ART. XVIII.—*The Microscopical Characters of Volcanic Tuffs—a Study for Students*; by L. V. PIRSSON.

THE recognition of fragmental volcanic material in fresh surficial deposits is usually relatively easy, both from characters which may be observed in the field and in thin section under the microscope. In proportion, however, as such deposits become altered increasing difficulties are met with and where they have been buried under later sediments, and in many cases metamorphosed to a greater or lesser degree, the task of determining them becomes one of the most arduous which confronts the petrographer. Every point of vantage yielded by field studies, the megascopic structure, thin section, and chemical analysis, must be made use of.

Moreover, the difficulty may be increased in another way. In the case where we have to determine whether a given rock is igneous or sedimentary; whether it has been formed by the solidification of a fluid magma or not; there is no transitional stage between them to consider. This is not the case with volcanic tuffs; they may fall on the land and show little or no evidence of bedding; they may fall into water and exhibit it in marked perfection. While falling into water they may be mingled with contemporaneously deposited land-waste brought by currents or streams; or, if fallen originally upon the land, after more or less oxidation, or none, depending on the length of their sojourn, they may be washed down into seas or lakes and mingled in the process with greater or lesser quantities of the ordinary products of land erosion. Thus every degree of perfection of stratification in pure tuffs may be expected, and every degree of transition into ordinary sediments—sandstones, and shales. The intermingling may be by pure layers of each, bed after bed, of any degree of thinness; or of grains of the different materials in the same bed.

It has seemed to the writer that in the various text-books on petrology the subject of volcanic tuff deposits has never been as adequately or systematically treated as it should be. In some works, especially the briefer ones, they are considered in such a general way that the student in search of information receives very little idea of the characteristics necessary for his guidance in their determination. In the more comprehensive hand-books, on the other hand, there is so much detail given, especially of local occurrences, that the student fails to obtain that comprehensive view of essentials which should form the basis of his knowledge. There are a number of excellent essays by investigators in the literature on particular occurrences, one of the best of which is on the so-called "Lenneporphyries" by Mügge,* with admirable plates, but these are not always accessible to the student, neither are they written in a form convenient for his use.

The writer during the past twenty odd years has had occasion to study tuffs in a number of cases in his own researches on particular areas,† and in supervising the work of students in his laboratory who were engaged in research on material collected in the preparation of their theses for the doctor's degree, he has had opportunity for the study of many more.‡ Sometimes the material under investigation was fresh distinct volcanic ash or tuff, but it has often been a question to be decided, if possible, whether certain older, more or less altered, interbedded rocks were volcanic tuffs or not. In the latter case it has then been necessary to start from the unaltered typical varieties and trace the various gradations into those which have been changed. During the course of this experience much has been learned, the details of which are not given in the various publications cited; only the final decisions arrived at. It has been thought, therefore, that a succinct account of some of these observations combined with the results of other petrologists would be of interest and value to students of petrology; more especially since the sedimentary rocks are

*Untersuchungen ueber die "Lenneporphyre" in Westfalen und den angrenzenden Gebieten," O. Mügge, Neues. Jahrb. für Min., B. B. viii, p. 533–721, 1893.

† Castle Mountain Mining District, Bull. 139, U S. G. S. 1896, pp. 73, 78, 127; Judith Mts., Mont., 18th Ann. Rep., U. S. G. S., Pt. III, 1898, p. 482; Igneous Rocks of the Highwood Mts., Bull. 237, 1905, pp. 56, 158.

‡ H. E. Gregory: Contributions to Geology of Maine, Pt. II, Bull. 165, U. S. Geol. Surv., 1911, pp. 120–131.

Jos. Barrell: Geology and Ore-deposits of the Elkhorn Mining Dist., Mont., 22d Ann. Rep. U. S. Geol. Surv., Part II, 1902, p. 523.

F. D. Laney: Gold Hill Mining Dist., Bull. 21, North Carolina Geol. Surv., 1910. pp. 29-37.

J. E. Pogue, Jr.: Cid Mining Dist., Bull. 22, North Carolina Geol. Surv., 1910, p. 43 et seq,

D. D. Cairnes: Wheaton Dist., Yukon Terr., Mem. 31, Geol. Surv. Canada, 1912, pp. 61-69.

G. F. Loughlin: Gabbros and Associated Rocks at Preston, Conn., Bull. 492, U. S. Geol. Surv., 1912, p. 67.

H. H. Robinson: San Franciscan Volcanic Field, Ariz., Prof. Paper 76, U. S. Geol. Surv., 1913.

R. D. Crawford: Geol. and Ore-deposits of Monarch and Tomichi Dists., Col., Colo. Geol. Surv., Bull. 4, 1913, p. 175.

M. E. Wilson: Kewagama Lake Map-Area, Quebec, Geol. Surv. Canada, Mem. 39, 1913, p. 45.

M. Y. Williams: Arisaig-Antigonish Dist., Nova Scotia, Geol. Surv. Canada, Mem. 60, 1914, p. 118.

C. W. Drysdale: Geology of the Franklin Mining Camp, Brit. Col., Mem. 56, Geol. Surv. Canada, 1915, pp. 96 and 128.

A. M. Bateman: Geology and Ore Deposits of the Bridge River District, British Columbia, Memoir, Geol. Surv. Canada, in press.

Bruce Rose: Geology of the Savona District, British Columbia, Memoir, Geol. Surv. Canada, in press.

being more and more studied by modern petrographic methods, and as previously noted, there are all gradational varieties of transition from them into tuffs.

Classification of Material.

