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ORIGINAL ARTICLES.

I.—THE METAMORPHOSIS OF THE LIZARD GABBROS.¹

By J. J. H. TEALL, M.A., F.G.S.

(PLATE XIII.)

IF we take a general view of the present position of geological science, we are struck by the fact that, although there is substantial agreement amongst geologists on matters relating to the origin of the rocks usually designated as aqueous and igneous, the greatest diversity of opinion prevails with regard to the circumstances under which the so-called metamorphic rocks have been produced. Every fragment of evidence calculated to throw light on the origin of these rocks, therefore, deserves the most careful consideration. Of recent years special attention has been directed to the effects of mechanical energy in modifying the mineralogical and structural characters of rocks originally formed by aqueous and igneous agencies; and a suspicion has been aroused that it is in this direction that we must look for a solution of many of the problems connected with the origin of the crystalline schists. A visit to the Lizard Peninsula of Cornwall during the present summer has convinced me of the immense importance of this view so far as that district is concerned. That portion of the peninsula which lies south of a line drawn from Porthalla on the east to Polurrian Cove on the west is formed partly of igneous rocks—such as gabbro, greenstone, serpentine, and granite—and partly of crystalline schists. The igneous rocks, in certain places, become foliated and schistose and sometimes show a definite banding due to a variation in the relative proportions of the different constituents. In other words they present characters which are usually regarded as distinctive of the crystalline schists. There is, moreover, evidence to show that these characters are mainly the result of a yielding to earth-pressure subsequent to the consolidation of the original rock. At the present moment, having just returned from the district, I am unable to treat the subject from a general point of view with any prospect of success; but it has occurred to me that some details with regard to one of the rocks may not be without interest to members of the Association.

The gabbros of the Lizard have been noticed by many previous writers, including Dr. Boase,² Mr. Majendie,³ Sir Henry de la Beche,⁴

¹ Paper communicated to Section C of the British Association.

² Trans. Geol. Society of Cornwall, vol. iv. p. 330.

³ *Ibid.* vol. i. p. 36.

⁴ Report on the Geology of Devon and Cornwall, 1839.

and Prof. Bonney.¹ Their mineralogical composition, geographical distribution, and structural characters were described by the older observers. Prof. Bonney added many facts on these points and gave in addition a description of their microscopic structures. As I wish on the present occasion to refer to them for the purpose of establishing a definite proposition with regard to the origin of certain structures which they possess, I must ask permission to recapitulate the facts, and at the same time to add one or two from my own observation.

Gabbro occupies an area of six or seven square miles in the neighbourhood of St. Keverne, and forms the elevated tract of land known as Crousa Down. This great mass comes down to the sea and forms the coast-line from Coverack to Manacle Point. It is traversed by veins and dykes of a fine-grained rock generally known as "greenstone." This greenstone is essentially composed of plagioclase and hornblende, the latter mineral often belonging to the uraltic and actinolitic varieties. It is, as Prof. Bonney has pointed out, an altered plagioclase-augite rock, and must be classed with the epidiorites (Gümbel) of the Fichtelgebirge and the Hartz. In some instances the feldspars give lath-shaped sections which penetrate the fibrous aggregates of secondary hornblende in such a way as to prove conclusively that the parent rock must have been an ophitic dolerite.

The amount of this "greenstone" or "epidiorite" associated with the gabbro increases towards the north until it exceeds that of the latter rock. Although the junctions of the gabbro and the greenstone are perfectly sharp, it is impossible to represent the distribution of the two varieties on a small scale map in consequence of the way in which they alternate with each other. Manacle Point, which is represented as greenstone on the Survey Map, consists for the most part of gabbro in which veins and dykes of greenstone are very common.

The northern limit of the gabbro-greenstone area above referred to occurs in the neighbourhood of Porthoustock. The adjacent rock is hornblende-schist, but the actual junction, which is probably a fault, is concealed by a small shingle beach. The southern limit of this mass comes out on the sea-shore by the small village of Coverack. The geology of this locality has been fully described by Prof. Bonney, to whose paper reference must be made for details. The only point that need be mentioned here is that the normal gabbro is seen to be intrusive in serpentine and also in a rock, intimately associated with the serpentine, which consisted originally of a basic feldspar and olivine and which appears to be identical with the troctolite or forellenstein of Neurode in Silesia.

