THE VULCANICITY OF THE LAKE DISTRICT.

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I. INTRODUCTION.

FOR some time past I have, as too rare opportunity offered, been trying to solve certain structural problems in the Lake District. For the most part this work has consisted in following certain geological lines across country, particularly the junctions of lavas and tuffs. This has involved or occasioned observations on the volcanic phenomena; and, as the district is readily accessible, of infinite variety, and of unequalled interest among British areas of igneous rocks, I have thought that a consideration of the vulcanicity, though as yet imperfectly known, and some discussion of the light which it throws on igneous action generally, would be of interest to the Geologists' Association.

The main strip of mixed intrusive and volcanic rocks covers a wild mountain area of over 400 square miles, containing such famous heights as Scawfell and Helvellyn, and surrounding wholly or partly the lakes of Ennerdale, Buttermere, Derwentwater, Ullswater, Thirlmere, Wastwater, Haweswater, Devoke Water, Coniston, Grasmere, Rydal, Elterwater and Windermere, with many lesser tarns. Every part is easily visited; the exposures are magnificent and the existence of complex systems of folding, intersected by deep valleys, enables the various horizons to be examined along numerous lines and some reconstruction of their original form and extent to be attempted. Unfortunately detailed mapping is but little advanced, and many of the most interesting questions are as yet untouched.

Certainly there is no district in Britain from which more far-reaching results may be expected when a thorough examination has been made from the point of view of the elucidation of volcanic phenomena, both superficial and deep-seated. I

hope that the succeeding pages will show that even the slight attention which it has been possible to give illuminates several subjects of interest to geologists.

The true founder of Lake District geology was Jonathan Otley, who not only sketched out the main outlines, but deduced from his observations principles of the utmost importance. His work was continued by Sedgwick, Sharpe, Harkness and Nicholson, the last-named summing up the state of knowledge in 1868 in a useful essay.*

It is not easy to appraise exactly the confusion then produced by the work of J. C. Ward. Older observers had distinguished clearly between "traps" and "ashes"; had recognised the chief lines of folding and repetition; and had rightly deduced the age of the intrusions from their field relations. Ward regarded most of the lavas as altered ashes, so that stratigraphical mapping became impossible; made the succession continuous, inserting faults for pitching folds; and displaced the intrusions on petrographic grounds. These errors were for the most part accepted by his colleagues and became embodied in the official one-inch and six-inch maps, persisting to the present day. Nevertheless, granted the assumptions on which the classification of rocks in these maps is based, they are trustworthy and record great numbers of valuable observations. Particularly is this true of the six-inch maps by W. T. Aveline of the southern part of the district, which are meticulously accurate and include some of the most beautiful maps that I have ever had the fortune to study. It must be admitted, however, that Ward's maps, valuable as they are, must be used with caution, owing to a decided tendency to subordinate observation to theory.

Since the Survey maps were published in the seventies and eighties many observers have worked at the igneous rocks, among whom may be mentioned Goodchild, Rutley, Professor Marr, Dr. Harker, Mr. W. M. Hutchings, Sir Archibald Geikie, Mr. E. E. Walker, Dr. Derryhouse, Mr. Rastall and Mr. J. Morrison. An immense amount of petrographic description has been accumulated, but cannot be fully utilised until the sequence and structural relationships of the rocks have been settled. I first determined these for a small area near the Duddon Estuary† and afterwards found my results to apply with little modification over the whole district. And it has proved possible to use them to attack the vexed problem of the age of the larger intrusions.

In what follows these results are assumed correct and the plutonic and hypabyssal rocks, apart from the Shap granite, its dykes, and a few minor intrusions, are treated as connections

* *An Essay on The Geology of Cumberland and Westmorland*, London 8vo.

† *The Older Palæozoic Succession of the Duddon Estuary*, London, 1913.

of the great series of volcanic material which begins in the Middle Llanvirn. Whether it is all of that age or, as is quite possible, when compared with such areas as Cader Idris, it extends up into the Llandeilo, is undecided at present.

There are large tracts of country, such as most of the Helvellyn range, over which I have as yet had no opportunity of traversing. There is, however, no reason to suppose that the succession in them differs substantially from that proved elsewhere.

II. EXPLOSION.

Tuffs in which the materials have dropped into place after being thrown out of a vent may be termed *explosion-tuffs* and distinguished from the more usual type of submarine tuff, in which the materials have been washed into place. The division between the two is not abrupt and most Lake District tuffs are more or less mixed. Large bombs or ejected blocks, distorting the finer sediments into which they have fallen, are rare, but may occasionally be seen, such as the example I have described on Lank Rigg.*

A volcanic episode frequently begins by blasting holes through the crust and ejecting a mixture of broken country-rock and igneous material. The resultant tuff may be expected to be ungraded and to be variable and discontinuous, the coarse fragments falling near the vents, the finer distributed in relation to the prevailing winds and currents. Until considerable cones are built up above sea-level, no detrital sediment of igneous origin will be added. If a supply of ordinary sediment is available, the tuffs may contain it recognisably and, owing to the discontinuity of eruptions, be interbedded with it.

For a long time before the opening of the Borrowdale episode the greater part of the British area was occupied by sea, but there appears to have been a continental shore-line running across the north-west of Ireland and Scotland. In later Cambrian times, what is now the Lake District was the theatre of deposit of a fine-grained silty micaceous mud, in which grains larger than 0.1. mm. were very rare, the usual size being about 0.02 to 0.03 mm. In early Ordovician times the supply of silt, perhaps owing to a recession of the shore-line, diminished and the only deposit was a delicately-bedded carbonaceous mud, with a small proportion of silt ("Skiddaw Slate"), showing every sign of deposition in deep quiet water. About the middle of Llanvirn time, slight movements took place and the mud became silty or sandy in places, in one area passing up into sandstone with occasional coarse grit (Latterbarrow sandstone). At the same time, lapilli and bombs make their appearance here and there, the lapilli including many of shaly and silty

* *Proc. Geol. Assoc.*, xxviii., 1917, p. 9.

material, exactly comparable with the neighbouring sediments.

We have here the explosive beginning of a volcanic episode in fairly deep water some way from a shore-line. The best-known of the deposits thus formed is the purple breccia of Falcon Crag, near Derwentwater. The fine-grained ground of this rock consists of red-brown glass dust, with beautiful "bogen-struktur." Imbedded in this are scoriae and lava-blocks, mostly andesitic, of all sizes and shapes, but often showing the outline of consecutive concavities characteristic of freshly broken lava, sometimes fantastic in form. (Plate 9, fig. 1); also numerous bits of Skiddaw Slate, both silty and argillaceous. Variations in the amount of coarse material lead to bedding; and a pause in ejection allows for a band of ordinary Skiddaw Slate.

With this chaotic aggregate may be contrasted the banded rocks of Baystone Bank in the Whicham Valley. Here deposition of carbonaceous mud went on uninterruptedly, while from time to time glassy ash of varying fineness, with little bits of ejected shale, was carried over by wind and dropped into the mud. Sometimes the shale-fragments are wholly or partly enveloped by a skin of glass (Plate 9, fig. 2.) Some of the glass-lapilli have a skin differing in appearance from the interior, usually by the absence of a dark dust (? magnetite), which obscures the inner part. These are drops of magma suddenly cooled.

In the eastern part of the Lake District and in the Cross Fell inlier, the opening stage of the episode is marked by a somewhat calcareous variety of the Mottled Tuffs (as I have termed these preliminary beds), containing much fine-grained felsitic material mixed with a little ordinary clayey sediment, and lapilli of shale, rhyolite and some andesite. I have termed this the Flagdaw type from the large exposures on Flagdaw Hill, near Knock, in the Cross Fell inlier. The rock often much resembles Skiddaw Slate and has indeed been mapped with it in places. Its general uniformity and relatively slow variations suggest that the felsitic material which makes up the greater part of it was washed down, not dropped into place. The rock, however, presents peculiar features, and I am still doubtful as to its genesis.

Near Falcon Crag, Derwentwater; on High Haulme, near Dalton-in-Furness; and at Capel Crag, near the River Calder, extremely coarse breccias occur in the Mottled Tuffs, suggesting the proximity of vents. The most remarkable is the last-named, which contains boulders of rhyolite, andesite and sandstone, apparently to some extent rounded and sorted by wave-action. It was probably formed on the flank of a cone of loose agglomerate.

III.—EFFUSION.

The greater part of the volcanic outcrops of the Lake District is compact igneous rock, mostly lavas, which probably compose three-fourths of the total. They build four main aggregations, the Lower, Wrengill, and Upper Andesites and at the top the Rhyolites, which are usually the highest rocks of the Borrowdale Series exposed, though at one point, viz., Beck Wood, near Millom, there seem to be later beds in conformable sequence.