Fragmental volcanic material may be roughly divided for convenience into pieces the size of an apple and upward as *volcanic bombs;* those the size of nuts, *lapilli;* ones like small peas or shot, *volcanic ashes*; while the finest is *volcanic dust.* The divisional points may be supposed to lie midway between these sizes. The coarser material, the bombs, lapilli, and much of the ash, may fall around and near the vent and produce beds of *breccia;* the lighter ashes and dust, supported and carried by air currents, tend to fall after these and at greater and greater distances from the vent; their compacted material is known as *tuff.* Naturally all gradations both in vertical and horizontal directions will occur between tuffs and breccias. The term *volcanic conglomerate*, sometimes used in the place of breccia, should be restricted to water-laid conglomerates consisting of volcanic materials which exhibit erosional wear. In the use of *volcanic agglomerate* it would be best to follow Geikie* and confine the use of the term to the tumultuous assemblage of blocks, often of large size, which may be found filling the upper portion of old volcanic conduits.

It is obvious from the sizes mentioned that the determination of volcanic breccia is a matter of megascopic study, best, perhaps, performed in the field. If the microscope is to throw any light on rocks which are supposed to have this origin it will be chiefly by a study of the tuffaceous filling between the larger pieces, aided perhaps by the nature of their contours. It is, therefore, the tuffs which must be the subject of microscopical study, and what knowledge they afford can be easily carried over to include the breccias.

Composition of Tuffs.—Tuffs are composed of three things: *a*, glass; *b*, crystals of individual minerals; and *c*, fragments of rocks which may be holocrystalline or partly glassy. While all degrees of purity and admixture of these three occur, accordingly as one or the other predominates or gives decisive character to the material, we may distinguish *vitric tuffs*, *crystal tuffs*, and *lithic tuffs;* the use of "vitric" and "lithic" is suggested instead of the more common "glassy" and "stony" in order to avoid the misapprehension that the outward appearance of the material is referred to. Tuffs also may be fresh, altered, or metamorphosed, and each of these three stages

* Text-book of Geology, 4th Ed., 1903, p. 173.

demands consideration. They may differ also in their petrogenic nature, the chemico-mineralogical differences depending on the kind of magma; whether rhyolitic, trachytic, andesitic, or basaltic, etc., and these also require attention. We will commence with the simplest type, the fresh vitric tuffs.

Vitric Tuffs.

Formation of Tuffs.—Since tuffs are produced by the sudden violent expansion or explosion of gases in a more or less viscous magma it may be well to consider this phenomenon for a moment. It is obvious, in view of the quantities of ash and dust that are almost instantaneously produced, sometimes reaching vast proportions, that it cannot be the result of bubbles merely passing out from, or forming at, the surface of the liquid melt. They must indeed be produced simultaneously through a body of the magma which is in the conduit. There is some analogy here to the sudden liberation of steam, on the relief of pressure by overflowage from the pipe of a geyser, occasioning its discharge. But it differs from that of a geyser in that in the latter there is only one medium, the water; while in the magma there are the volatile gases and the non-volatile more or less viscous silicate melt. If the sudden production of the gas bubbles does not take place with expansive force sufficient to rupture the magma, the latter would expand, sometimes enormously, in volume, and a pumice or rock froth would result. Where ash and dust are formed the rending of the magma must occur, and the more complete this is the finer the resultant product will be. The expansion of gas and rupturing begin in a liquid medium; the resulting product falls as a rigid glass. We do not know of course the exact march of events between these points; but it is clear that the magma ruptures into separated masses of different sizes, as the volume of mingled gases and molten glass rush out of the conduit. The separate masses are themselves swelling and flying apart into smaller ones as they ascend, and this continues until the stiffening of the glass and the lessening of the expansion of the gas through cooling bring the process to an end. This carries us to the point where we may consider the forms of the resulting particles.

Forms of Particles.—A bubble of gas expanding on the surface, either of the original magma or of one of the projected masses, forms a vesicle or bulb, whose wall is thickest at the top and whose sides become thinner and thinner as it expands away from the surface, until they are finally ruptured and the bowl-shaped body is driven from the parent mass. Such a form is shown in *a* of fig. 1. It is evident that unless excessively minute such vesicles will be broken into smaller fragments by violent collisions in the outrushing cloud of gas and ash, or by weight of superincumbent material after deposition. It is also to be noted that the form of such fragments, with the surface large in proportion to the weight, is an excellent one for floating and long waftage by air currents. In thin sections of vitric tuffs, sections of such vesicles, or their fragments, appear mostly as lune- or sickle-shaped pieces of glass, as illustrated in *b*, fig. 1. It commonly happens also that in the projected particles of magma a number of contiguous or even coalescing bubbles are forming and bursting at the same time. The fragments of the cell walls which are left will

Fig. 1.

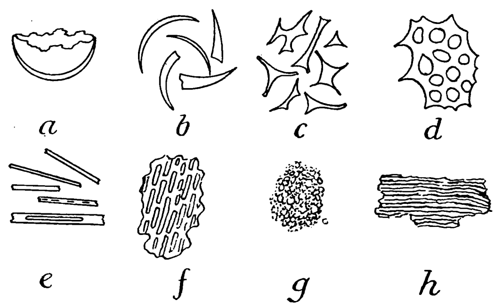

Fig. 1. Forms of glass strands and particles in tuff.

show various cusp-like shapes of the character illustrated in *c*, fig. 1. A further extension of this leads to cases where, owing to increasing viscosity, or to greater depth from the surface in the magma particle, not all of the bubbles are able to burst their cell walls and some remain imprisoned in the glass. The effect is then like *d* in fig. 1. Some of the spheroidal openings may of course be sections of bubble pits seated on the surface of the particle after *a* has been blown off. In the rending of the magma it may happen also that particles of it are driven apart while they still have points of attachment; if the magma is not too excessively viscous they will draw out threads of glass after them. Tiny broken pieces of such threads are seen as rod-like bodies, sometimes carrying inclusions or drawn-out vesicles; *e*, fig. 1. This is the same as the well known Pélé's hair.