South of Coverack the greater part of the district is occupied by serpentine in which veins and dykes of gabbro frequently occur. The mass of gabbro which ranks next in importance to that of Crousa Down is exposed on the sea-coast west of Lankidden Cove. It forms the headland of Karaklews, and may be followed along the coast

¹ Quart. Journ. Geol. Soc., vol. xxxiii. 1877, p. 884.

for a distance of about a quarter of a mile. A mass of precisely similar gabbro occurs inland at Gwinter. The two portions are doubtless continuous, as represented on the geological map; and if so, they form a dyke-like mass running inland in a N.W. direction. The Karakclews gabbro is bounded on both sides by serpentine into which it was intruded. Marked signs of disturbance occur near both junctions and throughout the mass; but, notwithstanding this, veins of gabbro may occasionally be seen running out from the larger mass into the surrounding rock.

Another considerable exposure of gabbro occurs on the shore north of Pen Voose,¹ near Landewednack. It is bounded on the north by serpentine with gabbro veins, and on the south by a remarkable group of rocks which Prof. Bonney terms "the granulitic series." The gabbro is here traversed by veins of granite and mica-diorite which will doubtless repay careful examination, but which need not be further referred to on the present occasion.

The principal mineralogical constituents of the Lizard gabbros are plagioclase, augite or diallage, hornblende and saussurite. Olivine is present in certain varieties, but does not appear to have been very widely distributed in these rocks. In the least altered rocks the plagioclase occurs in the form of grains of tolerably uniform size and having nearly equal dimensions in the different directions. The grains show broad lamellar twinning, and not seldom two sets of lamellæ are seen crossing each other at right angles. This is the feature which is usually regarded as indicating simultaneous twinning on the albite and pericline types. The extinction angles in thin sections of the rock show that the feldspar belongs to the labradorite-anorthite series, but I have not as yet been able to make a more precise determination. In the more or less altered gabbros we see various stages of the replacement of feldspar by white or cream-coloured saussurite. The first stage consists in the development of white spots in the glassy feldspar substance. These spots appear snow-white under the microscope by reflected light, and opaque or brown by transmitted light. They never exhibit any definite form or cleavages. By the increase in the number and size of these white spots and by other changes the feldspar gradually passes into saussurite. This substance sometimes occurs in masses of considerable size, and it is then remarkable for its toughness and hardness. Its specific gravity is about 3.1. Microscopic examination shows that it is an aggregate and not a simple mineral, but it is by no means easy to determine the precise character of the different constituents. Cathrein's² investigations led him to the conclusion that saussurite is an aggregate of zoisite or epidote and feldspar, usually albite; with variable quantities of actinolite and tremolite as accessory constituents.

¹ There is some confusion about the naming of this locality. The small bay to the north of which the gabbro is exposed is named the Balk on the one-inch map and Parn Voose on the twenty-five inch map. The inhabitants of this district say, that this bay is called Pen Voose and that the place where the life-boat is kept, otherwise known as Church Cove, is Parn Voose. As the maps do not agree, I have followed the inhabitants.

² Ueber Saussurit, Zeit. f. Krystallographie, vol. vii. p. 234.

I have not as yet been able to find a saussurite in the Lizard District answering to Cathrein's description.¹

The feldspars of certain gabbros in which the development of saussurite has not taken place at all, or has only occurred to a very limited extent, often give evidence of having been affected by profound mechanical disturbances. The twin lamellæ are frequently bent and, when the limit of elasticity has been exceeded, the crystal grains have been fractured. The extinction is not sharp and definite. Dark shadows sweep across the sections as the stage is rotated. In slides exhibiting these characters large feldspars are often seen to break up, in certain places, into aggregates of minute, colourless, and for the most part simple grains. Such aggregates must certainly be regarded as of secondary origin, for they are entirely unknown in the unaltered feldspar-diallage gabbros and frequently contain needles of actinolite, a mineral undoubtedly of secondary origin. They correspond to the feldspar-mosaic of Lossen.²

The pyroxene in the least altered rocks is a pale green diopside. In microscopic sections it is almost colourless. Cross sections show an optic axis in convergent polarized light and frequently the two pinacoidal as well as the two prismatic cleavages. Longitudinal sections give a maximum extinction of about 40°. The mineral is therefore a monoclinic pyroxene. In addition to the cleavages above mentioned, we find occasionally incipient stages of diallagic lamination. This lamination is not as a rule persistent throughout the crystal, but limited to the neighbourhood of cracks. In the ordinary gabbros the pyroxene is a true diallage with a decided bronzy lustre on the planes of easy separation, which planes run parallel with the orthopinacoid. In some of the coarse-grained rocks the diallage crystals often measure two or three inches across.