The rocks here termed andesites have a considerable range of chemical composition and, if they are to be classified by silica-percentages or other chemical characteristics, might receive various cacophonous names of little use for field purposes. Mineralogically they are closely related, and they grade into each other imperceptibly, the differences *inter se* being sometimes approached by differences within the same flow. They commonly contain phenocrysts of augite, felspar ranging from acid to basic labradorite (rarely bytownite), and ilmenite, in a more or less glassy ground with laths of felspar ranging from oligoclase to andesine. In the more basic examples augite and magnetite are found in the ground-mass and some of the pyroxene phenocrysts may be orthorhombic. Olivine is unknown. Almost every possible variation occurs in the proportions of felspar, pyroxene and glass; and so far as yet observed, there is no distinct chronological sequence of varieties. Near analogues to the well-known bytownite-bearing lava in the Lower Andesites of Eycott Hill are found in the Upper Andesites about Haweswater; and the relatively acid flows of the Lower Andesites of Falcon Crag, near Keswick, can be paralleled in the Upper Andesites of the Shap District.

The Rhyolites, which occur as infolds along the centres of synclines, are normal soda-rhyolites or quartz-keratophyres, with albite, orthoclase, ilmenite and often biotite phenocrysts. Quartz is rare. Certain curious rocks, apparently of a mixed nature, occur in places between the Rhyolites and Upper Andesites. These have so far been little investigated.

There is no doubt that those andesite lavas which flowed over Skiddaw mud were submarine. It will be argued later that there is reason to believe that the Middle Tuffs were also marine and deposited in fairly deep water, so that the lower members of the Wrengill Andesites must also have been submarine. If to these facts be added (1) the frequent presence of well-bedded tuff partings between consecutive flows, (2) the absence, so far as yet observed, of intra-Borrowdale eroded or weathered surfaces, (3) the absence of conglomeratic material with signs of wave action; the evidence for the submarine character of the flows generally appears very strong. It is therefore

desirable to consider what characters submarine lava-flows may be expected to present.

The problem of the texture of submarine flows has been subjected to physical reasoning by Professor Carlo Stefani* who arrived at the conclusion that the differences between submarine and subaerial flows would be imperceptible, although the formation of glass would be favoured at moderate depths. There seems no reason to dissent from this view. In discussing, however, the influence of pressure on vesicularity, Professor Stefani assumed that the tension of steam was principally concerned; but the probability that numerous rocks, notably rhyolites and quartz-porphyrries, have consolidated in the presence of water under slight or moderate pressure is very strong†, and this suggests that the fluxes are not present in the magma as gases, but in some form of loose chemical combination, perhaps as hydrates, which can be maintained without the enormous pressures theoretically required to sustain water-vapour at high temperatures. Further, the temperatures need not necessarily be very high. Lavas flowing subaerially have usually lost most of their fluxes and consequently basalts, which alone seem to have been tested, can only be fluid at a temperature approaching 1,000°C, though even in these cases there is sufficient volatile flux present to lower the melting point appreciably.‡ But the presence of ample water must lower the temperature of fusion by hundreds of degrees and with it lower the pressure necessary to retain the volatile constituents.

The process of solidification in lava, usually referred to by the question-begging term "cooling," is the result of two factors, firstly, loss of heat; secondly, rise of fusion point, due to loss of fluxes. If these are both retarded, flow may be continued indefinitely, as witness the wide extension of many sills. The rate of flow depends on the viscosity, which is related to the composition and to the difference between the actual temperature and the fusion-point. A basalt flows readily at a temperature slightly above fusion-point, a rhyolite does not. But again the rise of temperature necessary for a given reduction of viscosity is decreased by the presence of fluxes; and it must not be forgotten that however high the viscosity, if actual solidification is delayed long enough, the lava will assume a position and shape like that of a highly fluid melt. For, with sufficient time, a viscous fluid tends to the static form of a perfect fluid.

In a subaerial lava-flow the direct loss of heat does not appear to be rapid. A blanket of scoriae decreases radiation and conduction; and as important a factor as either must be loss of heat by emission of gas, working partly by convection

*Sui possibili caratteri delle lave eruttate a grandi profondità nei mari, *Ecll. Sc. Geol. Ital.*, xiv., 1895, p. 1.

†e.g. see E. Suess: *Das Auskitt der Erde*, Bd. iii., (2), p. 639.

‡Doelter, *Petrogenesis*, 1906, pp. 12, 16.

and partly by absorption of heat in work done by expansion within the magma. Flowing lavas, especially those of intermediate composition, are usually accompanied by clouds of water-vapour mixed with gaseous compounds of sulphur and chlorine*, while violent action takes place at the surface through the outrush, and probably also the burning, of these gases, the emission of which, even in a stationary lava, continues for years. The large amount of water in suddenly ejected and cooled lapilli, such as those of Krakatoa, is notorious.

The conclusion is that the main factor in deciding the solidification and the ultimate form of a subaerial lava-flow is the loss of fluxes.

The agents operating against the escape of volatile fluxes from a submarine lava would be pressure and an impervious cover. The pressure at a depth of 1,000 metres is approximately 100 atmospheres, which would balance the tension of water vapour at a temperature a little above 300°C. But at considerably higher temperatures, such a pressure might be expected to inhibit the dissociation of hydrates.

With regard to the crust, molten lava in actual contact with water will certainly harden instantaneously, so that diffusion towards the surface will be checked and the outrush of gas confined to places where the firm crust thus formed is breaking. This cover would be relatively stable. In subaerial lavas, if highly fluid, a roof, once formed, may have considerable stability over a wide extent, as in the case of the Iceland lava of 1766,† and the Hawaiian lava of 1843‡; and below sea-level the tendency to permanence would be strengthened, not only by the firmness of a rapidly cooled rock and by swift welding of fractures, but by a reduced difference in the density and compressibility of the fluid media above and below, with an equivalent reduction in the stresses set up in the crust. The experience of the Torre del Greco lava, which advanced quietly into the sea, so that it could be closely examined from a boat, shows that even the moving front may be sufficiently impervious to avoid violent reaction under water. At Santorin, Giorgios Island rose gently from the sea in 1866, as Nea Kameni did in 1707,§ and no explosive action took place till a considerable area was free from water.

It follows that an intermediate or acid lava at some depth below the surface of the sea might be expected to retain its fluidity for a long time, hardening being brought about chiefly by a slow loss of heat, and not being complete till a much lower temperature is reached than is required subaerially. Also that

*Even in such waterless basalts as those of Hawaii, see Day and Shepherd *Bull. Geol. Soc. America* xxiv., 1913, pp. 573-606.

†Tempest Anderson, *Volcanic Studies*, First Series, Plate liv.

‡Vélain *Les Volcans*, 1884, p. 30.

§Fouqué, *Santorin et ses éruptions 1879*, o. 42 etc.

the viscosity will be much less at temperatures near the fusion point. Consequently, such submarine lavas will behave like easily fusible basalts on land. They will consolidate as wide flat, nearly horizontal sheets.

These conclusions were arrived at by Scrope as early as 1825 in a passage which anticipates certain modern views to a surprising extent

"The great density of the medium with which the liquid lava is brought in contact, by the resistance it offers to the escape of its elastic vehicle, must have the effect of prolonging its fluidity, and consequently, *ceteris paribus*, must augment the extent of its lateral spread upon the same inclination of surface.

"Thus we should expect lava beds produced at the bottom of the sea to exhibit a greater lateral extension compared to their thickness, than those which have flowed under the pressure of the atmosphere alone; and that this extension should be proportionate to the depth of the column of water they supported. . . .

"Hence a submarine volcanic mountain will not present by any means so decidedly conical a form as one thrown up in open air, but will be far more depressed and flattened, and composed of comparatively horizontal beds."*

Scrope's views were developed at some length by the Italian geologist Stoppani† but seem to have been ignored in this country. Indeed, precisely opposite opinions have recently been expressed by high authority.

The crust formed at the surface of a submarine lava is not likely, owing to rapid cooling and to retention of fluxes under pressure, to be pumiceous; and vesicles, if present, will not increase rapidly in size from within towards the surface. This follows because the rate of change of pressure is comparatively slow. For example, the pressure 5 metres below the surface of a lava flowing on land near sea-level is approximately two and a half times that at the contact with air; but at 1,000 metres below sea-level the excess at 5 metres below the lava-surface would be less than one and a half per cent. A bubble rising through the melt would expand with corresponding slowness. Thus the difference of density, due to vesicularity, between the inner and outer parts of a lava under pressure will be slight compared to the differences in a subaerial lava. In consequence the increase of density due to the contraction of the magma on solidification near the surface will not be regularly overbalanced by the decrease due to expansion of vapour, as constantly happens in a subaerial flow.