Pieces of the character of *d*, fig. 1 are larger than *b*, *c* and *e* and represent transitions from dust into ash; as their dimensions grow they pass into lapilli. Not infrequently one discovers they have been pulled out; that is, they are the same as *e* on a larger scale. This is shown in *f*, fig. 1, where the vesicles are elongated. A transverse section of this does not exhibit the elongation, but appears as in *d*. If the elongation is very pronounced the particle may resemble a bundle of fibers, as in *h*, fig. 1. A transverse section of this shows the ends of the fibers in a berry-like grouping; *g*, fig. 1.

Section of a Vitric Tuff.—A typical example of a vitric tuff from a rhyolitic magma, which exhibits well the various forms of glass particles mentioned above, is shown by the drawing in fig. 2. This tuff is relatively little altered in that

FIG. 2.

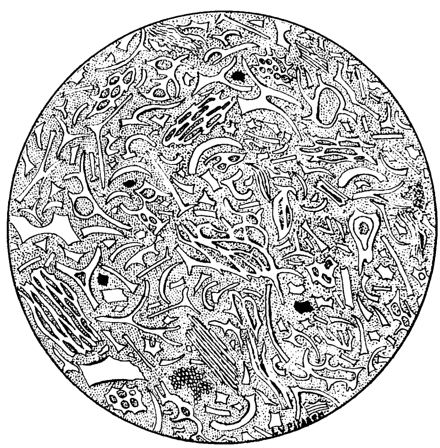

FIG. 2. Rhyolitic vitric tuff from Checkerboard Creek, Castle Mountain Mining District, Montana, showing typical vitroclastic structure. Actual diameter of field 2 mm.

the glass shards are unchanged in substance and do not act on polarized light. The interstitial material between them is in some cases more minute fragments of glass, while much of it appears by transmitted light excessively fine granular and largely of a brown color; the nature of the latter in part is indeterminable and it may consist of altered glass dust, and in large part it is chalcedony, deposited hydrous silica, in numerous areas and patches, as shown by its refractive index, double refraction and fibrous radiating nature; which causes it to yield between crossed nicols, on revolving the plate, a stationary black cross like that of as pherulite. This chalcedony has a rich brown color by transmitted light. While the tuff in the hand specimen, like so many others, is colored brownish by limonitic pigment, the color of the chalcedony, as well as that of other patches of finely aggregated particles, is so much deeper by transmitted than by reflected light that it is clear this brown color is in large part due to the unequal refraction and internal reflection of light in passing through aggregated fibers and particles, whereby the blue rays are absorbed and the red-orange ones transmitted, as explained by the writer in the case of spherulites.* This effect is seen in many tuffs. The tuff illustrated is not an absolutely pure vitric type in that occasional fragments of quartz, feldspar, augite, hornblende and iron ore occur in it; it has been analyzed and previously described.† It has about the strength and coherency of a firm chalk.

Loose Volcanic Dust.—With a series of excessively fine volcanic dust deposits of a loose uncompacted nature which, in some cases at least, have evidently been transported long distances from their original sources if we may judge by the places in which they occur, Oklahoma for example, a study has been made by directly imbedding the particles, without sectioning, in balsam. In these it has been found that while

FIG. 3.

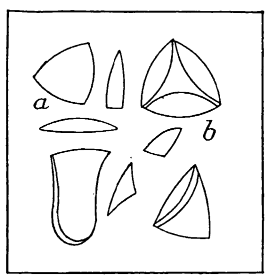

FIG. 3. Shapes of glass particles in volcanic dust.

the various shapes mentioned above occur to a greater or lesser degree, the most prevalent one is that of a thin film of glass of a triangular shape whose sides are curved, forming a spherical triangle. By raising and lowering the objective one may often observe that the film is not flat, but more or less slightly dished, like a wash-glass, thus indicating that it is part of the glass skin or bulb covering a large bubble. These occur with great variety in the detail of the forms, examples of which are shown in *a*, fig. 3. Some of these are thicker on one side than on the other, giving at times a sphenoidal or axe-like

* Artificial Lava Flow and Its Spherulitic Crystallization. This Jour., vol. xxx, 101, 1910.

† Castle Mountain Mining District, Bull. U. S. G. S., No. 139, p. 127.

effect. In other cases the films are ribbed, as illustrated in *b*, fig. 3, indicating the cell walls of other bubbles. Sections through such fragments shown in fig. 3 would obviously yield shapes like some of those seen in the tuff, fig. 2.

In some of these dusts there are great numbers of glass fragments of entirely irregular, haphazard forms and there may be some question regarding the influence of the viscosity of the magma, at the moment of explosion, on the shapes of the particles produced. For with increasing stiffness the less opportunity there would be for normal bubble expansion and the formation of vesicular structures, and the more sudden and complete would be rending and shattering of the glassy melt, with the production of irregular fragments. This would also be more likely to happen in highly siliceous magmas, since they are the more viscous ones. In addition it may be noted that the greater the distance a volcanic dust is carried by air currents from its source, the more purely glassy it will be, since the higher specific gravity of any crystalline material will tend more and more to sift the latter out.

