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ORIGINAL ARTICLES.

I.—ON SOME BRITISH PILLOW-LAVAS AND THE ROCKS ASSOCIATED  
WITH THEM.

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(By permission of the Director of H.M. Geological Survey.)

(Concluded from the May Number, p. 209.)

IF we take a rapid glance over the volcanic history of the British Isles we find that eruptions having the spilitic facies have occurred repeatedly, over a wide area and on a large scale.

*Pre-Cambrian.* Among the Dalradian Schists of the West of Scotland pillow-lavas were first recognized by Peach (30). They are well shown on the shore at Tayvallich on the Sound of Jura, and extend thence through Argyllshire past Loch Awe. Representatives of this series are met with at Ardwell in Banffshire. The accompanying sediments are the quartzites, black shales, and limestones of the Central Highlands. Albite-diabases represent the intrusive phase, and there are also keratophyres and soda-granites. The age of this series is uncertain, but perhaps it is pre-Cambrian.

In Anglesey and the Lleyn District of Carnarvonshire pillow-lavas with variolitic structure have been described by Raisin (31) and Greenly (32). With them there are diabases and cherts, but no acid rocks are known. These also are perhaps pre-Cambrian.

*Cambrian (?)*. Radiolarian cherts and pillow-lavas occur in a narrow strip along the southern border of the Scottish Highlands extending from Stonehaven into Arran. Diabases accompany them, but no acid rocks, though serpentine and gabbro are found in lenticles, the relations of which to the lavas and cherts are unknown. The sediments are black shales, grits, and limestones, and Dr. Peach thinks it likely that they will ultimately prove to be Upper Cambrian (33).

*Ordovician.* To this series belong the Arenig volcanics of the South of Scotland and the Arenig or Llandilo pillow-lavas of South Cornwall. In both places there are diabases, keratophyres, and soda-felsites or soda-granites.

About the same time there were eruptions in South Wales emitting keratophyres, soda-felsite, variolite, and diabase, and Thomas (34) has found a remarkable suite of rocks on Skomer Island that presents many resemblances to the Arenig igneous rocks of South Scotland, though only one or two flows of pillow-lava have been detected in it. They include keratophyre, soda-trachyte and soda-felsite, diabase (not

albitized), and basic rocks rich in albite, called skomerite and marloesite. In Ireland Reynolds and Gardiner have found typical pillow-lavas, cherts, and diabases of Arenig age.

In Upper Silurian times no spilitic eruptions have yet been recorded in Britain.

*Devonian.* The great development of spilite and schalstein in Cornwall and Devon perhaps began in Middle Devonian times, and attained its maximum in Upper Devonian or Lower Carboniferous times. They are accompanied by albite-diabase, minverite, quartz-diabase, picrite, and quartz-keratophyre.

The subjoined table shows the facies developed from the magma in each epoch at different localities:—

	Soda-granite.	Soda-felsite and Quartz-keratophyre.	Keratophyre.	Spilite.	Diabase.	Quartz-diabase.	Minverite.	Picrite.
Argyllshire . . .	1	—	1	1	1	1	?	—
Anglesey and Lley	—	—	—	1	1	—	—	—
Stonehaven . . .	—	—	—	1	1	—	—	—
Southern Scotland	—	1	1	1	1	—	—	—
South Cornwall . .	1	—	1	1	1	—	—	—
South Wales . . .	—	1	1	1	1	—	—	—
Devon and Cornwall	—	1	1	1	1	1	1	1

Harker (35), Prior (36), and Becke (37) have of recent years established the existence of two great suites of eruptive rocks, the Atlantic and the Pacific, and their conclusions have been accepted by Suess (38). In the British Isles we have many examples of these in past time. The Tertiary eruptions of Scotland are of Atlantic facies; the Carboniferous of the Scottish Lowlands are Atlantic also, but the Old Red are Pacific, while the Ordovician are of the spilitic type.