Consequently the density of the crust of a submarine lava may be expected to be near that of the still fused material, and often greater. When broken up, instead of floating like a scum, it will readily mix and sink into deeper parts of the stream with more heat and flux, thus becoming liable to refusion. The

* *Considerations on Volcanoes*, 1825, pp. 177, *et seqq.*
 † *Corso di Geologia*, 1873, Vol. III., cap. v.

mixed mass again cooling and again breaking up will form an intricate mixture of blocks differing slightly in vesicularity, crystallisation, proportion of phenocrysts, etc., cemented by similar material.

These mass-characteristics that have been deduced as probable features of submarine flows, namely, flat extension, auto-brecciation and vesicular uniformity, are everywhere noticeable among the Lake District lavas. Their uniform distribution cannot be in any degree due to fissure-eruptions, as the underlying Skiddaw Slate, where exposed, is almost free from dykes, except a very few of distinct composition. The lavas must have risen up a few vents and it will be shown later how it may be possible to approximate to the position of the latter.

No attempt has yet been made to map individual flows on a large scale, though it would not be difficult to do so, but certain examples may be noted.—

At the base of the rhyolites of the Kidsty Pike infold near Haweswater a nodular mica-rhyolite has been recognised over a distance of $3\frac{1}{2}$ miles north east-south west, and, being in full force at both ends of the infold, must have extended much further. The frequent exposure of a thin band of bedded ash below this rock points to virtual horizontality. The Bala Stockdale Rhyolite, which flowed on marine sands and shales and is overlain by shales and limestones, extends $7\frac{1}{2}$ miles from its termination at Stile End to Shap, whence it must run under the Carboniferous Limestone for some miles more. Immediately below the rhyolites north-west of Haweswater, a basic vesicular andesite has been recognized for three miles. In a number of other cases particular andesites have been noticed for about the same distance. Near Keswick andesite flows have been followed for three miles and appear to extend much further.

These examples merely illustrate the general impression of horizontality and wide extension formed when traversing the lava outcrops. This is confirmed by the flat shape of the great lenses of andesite, particularly the Lower Andesites, which extend with little observed variation of thickness over the whole of the main area. The most rapid thickening yet noted is that of the Wrengill andesite-lens from east to west, but a maximum estimate of the difference of slope between their upper and lower surfaces from Mosedale to Grasmere is only 4° , and for the most part it must be less. This flatness points to the formation of cones, not of the Pelean or general Andes type associated with subaerial pyroxene-andesites, but of the Hawaiian type, best developed in the numerous *dyngjur* of Iceland, which have a slope varying from 1° to 8° , whereas Dana gives the slope of the andesite cones of Western America as 25° to 34° . The Wrengill and Upper Andesites lenses may fairly be compared with Trolladyngja,* a pile 600 metres thick in the centre, with a slope of 3° to 4° in the lower and 6° to 7° in the upper parts. Such flat *dyngjur* are only formed subaerially by highly fluidal

*Thoroddsen, *Petermann Mitth*, Erganz xxxii, 1906, Heft. 152, p. 127.

basalt ; and it therefore follows that under submarine pressure pyroxene-andesites and even soda-rhyolites may retain high fluidity.

The vesicles of Lake District andesites are remarkably uniform in any particular flow and only show a slow change of size with decreasing depth. The basic rock immediately underlying the Kildale rhyolitic infold is a good example. There is little scoriaceous structure on the surface of flows, large parts of which are often almost without amygdalae. Highly vesicular blocks are more common at the base, where they often appear to be over-rolled ; but they never appear to be so plentiful as descriptions suggest for subaerial lavas. It is quite common to find compact, moderately vesicular, andesite resting on tuff or Skiddaw Slate with scattered pumiceous fragments imbedded in the substratum. (See Plate 10, fig. 3, and Plate 11, fig. 3.)

Nothing in the Lake District lavas is more noticeable or at first sight more surprising than the great proportion which weather with a brecciated structure,* sometimes invisible on a freshly broken surface, but detectable under the microscope by variations in the size and quantity of the little felspar-laths and in the colour of the glass. (Plate 10, fig. 2.) It must be understood that these breccias are solid lava throughout,† and are not comparable to the piles of *aa*, ten or more metres thick, that encumber the surfaces of Hawaiian basalts, nor to the masses of discrete blocks that push down the slopes of Vesuvius. Indeed in the Lake District the actual top of a flow often consists of solid andesite with clefts infilled by tuffy material from above ; perhaps at least partly derived from explosions and blow-holes at the surface of the lava itself.‡

Near the surface the appearance of the included fragments is variable, some showing strong flow, others none, the proportion of phenocrysts and vesicles changing from block to block, many of which may be themselves flow-breccias. Deeper down, the fragments are usually more uniform. The finest known example of such flow-breccias is developed at the top of the Wrengill Andesites by Sour Milk Gill in Gillercomb above the Styhead Pass, where some of the blocks are six metres in diameter. But generally a walk of a few hundred yards across the strike of the lavas in any part of the district reveals examples.

Cracks in the crust are not infrequently filled from below with thin sheets of glass, which may be seen extending for several

*This structure is best seen in bright weather, as its development is due to a difference in the resisting power of matrix and fragments, so that one or the other stands out in low relief. Unless this difference is very marked (as usual near the actual top) or is accompanied by strong colour variation, it is not obvious in mist. It photographs well with slanting illumination.

†The same appearance has been noted in modern subaerial lava. See Johnston-Lavis *Geol. Mag.*, 1892, p. 509 (Vesuvius) ; E. S. Moore, *Journ. Geol.*, 1917, p. 693. (Ngauruhoe).

‡The fine photograph published in *Quart. Journ. Geol. Soc.*, vol. lx., 1904, p. 92, seems to be one of these surfaces, but I am not acquainted with the exposure. It is probably the top of the Wrengill Andesites.

metres, though less than a centimetre thick. They tend to stand out boldly. On a larger scale a fine example of an infilled crack in a fluidal flow-brecciated crust at Woof Crag, Near Swindale, has been published in the *Proceedings*.* Flow and re-fusion may combine to round the included fragments, producing flow-conglomerates, which at first sight have a remarkably sedimentary appearance. These seem to be associated with lavas having a high proportion of pyroxene.

The appearances at the base of a lava are equally interesting. Over-rolled scoriae, which have fallen down the advancing front, are present in variable quantity. The rock above may or may not be flow-brecciated, the former being more common, but not usually to a greater thickness than a few metres. The unbrecciated lava tends to show very marked flow-banding near the base. Underlying sediment is squeezed up among the scoriae and into interstices of the lava for one or two metres. Frequently tongues are pushed into the substratum, as may be seen at Whitfield Cottage, near Binsey,† and at an interesting little exposure of a junction between Skiddaw Slate and andesite in a small gill near the road from Keswick to Thirlmere, a little beyond the second milestone. My attention was drawn to this by Mr. J. Postlethwaite.

The continued flow of fluid over the hardened base has a dragging effect, which produces little drag-folds, and sometimes overthrusts, in sediments immediately underlying. This is so constant that the occurrence of such folds is an excellent guide to the proximity of lava. The special interest of this structure is that it enables the direction of flow to be ascertained, so that a systematic series of observations would, especially if combined with work on the extension and brecciation of flows, afford indications of the points of effusion and mode of accumulation. For instance a beautiful example in Brimful Beck, Wastwater, shows overfolding and therefore flow, from the south-east.

On the whole the above remarks on andesites apply also to rhyolites. But here another factor comes into play, namely, high viscosity over a wide range of temperature, with indefiniteness of fusion-point. Further, for some reason, vesicular structure is very rare in Lake District rhyolites, so that the increase of density with solidification has full effect. This may account for the fact that included fragments, usually rounded or lenticular, are found throughout nearly all the rhyolites. They are often drawn out and bent, following flow-lines, and there is a complete gradation from rhyolites with rounded or subangular enclosures, having a disquieting resemblance to a tuff when weathered, to a well-banded rock. It is curious that bits of andesite are not infrequently seen—possibly picked up by the advancing

* *Proc. Geol. Assoc.* vol. xxvi., 1915, Pl. 17.

† *Proc. Geol. Assoc.*, vol. xxviii., 1917, pp. 6 and 10.

flow and incorporated owing to the rolling motion of a viscous fluid.