Vitroclastic Structure.—The particular type of microstructure which distinguishes vitric tuffs and is illustrated in fig. 2 deserves a special name. It is as characteristic for these rocks, both when fresh and when altered, as certain textures are for some igneous ones, or particular structures are for certain organisms occurring as fossils in the sedimentary rocks. It has been designated "ash structure" by Mügge,* a term also used by Rosenbusch: but there are objections to this name in that volcanic "ash," as the term is commonly used, indicates coarser material than that which composes the dust that characteristically exhibits this structure. Most "ash" is really composed of fine lapilli, is largely crystalline, and under the microscope is a very fine breccia. If the structure is seen in rocks composed of ash it is in the finer portion composed of dust that fills in between these micro-lapilli. Hence it is proposed to name it the *vitroclastic* structure, a term whose meaning is sufficiently obvious and whose faulty construction, like that of vitrophyre, from the standpoint of etymology, in that it is composed of roots from two languages, it is hoped may be forgiven since both components are so well known to all petrographers. There is a suggestion of the sedimentary rocks also in the term, which is not bad, since the tuffs often form gradations between that great group and the igneous ones, as previously mentioned.

Magmatic Relations of Vitric Tuffs.—While many exceptions to this general rule may be found, it is true that the most frequent examples and largest masses of vitric tuffs are found

* Op. cit.

in those derived from rhyolitic and dacitic magmas; less frequently from those of trachytic or andesitic composition: and still less so from basaltic ones. This of course depends in great measure on the inversely varying viscosity and crystallizability of the different magmas; the more viscous felsic ones forming glass under conditions where the more fluid mafic ones readily crystallize. The exact magmatic relations of a vitric tuff can only be determined by chemical analysis, but it may be noted that the glass of fresh felsic varieties is usually clear and colorless; that of basaltic ones colored brown. This applies to them of course only as they appear in thin section by transmitted light and to the glass particles themselves, not to interstitial matter which may be colored, as previously discussed.

It should be mentioned here that basaltic tuffs, composed of angular or concave edged particles of brown glass, are called *palagonite.* They are often vesicular and may enclose microlites of plagioclase or crystals of augite or olivine; often the fragments are outlined by bands of a lighter or different color, which are sometimes isotropic like the glass cores, sometimes weakly birefringent. Such banding indicates a certain degree of alteration.

Crystal Tuffs.

While it has happened, and perhaps not infrequently, considering the number of instances which have been observed, that volcanoes have projected material consisting of practically nothing but crystals of a particular mineral, such as augite, olivine, feldspar, leucite, etc.; and even masses of loose titanite crystals are mentioned by Doelter* as occurring on one of the Cape Verde volcanic islands; tuffs, composed entirely of crystals, must be very rare, and their origin as such might be difficult to determine. On the other hand, crystals of minerals, the kinds depending largely on the nature of the magma, either perfect in form or more or less fragmental, are found in nearly all tuffs; and when they become a dominating or striking feature of them the rocks may be referred to this division. It may be said, however, at the outset that while crystal tuffs of acidic felsic magmas are common, those of basaltic ones are at least comparatively rare.

Origin of the Crystals.—This may be two fold; they may have originated in the magma itself, which, caught in the act of crystallizing by the explosion, consisted of a mass of crystals mingled with liquid; or they may have come from disrupted and shattered portions of the rocky walls through which the vent has been drilled. Not infrequently a mingling of both

* Petrogenesis, p. 147, 1906.

may be found in the same tuff. To determine which origin the crystals of a particular mineral in a tuff may have had, two features should be considered. The first is whether, regarding the general petrologic nature of the tuff, as determined by its association with other igneous rocks in the field, its chemical composition provided an analysis is made, or in lack of it by the character of the general assemblage of crystalline material it contains, such a mineral could be considered one of its normal components. Thus in a tuff which examination had shown to be of trachytic or phonolitic nature, crystals of quartz would have to be regarded as of an origin foreign to the magma and therefore in the second class. The second feature relates to peculiarities which the crystals themselves may show. The ones of the first class, produced in the liquid magma, may be regarded as prematurely born phenocrysts and, like the phenocrysts of the lavas, they may be spongy, filled with inclusions consisting of other minerals, indeterminate microlites or blebs of glass, or contain cavities filled with liquids or gas. They may also be corroded, with deep embayments, the latter filled perhaps with glass, as so often seen in quartzes and olivines; and in addition they may have, especially with feldspars, the clear glassy appearance associated with sanidine, in contrast with the ordinary habit of the feldspars of the granular rocks. On the other hand, fragmental crystal material torn from older, deeper-seated rocks of the basement, or projected by explosion, may be quite lacking in such distinctive properties. The student, however, should guard against thinking that these features can be always used as an invariable receipt for making such a distinction. They may be quite wanting, or the crystals may have been derived from older lavas forming part of the cone, which may have been projected by explosion. But if used with discretion, in combination with other circumstances to be described later under lithic tuffs, they may be of great service. In case the crystals show corrosive embayments filled with a crystallized groundmass, like the quartzes of rhyolites or the olivines of basalts, it may be safely inferred that they have been derived from older lavas.

Forms of the Crystals.—The forms exhibited by crystals in tuffs may be in places, as is well known, strikingly perfect, furnishing when they are of sufficient size some of the best of cabinet specimens, like the augites from the tuffs near Aussig in Bohemia. With the lens, quite minute ones of perfect development may be observed, and if the tuff is not too indurated, picked out with a knife or needle point and examined under a low power on the microscope stage. Such crystals, complete in their outward crystal form, must be of the first class mentioned above, for if embedded in solid rock they would of necessity have been shattered by the forces which fragmented it. More commonly the crystals seen in these tuffs consist of broken pieces which in thin section exhibit here and there a crystal outline, but in general show no definite shape. The student must guard against imagining that he can see in them the cuspate and lune-like forms which are characteristic of the vitroclastic texture shown by glass shards; obviously such structures could not be produced by the shattering of solid substances. The resemblances to it are most frequently seen in pieces of quartz and are due to the conchoidal fracture of the latter.

