicating sedimentary bedding, for there are bands rich in pseudomorphs and bands comparatively free from them.

Specimens of pseudomorphs were detached for goniometric measurement, but even when glass slivers were cemented on to the faces, no exact measurements could be obtained. This was due to the rough nature of the faces and to the long groove which runs down them, giving a rather chiastolite-like form. Although the pseudomorphs are not definitely proved to be after andalusite it is highly probable that they are, and with this reservation in mind they are referred to as andalusite pseudomorphs in the sequel. In none of these types has tourmaline been detected in any significant amount.

(*a*) *Types with quartz-chlorite-rich pseudomorphs* (fig. 8 A).—The pseudomorphs are made up of coarse, slightly elongated grains of quartz, often full of dusty inclusions of chlorite and ores. A very subordinate amount of granular leucoxene may occur in small patches. The interstices of the quartz grains are filled with a very fine-grained, pale yellow-



A B

FIG. 8 A. Adinole with quartz-chlorite pseudomorphs after 'andalusite', set in a very fine-grained matrix of albite and quartz with granules of leucoxene. $\times 5$.
FIG. 8 B. Chlorite-rich adinole. A base of fine-grained albite and chlorite with chlorite-rich patches and rounded areas of coarser albite with rays of chlorite. Granules of fine leucoxene occur throughout. $\times 27$.

green chlorite, which has positive elongation, negative sign, birefringence greater than 0·004, and the average refractive index varies in different specimens from 1·61 to 1·625, so that this chlorite is also a member of the diabantite-aphrosiderite group. The junction between groundmass and pseudomorph is always very sharp and the change of grain size is sudden.

Carbonate also may be present in small amounts. It is found replacing, in part, the groundmass adinole at the margins of the pseudomorphs and is now represented by limonitic rhombs.

As in the normal adinoles, the groundmass is a very fine-grained aggregate of albite and quartz, with a little chlorite, leucoxene, and carbonate; it occasionally shows a very fine banding, but no coarser patches or pools of albite are present.

(*b*) *Types with carbonate and chlorite-rich pseudomorphs.*—These pseudomorphs are made of coarse-grained ferriferous calcite as sutured grains, a chlorite similar to that in the quartz-rich pseudomorphs, and minor amounts of albite and quartz. On the weathered surface these pseudomorphs are rod-like and do not show the andalusite habit but are more irregular. This may be due to their replacing a different mineral, to the greater ease with which they are weathered, or to the reaction of the carbonate with the groundmass with the resulting obliteration of any crystal boundaries.

(*c*) *Chlorite-rich adinoles with chlorite pseudomorphs.*—These rocks occur only on the south side of Dinas Head associated with the other pseudomorph-bearing adinoles. The bands in which they occur can sometimes be traced laterally into bands containing quartz and chlorite-rich pseudomorphs, sometimes into bands containing the carbonate-rich type of pseudomorph. The relative amounts of albite and chlorite vary. On the whole, albite increases towards the main igneous contact. Some of the rocks of this type weather more readily than others.

The less altered type is a grey-green splintery rock, weathering with a greeny-white colour and covered with pinhead excrescences. It is a chlorite-albite-quartz-rock. The chlorite is a pale olive diabantite, γ 1·62, optically negative, birefringence greater than 0·004, and is the predominant constituent of the rock. It occurs with subordinate albite, concentrated in rounded patches in bands of very fine grain-size which merge into the groundmass and also scattered among the very fine-grained interlocking albite and quartz of the groundmass. Enclosed in this fine-grained albite and quartz are coarser albite and quartz areas with interstitial chlorite which correspond to the pinheads on the weathered surface. These are about 1 mm. across and either rounded or rectangular in form. In the former the chlorite may form irregular rays; in the latter the rectangular outline is seen in ordinary light only when the source is cut down to a pinpoint by a diaphragm. They may be pseudomorphs after incipient andalusite or cordierite or the first-albitized spots of the original sediment (fig. 8 B).

The more altered type is pinky-white on the fresh surface and has occasional large chlorite patches which weather green in a groundmass which weathers white. This type is exactly the same mineralogically as the less altered type described above, and contains similar coarse albite patches, but the chlorite-rich areas are fewer. The groundmass is of very fine albite and quartz in interlocking grains and contains little chlorite; leucoxene is gathered into larger patches. Albite crystals as irregular grains coarser than usual may be scattered evenly throughout the rock, corresponding to those in normal adinoles.

In these types, simple banding marked by relative concentration of chlorite and albite is common. Also, on the weathered surface the rock is seen to be made up of small lenticles, 5–10 cm. in length and packed together rather like a small-scale current bedding, but differing in the fact that the banding within each adjacent lenticle usually dips in opposite directions. This has been observed in one or two other specimens, especially of the carbonate-rich adinoles, but the structure cannot be matched with any known examples.

Pseudomorphs after andalusite similar to those in (*a*) and (*b*) are represented by angular areas of chlorite and calcite, with a little albite, quartz, white mica, and leucoxene; these being confined to occasional bands. The chlorite is a bright yellow-green with γ 1·625, and birefringence greater than 0·004, is optically negative, and again one of the same series as has been described in the normal adinoles. It is very fine-grained and sends stringers into the carbonate which occurs in it as rounded or irregular pools. Generally the chlorite lies between the carbonate and the groundmass adinole.

3. *Carbonate-rich adinoles.*

Calcite or ankerite occur in most of the adinoles, either as isolated crystals associated with late veining or as bands which may represent lime-rich bands in the sediments. Certain adinoles, however, have carbonates showing a very peculiar structure which warrants their being put in a class by themselves. These are found below the adinoles with the andalusite pseudomorphs on the south side of Dinas Head, between them and the top of the igneous intrusion. They are characterized by globular masses of ankerite ($CaMg(CO_3)_2$ 73%) up to 1·5 cm. in diameter, which are evenly distributed throughout the adinole. The four feet of adinole adjacent to the contact is free from carbonate, and is generally followed by three or four feet where the globular masses are solid and pass upwards (in about ten feet) into a type with concentric structures (fig. 14, pl. XI). These pass gradually into the pseudomorph-bearing adinoles.