Some of the supposed ashes in the historic section at Falcon Crag are actually fluidal lavas. Others are flow-breccias (e.g. "d") or flow-brecciated in places (e.g. "m"). A convenient place to see flow-breccias is near Thirlmere, as several occur by the road round the lake and they are plentiful on the slopes between Fisher Place Gill and Helvellyn Gill. Near Wastwater they may be seen about Low Water, and on the road by the lake, a quarter-mile north-east of Smithy Beck. No place is known where their varieties can be studied so easily in a small area as on the slopes above Po House, on the road from Whicham to the Green and Duddon Bridge. Just a quarter of a mile north-east of Po House a little stream crosses the road, on the banks of which is exposed a thin lava with a flow-brecciated base containing squeezed-up Skiddaw mud. Above is Mottled Tuff, on which, 150 yards from the road, rests a basic flow-breccia, partly conglomeratic, thrusting a tongue into the tuff. A crust injected with films of glass is well exposed 150 yards further east, overlain by thin banded tuff and then by strongly fluidal andesite. Along the crest of the ridge an extremely fine flow-breccia is exposed, which has been mapped in detail for three-quarters of a mile from a point on the road 250 yards from Bankside to 800 yards west of Low Scales Farm. [At the time these were mapped, the manner in which a lava injects its own crust was not understood and sills were mistakenly supposed to be present.] In the Haweswater District, mention may be made of exposures near the track up Gatesgarth Pass, just where it diverges from the road to Nan Bield. Large glaciated exposures occur near the old Rydal-Grasmere road, immediately south of Whitemoss Tarn. A number of junctions with Skiddaw Slate are mentioned in *Proc. Geol. Assoc.*, vol. xxviii, 1917, p. 6. Good basal junctions of flow-breccia and tuff may be seen by the path east of Goat's Water, near Conistone, and just north-west of Joppley How, west of Watendlath; but they can be found almost everywhere. Flow-conglomerates are well-developed within the southern part of the Eskdale Granite aureole at Charity Chair on Stoneside Hill and at Peg Crag, south of Buckbarrow; also on Louthwaite Fell, Uldale, and on Bleaberry Fell. Broken crusts, infilled from above, are well seen by the fence that runs up White Pike, the north-west spur of Pillar, at a height of 1,777 feet; and north of Dock Tarn. Cracks with glass films may be easily found 300 yards north-east of Bank House, Howtown and by the main road to Wastwater, just west of Harrow Head, north of Strands. A very fine exposure of a flow-breccia with fragments dragged out while still viscous is seen at Galleny Force, Langstrath; another is on Kirksanton Bank, between Whicham and Millom. For the rhyolite mixtures that simulate tuffs, there are no better examples than those in the area immediately south of the summit of Scafell proper (not the Pikes).

In order to appreciate the Survey maps, it is necessary to understand the interpretation given to these structures by the Surveyors at a time when microscopical petrography was in its infancy. It was observed in the Lake District that continuous with and parallel to the bedded ashes were breccias with an undoubted fragmental matrix. These passed into rocks which showed brecciation excellently on the weathered surface, but only obscurely or not at all on a fresh face; and these passed

insensibly into porphyries and amygdaloids without trace of brecciation. In the same way tuffs clearly passed into flinty rocks (*i.e.* "hällefintas") which closely resembled other, apparently bedded, rocks (*i.e.*, fluidal lavas) which passed into breccias. These observations were believed to indicate progressive metamorphism of original tuffs, so that all these rocks were coloured together as breccias and ashes, and only those small, and usually irregular, portions of massive lava, which did not seem to pass into brecciated rock, were mapped as "traps." Ward believed that not only did ashes pass into traps, but that there was an equally gradual change from traps into granite, though this was often masked by the intrusive phenomena consequent on complete fusion.

The realisation of this point of view enables use to be made of the mass of observations embodied in the six-inch maps, published and manuscript, of the volcanic area. For example, Aveline laid down with minute accuracy the junction between the Upper Andesites and the Harrath Tuffs for two miles from West Side Edge, Tilberthwaite, over the top of Grey Friar. The concurrence of numerous dip-arrows reveals a tuff (isolated dips may be on flow-bands or "streaks"); "altered coarse breccia" and "rough altered ash" are flow-brecciated andesite; "felstone-like ash, weathering white" is rhyolite; "felspathic ash" is usually cleaved porphyritic andesite, and so forth.

According to von Buch, "Alles ist Lava was im Vulkane fließt und durch seine Flüssigkeit neue Lagerstätten einnimmt"; and if the division is made, not, as has often been attempted, between solid and fragmentary rocks, but between materials which have flowed into position and those which have been deposited, it is possible to arrive at a just appreciation of the sequence of events.

IV.—TUFFS.

By the term "tuff" I understand a fragmental volcanic rock, the material of which has been dropped or washed into place. Tuffs may be divided into *contemporaneous* and *non-contemporaneous*, the latter being best removed from the category of tuffs altogether and termed *volcanic conglomerates*, *sands* and *mudstones*. Contemporaneous tuffs may again be divided into *explosion- and detrital-tuffs*.

In the Borrowdale Series the tuffs, apart from the early explosion-tuffs already described, are for the most part included in two great bands or lenses, which I have named the "Middle Tuffs" and the "Harrath Tuffs" respectively. They both differ from the Mottled Tuffs in their continuity, slow lateral variation and general uniformity. They are usually well-bedded. In addition there are numerous thin bands of similar

tuff, a few feet thick, intercalated between lavas, some of which are very persistent, notably a band which is frequently seen between the Rhyolites and the Upper Andesites. Where best developed the total thickness of the tuffs is perhaps 1,500 feet.

The recognisable material in the Middle Tuffs is nearly all andesite without augite. The higher Harrath Tuffs are a mixture of soda-rhyolite, andesite often with augite, and an altered tachylyte to which I have referred provisionally as "variolite." Rhyolite is, however, lacking in the lower beds. Fine-grained material predominates in the Middle Tuffs and fine-grained bands are interspersed in the Harrath Tuffs. Over much of the area between Coniston and the Duddon, the upper part of the Harrath Tuffs is fine-grained. The best slates are obtained from the beds where the amount of coarse material is small and homogeneous, for the most part in the Middle Tuffs. The only slate quarries of any importance outside the Middle Tuffs are those in the top of the Harrath Tuffs in the above-mentioned area. Variation in the thickness of the two great bands is not rapid and the material on the whole is very uniform, especially in the Middle Tuffs, which show but slight changes in appearance over the whole district. In the Harrath Beds conspicuous bands a few feet thick can be followed for hundreds of yards.

The bedding is often exceedingly close and delicate, as may be seen in many of the slates. False-bedding is rare and ripple marks are only seen occasionally.

The nature of the fine-grained matrix differs from that of the lower part of the Mottled Tuffs. Typical explosion-tuffs are cemented by a material which consists of ordinary sediment and minute glass or crystal chips in varying proportion. Either may be absent. But the cement of the rocks now under consideration is a green paste, resembling ordinary mudstone or slate in structure, but with much less action on polarised light; it seems composed in the main of scales of a chloritic mineral. It contains a variable amount of a clear mineral* and when this increases, passes into "hällefinta." It does not contain rutile-needles, but minute grains of leucoxenic appearance are common, especially in the hällefintas. This green paste resembles the finest sediment produced from the wearing down of volcanic rocks, as may be seen in the basal beds of the overlying Bala and in the Cambrian sandstones laid down round the Pembrokehire Pebidian. It seems to bear the same relation to the less acid volcanic rocks as clays to granites and ordinary sediments, and to be the result of their decomposition under weathering.

The nature of the cement supports Sedgwick's view that the fine-grained tuffs were brought to the sea by ordinary erosion.

*In highly sheared rocks the proportion of sericitic material increases largely. This suggests that much of the clear mineral is secondary feldspar, not quartz.

an explanation obviously suggested by the mass-characteristics ; and the peculiarities of the coarser fragments add force to this inference.

These recognisable fragments show quite a noticeable uniformity in size among themselves in any particular lamina ; they are far more glassy than the flows, quite nine-tenths showing no trace of lath structure ; they are more scoriaceous, frequently pumiceous ; they usually present the concave outlines of broken lava and are rarely rolled, though volcanic sands occur in places ; undoubted lapilli, such as the glass drops of the Mottled Tuffs, are very rare ; the fragments are usually not packed, but more or less separated by finer material, thus being distinguished from the non-contemporaneous volcanic conglomerates and sandstones, in which the rolled pebbles usually touch one another. Clastic mica and quartz are only seen exceptionally, another point of distinction locally.