It is stated by Harker* that in crystal tuffs there is frequently a characteristic arrangement, by which the crystals stand in the finer matrix with their longer axes at right angles to its lamination, as if they had fallen into it from above.

Interstitial Filling.—In a fresh crystal tuff, whose substance is of direct magmatic origin, the material between the crystals is composed of glass shards and the finest dust, often almost sub-microscopic particles of both, produced partly by the explosion and partly by attrition of the larger fragments upon one another. It may, therefore, exhibit the vitroclastic structure and be itself the best proof of the tuffaceous nature of the deposit. But since the crystals may not always be of direct magmatic origin, that is, of the first class previously mentioned, so also much of the filling between them may be derived from previously formed rocks. In this case the tuffs form gradations into the lithic types described later. Generally speaking, however, the filling in these tuffs is more or less altered, as will be described later. An example of a typical crystal tuff of rhyolitic origin is shown in fig. 4. The crystals are mostly quartz and feldspar with a few of biotite and hornblende.

Lithic Tuffs.

The essential feature of tuffs of this class, as previously explained, is the presence in them to a striking or dominating degree, of fragments of previously formed rocks. Several different modes of origin of these may be conceived. Thus instances are known where volcanic vents have been blown through a sedimentary series, shattering and powdering the beds and projecting the comminuted material, without, however, being followed by any rise to the surface or escape of magma, or but very little, as in some of the maaren of the volcanic Eifel. Crater pits formed by such "blow outs," to use

* Harker and Marr: Shap Granite and Associated Rocks, Quart. Jour. Geol. Soc., xlvii, p. 299, 1891.

a miner's term, would be surrounded by a deposit in fragmental condition of the bedded rocks affected, with little or no volcanic material; whether they should be called "tuffs," or not, must be largely a matter of individual opinion. Also, at any time during eruptions, material may be torn from the walls of the conduit where it passes through the sedimentaries or crystallines forming the basement of the volcano, and appear in the tuffs. But the most prominent kinds of fragmented

FIG. 4.

FIG. 4. Rhyolitic crystal tuff from the Antelope Range, Utah. Crystals shown polarizing between crossed nicols; filling of glass dust, etc., in plain light. Actual area, 5^{mm} in diameter.

rocks present in lithic tuffs are, in general, lavas of a class similar to that of the exploding magma, or genetically related to it. While they may be portions of the cone already formed it may be suspected that more often they are parts of a solidified and more or less completely crystallized crust, which has formed by the freezing of the upper layers of the magma column during a period of quiescence in its volcanic activity, and which, by the rising pressure of the accumulating vapors below it, is finally comminuted when explosion occurs. An average lithic tuff consists then largely of tiny fragments of rhyolite, trachyte, phonolite, or andesite, etc., as the case may be, with their characteristic minerals and textures in those stages of development which the particular rock had attained on solidification, and with an interfilling of glass shards, bits of pumice, mineral dust, etc., mingled usually with more or less distinct crystal fragments. The interfilling may exhibit clearly the vitroclastic texture, but as in all tuffs, this depends in great measure on the recency and state of preservation of the rock, as described later. The size of the stony particles, which must be large enough in general for the particular kind of lava to be recognized, takes them out of the class of volcanic dust, into that of volcanic ash, mentioned at the beginning of this article, and we see, therefore, that there is, in a general way, a progression in tuffs from vitric types—the finest—through crystal tuffs, into lithic ones and then into breccias. An example of a lithic tuff is seen in fig. 5.

FIG. 5.

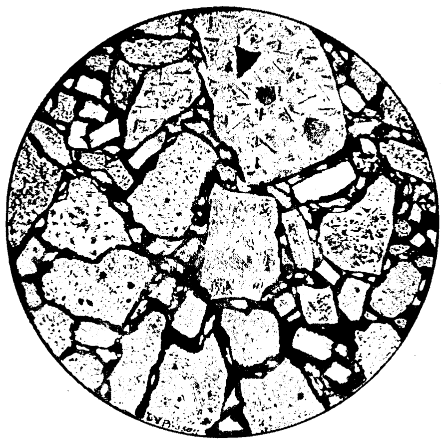

FIG. 5. Lithic tuff of trachyandesitic nature, from the Euganean Hills, Italy; actual size, 5^{mm} in diameter; nicols crossed.

In determining the position of a tuff in petrographic classification, that is, whether it is rhyolitic, trachytic, andesitic, etc., the student should bear in mind, and this applies more especially to the crystal and lithic varieties, that he is liable to encounter among the ash particles, as may be inferred from what has been previously stated, bits of rocks and minerals quite foreign to a lava of the particular kind with which he may collate it. His determination, therefore, should be based on the average character of the dominant ash particles.

Average Tuffs.

In the foregoing discussion three special types of tuff have been selected and described for divisional purposes in classification. It should not, however, be supposed that all tuffs will clearly fall into one or the other of these three classes. While many will, the majority of these rocks will be found to be intermediate in character; for all gradations between the three will be found in nature, with the exception that tuffs composed of glass dust with stony ash particles, but devoid of individual mineral crystals, must be extremely rare if indeed they can occur. The most common kinds are those containing in variable proportions all three ingredients; such transitional character should be taken into consideration in determining and naming them.