In the hand-specimen, the core of ankerite seems sharply separated from an outer shell of ankerite by a distinct shell, 1–2 mm. wide, of very fine-grained quartz and albite. The outer shell of ankerite, 2–4 mm. in thickness, may have a sharp or a transitional outer margin into the normal adinole in which the globular masses are set. The adinole weathers white with many small pinhead brown specks representing ankerite scattered in the groundmass.

In slice, the core of ankerite is seen to be composed of only a few crystal units, with an irregular outer margin. The intermediate zone of adinole is often difficult to distinguish, as it carries much carbonate. The outermost zone has the same composition as the inner, and has a comparatively sharp inner margin and a very irregular outer one which occasionally fingers out into bands replacing the main mass of the adinole, relicts of which can be seen within the ankerite. Apart from the above carbonates, the rock is composed of albite and quartz as very fine interlocking grains, in which are set sporadic albite grains up to 0·1 mm. in diameter and with sutured margins. Traces of banding due to minute chlorite flakes are occasionally seen and small patches of ankerite with irregular rhombohedral outlines are scattered all through, as also are small mossy patches of leucoxene.

Between the adinoles with pseudomorphs and the adinoles with globules of carbonate, a band occurs which, on the white-weathered surface has many rounded and sub-angular excrescences, each about 2 mm. long. These give the rock the appearance of a fine-grained porphyritic igneous rock; but in slice, the majority of these excrescences are seen to have exactly the same structures as the replacements in the chlorite-rich adinoles with the andalusite pseudomorphs, namely, rounded form, grain-size coarser than that in the groundmass, and irregular rays of chlorite running into the centre. When the illumination is cut down to a pinpoint, some show rectangular forms, but this outline is not defined by the change in grain-size between the coarser patches and the groundmass.

Carbonate-rich adinoles, rather weathered, occur at the top of the cliff on the south side of the neck adjoining Dinas Head to the mainland. A partial analysis showed Na_2O 5·96, K_2O 1·74 %. In the fine-banded adinoles associated with and below these, there was found the complete and undistorted cast of a trilobite, identified by P. Lake as a *Cyphaspis*, which is shown in fig. 12, pl. XI.

At the same locality, the lower part of the cliff shows rocks with interesting structures (fig. 11, pl. XI): they consist of flattened bodies lying in the bedding planes, with cores of ferriferous calcite surrounded by and replacing a shell of very fine-grained albite and perhaps quartz. These bodies are sharply marked off from the surrounding rock which, in slice, appears as a mass of very fine sericite with much carbonate now represented by limonite. Partial analysis of this groundmass shows Na_2O 1·37, K_2O 2·95 %, indicating that the rock is only partially albitized. The nodules may be interpreted as the result of localized reactions of solutions which found an easier path along the bedding planes: first, soda-rich solutions giving the adinole shell, and then solutions rich in the carbonates of lime and iron. Very similar nodules occur at the contact of the Stepper Point dike and the purple Upper Devonian slates at Stepper Point quarry [17, plate 2]. This explanation does not hold for the compound globules so typically developed and no satisfactory explanation has been found for this rhythmic phenomenon. It may represent some process at a late stage in metamorphism, either the introduction of carbonates or the recrystallization of the original carbonates in the rock.

4. *Polygonal and spherulitic adinoles.*

The typical spherulitic adinole found by Fox [6] occurs only in two places: in the small projection of Dinas Head into Stinking Cove and at the top of the cliff directly above this. The development of the rocks is clearest at the latter locality. The outcrop of adinoles in which the spherulitic type occurs has been torn away from its igneous contact and folded into the slates. On its western side it is separated by a quartz-filled fault from normal adinoles which can be seen to pass into slates, although the tracing of any one particular band is a matter of great difficulty. It is probable that the spherulitic adinoles and associated rocks lay between these normal adinoles and the igneous contact, for on the whole they are more altered. The actual outcrop of the typical polygonal and spherulitic adinoles occupies a band not more than two feet thick in between adinoles showing the simplest of structures. The structures to be described must therefore depend to some extent on the original composition of the band.

(*a*) *The polygonal adinole* is a fine-grained white-weathering rock composed of a series of irregular polygons 5–10 mm. in diameter and showing no elongation, and through which in sections across the bedding, a fine banding can be seen (fig. 9 A). It is composed of an aggregate of very fine albite and quartz with a little chlorite and leucoxene, and with banding marked by rather thin and diffuse carbonaceous films. Analysis of this rock shows Na_2O 8·94, K_2O 0·14 %. The polygons are defined by cracks in which occur carbonaceous and ore minerals. Ankerite may occur in them as small rhombs and stringers replacing the adinoles at the margins of the polygons and therefore of a later date. Very thin quartz veins cut all these features.

These polygonal adinoles have been observed at the margins of joints in a fine structureless adinole, where they bear the same relation to this adinole as the spherulitic variety bears to them. This would seem to indicate that the structure post-dates the metasomatism or is a late feature of the process.