The glassy nature of the fragments points to rapid cooling ; high vesicularity to low pressure. Thus it is suggested that the material was washed from cones, built chiefly of scoriae and ashes. In fact, that, on the submarine pile reaching the surface, the viscosity of the magma and the expansive power of the contained fluxes asserted themselves, as at Santorin, and eruptions of the Strombolian or Peleán type provided steep islands of loosely compacted rubbish. Lavas however, though more resistant, joint and decay readily, and may well have helped. The absence of rolling and the mixture of fine with discrete coarse material (resembling continental rather than marine sediments) are less easy to explain, but may be connected with the brittleness of fresh lava, the steepness of the slopes, and the low density of much of the vesicular ash, which would be little heavier than water till saturated.

No doubt ejection added to the deposits, as evidenced by occasional bombs * and by the occurrence of pumice-tuffs, quite comparable to those of Falcon Crag, here and there in the Harrath Beds. But I consider that the bulk of the material was clearly detrital and, in particular, that the Middle Tuffs must have marked a considerable pause in the local activity and were deposited in a sea of moderate depth.

The form of the lenses of tuff will be considered under "Arrangement," but a few words may be said on variation of composition. The Middle Tuffs change very little, but are perhaps on the whole rather coarser in the north than in the south. They are green or bluish, but when affected by selective staining may become a green-and-purple or green-and-red rock. The most strongly felsitic Harrath Tuffs observed are those at the head of Riggindale, some of which are nearly pure rhyolite-

*A good example is seen 90 yards north of the northernmost bend of Logan Beck, near Plough Fell.

tuffs. The coarsest yet seen are those exposed in the River Sprint, north of Sadghyll, where boulders 20 and 30 centimetres across are common ; but many of the tuffs east of this are nearly as coarse, suggesting an origin not far to the south. The Harrath Tuffs are often very striking in appearance on a fresh surface, the " variolite " being satiny black, the rhyolite white, yellow, grey or pink, the andesite various shades of green. Staining may give a red or red-and-green rock.

The volcanic sandstones and conglomerates (non-contemporaneous tuffs), which make up the basal beds of the Coniston Limestone series * have in many cases been confused with the underlying beds of much earlier age. They are distinguished from the true tuffs—

(1.) by the rolled appearance of the fragments, which rarely show the irregular outline of those which are contemporaneous. (Plate 9, fig. 3.).

(2.) by the arrangement of the pebbles, which are usually in contact, as in ordinary marine sediments, and are not spaced out (compare Plate 11, fig. 1.).

(3.) by the presence of clastic quartz and mica, both of which are rare in the Borrowdales.

V. ARRANGEMENT.

The general arrangement of these materials is in great lenses of varying size. The variety of the scenery in the volcanic regions of the Lake District and the notable differences apparent in the composition of the sequence at different points are largely due to the dying out of certain horizons.

The sequence where most complete is as follows in descending order :—

Borrowdale Rhyolites
Upper Borrowdale Andesites
Harrath Tuffs
Wrengill Andesites
Middle Borrowdale Tuffs
Lower Borrowdale Andesites
Mottled Tuffs (occasionally associated with or
preceded by andesites).
Skiddaw Slate.

The Skiddaw Slate is a black or bluish-black, fine-grained, hardened, carbonaceous mud. It contains much clastic mica. Fossils are rare, but some way down a band occurs with graptolites of the *bifidus*-zone.

The Mottled Tuffs, mostly made up of products of the pre-

* *Older Palaeozoic Succession* Dutton, pp. 17-18 ; *Proc. Geol. Assoc.* vol. xxvi., 1915, pp. 216-7.

liminary explosive stage, are discontinuous in distribution. They are found in force about the Duddon Estuary, but are completely absent on the other side of Blackcombe to the north-west, having disappeared in less than three miles. The distance was, however, originally greater, as a thrust intervenes. A lens some miles in diameter is exposed about Latterbarrow, near Egremont; and another, the outcrop of which is three miles across, near Keswick. Traces in the form of slightly tuffy bands of siltstone occur on Binsey Fell, far to the north, but in the adjacent Cockermouth area they are absent. To the north-east the Mottled Tuffs are much more persistent. The felsitic Flag-daw type is found all over the Shap-Bampton district and throughout the Cross Fell inlier, thus covering a wide area, not less than 15 miles across. It dies out south of Ullswater. Andesite flows occur in and under the Mottled Tuffs near Keswick, and in places under them in the Duddon Estuary.

The next series, the Lower Andesites, is highly persistent, having been found in every part of the Lake District volcanic area. An andesite appears to occupy part of the equivalent horizon in the Cross Fell inlier, but until it has been mapped in detail, the point is uncertain.

The Middle Tuffs are also persistent and regular. They seem to mark a pause in the volcanic activity, during which exposed andesite-ash and lava was being quietly eroded. They are usually two to four hundred feet thick and are found in force all over the eastern and southern parts of the main volcanic area. They have been mapped from the Buttermere granophyre up to Watendlath, but it is not yet known what becomes of them between Watendlath and Patterdale, where they are highly developed. They are thick north of Coniston, and about Grasmere. They are greatly diminished in the central mountain district about Wastwater, and it may be of interest to explain in what manner they were identified there, although they have not yet been run into any exposure of the normal type.

The Wastwater district has only been superficially examined as yet; when the first traverses were made across it, there seemed to be continuity between the andesites in contact with the Buttermere granophyre and Eskdale granite on the one hand and the Wrengill Andesites of Pillar Mountain and Kirkfell on the other. It was therefore supposed that the intrusions were in the Wrengill andesites. But it soon became apparent that on the west side of the Wastwater fault, which runs across Devoke Water and the foot of Wastwater, the Eskdale and Buttermere intrusions were both at the base of the Lower Andesites. As it was obviously out of the question to suppose that both

changed horizon in crossing the fault, the andesites in contact on the east of the fault were settled as Lower Andesites.

The thinning out of the Harrath Tuffs in the Wastwater region was then discovered, as described later, and the question arose whether the Middle Tuffs did not thin out also. It was not apparent how the point could be tested directly, but on ex-

FIG. 25.—Map of the country round Wasdale Head, Cumberland.
(Scale one inch to the mile,)—J. F. N. Green.

amining the steep slopes of the wild crags near the road by the lake, at the height where theoretically the Middle Tuffs might be expected to occur, viz., at about 500 feet O.D., a persistent band of Middle Tuff type, about 30 feet thick, was found and mapped without difficulty for over a mile (map, fig. 25). A similar band with an easterly dip occurs several hundred feet above the granite on the lower slopes of Lingmell; and it

appears again in the Black Beck, north of Yewbarrow, where it has been quarried for slates, and whence it may run north-westward to join the main Middle Tuff outcrop. I identify this band with the Middle Tuffs.

The next three series, the Wrengill Andesites, the Harrath Tuff and the Upper Andesites will be considered together.

Over the eastern part of the Lake District, between Ullswater and Shap, the Wrengill Andesites are absent, so that the Harrath and Middle Tuffs form a single band. They are first seen east of Wrengill and thicken west. They are fairly thick about Ambleside and still important about Levers Water, whence, however, they thin south-east and south-west, dying out south of Walney Scar, so that the Harrath and Middle Tuffs come together again. As the Wrengill Andesites are in great force round Borrowdale and Wastwater it is clear that about Coniston and Ambleside there was a southerly lobe of the great *dyngja*, whose centre lay somewhere to the north-west.

On the other hand the Upper Andesites are in great strength in the eastern Lake District, but on the whole tend to thin west and south-west. Towards Ambleside they may die out entirely in places and they are very thin near Coniston but set in again south-westward and are rather thick over the Ulpha neighbourhood. They are moderately developed over part of the Duddon Estuary area, though certainly absent near Millom. It looks, therefore, as if there were two centres of effusion, one to the east, another to the west.

The Harrath Tuffs are very thin and almost disappear near Ullswater. They thicken southward and about Sadghy, in Long Sleddale are in great force. Round Ambleside and Rydal they are thick and it would seem that here and toward Coniston the Middle Tuffs are also rather thick. The result is that about Grasmere and Elterwater, and to the south, is an area where andesites are not so prominent as in the surrounding volcanic country. It is this circumstance which has determined an inhabited and cultivated enclave, containing Rydal, Grasmere, Elterwater and Skelwith. The rapid variation in resisting capacity from bed to bed of the fragmental rocks contributes to the grotesque chiselling for which this bay is famous.