Tuffaceous Sedimentaries.

Where tuffs have fallen into water, or have been quickly washed down into it after their deposition, they may not have been essentially altered in composition or characteristic micro-textures, and although, perhaps, beautifully stratified their recognition by microscopic study may be relatively easy. In such cases also they may grade into, or be alternated with, distinct volcanic conglomerates or breccias, and the microscopic studies of the latter in the field may greatly aid in their determination, especially when the tuffs are altered. But when tuffs have been exposed to weathering for some time, so that a considerable amount of the alterations, which they so readily undergo and which will be described later, has occurred in them and they are then washed down, mingled with greater or lesser quantities of ordinary land waste, and deposited anew, it is often very difficult to decide in such beds whether tuffaceous material is present or not. Under such circumstances the glass shards are usually destroyed and with them the characteristic vitroclastic structure. If, fortunately, they are found, then decisively tuffaceous material is present. If not, search should be made for ash-sized particles of pumice, which may exhibit the vesicular structure and may possibly still prove to be of glass; for crystals with the peculiarities mentioned under crystal tuffs; and for tiny fragments like those of lithic tuffs. If no glass can be found, or proved to have been present, the determination cannot be certain if it rests on only one observed characteristic; it can only become so when a sufficient assemblage of them is shown to be present. As petrographic studies are progressively made of the later bedded rocks of the region of the American Cordillera, it is certain that vast amounts of tuffaceous sediments will be found in them; in studying them criteria of the nature advanced in this paper will be found most useful.

Alteration of Tuffs.

It is the exception, rather than the rule, to find tuffs in the condition in which they are when freshly deposited. For one thing their loose porous texture permits the ready passage through them of meteoric waters carrying substances in solution, which may attack them and at the same time by deposition introduce foreign substances into them, which in many cases serves to cement them into more or less firm rocks. For another thing, the glass, which may be a prominent or even dominating ingredient, is a substance chemically in unstable equilibrium and therefore ready on the slightest pretext to alter into other and more stable forms of matter. The same is true, only in lesser degree, of many of the crystalline minerals they contain, in that these compounds have formed originally, and are in equilibria, under a very different set of physical conditions from those in which they are subsequently placed. In this latter respect tuffs, however, are not of course different from any of the crystalline igneous rocks. In addition to these causes of alteration tuffs, like all other rocks of whatever origin, may be subjected to metamorphism, both contact and general, and may be more or less modified and even so profoundly that no trace of their original character may remain. To undertake to discuss fully all such possibilities would be almost equivalent to a treatise on the general subject of metamorphism and far beyond the limits of this article. It is proposed here, therefore, only to sketch some of the more important features of these changes and the results that follow from them, with special reference to the tuff nature of the material operated upon. These broad outlines must be regarded by the student as indications of the paths to be followed in the investigation of particular cases. They may be discussed under the following general headings: *Weathering and Consolidation; Devitrification; Contact Metamorphism;* and *General Metamorphism.*

Weathering and Consolidation.

Weathering and consolidation are not of course one and the same process and yet where the first is taking place the second in a measure, in depths below, must be also occurring. The weathering of tuffs is comparatively easy where they are loose and uncompacted, owing to the ready access of air and moisture and also to the relatively large surface areas exposed by such fine grains. Hence the feldspathic tuffs are readily kaolinized and converted into soft earthy masses. One of the earliest indications of a change in tuffs, when examined in section, is the deposition in them of some form of hydrated silica, opal, chalcedony, etc. This has been already mentioned in the description of the vitroclastic tuff from Castle Mountain. Every stage of this saturation of the felsic tuffs by hydrated silica may be found until eventually they may pass into extremely dense flinty rocks, resembling so closely dense rhyolites, novaculites, jaspers, etc., that it becomes impossible to distinguish their real nature in the field, more especially as they may assume lively colors of green, red, yellow and brown. Some striking instances of these rocks have been found in North Carolina and Georgia among the ancient volcanics of the Piedmont plateau. In thin section evident remains of the vitroclastic texture may sometimes be observed, establishing in connection with the shattered condition and nature of the accompanying crystals, their tuff-like character; but often these are not present in any decisive fashion and in this case, while chemical analysis may prove their igneous origin, in contrast with jaspilites and novaculites, it cannot be determined whether one is dealing with tuffs or the lavas corresponding to them. There is apt to be in these cases thorough devitrification, as described later, which is another obscuring element. Where the tuffs have been merely altered by weathering the particles become turbid from the separation of kaolin, hydrated iron ore, and carbonates, and lie in an impure cement of minute granules of these substances which tend to obscure the characteristic structure. An excellent example of an altered tuff has been figured by Professor Bascom* from South Mountain, in which the structure is well preserved. Some altered tuffs, more especially those of the less siliceous and more andesitic types, appear almost wholly like aggregated masses of carbonates in the section; one feels inclined to believe at times that they must have been overlain by limestones whose substance has been leached down and deposited in them. Mingled with these carbonates are earthy masses of iron ore.

Probably from a somewhat different type of alteration the fine tuffs may be changed into minute scales of sericitic mica mingled with granules of quartz. Along with them is apt to occur leaves and shreds of chlorite. It is often extremely difficult, or even impossible, to distinguish in the finer granules whether one is dealing with sericite or kaolinite; a difficulty alluded to by Rosenbusch.† In basaltic tuffs, as in the so-called palagonites, the alteration leads to the formation of secondary silica, zeolites, chloritic minerals, carbonates, and limonite. The cement between the ash particles is first attacked and as the alteration proceeds with the particles themselves, the original structure may be more and more obscured until it is finally lost. Yet even when the vitroclastic texture has disappeared, the fragmental appearance

*Ancient Volcanic Rocks of South Mountain, Penna., Bull. 136, U. S. G. S., Pl. XXV, 1896.