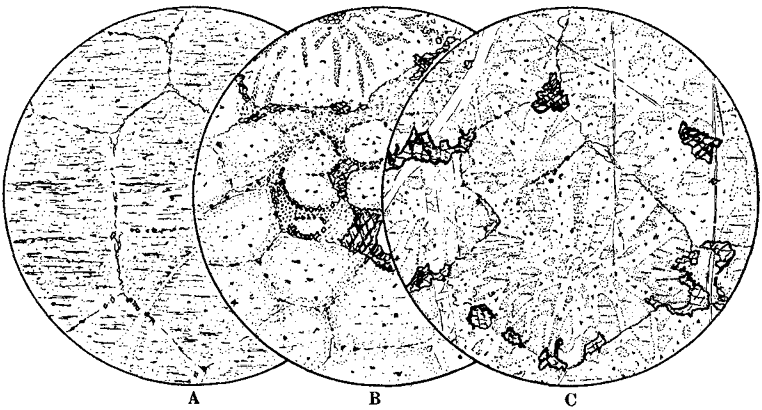


FIG. 9 A. Polygonal adinole. Very fine-grained quartz and albite with banding marked by carbonaceous films and polygons defined by limonite and ores; cut by a thin quartz vein. $\times 4$.

FIG. 9 B. Adinole showing transition from polygonal to spherulitic structures. $\times 4$.

FIG. 9 C. Spherulitic adinole. Radiating blades of albite are set in a matrix of fine-grained albite and quartz; the matrix partly replaced by ankerite between the spherulites. $\times 4$.

(*b*) *The spherulitic adinole* is developed in most cases within 15 cm. of joints in the polygonal adinole and away from these is very local, disappearing both along and across the sedimentary banding. It weathers with a rough surface, as the individual crystals and spherulites stand out; and the finer details of the sedimentary banding are not generally visible on the weathered surface.

Examination of slices shows that the following changes take place in passing from polygonal to spherulitic adinole:

i. There is a marginal increase in the grain-size of the albite of the polygons, the grains still retaining their sutured interlocking margins.

ii. A disappearance of the fine banding marked by the carbonaceous films in the groundmass.

iii. Associated with the ankerite between the polygons, tabular albite and a little quartz are developed (fig. 9 B). Both these may replace to some extent the fine adinole between the spherulitic blades of albite.

iv. Albite develops as coarse blades up to 0·5 mm. across and arranged in a spherulitic manner [cf. 7, fig. 57 C]. There are three distinct types of this development. (*a*) Blades radiate from the centre of a polygonal area and increase in width towards the margin. Albite twin-lamellae occur parallel to the length. Where these blades are not in contact with each other they have crenulate margins, the end in particular being very irregular and also fan-like, due to many new growth-centres being set up. The blades are always cloudy and often have trains of carbonaceous inclusions through them parallel to the original sedimentary banding, and independent of the orientation of the crystal (fig. 9 C). The blades of albite may be strongly curved and the twin-plane is also curved, and the extinction varies parallel to it, but is constant with reference to the portion of the twin-plane to which it is adjacent. The number of spherulites increases towards the joints. (*b*) Blades may radiate from within the polygon but not from its centre, which is still fine-grained adinole. The blades in this case show features similar to those just described. It should be noted that in both these cases the blades may not reach the margin of the polygon, and if they do so, they do not grow into the adjacent polygon. The albite of the margin may be sutured and interlocking, or tabular; that of the interior may be coarse, as in iii, and show no banding. Opaque masses of zoisite are occasionally developed at the centres of some of the polygons. (*c*) Blades of albite radiate from thin quartz veins in the joints, and together with late ankerite may show a fan-like form due to the periodic appearance of new centres of growth. These are usually set in irregular coarse albite.

v. Leucoxene is found most abundantly in the fine adinole between the spherulitic blades, or, if this is absent, at the mutual interference of two blades, where it occurs as coarse granules. It occurs only sporadically as fine grains in the blades.

vi. Thin quartz veins, with albite crystals growing from the adinole which forms the margin of the vein, are common.

Partial analysis of a spherulitic adinole immediately adjacent to the polygonal adinole, whose Na_2O and K_2O content has already been given, shows Na_2O 8·33, K_2O 0·17 %. A similar adinole showing both polygonal and spherulitic structures has been analysed by Fox [5, p. 723] and the composition is given under D in table II.

(*c*) *The origin of the polygonal and spherulitic structures.*—The polygons are confined almost entirely to one band in the adinole, and must either represent some original structure in the sediment, or be due to a slight contraction during the process of metasomatism. Any other explanation meets with difficulty, because the very fine banding which runs undisturbed across from one polygon to another can be only of sedimentary origin.

The spherulites occur everywhere associated with the polygonal adinoles. They are more concentrated near small joints, and this fact, together with their common development within polygons, shows that they have grown after these were formed, possibly at a later stage in the metasomatism by the influence of water vapours acting along the joints. The change is one of gradual recrystallization, for the percentages of potash and soda are nearly identical in the polygons and spherulites, and the fine carbonaceous banding of the original polygonal adinole is preserved in the diversely orientated crystals of the spherulites. Those blades which start growth from thin quartz veins have done so because the water made conditions most suitable for recrystallization. These spread through the rock, the fan-like form being due to several points on the outside of the limit of crystallization starting as independent growth-centres.

(*d*) *Other types of spherulitic adinole.*—Just west of the typical spherulitic adinoles in the cliff on the north side of Dinas Head occur some highly folded adinoles composed essentially of albite and quartz. In these occur some bands which weather with rounded blebs about ¼ inch in diameter. In slice, the groundmass is almost entirely albite as sutured, interlocking grains of very variable size with many larger cloudy crystals with crenulate margins, the whole appearing as if it were being recrystallized into these coarser grains. Set in this groundmass are spherulites showing both a radial and a concentric structure. Sometimes these spherulites are joined together in a line parallel to the banding of the rock and appear like a vein with regular constrictions. Equiangular crystals make the core and are sometimes followed by a thin zone of fine-grained adinole. This is succeeded by a zone of radially arranged albites, then by a fine-grained zone which merges into the groundmass. No explanation of this rhythmic phenomenon is known.