The change of pyroxene into hornblende has been described and illustrated by Prof. Bonney. It is a common feature in the Lizard gabbros and often accompanies the change of feldspar to saussurite. Many different varieties of secondary hornblende may be observed depending on variations in colour and habit. Sometimes the hornblende occurs in the form of homogeneous crystalline grains with strongly marked cleavages. This variety may be termed compact hornblende. At other times the hornblende is distinctly fibrous, and at others it occurs in the form of needles. The two latter varieties are generally termed uralitic and actinolitic respectively. Actinolitic hornblende frequently forms radiating fringes round the

¹ A saussurite composed of zoisite and albite occurs in Sangomore Bay near Durness, Sutherlandshire. Under the microscope this is seen to consist of minute colourless prisms embedded in a colourless feldspathic matrix. The prisms possess a high refractive index, weak double refraction, cross-jointing at intervals, and give straight extinction. Small fragments of the feldspar with which they are associated may occasionally be obtained and when tested in the Bunsen's burner give the flame colouration and fusibility of albite. In the mass this saussurite is white or a very pale pink. It contains hornblende and is associated with a feldspathic gabbro in which the diallage has been converted into uralite and actinolite.

² Studien an metamorphischen Eruptiv- und Sedimentgesteinen, Jahrbuch d. k. preuss. geol. Landesanstalt für 1883 und 1884.

uralitic variety or round a crystal of diallage partially changed to uralite. The hornblende may be either green, brown, or colourless. One of the green varieties is remarkably brilliant and of that tint which led to the introduction of the term *smaragdite*. The gradual replacement of diallage by hornblende is a most striking feature in the Lizard gabbros. The two minerals bear an inverse relation to each other so far as distribution is concerned. As the one increases, the other diminishes.

Olivine does not appear to have been abundant or widely distributed in the normal gabbros. It occurs sparingly in an unaltered rock from Coverack, and in this case is perfectly colourless in thin sections and traversed by irregular cracks, along which magnetite has been formed. In some of the more altered gabbros it is represented by serpentinous pseudomorphs.

The minerals above referred to occur in very different proportions in the different rocks, and in different portions of the same rock-mass. We thus have an endless number of mineralogical varieties. The principal variations are due to the gradual replacement of felspar by saussurite and of diallage by hornblende. The two extreme types may therefore be designated felspar-diallage gabbro, and saussurite-hornblende gabbro; the former representing the original rock and the latter the extreme of mineralogical metamorphism. Between these two extreme types there are innumerable intermediate varieties. As a rule the change in one mineral is accompanied by a change in the other; but this is not invariably the case. We may thus have felspar-hornblende gabbros and saussurite-diallage gabbros. If we wish to indicate the mineralogical character of any intermediate form, we can do so by using a compound term made up of the names of the substances occurring as constituents. The number of actual varieties present is the number of possible combinations of the four principal constituents taken two, three, and four together. The introduction of olivine gives rise to other varieties, but, as already stated, I am inclined to think that this mineral was absent from considerable masses of the original rock.

If we eliminate hornblende and saussurite, both of which are undoubtedly secondary minerals, then the original felspar-bearing rocks of the gabbro-type occurring in the Lizard Peninsula must have comprised plagioclase-augite rocks, plagioclase-augite-olivine rocks, and plagioclase-olivine rocks. By the gradual disappearance of the felspar these rocks passed through the picrites into the peridotites, which are now represented by the serpentines. Felspar-bearing serpentines occur at the Rill Head near Kynance. Looking at the Lizard district as a whole, we are struck with many points of resemblance between it and the Tertiary volcanic district of the West of Scotland described by Prof. Judd.

We have now to consider the structural characteristics of the Lizard gabbros. In the first place, we notice varieties depending on variations in the sizes of the individual constituents. Such variations are characteristic of all masses of gabbro. In the coarsest varieties the individual crystalline grains often measure as much as

two or three inches across. These extremely coarse varieties are often distributed with considerable irregularity through large masses of the finer-grained rocks; not seldom, however, they occur as narrow veins and dykes in the serpentine. The dominant gabbro is a rock which would simply be described as coarsely crystalline. Fine-grained varieties are not known. The junction with greenstone or epidiorite is always sharp, and there is no evidence in the Lizard district, so far as I know, of a gradual passage from gabbro into dolerite and basalt. The "greenstones" are undoubtedly altered dolerites, some of which were ophitic, but their junctions with the gabbro are, as already stated, always sharp.

The mutual relations of the individual constituents in the unaltered gabbros are those of typical granitic rocks; in other words, no single mineral appears to have possessed any special advantage over any other so far as the conditions favourable to the development of crystalline form are concerned. Each mineral occurs in the form of crystalline grains.