Now turn to the steep and dangerous mountains that surround Wastwater. The thinning of the Middle Tuffs has already been described. What happens to the Harrath Tuffs? They are in great force over the rough ground north of the summit of Glaramara. On Rosthwaite Fell, on the northern side of the syncline which brings in the Rhyolites of Rosthwaite Fell and Base Brown, probably not less than 500 feet; traced westward over Thornycroft Fell they cross the road at Seathwaite, run up the steep slopes near the Plumbago mine, and enter Gillercomb on both sides of Sourmilk Gill, with a thickness of between 300 and

400 feet (map, fig. 26). They thin steadily along the steep south-eastern wall of the combe and three-quarters of a mile further on, under Blackmoor Pools, are 130 feet thick. Here they are covered by scree for a space, but seem to be heaved by a small fault, reappearing in the western cliff of the combe with a thickness of 70 feet. At the top of the cliff three tuff-

FIG. 26.—Map of Gillercomb, near Seathwaite, Cumberland.

(Cross-hatching represents dolerite.)—J. F. N. Green.

partings between lavas are seen in a space of 60 yards across the strike, dipping at 50° S.S.E. The strongest is only 30 feet. A quarter of a mile along the strike a thin tuff-parting is again seen.

Thus on Gillercomb Head the Harrath Tuffs have thinned down to insignificance, so that the Wrengill and Upper Andesites become practically united. The explanation of the almost

continuous sections of lava that rise two to three thousand feet above Westwater is to hand. As the delicate sculpturing around Grasmere, haunt of poets, is due to the thinning of the andesites, so the grim scarps of the western mountains, beloved of cragsmen, owe their terrors to the dying of the tuffs.

From the above it seems likely that the Harrath Tuffs, thinning out near Ullswater and Westwater, and only doubtfully represented in the south of the Cross Fell inlier, had a southerly origin, possibly entering the Borrowdale sea in the neighbourhood of Kendal. The fan must be fully forty miles across.

The Rhyolites are found at the top of the Borrowdale Series all over the area, including Cross Fell. Their thickness is usually unknown, but it is not less than a thousand feet in places. At one point near Millom there appear to be higher beds under the Bala unconformity, the rhyolites being succeeded by tuffs which pass upwards into concretionary argillaceous beds, looking hopeful for fossils. The structure of the district was very imperfectly understood when I examined these beds in 1910 and the conclusions then arrived at need verification.

Later volcanic episodes recorded in the Lake District must be referred to briefly. A rhyolite of Bala age comes in below the Conistone Limestone from Stile End to Shap, and rhyolite is met with in a corresponding position at Watch Hill, near Cockermouth, and the Dry Gills in the Caldbeck Fells, twenty miles to the north-west. This flow is clearly submarine. Ashes, and sills probably related to them, occur in the Ashgill Beds and rhyolitic flows assume importance at the same horizon in the Sedbergh inlier.*

These are merely marginal facies of episodes with centres far outside the district. The latest evidence of Lower Palæozoic contemporaneous vulcanicity is the remarkable "green streak" of the *Monograptus argenteus*-zone of the Skelgill (Llandoverly) Beds, to which Professor Marr has drawn attention. This little band is found at the same horizon throughout the north-west of England and north Wales. It is the record of a distant eruption, possibly in the West of Ireland, the finest dust of which was carried by the wind into the British area. A similar green streak must have been formed over the Antillean area by the Soufrière eruption of 1902 and over much of the North Atlantic by the outburst of Skaptar Jokull† in 1783.

The Devonian Shap granite with its entourage of dykes has been so fully described by Professor Marr, Mr. Harker and Mr. Morrison that nothing need be said here. With the possible exception of the two little olivine-basalt dykes in the Mell Fell conglomerate, nothing is known at present of the more superficial development of these intrusions.

**Mem. Geol. Surv.* (Mallerstang), 1891, pp. 13 to 27.

†i.e. Skapta glacier, in the neighbourhood of which the vast eruptions took place. The position of the craters is unknown.

VI. INTRUSIONS.

The petrographic study of the intrusions is more advanced than the knowledge of their field-relations. All the larger appear to be flat laccoliths, which contain an interesting series of rocks ranging from almost pure quartz in the case of some marginal varieties through granophyres, adamellites and quartz-dolerites to hornblende-picrite. They come in at various horizons. The Skiddaw granite in the Cambrian; the Great Cockup picrite and certain dolerites in the Upper Skiddaw Slate (mostly Arenig); the Eskdale, Buttermere, Carrick Fell and St John's Vale masses at the junction of the Skiddaw Slate and the Borrowdale Volcanics; the Gillercomb dolerite near the junction of the Wrengill Andesites and the Harrath Tufts; the Haweswater dolerite, and apparently also the dolerites of Swirrel Edge, Shelter Crag, and Oxendale, at the base of the Rhyolites.

Of the thinner sills and dykes, the Armboth-Helvellyn quartz-porphyry, which is about four miles long, is the most notable. It resembles the St John's Vale intrusion and, though it has always been termed a dyke, its relationships have never been properly examined, so that it may turn out to be a sill. A vast number of dykes have been mapped by the Geological Survey, but have been little noticed by modern workers. They are most numerous and complex around Wastwater, whence Dr. Derryhouse* has given some valuable descriptions. He considers that they occur in the following order: (1) andesitic dykes; (2) felsitic dykes; (3) dioritic† bosses and dykes; (4) granite-porphyry dyke connected with the Eskdale granite; and (5) olivine-dolerite dykes. I agree with Dr. Derryhouse that the last (which are connected with post-Carboniferous movements), must be separated off as of later, possibly Tertiary age. They may be related to the olivine-basalt dykes in the Upper Devonian near Ullswater‡. The order of the first two is not invariable, as a fine intrusion-breccia composed of felsite broken up by andesite has been quarried by the roadside at Cathow Bridge, near Strands.

Sills are not so numerous as I formerly supposed. When first examining the Borrowdales I was misled by the manner in which a lava often intrudes its own roof. Probably, too, some occurrences are of the same nature as those described by Dr. A. H. Cox near Aberiddy and

"represent what were practically lavas which burrowed among the mud of the sea-floor rather than actually flowed over that floor."§

Such are those at the base of the volcanics at Nicle Wood and

**Quart. Journ. Geol. Soc.*, vol. lxxv., 1909, pp. 55-80.

†These interesting rocks, which seem to be related to the monzonites, deserve closer examination. They should throw light on the magmatic differentiation. Mr. Rastall has noted rocks of quartz-monzonitic affinities in the Buttermere complex.

‡*Proc. Geol. Assoc.*, vol. xxix., 1918, p. 118.

§A. H. Cox: *Quart. Journ. Geol. Soc.*, vol. lxxi., 1916, p. 308.

Greenscoe, in the Duddon Estuary area. Clearly, when an unconsolidated mud at a considerable depth is concerned, differences between lavas and sills must tend to be blurred, but I have not had an opportunity for re-examining the exposures in the light of Dr. Cox's work.

At present too little is known of the field-relationships of the various series of dykes of the Borrowdales to allow trustworthy inferences on the vulcanicity to be drawn. Thanks however to Dr. Harker* and Mr. J. Morrison,† the comparatively simple entourage of the Devonian Shap granite is more thoroughly known.

The metamorphism accompanying the intrusions is of special interest, because it is possible to compare the effects of masses of much the same composition, size and date intruded at different depths, and thus to isolate one factor in the causation of the differences. It is probable that a complete study will throw much light on the processes of vulcanism.

So far, it can be said that there are two sharply contrasted types of metamorphism round the larger intrusions of Borrowdale age. The first, which may be seen near the Eskdale, Carrick Fell and Buttermere laccoliths, all intruded at the junction of the volcanics and the underlying Llanvirn shales, decolorises the black sediments to a pale buff; the other, related to the Skiddaw granite, intruded in the Cambrian, does not decolorise, but produces more marked mineralogical changes. Unfortunately the exposed aureole of the Eskdale granite, the largest of the Lake District intrusions, is only seen in Skiddaw Slate at the extreme inner and outer margins,‡ in both cases at the junction with the Borrowdales. The exposure in contact with the granite at Devoke water is a buff micaceous hornfels, which shows under the microscope numerous minute opaque grains (? magnetite), with outlines approaching squares and hexagons, unlike the graphite globules. Along the Crookley Beck at the outer edge of the Eskdale aureole, Skiddaw Slate is folded up with andesite, in which the augite has been inverted into compact hornblende and some biotite has been developed. The slate has become patchily isotropic, and in places an obscure mineral resembling ottrelite appears, but no recognisable aluminous-silicate. In hand specimen it is somewhat paler and harder than the normal Upper Skiddaw Slate.