In the most easterly knoll, sticking up through the grass on the south side of Dinas Head, adinoles of normal type occur, and interbanded with them are some which show spherulitic structures. The coarsest type is evidently an adinole breccia of rounded and angular masses of normal adinole which sometimes shows a zonary structure of a coarser core and finer shell, surrounded by radially arranged blades of albite up to 1 cm. in length. These are turbid as a result of weathering. They could represent some easily albitized rock of which no trace remains, and which may have lost volume on metasomatism, and in the cavities resulting albite developed. This, however, is unlikely, as the blades of albite are set in a fine-grained groundmass like that of the normal spherulites. It is also possible that they represent a rock with structures which have since been replaced, and a more easily albitized groundmass, but no parent rock suitable has been found at Dinas Head.

5. *Sheared adinoles.*

At several places to the north and south of Dinas Head the adinoles have been sheared, either in faults or in the drawn-out limbs of folds. Potash and soda were determined in one example of a rock from the limb of a folded and sheared adinole. The rock was composed entirely of white mica and some small needles of rutile, and it was thought that the former might be paragonite produced by the shearing of the adinole. Analysis, however, showed Na_2O 0·38, K_2O 5·29 %. This indicates that the mica is a normal muscovite.

VIII. The Chemical Constitution and Origin of Adinoles.

The chemical composition of adinoles given in table II is, as is to be expected from the mineralogical composition, essentially that of albite and quartz. As a result they show a very close chemical similarity to quartz-keratophyres, an average analysis of which is quoted in column F. Keratophyric tuffs with more alumina-rich material would show a close resemblance to the chemical composition of spilosites.

These resemblances have been brought out in a general way by plotting the fields of the available analyses of adinoles, spilosites and spotted slates, pelitic sediments, and keratophyres on a ternary diagram (fig. 10) whose co-ordinates are: $Na_2O+Al_2O_3$, 1:1, i.e. equivalent to albite; K_2O+residual Al_2O_3, i.e. equivalent to orthoclase and sericite; $Fe_2O_3+FeO+MgO+CaO$, i.e. ferromagnesian minerals.

It should be noted that there is a transition between the fields of adinoles, spilosites, and slates, as would be expected if the origin of the two former be due to the metasomatism of unaltered pelitic sediments. The similarity of mineralogical and chemical composition of adinoles and keratophyric lavas and tuffs suggests the possibility that some rocks, which have been described as adinoles and hence as of metasomatic origin, are, in reality, keratophyric lavas or tuffs which have been altered by pure thermal metamorphism at the contact of basic dikes and sills.

TABLE II. Chemical analyses of adinoles and spilosites.

	6.	B.	7.	8.	C.	D.	E.	F.
SiO_2 ...	52·70	54·02	70·86	69·03	66·6	64·6	72·63	75·45
TiO_2 ...	0·64	—	0·50	0·47	0·8	1·2	—	0·17
Al_2O_3 ...	25·28	21·22	15·17	17·42	19·6	20·4	15·81	13·11
Fe_2O_3 ...	0·68	2·51	1·52	0·17	0·9	0·7	—	1·14
FeO ...	1·59	6·48	1·06	0·71	0·2	—	0·74	0·66
MnO ...	trace	1·74	0·00	0·00	—	—	—	0·29
MgO ...	2·16	3·01	1·08	0·47	0·3	0·1	1·21	0·34
CaO ...	2·48	1·64	0·64	1·00	0·4	1·3	1·02	0·83
Na_2O ...	3·35	3·36	7·58	8·89	9·8	10·1	8·33	5·88
K_2O ...	5·16	3·71	0·25	0·31	0·7		0·75	1·26
H_2O+ ...	3·62	1·97	1·05	0·64	0·8	1·6	0·61	0·69
H_2O- ...	0·70	—	0·38	0·24	—	—	—	—
B_2O_3 ...	0·15	—	0·35	0·00	—	—	—	—
P_2O_5 ...	0·12	—	trace	0·12	—	—	—	0·18
CO_2 ...	1·48	—	0·00	0·66	—	—	—	—
C ...	0·00	—	0·00	0·00	—	—	—	—
Total ...	100·11	99·66	100·44	100·13	100·1	100·0	101·10	100·00
Sp. gr....	2·59	2·78	2·63	2·62	—	—	2·68	—

6. Spilosite showing albite-rich spots with tourmaline needles in sericitic groundmass, Dinas Head (figs. 3 and 6A). Analyst, W. H. Herdsman.
B. Spilosite, Heinrichsburg, Mägdesprung, Harz [10].
7. Adinole, interbanded with 6, and showing fine-grained albite and quartz with coarser, and needles of tourmaline, Dinas Head (fig. 6 B). Analyst, W. H. Herdsman.
8. Adinole, very fine-grained structureless albite-quartz-rock, Dinas Head. Analyst, W. H. Herdsman.
C. Adinole, very fine-grained structureless albite-quartz-rock, Dinas Head [6].
D. Adinole, showing polygonal and spherulitic structures, Dinas Head [6].
E. Adinole, Heinrichsburg, Mägdesprung, Harz [10].
F. Average quartz-keratophyre. (R. A. Daly, Igneous rocks, 1914, p. 20.)

The rocks from Dinas Head described as adinoles are very much thicker than other recorded adinoles, especially those associated with dikes and sills of the same province in Devon and Cornwall. Also, these adinoles from Dinas Head occur at about the same horizon as the calcareous slates and keratophyric ash of Greeb Point in Veryan Bay [8, table I], and must resemble the latter very closely in chemical composition. It is evident, therefore, that keratophyric material was available in Devonian time in south Cornwall, and the existence of keratophyric tuffs in north Cornwall would not have been unexpected.