In addition to variations of structure depending on variations in the sizes of the individual constituents, there are others, of a most important character, dependent on the mode of arrangement of these constituents in the rock-mass. From this point of view the gabbros of the Lizard may be divided into two groups: (1) the massive, and (2) the foliated gabbros. These two varieties are not, however, separated from each other by any hard and fast line. In the massive gabbros the individual constituents are not arranged in any definite manner; in the foliated gabbros a parallel structure is more or less pronounced. It is convenient in speaking of the foliated gabbros to recognize two principal types which may be designated by the terms *flaser-gabbro* and *gabbro-schist*. In the *flaser-gabbro* the parallel structure, though distinct, is not accompanied by any marked fissility. The constituents are white saussurite and dark aggregates of diallage and hornblende. These constituents are more or less lenticular in form and the flat surfaces of the lenticles lie parallel to each other, thus producing the foliated structure. The *gabbro-schist* is a rock of finer grain, with a strongly-marked schistosity. It can be broken into flat slabs like a hornblende schist. Indeed the rock may sometimes be called hornblende-schist without doing any violence to the latter term. Although it is convenient to use the expressions *flaser-gabbro* and *gabbro-schist*, it must not be supposed that there is any hard and fast line between the rocks designated by these terms. They shade into each other by the most insensible gradations. One very interesting structural variety which is, in some respects, intermediate between *flaser-gabbro* and *gabbro-schist*, may be termed *augen-gabbro*. In this variety the streaks which define the schistosity sweep round "eyes" of diallage, which thus remind one strongly of the "eyes" of felspar in *augen-gneiss*. (See Plate XIII.)

We have now to consider the distribution of the different structural varieties. The gabbro to the north of Coverack is on the whole massive; nevertheless here and there foliation makes its

appearance. In the neighbourhood of the village the veins and dykes of gabbro are often foliated, and every transition may be observed from massive gabbro to gabbro-schist. At Karaklews Headland foliation has been developed in a most striking manner, and affects, with a few local exceptions, the entire mass, which is more than a hundred yards in width. The general strike of the foliation is approximately N.W. and S.E., but there is no absolute constancy in the direction; slight deviations occur sometimes on the one side and sometimes on the other. One important feature in the Karaklews mass is the distinctly banded character of certain portions, particularly those near the southern junction with the serpentine. Light and dark bands several inches in thickness alternate with each other, and with the ordinary flaser- and augengabbro, so that the mass as a whole simulates a stratified series. The small dykes of gabbro in the serpentine near Karaklews are often foliated, and not seldom one may see the transition from massive gabbro to gabbro-schist taking place in the space of a few inches.

Another locality where foliation is well developed is north of Pen Voose near Landewednack. The main mass of gabbro is separated from serpentine and other rocks on the north by a well-marked fault-plane. In the immediate neighbourhood of this plane the gabbro is foliated, and passes into a fine gabbro-schist. Foliation also makes its appearance in the main mass, which is here intimately veined with mica-diorite and granite. It is frequently developed near the junction of the gabbro with one of the other rocks. In the small bay known as Pen Voose a lenticular mass of saussurite-hornblende gabbro, measuring about five feet in the longest diameter, occurs in Prof. Bonney's granulitic series. This is evidently not an intrusive tongue, but a lenticular mass which owes its form and position to earth-movements acting after the consolidation of the rock. It is conspicuously foliated parallel with the junction surfaces.

It is instructive to compare the mineralogical with the structural varieties. Foliation is absent from the felspar-diallage rocks. As the foliation becomes more and more pronounced, the diallage is gradually replaced by hornblende, and the felspar undergoes a change resulting for the most part in the development of saussuritic aggregates. In the most perfect gabbro-schist the diallage has entirely or almost entirely disappeared, and its place has been taken by hornblende. It must not, however, be supposed that the mineralogical change is invariably accompanied by the development of foliation. Many of the saussurite-hornblende gabbros are as massive as the original rock. In a paper on the "Metamorphosis of Dolerite into Hornblende-schist" I have pointed out similar relations between structural and mineralogical characters in the case of the Scourie dykes. A molecular rearrangement may take place in a massive rock without the development of foliation; but there is no reason to believe that foliation of the kind referred to in this communication can take place without molecular rearrangement.