In Devon and Cornwall the Ordovician eruptions were spilitic, the Devono-Carboniferous were spilitic, but the Permian were Atlantic, and characterized by trachytes rich in potash. From this we see that the same region may in successive geological epochs be the focus of eruptions of entirely distinct suites of volcanic rocks.

The Pacific volcanic rocks are generated by epochs of active folding, the Atlantic by vertical movements attended by faulting. The spilitic group is characteristic of off-shore subsidences. They are the characteristic volcanic rocks of districts that have been undergoing long-continued subsidence (39). Hence they are not found on the land at the present day, and, in the past, their commonest associates are fine black shales, limestones, and radiolarian cherts.

It is interesting to recall that in Lower Ordovician times, while the spilites and keratophyres of Southern Scotland and the South of

Cornwall were being poured out, eruptive centres in Cumberland were emitting hypersthene andesites and other rocks of Pacific type: on the other hand, in the Lower Carboniferous period, spilites and quartz-keratophyres were the characteristic lavas of Devonshire and Cornwall, while trachytes, phonolites, olivine-basalts, teschenites, and nepheline-basalts of Atlantic facies were the dominant igneous rocks of East Lothian in Scotland.

In 1899 Teall (25) remarked that "it is interesting to note that at Ballantrae in Cornwall and in Mont Genève diabasic lavas with pillow-structure occur in the immediate neighbourhood of gabbro and serpentine, and that in all three localities some difficulty is experienced in determining the precise relations of these rocks". The constant association of diabase (spilite), serpentine, and gabbro in the northern Alps with radiolarian cherts has led Steinmann (37) to regard these 'ophiolitic eruptives' as the typical volcanic rocks of abysmal depressions. Suess has accepted and extended this hypothesis, considering the 'green rocks' to be injections into folded ranges associated with dislocations, but not invariably with deep-sea conditions (38). The 'ophiolitic eruptives' of Steinmann are not coextensive with the spilitic suite of igneous rocks as here defined, and still less so are the 'green rocks' of Suess. In several parts of Britain the association of gabbro and serpentine with spilitic lavas is difficult to explain as a mere accident, but we have not been able to establish definitely, in those parts of Cornwall or of Scotland with which we are personally familiar, that the one series is the plutonic representative of the other. For the present we prefer to regard this as an open question, hoping to return to its consideration at some future time.

#### THE ADINOLES.

That type of alteration by which shales and slates are converted into adinoles has been produced by basic intrusive rocks of more than one class. In the Lothians, for example, it occurs at the margins of some teschenite sills, and quartz-diabases sometimes also induce it. But there can be no doubt that the albite-diabases that belong to the spilite suite of igneous rocks are more efficient in changing shales to adinoles than all the other kinds of diabase. In Cornwall and Devon adinoles occur with great frequency both in the Devonian and Culm, and the adinole of Dinas Head is especially well known through the descriptions of Fox and Teall and the analyses of Hort Player (40). We may further remind our readers that an extensive literature has been written about the similar rocks of the Rhine district, which also occur in contact with the late Devonian and early Carboniferous intrusive sills that belong to the spilitic volcanic series.

The adinoles in their highest development are nearly pure albite rocks. No shales have a similar composition, for none are so rich in alkalis, yet the transformation of a shale into an adinole often takes place within a few inches. Hence there is no escape from the conclusion that there has been an infusion of new substances, principally soda, into the sediment, and this has been generally

admitted by petrographers for many years. For a summary of the literature on this subject we may refer to Roth (41).

In its microscopic structures the adinole is no less evidently a re-crystallized sediment. The lamination, cleavage, and bedding are soon lost, and a cryptocrystalline or finely crystalline rock is produced that has the closest resemblance to a chert. In North Cornwall and Devon cherts and adinoles constantly occur together in the same quarry. Very often they can hardly be distinguished except for the fact that the feldspar of the adinole has a lower refractive index than balsam, while the quartz has the same or slightly higher; moreover, the adinoles are fusible while the cherts are not. By further re-crystallization the adinoles become a mosaic of albite grains that have very closely the same mode of aggregation as the silicified shales found associated with some mineral veins (such, for example, as the flinty Ordovician shales of Parys Mountain in Anglesey). Now the cherts are admittedly rocks that have been recrystallized from colloid organic silica through the agency of aqueous solutions, and an allied mode of origin seems probable for the adinoles. In the latter we may often note the meshwork of veins filled with albite slightly more crystalline than the matrix, through which the solutions were introduced. The adinoles consist of quartz, albite, and chlorite (with rutile and iron oxides), and these are also the minerals that most characterize the post-volcanic or pneumatolytic stage of crystallization in the albite-diabases.