With these points in mind, a careful examination was made of all the evidence at Dinas Head. The following features indicate that the adinoles were derived from a sediment, but do not indicate whether this sediment was tuffaceous or not:

i. A very prominent banding shows well in the differential weathering of the adinoles. This banding is sometimes so fine as to be most prominent when seen under the microscope. It is not prominent in the group 3 adinoles with the globular ankerite structures.

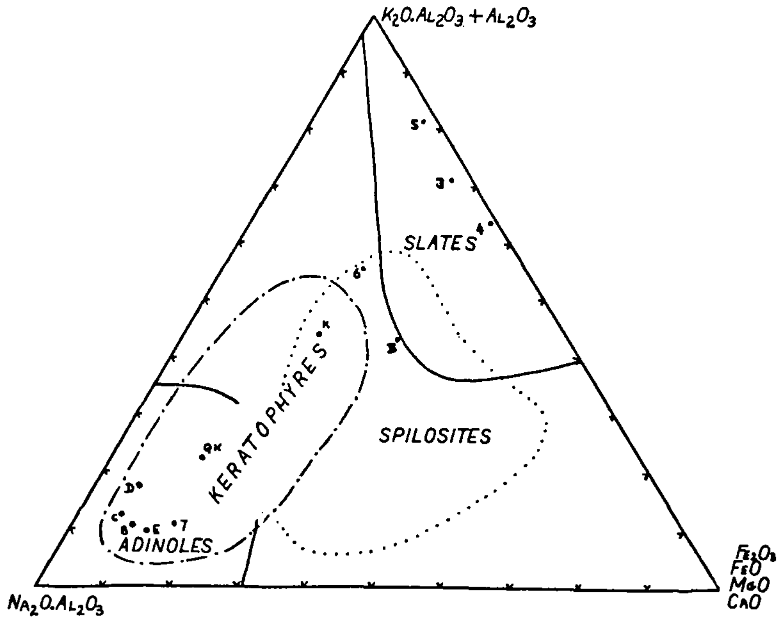


FIG. 10. Diagram to show the fields of slates, spilosites, adinoles, and keratophyres, based on 170 analyses. The numbers correspond to analysed rocks from Dinas Head. QK = average quartz-keratophyre. K = average keratophyre.

ii. Fossils, completely undistorted, are present in some of the adinoles (fig. 12, pl. XI).

iii. The adinoles form a shell over the dolerite intrusion and lie between it and the unaltered slates and limestones. It should, however, be noted that this would also describe a concordant intrusion into a lava or into a tuff horizon.

The following additional features point to a metasomatic as well as a sedimentary origin:

iv. There is a general increase in albitization towards the contact with dolerite, visible where the rocks are not folded or torn away from it.

v. Pseudomorphs, presumably after andalusite, occur in one of the common types of adinole.

vi. Spilosite with small albite and dravite spots in a sericitic base like that of a normal slate is intimately interbanded with adinole in which the spots are preserved as coarser patches in a fine-grained adinole representing the altered groundmass of the spilosite.

vii. Pyroclastic characters, some trace of which might be expected to be preserved, are completely absent in all the types of adinoles. Except for the thin band of schalstein in the unaltered sediments, tuffs are absent.

The only adinoles which do not show an abundance of sedimentary features are the types with the globular masses of ankerite from the south side of Dinas Head, but even these show a rude banding and sometimes the relicts of initially albitized spots in the groundmass of fine adinole. Their lack of positive volcanic or pyroclastic features makes it more probable that they are of sedimentary and metasomatic origin like the rest of the adinoles.

The metasomatic origin of these adinoles being thus extremely probable, an attempt can now be made to investigate the process of adinolization more closely.

The earliest workers, Kayser [10], Lossen [12], Fox [5, 6], and Clements [2], all based their suggestions on evidence from the minerals developed in adinoles and albite-dolerites and on analyses of these and slates without any definite calculation as to the amount of material transferred. The first attempt to calculate the material added to a slate to form adinole was made by Dewey [4, p. 75], who used a straight line variation diagram and arrived at the conclusion that it was necessary to add four parts of albite and a small quantity of magnetite to one part of slate to give the adinole. Holmes [9], using Dewey's diagram slightly modified, calculated that to one part of shale, six times its weight in albite has been added. Blyth [1] concluded that albitic solutions permeated the shales, but he made no suggestions as to the amount of material involved. Milch [14] added material, of a composition which it seemed reasonable to regard as corresponding to the late liquids of the albite-diabases, to a given amount of sediment until the average composition was that of the analysed material.

All the above methods of calculation imply a great increase in volume (or a great increase in density) accompanying metasomatism, and for this there is no evidence anywhere whence adinoles have been described. One finds that everywhere there is essentially a volume-for-volume replacement of the slate. The evidence upon which this is based is as follows:

i. In some of the adinoles the very finest of banding, presumably sedimentary, is visible and shows no sign of the distortion which might be caused if the chemical change was accompanied by an increase in volume. The irregular banding described in the chlorite-rich adinoles may be a result of such an increase, but even so, this type is relatively restricted in its development.

ii. The larger scale bedding of the adinoles themselves, or of the adinoles and spilosites, shows all the features of a normal sediment with parallel-sided beds.

iii. There is a complete absence of cavernous structures in all adinoles, except possibly in the third of the spherulitic types.

iv. The fossils found in adinole both at Dinas Head and at Port Quin [17, p. 26] are perfect casts and show that the replacement of slate by adinole is a gentle replacement of the original structures by the new minerals.

v. The early-formed andalusites, now pseudomorphed by quartz and chlorite, are undisturbed by the process which albitized the micaceous groundmass in which they are set.

vi. There has been no great increase in the density of the rocks such as might be accounted for by the addition of much material.