† Mikrophysiog. Ergussgesteine, 4th Aufl., p. 870, 1908.

of the rock in the section with the remains of the vesicular character of many of the particles, often made clear by the filling of the vesicles with secondary substances, may greatly aid in determining its original tuff-like nature.

Devitrification.—In course of time, and aided perhaps by heat and pressure, vitric tuffs like other glassy rocks may become devitrified and pass into a crystalline condition. Considering first the tuffs formed from felsic magmas, the more common kinds, this process consists essentially in a change of the glass into feldspars and quartz; it is quite similar to the

FIG. 6.

FIG. 6. Devitrified and partly silicified rhyolite tuff from the Oelberg, Schriesheim, Baden. Actual diameter 2mm.

devitrification of glassy rhyolites which has been mentioned by many writers and fully described by Professor Bascom.* The result between crossed nicols is that the whole rock appears composed of a mosaic of feebly polarizing particles, producing a so-called "pepper and salt" appearance, which becomes so minute in texture in places as to be almost micro-cryptocrystalline. Along with this change there is liable to be some chemical alteration and the introduction of new material; thus secondary silica in the form of chalcedony; shreds of sericite, patches of carbonates, and limonitic material in greater or lesser amounts may be found here and there. Between crossed nicols little or nothing as to the origin of such rocks may be gathered from the section; they resemble glassy lavas which

* Ancient Volcanic Rocks of South Mountain, Penna., U. S. G. S., Bull., 136, 1896.

have experienced similar changes. But without the upper nicol, the condenser lowered, and by using a fairly high powered objective, careful study of the section will often bring out the original vitroclastic texture. By raising and lowering the objective the shapes of the original dust and ash particles become visible by the lightening of their edges from a Becke light band, due to differences in refractive indices. One can then trace out the forms of the shards, threads, cusps, vesicles, etc., that have been previously described. An example of this kind is seen in fig. 6; it should not be thought that the texture shows as clearly in the section as in the illustration; if the writer had depicted it as faintly as much of it actually appears, the drawing could not have been reproduced. The vitroclastic nature of the rock from the Oelberg was first determined by Andreae and Osann* and a somewhat similar instance has been described and figured by G. H. Williams.† In other cases the recognition of the texture in plain light may be aided by slight differences in coloration or outlining of the parts by ferritic material. In tuffs from mafic magmas devitrification is a process of alteration into secondary minerals as described above under alteration.

Metamorphism of Tuffs.

Contact Metamorphism.—The effect of invading magmas upon already solidified igneous rocks is a problem which has not yet received the attention from petrographers which its importance demands, and this is probably most marked in the case of volcanic tuffs. Except in one instance mentioned later it has not been studied by the writer or his students, and reference must be had therefore to the literature of contact metamorphism. The most detailed study appears to be that made by Harker and Marr‡ on ancient rhyolitic and andesitic tuffs in the contact zone of the Shap granite in Westmorland, England. The former are recognized in the field as of explosive nature by the angular fragments of rhyolite and some andesite which they contain, and are thus classed as breccias; in addition crystals of feldspar, quartz, etc., occur. The proportion of fine matrix to fragments varies in different beds. The fine ash and dust away from the contact zone is seen to be considerably altered, having been extensively silicified, and with the feldspar phenocrysts replaced by masses of epidote; this alteration is believed to have occurred before intrusion of the granite. As one passes into the contact zone the first stage is the forma-

* Erläut. zu Blatt. Heidelberg d. geol. Spezial Karte Baden, 1896.

† Silicified Glass Breccia of Vermilion River, Sudbury Dis't., Bull. Geol. Soc. Amer., vol. ii, p. 138, 1891.

‡ The Shap Granite and Associated Rocks, Quart. Jour. Geol. Soc., vol. xlvii, p. 266, 1891.

tion of a brown mica so minutely divided as to act like a pigment and to be individually indeterminable; but as one approaches nearer the granite the particles increase in size until they can be definitely recognized and, eventually, they pass into fewer, relatively large biotite flakes. In addition the rock is spotted minutely, and these spots also increase in size; in the section they are perceived to be areas free from biotite. In the next stage near the granite, although megascopically the rock has retained its structure, by which it may be recognized in the field, the thin section shows it has been completely recrystallized. Brown mica, derived from a green chloritoid mineral, and iron ore, occur in streaks showing the original lamination. The rock is mostly composed of a fine aggregate of clear feldspar with probably some quartz, formed during the metamorphism, with which are associated white mica and granules of cyanite. In some cases the last two minerals are wanting, but always the mosaic of new feldspar, quartz, and brown mica is present. Where the original rocks were greatly silicified the effect is much less marked and brown mica is the only new mineral.

With respect to andesitic tuffs the changes are of a similar nature, and quite like those observed in flows of andesite, with which the tuffs are associated. The tuffs were of the crystal-lithic type with fragments of andesite, some of rhyolite, and crystals of the same character as the andesitic phenocrysts. They had been much altered previous to the metamorphism; the feldspars were turbid and the augite changed to a chloritic mineral, while calcite and secondary quartz were present. As in the rhyolites the first sign of metamorphism is the appearance of brown mica, while green hornblende and actinolite are also found with it. Octahedrons of magnetite occur, and these minerals are seen in a fine granular groundmass of recrystallized feldspar and quartz, the former showing the albite twinning. The original phenocrystic feldspars are replaced by aggregates of new feldspar and quartz with some biotite.