That adinoles should accompany albite-diabases is exactly what might be expected, for the pneumatolytic or post-volcanic vapours by which the intrusive rocks were albitized provide also the necessary constituents for the albitization of the sediments. In this respect the adinoles are not unlike the tourmalinized killas that occurs at the margins of the Cornish granites, where the same vapours as attacked the sediments also attacked the granite itself, converting it into schorl rock. The remarkable chemical changes that take place in the transformation of shale into adinole are the clearest evidence that could be adduced to show that vapours or solutions rich in soda were emitted by the igneous rocks during the later stages of their crystallization.

#### THE CHERTS.

That pillow-lavas are usually accompanied by radiolarian cherts is now a well-established fact. Attention has been directed to this paragenesis by Teall (42), and in all parts of Britain in several geological epochs it has since been proved to hold good.

As already stated, the spilitic rocks occur typically as submarine lavas in regions remote from shore-lines where the water is of considerable depth. These also are in a high degree the conditions that seem favourable for the deposition of siliceous organic deposits. The association then is a natural one, just as radiolarian cherts occur with fine graphitic shales and limestones.

But this is not the whole truth. How often do we find the cherts nestling in the hollows between the pillows even where limestones are few or absent, and where the sediments are of rather coarse grain and belong to shallow-water facies. In Cornwall pillow-lavas are

found in the Middle and Upper Devonian; the attendant sediments are shales and grits, but Ussher (43) found that between the pillows of the lava on the shore at Saltash a few thin beds of chert occur, and in microscopic section they appear to be of radiolarian origin. No cherts are found in the Devonian rocks at lower levels, but as soon as the spilites are met with the cherts also make their appearance, and at first are only found on the upper surfaces of the flows. This fact awakens a strong suspicion that there must be some genetic connexion between these two kinds of rock. At higher horizons in Upper Devonian and Culm the pillow-lavas abound, and there are great masses of chert, but we cannot be sure that this is more than a coincidence, since in South Wales at the same time radiolarian cherts were being laid down in great sheets, and there are no pillow-lavas. Again, in the Lower Palæozoic rocks of Cornwall, as Fox (44) has shown, there are sometimes a few lenticles of chert among the black shales, but when the pillow-lavas flowed out on the sea-bottom in Arenig or Llandeilo time the cherts appeared at once in great quantity, and on Mullion Island they fill up the gaps between the sack-shaped masses of the igneous rock.

Recent researches on the plankton of the northern seas have proved that the modern organisms which form siliceous tests are dependent on the supply of silica in the water which they inhabit (45). At certain seasons a large increase in the amount of dissolved silica takes place, and this is followed almost immediately by rapid proliferation of the diatoms, etc., that inhabit the water. There seems no inherent reason why the 'law of the minimum', as it has been called, may not also have held good in Palæozoic times; if so, it explains the occurrence of organic cherts with pillow-lavas. The igneous rocks as they cooled down exhaled vapours or solutions of magmatic origin, rich in dissolved silicates of soda and other bases. These were the agencies which albitized and decomposed the lavas, and any excess must have escaped into the sea-water. In this way precisely those conditions were provided which are most favourable to the rapid multiplication of siliceous protozoa such as the radiolaria. As the spilitic rocks are generally found at some distance from the shore, in quiet waters where there was little sediment and current action was at a minimum, the radiolaria, though they may have been of slow growth, were not carried away. The dead shells fell to the bottom and rested on the surface of the lava, while there was comparatively little clastic or land-derived sediment to mingle with the siliceous organic deposit. Where there are no cherts with the spilites, as for example at Tayvallich, Argyllshire, we may infer either that the dissolved mineral substances were not in excess of those required to albitize the lava, or more probably, that the local action of currents bore away the minute siliceous shells and brought other sediment in their place.