But in the outermost part of the Skiddaw aureole, the slate keeps its black hue and contains numerous large crystals of chiascolite, while the inner part retains carbon in the form of globules scattered through the rock § and therewith most of its

**Quart. Journ. Geol. Soc.*, vol. xlvii., 1891, p. 266. *Geol. Mag.*, 1892 p., 199.

†*Quart. Journ. Geol. Soc.*, vol. lxxiv., 1919, pp. 116.

‡Unless the rocks of Knott Hill, near The Green, prove to be part of it. Their structural relations are at present unknown, but they show a hypabyssal type of metamorphism.

§*Proc. Geol. Assoc.*, vol. xxix., 1918, Pl. 12, fig. 3.

dark colour; and developes cordierite and andalusite, often with garnet.

Clearly the difference between the two types of alteration is one, not of degree, but of kind, which must be connected with the absence or presence of volatile mineralisers. Where the carbon has been driven off, and presumably with it water, sulphur and perhaps other fluxes, the production of new minerals was relatively difficult: this is the hypabyssal type. But where the carbon was retained, large chiasolites could be developed even where delicate fossils are preserved, as at Randal Crag: this is the deep-seated type, transitional to regional metamorphism. In the Skiddaw aureole, the carbon does not seem to have travelled more than 0.01 mm. as a rule. In a slide from near the central granite (junction of Blackhazel Beck and River Caldew) the graphites are more scattered and the carbon may have travelled as much as 0.1 mm.

The thickness of highly impermeable rock between the two horizons of intrusion is very considerable, comprising the upper part of the Cambrian and the whole of the Arenig, probably not less than 2,500 feet. This would seem to be ample to account for the difference in the conduct of the mineralisers of the aureoles. It is noteworthy that there is no corresponding difference between the textures of the Eskdale and Skiddaw granites: indeed, if anything, the former is the more "granitic" of the two, which suggests that the size of the intrusion has at least as much influence upon its texture as the depth of consolidation. It is now being realised that coarsely granitic rocks may result from intrusions without a great thickness of cover* and the Eskdale granite may be compared with the quartz-monzonite of Boulder, Montana,† which is also intruded below an andesitic series.

What became of the volatile matter driven off? At a point above, or nearly above, the north-eastern edge of the Eskdale granite, there occurs in the Wrengill Andesites of Seathwaite the famous Borrowdale plumbago. (Plate 12, fig. 2.) The sublimation of graphite by igneous rocks acting on carbonaceous material is well-known.‡ It can hardly be doubted that the graphite of Borrowdale is part of the carbon driven off from the Upper Skiddaw Slates by the Eskdale intrusion.

The importance of this Lake District metamorphism lies in the fact that one of the volatile constituents of the altered rock can be definitely identified and traced. It can be seen in the deep-seated hornfelses, is absent from the hypabyssal contact-rocks, but in that case is found collected in the overlying volcanics. It is reasonable to infer that the invisible

*Suess, *Das Auslit der Erde*, Bd. iii. (4), p. 639.

†Weed, *U.S. Geol. Surv. Prof. Paper* 74, 1912.

‡Stutzer, *Zeitschr. Prakt. Geol.*, Bd. 18, 1910, pp. 10-17.

mineralisers behaved in the same way, and that the differences in the type of metamorphism are consequent. Presumably difference of pressure had also some direct effect, but it does not seem likely that there was any substantial difference between the Skiddaw and Eskdale intrusions in respect of temperature or time of action.

VII. SOLFATARIC.

Under this head may conveniently be considered all the characters due to circulating solutions, liquid or gaseous, connected with a volcanic episode. They are of great importance, as in many cases they give evidence of mineralising agents which have played a part in determining the texture and nature ("mode") of the mineral aggregates which build up igneous and metamorphic rocks.

The minerals now most commonly found in the vesicles of the andesites have a normal succession which has been noted in a large number of microscope slides, and, so far as observations have been made, holds also in the larger amygdalae. This is (1) chalcedony, often recrystallised into quartz; (2) chlorite of pennine affinities; (3) quartz or calcite. Quartz and calcite seem to occur quite indifferently, contiguous vesicles containing, beside the earlier minerals if present, either alone or both intermixed.* A good example may be seen in a little quarry by the main road to Troutbeck, a quarter of a mile south of the Inn on the Kirkstone Pass. The quarry cuts the junction of the Middle Tuffs and the Wrengill Andesites, the latter with many amygdalae up to three decimetres in length, lined with chalcedony followed by chlorite and filled in with quartz-calcite. Epidote is found with or instead of chlorite in some cases, usually near the outer margin of an aureole..

In one interesting case of an andesite from the Millom district, the earliest mineral takes the form of globular outgrowths from the walls of the vesicles, with radial streaks. They appear to be pseudomorphs of quartz after a zeolite, and are followed by chlorite and quartz-calcite.

Occasionally the amygdalae are composed of a bright green fibrous substance† replacing all the usual minerals, only fragments of which remain.

Considerable masses of calcite, as much as a metre in diameter, have been noticed in places, as, for example, the road cuttings round the north of Thirlmere. These may fill spaces created by the onflow of partly solidified lava.

Certain forms of katamorphic alteration seem to have been

*See Harker and Marr, *Quart. Journ. Geol. Soc.*, vol. xlvii., 1891, p. 293. I have noticed the same indifference elsewhere, e.g. in the Chipley spilitite.

†Perhaps delossite, but the refractive index seems high. The same mineral sometimes replaces felspar.

effected at an early stage and are probably due to solfataric action (propylitisation). Such are the bleaching of the biotite in the soda-rhyolites and probably the change of rhombic pyroxene to bastite. The alteration of augite seems to have been later, as the mineral is regularly replaced by compact hornblende in the Eskdale aureole, which would hardly be the case if the common quartz-chlorite pseudomorphs had been present at the time of intrusion. More notable is the production of minerals within the rocks themselves by the introduction of new material. Such are pyrites, pyrrhotite, garnet and probably epidote and mispickel, with much of the silicification occasionally found in the rhyolites. Almandine garnet is certainly formed at times by the replacement of felspar * and is of interest because garnetiferous rocks of the type common in the Lake District are extremely unusual. When previously discussing their origin, I was aware of only one dubious comparison, from South America. But simultaneously Mr. N. R. Junner† was publishing a paper on the petrology of the igneous rocks near Healesville and Narbethong in Victoria, which shows that they present many analogies to those of the Lake District. Almandine occurs there in the same sporadic manner in Devonian granodiorites, dacites, rhyolites and tuffs; as in England it is associated with pyrrhotite and chloritised biotite. Mr. Junner, while arriving at no definite conclusion, suggests the possibility of abyssal magmatic assimilation, citing the presence of sedimentary xenoliths, cordierite,‡ and sillimanite. It would be difficult to explain the Lake District garnets in this way, and the probability of solfataric origin in the case of the Australian rocks is strengthened by the occasional presence of fluorspar and tourmaline.

I concluded that the exceptional cause for the production of this exceptional type of garnet-rock was hydrostatic pressure, as it appeared that high pressure was required for the formation of the almandine molecule; and almandine may ultimately prove to be characteristic of lavas and tuffs consolidated at a considerable depth below sea-level. It is possible that some of the anomalous plutonic rocks containing garnet, such as Kodurite,§ owe their characters to alteration by solutions under pressure. The tendency to opalisation|| in the Kodurite series points to such an explanation.

We may hope that in time a critical pressure for the formation of almandine-garnet may be determined, in which case both higher and lower limits of pressure may be obtained for the solfataric phenomena of the Lake District, the higher being

**Min. Mag.*, vol. xvii., No. 81, 1915, pp. 207-217.

†*Proc. Roy. Soc. Victoria*, vol. xxvii. Pt. II., 1915, p. 261.

‡Cordierite has been found in Lake District lava; see Harker, *Geol. Mag.*, 1906, p. 176.

§Fermor, *Mém. Geol. Surv. India*, xxxvii., 1909, pp. 243-279.

||*Ibid.*, p. 264.

inferred from the fact that graphite, not diamond, was sublimed at Borrowdale; if, indeed, pressure is the effective condition for the formation of diamond, a view not free from doubt in the light of recent experiments.

A common and remarkable mode of alteration, as yet undescribed elsewhere, is the production of "streaks" in soda-rhyolites. These streaks, which are films or lenticles of secondary minerals; quartz, chlorite, epidote, sericite, calcite, pyrites, garnet and material resembling serpentine; are certainly older than the main crust-movements. (Plate 12, fig. 3.) They frequently follow flow-planes and appear to be due to infiltration* along a previously existing structure in the rhyolites, of the type called "platy" by Iddings and others. They have a surprising resemblance to bedding, and were for long supposed to indicate altered felsitic tuffs. In some cases epidotic streaks broaden to such an extent as to make up the greater part of the rock.