Quite similar effects were found by Barrell* to have been induced in andesites and andesitic tuffs by the intrusion of the Boulder bathylith at Elkhorn, Montana. He says that "sprinkled like a veil over all the rock, both phenocrysts and groundmass, are flakes of biotite and hornblende. These tend to be confined to strings and patches over the plagioclase phenocrysts, and are taken to show a recrystallization during a period of intense metamorphism, accompanied by a dissemination of the elements of the hornblende and biotite into the cracks of the feldspars."

* Geology of the Elkhorn Mining Dis't., 22d Ann. Rep. U. S. Geol. Surv., Pt. II, p. 526, 1902.

Contact metamorphism of trachytic ("orthophyre") tuffs near Harzburg by the Brocken granite has been studied by Erdmannsdörfer,* who states that the altered rock has the hornfels texture and consists mainly of brown biotite, considerable enstatite and anthophyllite, the latter often in fine needles which may aggregate into spherulites, some augite, much orthoclase with a little plagioclase and quartz. The former large embedded crystals of orthoclase have been changed into aggregates of various minerals.

The effect of contact metamorphism upon basaltic tuffs has been studied by few observers.† Probably where the alteration of diabases has been described in the literature, as by the English and Saxon‡ geologists, the metamorphism of tuffs has been included; Rosenbusch suggests this in one case.§ It might be much more difficult to decide in the changed rock whether it had been a basalt (or diabase) or its tuff than with more felsic, siliceous types. In some cases the action leads to the formation of schistose rocks composed of actinolite or anthophyllite in needles, or common green hornblende in granules with a background of plagioclase, augite, biotite, garnet, and other minerals in varying amounts. Harker mentions biotite as the most prominent mineral and states that large feldspars are recrystallized into mosaics or replaced by pseudomorphs of epidote; this is much like the effects mentioned above as occurring in the andesitic tuffs.

General or dynamic metamorphism. — The distinction between the effects produced by the various processes which tend to alter tuffs, such as contact metamorphism, devitrification and silicification, previously described, and general metamorphism, is for the most part a theoretical rather than a practical one. In metamorphic complexes there occur rocks which investigation will show to be of tuffaceous origin and whose characters will be similar in the main to those which have been described above. The especial feature which is to be added in dynamic metamorphism is mashing and shearing which destroy and obliterate the diagnostic characters of tuffs in proportion to the extent to which they have operated. In felsic tuffs the new mineral which is generated by their effect upon the feldspar is sericite and the final result is to reduce such tuffs to fissile sericite schists or phyllites. Since the same

* Devonischen Eruptivgest. und Tuffe bei Harzburg, Jahrb. d. k. preuss. Geol. Landanst., xxv, p. 45, 1904.

† R. Beck, Amphibolitizirung von Diabasgesteinen, etc., Zeitschr. d. D. G. Ges., xliii, p. 259, 1891; Harker and Marr, Metamorphic Rocks around Shap Granite, Quart. Jour. Geol. Soc., xlix, p. 360, 1893.

‡ Conf. Rosenbusch, Mass. Gest., 4th Aufl., p. 120, 1907.

§ Barrois, Excursion aux environs de Morlaix, Bull. Soc. Geol. Fr. (3), xiv, 888, 1886.

thing may happen to the corresponding lavas a decision in the case of end products, as to whether the rock was originally tuff or lava, is generally impossible. Quite an analogous result is reached with mafic, or basic, tuffs which in their turn become converted into greenstone or hornblende schists, just as happens with their corresponding diabases or basalts. Doubts may even arise in some cases as to whether such schistose rocks are really of igneous origin, and a chemical analysis may then be of the greatest service in supplementing the field and microscopic observations.

In general it may be said that while sericite is the most characteristic mineral of completely metamorphosed felsic tuffs, it is usually more or less accompanied by quartz, biotite, chlorite, epidote and clinozoisite; while in the mafic ones actinolite and chlorite, also accompanied by more or less biotite, clinozoisite and epidote are common.

Where the destruction has not been so complete, however, then the characteristics of tuffs should be carefully sought in the sections. It may be remarked in this connection that the chances of their survival are much better in felsic than in mafic ones. Remains of the vitroclastic texture, as indicated in fig. 2, if found, may be conclusive; if not, a secondary line of evidence may be sought in the nature of the included crystals or their fragments if such are present, as discussed previously under crystal tuffs. Evidence of this kind by itself will probably not be decisive as between lavas and the corresponding tuffs, but supplemented by facts to be seen in the field it may become so; for it must not be forgotten that tuffs, like sediments, are often well bedded and a combination of bedding and angular phenocrystic fragments speaks strongly in favor of tuffaceous origin. An excellent example of the determination of this source for the material of a gneiss (hälleflintgneis) has been given by Bäckström.* It is to be understood that only fine tuffs are here referred to; in the case of breccias the evidence afforded by the megascopic structure of the rocks is of the highest value and may be quite decisive by itself, without reference to microscopic or chemical determinations, as shown for example in various parts of the Piedmont plateau by the work of Professors Bascom, Pogue, and Dr. Laney whose papers have been previously referred to in this article.

Sheffield Scientific School of Yale University,
New Haven, Conn., March, 1915.

* Vestanåfältet, K. Svensk. Vetenskaps. Akad. Hand., xxix, No. 4, pp. 52, 122, 1897; Conf. also, O. Nordenskjöld, Archaeische Ergussgesteine aus Småland. Bull. Geol. Inst. of Upsala, No. 2, vol. i, p. 81, 1893.