#### CONCLUSIONS.

1. The pillow-lavas are members of a natural family of igneous rocks, the spilitic suite, that can be clearly distinguished from the Atlantic and Pacific suites.
2. This family comprises a great variety of types—picrites, diabase,

minverite, quartz-diabase, spilite, keratophyre, quartz-keratophyre, soda-felsite, and albite granite, ranging from ultra-basic to acid in composition.

3. Their essential characteristics are the abundance of soda-felspar, and the remarkable frequency with which they have been albitized.

4. The albitization is not characteristic of the whole suite, but is especially frequent in certain members of it, such as the spilites and diabases, while others like the quartz-diabases are less liable to this change. It is not due to weathering or shearing. Good evidence exists to prove that the albitization took place soon after the rocks had solidified, and consequently it may be grouped among the post-volcanic or juvenile changes of rock-masses.

5. The constant association of adinoles (albitized shales) with the albite-diabases, and of radiolarian cherts with pillow-lavas, finds a simple explanation on this hypothesis, and at the same time affords the strongest confirmation of it.

6. The composition of the pneumatolytic emanations cannot be exactly defined, but it is certain that they consisted of water with soda and silica in solution; probably also carbonic acid was abundant, and many other substances may have been present.

7. In the British Isles spilitic eruptions have appeared in great numbers in all the Palæozoic formations (with the exception of the Upper Silurian and the Permian), and in the Tayvallich Volcanic Series have an important development among the metamorphic schists of the Scottish Highlands.

8. Like the Atlantic and Pacific igneous suites they have an intimate connection with certain types of geographical conditions. They are essentially rocks of districts that have undergone a long-continued and gentle subsidence, with few or slight upward movements, and no important folding.

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## II.—THE FUNDAMENTAL PROBLEMS OF PETROGENESIS, OR THE ORIGIN OF THE IGNEOUS ROCKS.

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### *Introduction.*

THE question of the origin of igneous rocks, their diversity and genetic relationships, represents that fundamental problem of petrography which has been for many years the object of inquiry for petrologists as well as for geologists and chemists. Whilst the amount and scope of detailed observation were growing, the methods of experimental investigation improved, and as the eruptive rocks came to be studied from the point of view of physical chemistry, so the petrogenetical horizon became larger and wider. Thus, on the basis of numerous minute and detailed observations were built broad generalizations that gave rise to new problems.

If we try to determine by one word the successively predominant ideas in petrogenesis, we can say that, notwithstanding a certain diversity of opinions, from 1890 and for nearly fifteen years petrology was dominated by the idea of differentiation; from the middle of the last decennium the chief rôle belongs to the theory of eutectics; and during the last few years there has been slowly growing and advancing, as a necessary corollary and even as a dominant factor, the hypothesis of refusion and assimilation by fusion. A rational combination of the principles of assimilation, refusion, differentiation, and eutectics seems to be the best basis for a theory of the genesis and diversity of the igneous rocks, and probably the nearest approximation to the solution of the question may be my syntectic-liquational hypothesis<sup>1</sup> enlarged according to the progress of later years.

In the present paper<sup>2</sup> I propose to give my revised views on the genesis of the igneous rocks and the factors governing their diversity.

### § 1. *The Average Chemical Composition of the Earth's Crust and the Primordial Magma.*

Before entering into the problem of the genesis of the igneous rocks it is necessary to deal critically with a question of general interest, which has often been an object of inquiry for petrographers and chemists.

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<sup>2</sup> Originally written in Russian, August 27, 1910, and printed in the Annales de l'Institut Polytechnique de St. Pétersbourg, v, xiv, 1910, p. 111.