A relationship between this streaky infiltration of the rhyolites and the deposition of the amygdale-minerals of the andesites is suggested by occasional evidence of a definite chronological order among the minerals of a streak, identical with that normal to the vesicles. A striking instance has been found in a rhyolite infold which crosses the Knott, near Appletreeworth (Plate 12, fig. 1). The streaks in this rock are chalcedonic—perhaps originally opal—enclosing chlorite, which in its turn encloses comby quartz, or sometimes, calcite. There are also irregular scattered patches of chalcedony and calcite. It might be supposed that the streaks in this case were elongated vesicles, did they not cut and replace felspar phenocrysts in the same way as other streaks. I have, however, argued in the paper already referred to that their production was closely connected with the introduction of garnet and pyrites, and was dependent on the presence of high hydrostatic pressure.

The question whence the material carried in the solutions was derived is of interest. I have given reasons above (page 176) for believing that the graphite was derived from underlying sediments. Some of the sulphur may have been obtained in the same way. On the other hand iron and manganese,† of which the garnets contain a considerable proportion, may well have been leached out of the volcanic rocks themselves. There are many curious facts connected with mineral distribution in the Lake District which need elucidation, such as the localisation of arseniates in a comparatively small area in the northern part. But the mineral veins are for the most part post-Carboniferous,‡ and no undoubted case is known of a pre-

**Min. Mag.*, xvii., No. 81, 1915, pp. 215-216.

†From the available analyses the andesites appear to contain about 0.4 per cent. of Mn O.

‡*Finlayson Quart. Journ. Geol. Soc.*, vol. lxvi., 1910, p. 285.

Silurian ore-bearing vein, so that any influence of the Borrowdale episode on the ores must have been indirect.

Evidence is constantly found of the existence of mineral springs on the sea-floor in the curious "birds'-eye slates," which are crowded with squeezed concretions. Similar bodies from the Devonian "Lenneporphyre" of Westphalia have been elaborately described by Mügge,* who compares them with the Karlsbad sprudelstein. Though most obvious and plentiful in the Middle Tuffs, especially in the Coniston-Kentmere district, which seems to have been then the main theatre of hot-springs, they are by no means confined to that horizon, but have been found in the Mottled Tuffs and Harrath Tuffs, and in comparatively coarse material, as at Brunt Stones, near Howtown. Usually quite small, a centimetre or thereabouts, such concretions are known on a larger scale. The best yet seen are in a little slate-quarry north of Hole Rake, near Coniston, in which Professor Marr† discovered a limestone. Here are scattered balls, one to two decimetres in diameter, of grey, slightly tuffey, limestone with traces of concretionary structure. The cleavage winds round them. The main limestone, a lenticular interbedded mass about half a metre thick, with films of tuff, is clearly a small boss of tufa deposited by a mineral spring on the floor of the Middle Tuff sea. Like the concretions, it contains a good deal of fine-grained scaly material resembling the matrix of the slates.

VIII. MOVEMENT.

The movements connected with the volcanic episode have been very little worked out and only a brief reference can here be made to them. I have given reasons‡ for believing that the great Skiddaw anticline, a fold with an amplitude certainly much greater than a mile, is not the result of regional pressure, but a simple curvature connected with the vulcanicity; and that the Skiddaw granite was, so to speak, sucked into the anticline. Thus the intrusion has probably a concave lower surface and in Dr. Harker's nomenclature would be described as a *phacolite*.§ The existence of other large folds of similar age and character is evident from the fact that to the south the Coniston Limestone Series cuts down to the Skiddaw Slate at Greenscoe, near Dalton-in-Furness, and to the Middle Tuffs at Torver, south-west of Coniston. There is some ground for believing that the Eskdale granite and Buttermere granophyre may be phacolites connected with pre-Bala folds in the same way as the Skiddaw granite. Should this generalisation ultimate-

* *Neues Jahrb. für Min.*, 1893, BB. viii., p. 653, *et. seqq.*

† *Geology in the Field*, 1910, p. 633.

‡ *Proc. Geol. Assoc.*, vol. xxix., 1918, pp. 134-5.

§ The form *phacolith* is preferable as *phacolite* is also the name of a zeolite.

ly be proved in the Lake District—a condition which will require a large amount of detailed surveying—the result would be of the first importance in the mechanics of vulcanism.

IX. CONCLUSION.

The Lake District is an area in which every aspect of vulcanicity is open to study. It presents a remarkable completeness of development and a vast field for research.

The obvious generalisation that emerges from this partial study is the fundamental importance of the evanescent constituents of a magma, which are not revealed by chemical analysis of a rock. Any classification of rocks which ignores this factor in their origin must be essentially artificial. For this reason a classification based on mineral composition and on texture is superior to one based on chemical composition.

The lava flows and tuffs have features which are best explicable on the view that they were submarine, probably for the most part at a considerable depth.

A genetic classification of tuffs is suggested, and certain criteria of origin indicated.

My thanks are due to Mr. G. S. Sweeting for the beautiful photographs which illustrate this address. The subjects presented unusual difficulties, which he has overcome with great ingenuity.

DESCRIPTION OF PLATES.

PLATE 9.

Fig. 1.—Explosion-tuff ("Purple Breccia") of Falcon Crag, Derwentwater. The large fragment of dark pumice shows well the fantastic shape often assumed by the lapilli. The ground is made up of glass-dust with "bogenstruktur," too minute to be visible without higher magnification. $\times 30$.

Fig. 2.—Explosion-tuff, Pohouse Bank, near Millom. In the centre is a composite lapillo of slightly contact-altered shale, almost enveloped in pumice, the ends projecting. Other lapilli are mostly of similar pumice but a bit of unaltered shale lies below and a little to the right of the central flake. Vesicles filled by calcite. $\times 25$.

Fig. 3.—Volcanic sandstone. From a boulder of the basal Bala in the Devonian conglomerate of Little Mell Fell. Grains of quartz and felspar with a silty chloritic cement. A large part of the lower portion of the field is occupied by a fragment of coral (? *favosites*). At A micaceous siltstone of Skiddaw type. B, dark glass with some small vesicles. C, a bit of an echinoderm, across the end of which is a flake of carbonaceous shale. D, a quartz-pebble enclosing some felspar. From A to D stretches a fragment of partly carbonated rhyolite, not easily distinguishable in the photograph. $\times 23$.

PLATE 10.

Fig. 1.—Explosion-tuff composed of andesitic lapilli with interstitial sand. River Calder. A lapillo of epidotised siltstone is at the left centre. $\times 18$.

Fig. 2.—Flow-brecciated glassy andesite. North of Kentmere Pike. The largest fragment shows well the breaking-up of sinking fragments under viscous stress of the surrounding paler material. Neighbouring smaller fragments show corroded edges due to refusion. $\times 16$.

Fig. 3.—Contact of andesite and Skiddaw Slate. Whitfield Cottage, near Binsey. The sediment consists of carbonaceous mud with films of tuffaceous silt, contorted by the pressure of the lava. $\times 7$.

PLATE II.

Fig. 1.—Harrath tuff. Gill Scar, Millom. The pale ragged fragments are "variolite" and show well the characteristic shape of the tachylyte. The fragments with straighter outlines and visible internal structure are felspars, partly carbonated. The ground is a chloritic paste. $\times 25$.

Fig. 2.—Vesicle in lava. Wharleycroft, near Dufton. The peculiar shape, which is of the type found in many Borrowdale lavas, is probably due to slow expansion in an almost stationary highly viscous fluid. $\times 25$.

Fig. 3.—Contact of andesite and Skiddaw Slate. Clough Head, St. John's Vale. A hardened film of brecciated shale with some igneous grains has been dragged over the unaltered mud, producing oblique strains. $\times 6$.

PLATE 12.

Fig. 1.—Streak in soda-rhyolite. The Knott, Appletreeworth. The streak consists of chalcedony (perhaps after opal) enclosing chlorite. At A the chlorite encloses quartz, behaving as a single crystal, but with traces of comby structure, extending one third the length of the streak. $\times 16$.

Fig. 2.—Graphite in propylitised andesite. Plumbago mine, Seathwaite. Replacement is seen along cracks. $\times 25$.

Fig. 3.—Sheared streak in soda-rhyolite. Sealhole, Cawdale. The cleavage lies vertically in the figure. The pale part of the streak consists of sericite-like material, with some quartz. The dark borders represent a brown tint in the rhyolite, apparently an early stage of decomposition. Part of a parallel streak, composed chiefly of quartz and calcite, is seen at the bottom of the figure. $\times 25$.

PHOTOMICROGRAPHS.

Photo. G. S. Sweeting.

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