That this constancy of volume must be the control we use in calculating the changes that take place in metasomatism was pointed out by Ransome [15]. Calculations are made on 100 c.c. of material. The weights in grams of the various oxide components per 100 c.c. are obtained from the weight present in 100 grams of rock, by multiplying this percentage value by the specific gravity of the rock. In table III such a calculation is worked out on the assumption that the grey-black slate analysed is the parent sediment. Columns A_1, B_1, C_1, D_1, and E_1 give weights in grams of each oxide per 100 c.c. of rock. Columns B_2, C_2, D_2, E_2 show the gains and losses of each oxide in each of the altered rocks as compared with the grey-black slate. The values are obtained by direct subtraction, the plus values indicating material added and the minus values material lost during the adinolization. The total amounts of material lost and gained are obtained by adding the plus and minus values respectively, and the net gain or loss of material in adinolization of each rock is given by the difference in these totals. This indicates that about 47 grams of material were added and 76 grams lost per 100 c.c. of slate adinolized, or 17 grams replaced 23 grams in 100 grams of rock.

This is a much more reasonable result than the addition of three to six times the weight of slate in albite and quartz.

TABLE III. Gains and losses during adinolization, assuming the black slate (analysis 3, table I) to be the parent sediment.

	Weight of each constituent as grams per 100 c.c. of rock.					Gains and losses as grams per 100 c.c. of rock, compared with 100 c.c. of the black slate.				Gains and losses as percentages of the original rock mass, i.e. as grams per 100 grams of rock.			
	A_1	B_1	C_1	D_1	E_1	B_2	C_2	D_2	E_2	B_3	C_3	D_3	E_3
Analysis No.	3.	5.	6.	7.	8.	5.	6.	7.	8.	5.	6.	7.	8.
SiO_2	160·1	176.2	136·5	187·1	180·8	+16·1	−23·6	+27·0	+20·7	+5·7	− 8·4	+ 9·6	+ 7·4
TiO_2	1·7	1·6	1·7	1·4	1·2	− 0·1	—	− 0·3	− 0·5	—	—	− 0·1	− 0·2
Al_2O_3	62·8	56·7	65·5	40·1	42·3	− 6·1	+ 2·7	−22·7	−20·5	−2·2	+ 0·9	− 8·1	− 7·4
Fe_2O_3	1·8	2·4	1·8	4·0	0·5	+ 0·6	—	+ 2·2	− 1·3	+0·3	—	+ 0·8	− 0·5
FeO	14·5	5·1	4·1	2·8	1·9	− 9·4	−10·4	−11·7	−12·6	−3·3	− 4·1	− 4·2	− 4·5
MgO	8·0	4·2	5·6	2·9	1·2	− 3·8	− 2·4	− 5·1	− 6·8	−1·4	− 0·9	− 1·8	− 2·4
CaO	1·7	—	6·4	1·7	2·6	− 1·7	+ 4·7	—	+ 0·9	−0·6	+ 1·7	—	+ 0·3
Na_2O	1·4	0·9	8·7	20·0	23·3	− 0·5	+ 7·3	+18·6	+21·9	−0·2	+ 2·6	+ 6·6	+ 7·8
K_2O	12·8	13·1	13·4	0·7	0·8	+ 0·3	+ 0·6	−12·1	−12·0	+0·1	+ 0·2	− 4·3	− 4·3
H_2O+	12·1	9·4	9·2	2·8	1·7	− 2·7	− 2·9	− 9·3	−10·4	−1·0	− 1·0	− 3·3	− 3·7
H_2O-	1·7	1·8	1·8	1·0	0·6	+ 0·1	+ 0·1	+ 0·7	− 1·1	—	—	+ 0·3	− 0·4
B_2O_3	—	—	0·4	0·9	—	—	+ 0·4	+ 0·9	—	—	+ 0·2	+ 0·4	—
P_2O_5	0·3	0·3	0·3	—	0·3	—	—	− 0·3	—	—	—	− 0·1	—
CO_2	—	—	3·8	—	1·7	—	+ 3·8	—	+ 1·7	—	+ 1·4	—	+ 0·6
C	2·5	0·9	—	—	—	− 1·6	− 2·5	− 2·5	− 2·5	−0·5	− 0·9	− 0·9	—
Total added per 100 c.c., in grams						+17·1	+19·6	+49·4	+45·2	+6·1	+ 6·8	+17·7	+16·1
Total displaced, do.						−25·9	−41·8	−64·0	−67·7	−9·2	−15·3	−22·8	−24·3
Net gain or loss, do.						− 8·8	−22·2	−14·6	−22·5	−3·1	− 8·5	− 5·1	− 8·2

	Composition of added material as weight %.				Na_2SiO_3
SiO_2	94·7	—	55·3	46·0	45·4
Al_2O_3	—	13·4	—	—	—
Fe_2O_3	3·6	—	4·4	—	—
CaO	—	24·3	—	2·0	—
Na_2O	—	38·0	38·1	48·5	54·6
K_2O	1·8	3·0	—	—	—
B_2O_3	—	1·5	1·2	—	—
CO_2	—	19·6	—	3·7	—

From the plus values the composition of the material added to the sediment has been calculated and is essentially Na_2O and SiO_2 with a little B_2O_3 and possibly a little Fe_2O_3. It is interesting to recall at this point that Clements [2] suggested that adinolization consisted of the addition of soda and silica to slates.

These ingredients need not correspond to the actual composition of the fluids permeating the rocks, but are the materials that have been 'fixed' in the slate to give adinole. This 'fixation' may be the result both of a simple chemical reaction capable of representation by an equation and of a replacement in which stoichometric relations do not hold, and because of this, one cannot give a balanced equation to express adinolization.