The principal question which now remains for consideration is the

origin of this foliation. Is it an original or secondary structure? That it is due to a differential movement in the mass after the separation of the individual constituents will I think be admitted on all hands. The only question that can arise is whether this movement was in any way connected with the intrusion of the rock. The facts appear to me to point very decidedly to the conclusion that it is a secondary structure due to earth-movements acting upon the solid rock. That the Lizard district has been profoundly affected by earth-movements is apparent on every hand. The rocks have been folded, faulted, crumpled, twisted, and in some places brecciated by the intense pressures that have acted upon them. The evidences of mechanical disturbance are not limited to any one variety of rock or to any one district. They abound in every portion of the district, though their effects are more pronounced in certain localities than in others. If we attempt to determine the precise nature of the earth-movement, we are met with considerable difficulty on account of the superposition of the effects of distinct movements. The earlier movement, and the one which I suspect produced the greater part of the foliation in the gabbros, appears to have acted so as to produce a strike about N.W. and S.E. or N.N.W. and S.S.E. This earlier movement was, however, certainly followed by one producing faults which run approximately in an E. and W. direction. The latter direction agrees with one of the great post-Carboniferous disturbances, and the faults which run in this direction probably belong to those disturbances. That the two sets of earth-movements above referred to are the only ones that have acted upon the district I am by no means prepared to say; but that these two have acted is shown by facts which may be observed at Porthalla, George Cove and Kynance.

That the foliation in the gabbros is one of the results of the pressure- or regional-metamorphism which has operated upon the district, is rendered at once probable when we compare the Lizard gabbros with those of the West of Scotland. The latter consist mainly of felspar-diallage rocks, and are not foliated; the former are largely composed of saussuritic and hornblendic rocks, and are often conspicuously foliated. The Lizard district has been profoundly affected by earth-movements, whereas the Tertiary volcanic district of the West of Scotland has not been so affected.

This argument is in itself not conclusive, but it becomes greatly strengthened when we consider the distribution of gabbros of the Lizard type. They have been described by Dr. Reusch¹ from the Bergen Peninsula, by Prof. Lehmann² from the granulitic region of Saxony, and by Mr. Hatch³ from the Tyrol. Each one of these districts gives independent evidence of having been subjected to pressure-metamorphism. Perhaps the most convincing proof that the structure is the result of movement after the consolidation of the

¹ Die Fossilien führenden krystallinischen Schiefer von Bergen in Norwegen, Leipzig, 1883.

² Die Entstehung der altkrystallinischen Schiefergesteinen, Bonn, 1884, p. 190.

³ Tsch. Min. Mitth., Band VII. (1885), p. 75.

rock is, however, furnished by its relation to fault-planes. A rock must necessarily be solid before it can be faulted. Now, we find at Pen Voose near Landewednack, that massive gabbro passes over into gabbro-schist at a fault-plane, and that the foliation in the gabbro is such as would be produced by a shearing motion parallel with the fault-plane. Taking all the facts into consideration, we appear to be justified in concluding that the foliation in the Lizard gabbros is the result of pressure- or regional-metamorphism. It seems also probable that the replacement of felspar and diallage by saussurite and hornblende has been largely determined by the same agency.

DESCRIPTION OF PLATE XIII.

The Plate represents the appearance of a polished slab of the augen-gabbro of Karaklews. The "eyes" are formed of diallage. The dark bands are formed mainly of green hornblende; the white bands, of the aggregate generally known as saussurite. The white spots seen in certain parts of the Plate represent an undetermined mineral which is almost constantly present in the Lizard gabbros. It appears in the glassy felspar of the comparatively unaltered rocks, and increases in amount as the felspar passes into the condition of saussurite. There is much greater detail in the dark bands than is represented in the Plate. The block is traversed by narrow veins which cut the planes of foliation at angles of about 15°.

II.—ON THE FFYNON BEUNO CAVES.

By Prof. T. McKENNY HUGHES, M.A., F.G.S.

MUCH interest has been recently aroused in the exploration of the caves of the Vale of Clwyd, partly by the enthusiasm of the principal promoter of the investigation, Dr. Hicks, but chiefly owing to the inferences he has drawn from the observations made. When reading the Report of the British Association Committee for the Exploration, of which he was Secretary, he assumed the entire responsibility of those theoretical deductions. In these, however, he was supported by all the speakers who followed him on the subject, including the other members of the Committee excepting myself. He had previously anticipated the report by the announcement in *Nature* of his discovery of Pre-Glacial Man in the Vale of Clwyd. I therefore ask leave briefly to state my reasons for differing from his conclusions.

First, I recognize in the Vale of Clwyd four drifts which must be distinguished in this inquiry.

1. *The Arenig Drift*, which contains fragments from the W. and S. only, and which is the only true glacial deposit in the Vale of Clwyd, as there is no evidence of any glacier having ever come down the Vale.

2. *The Clwydian Drift*. — (A) a marine deposit due to the submergence which followed the age of extreme glaciation and containing, in addition to the re-sorted débris of the older drift, flint and fragments of granite and other north-country rocks. (B) the still further winnowed débris belonging to the age of emergence.

I am not very clear about the possibility of often distinguishing