The values calculated in table III give the minimum amount of material gained and lost in metasomatism, for only that amount of material necessary to bring the composition of the slate to that of the metasomatized product is removed and added in the calculation. There is nothing to indicate to what extent there has taken place a complete replacement, such as, to take an extreme case, Sericite (solid)+Albite (in solution) $\longrightarrow$ Albite (solid)+Sericite (in solution).

Very similar results are obtained from a volume-for-volume calculation with the green spotted slate (analysis 4) as parent. It should, however, be pointed out that one does not know for certain whether the slates analysed were the actual parents of these particular adinoles, for, although they occur near them, one cannot trace exactly the same band of sediment into adinole.

The tourmaline (dravite) was possibly formed by reaction of the introduced boron with the chlorite of the original sediments; that it was introduced along with the soda and silica is shown by its presence in the early metasomatic spots of the spilosites and by its association with albite of two generations in the spilositic adinole interbanded with the spilosites. If all the sediments were affected by similar solutions carrying Na_2O, SiO_2, and B_2O_3, the amount of tourmaline developed must be controlled by the initial composition of the sediments. Tourmaline is typical of the normal adinoles and occurs occasionally in the spherulitic adinoles, but varies in amount. In some rocks it may be absent, in others it is an accessory mineral, and in others is the predominant constituent. The presence of tourmaline so obviously formed along with the albite and associated with basic igneous rocks is of much interest, and the description and discussion of the origin of these types is reserved for a separate communication. It may, however, be recorded here that no tourmaline or boron-bearing mineral has, as yet, been found in the albite-dolerite, except an axinite-epidote gash vein in a newly opened quarry.

There is some evidence to show that prior to the metasomatism there took place a thermal effect due to the heat of the dolerite. Thus between the adinoles and spilosites showing metasomatic effects and the unaltered sediments there are, in several places, slates which show a characteristically thermal spotting, such as is found at the contact of many dikes and sills in the Devonian slates of north Cornwall. These spots show no evidence of added material and are due to the selective concentration of chlorite, sericite, ores, and graphite, and may be attributed to the active nature of the water contained in the rock, as a result of a slight rise in temperature in the vicinity of the igneous intrusion, but outside its sphere of metasomatism.

Other spotted slates show a variety of chevron-like forms such as have elsewhere been ascribed to incipient andalusite or cordierite [17, pp. 49–50; 18, p. 65]. This may quite well be the case, as the examples analysed agree closely with class I hornfelses near the andalusite-cordierite join. In the chlorite-rich adinoles there are coarser patches of albite with these chevron features marked in chlorite. These may represent replacements of what is described as incipient andalusite or cordierite in the spotted slates.

Within twenty to thirty feet of igneous contacts are found bands containing pseudomorphs of andalusite replaced by quartz and chlorite (group 2 *a* and 2 *b*), set in a fine-grained matrix of albite and quartz. This andalusite must have formed in the argillaceous sediment prior to the metasomatic development of albite. The pseudomorphs are found close to the contact, as only here was the heat of the dolerite sufficient to complete the mineralogical change. The presence of andalusite so well developed at a dolerite contact is very exceptional, but as no other intrusion is to be seen, all the evidence points to the dolerite being the source of both the supply of heat and of the metasomatizing fluids.

In the metasomatic stage there are two facts which indicate that silica-rich fluids may have preceded the soda-silica-rich fluids responsible for the albitization. Firstly, some of the spilosites on the outside of the metasomatic aureole show small quartz-rich spots. It is not proven, however, that these represent material added from an external source. If this rock is to be regarded as a parent of the adinoles, a volume-for-volume calculation shows that it would be necessary to add soda and accessory silica to it to give adinole. Secondly, the andalusites formed in the early thermal stage of metamorphism are commonly replaced by coarse quartz and chlorite, and set in a matrix of very fine-grained albite and quartz.

Carbonates everywhere crystallize after the albitization and are found as isolated crystals, veins, nodules, and bands, all showing some replacement features against the adinole. Both ankerite and calcite occur in the adinoles, and the igneous rock is so highly carbonated that there is no doubt that all of it could have been derived from the intrusion. On the other hand, calcite is plentiful in some of the unaltered slates among which limestone bands also occur, so that the calcite at least might be derived from these sediments, and shows late crystallization and replacement features because of its ability to exist in solution in the rock at lower temperatures when albitization has ceased. In all probability, however, both these sources were important.

In table III it will be noted that the spilosite 6 gives very different results from the adinoles 7 and 8. This must be due to a difference in composition of the original sediment, for 6 and 7 are interbanded (fig. 3). From the analysis it would appear that this spilosite was much richer in alumina than any of the analysed slates, but there is no evidence to show that this factor alone is the reason for the resistance of this rock to albitization. Had this spilosite been completely adinolized—and no doubt beds of an initially similar composition are represented among the adinoles—it would have been very similar chemically and mineralogically to the analysed adinoles 6 and 7.

In this connexion it is worth noting that red and purple slates may be adinolized close to dolerite contacts, contrary to Dewey's statement [4, p. 72] that they are converted only into spotted slates. Thus at the contact of the Stepper Point dike and the red and green slates of Butter Hole and Pepper Hole [17, p. 22] there is a six-inch band of adinole immediately adjacent to the dike. Between this and the unaltered slates there is a zone, 50–80 feet wide, of spotted slates which sometimes show incipient andalusite. Below the quarry at Stepper Point, the spotted purple slates have nodules of adinole close to the contact [17, plate 2].

It seems, therefore, that in the initial stages of adinolization the velocity of reaction is controlled by the composition of the sediments, and, as Dewey suggests, it is probably the richness in Fe_2O_3 of the red slates which inhibits their reactions with the metasomatic fluids, together with the fact that in black slates the iron is mostly in chlorite and therefore in the ferrous condition and so more susceptible to reaction. If this were the only cause, the pale-green slates which are richer still in FeO ought to develop adinoles easily, but this is not so, as adinoles in the pale-green slates are very thin. It is suggested, therefore, that the grain-size of the original sediment exerts an important influence on the ease with which the rock is albitized: for the red and pale-green slates in the centre of the St. Mabyn syncline are much coarser in grain-size than are the black slates occurring on the flanks of the syncline.

The composition of the minerals formed, and hence of the end-product adinole, are controlled by the metasomatic fluids emanating from the igneous rock. The end-product will have exactly the same minerals as those formed in the earliest stages of metasomatism provided that the composition of the fluids has not changed. Thus, in the first stages of metasomatism, albite, quartz, and chlorite, with or without dravite, are formed. In the adinoles which represent complete metasomatism, the rock is built up entirely of the same minerals with or without carbonates. These carbonates, in part at any rate, correspond to an addition of carbonate to the original fluids containing soda, silica, and boric oxide. It is also evident that very different replacements must take place in the adinolization of different rocks, for adinoles which are mineralogically and chemically identical are formed from a variety of argillaceous types.

All the metasomatizing material has been derived from the albite-dolerite, and it can be shown that if it were added back to the rock, it would still have the composition of a fairly typical member of the suite of Devonian hypabyssal intrusions allied to the spilites. Thus, assuming that there is four times as much dolerite as adinole—and there is certainly more than this—from table III the following figures are obtained: 100 c.c. slate become 100 c.c. adinole by the addition of 20 grams (approx.) of Na_2O and 24 grams SiO_2. This adinole we have assumed is derived from 400 c.c. of dolerite, so to each 100 c.c. of dolerite, 5 grams of Na_2O and 6 grams of SiO_2 must be added. The dolerite has 46·9 % SiO_2, equivalent to 135·1 grams of SiO_2 per 100 c.c., and 3·8 % Na_2O, equivalent to 10·9 grams of Na_2O per 100 c.c., since the specific gravity is 2·88. With the added material this becomes 141 grams SiO_2 and 16 grams Na_2O per 100 c.c., which, as weight per cent., is SiO_2 48·9 %, Na_2O 5·5 %. The reason for this great bulk of adinole at Dinas Head compared with other localities must lie in the greater bulk of igneous material which supplied the metasomatic fluids. These fluids were probably identical with the late autolytic fluids which albitized, carbonated, and chloritized the dolerite. On account of the thickness it is possible that the intrusion is a small plug-like mass with sill-like offshoots on its upper surface, as was suggested when the igneous rocks were described. The offshoots enabled a more intimate penetration of the sedimentary series to be brought about.

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Explanation of Plate XI.

Adinoles of Dinas Head, Cornwall.

Fig. 11. Disk-like nodules lying in the bedding planes of a partially adinolized slate; showing the core of calcite surrounded by a shell of adinole. From the south side of Dinas Head.

Fig. 12. Trilobite (*Cyphaspis*) in adinolized slate from the south side of Dinas Head. $\times 2$.

Fig. 13. Pseudomorphs of andalusite replaced by quartz and a little calcite, set in adinolized slate. From the south side of Dinas Head. $\times \frac{1}{2}$.

Fig. 14. Adinole with concentric structures of ankerite. From the south side of Dinas Head. $\times \frac{3}{4}$.

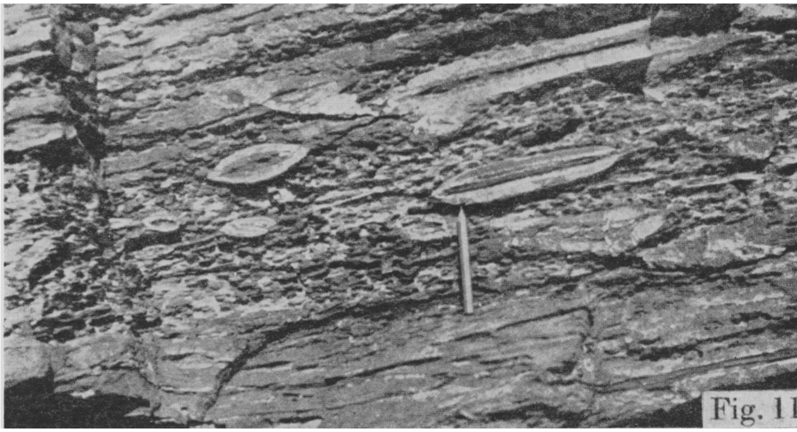

Fig. 11

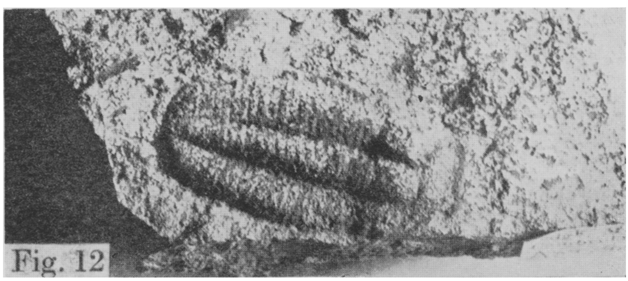

Fig. 12

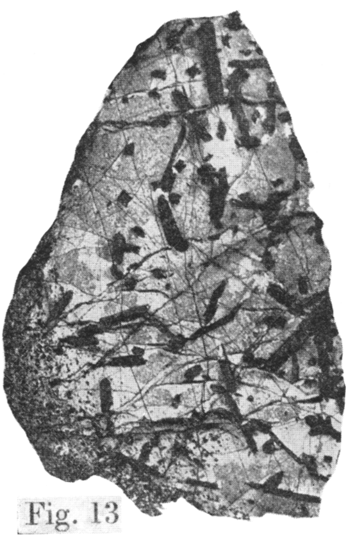

Fig. 13

Fig. 14

S. O. Agrell: Adinoles from Cornwall