The amygdale minerals in the Tertiary lavas of Ireland. I. The distribution of chabazite habits and zeolites in the Garron plateau area, County Antrim.

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1. INTRODUCTION.

THE origin of the zeolites and associated minerals in vesicles in lavas is a subject on which there is considerable difference of opinion. In general there are two main views: that they are due to the action of percolating surface waters upon the original minerals of the rock; or are associated with some stage of the cooling processes, as an after-effect of volcanism.

Some years ago the writer made a study of the amygdale minerals in the Tertiary basalt lavas of the south of County Antrim, Ireland. So striking were the differences in the mineral assemblage found during later visits to the east of Antrim that it was felt that important evidence on the origin of the minerals might be obtained if their distribution within the lavas was known. Accordingly construction of a zeolite distribution map of the Antrim basalts was commenced.

As the work progressed the scope widened, and in fact the main purpose of the present paper is to trace the distribution of habit shown by the zeolite chabazite in a selected area of basalts. The distribution of the zeolites associated with the chabazite is also considered. In succeeding papers it is hoped to deal with the distribution of the amygdale minerals in the remainder of the Antrim basalts.

Previous work.—In the early days of mineralogy Antrim was one of the classic zeolite areas, but since the mid-nineteenth century, very little has been added to the knowledge of the Antrim zeolite localities, although during the early part of the present century a considerable amount of collecting was done by the late F. N. Ashcroft and R. Bell, and three valuable papers appeared in this Magazine[1] as a result. More recently

[1] F. N. A. Fleischmann, On the occurrence of gyrolite in County Antrim. Min. Mag., 1910, vol. 15, pp. 288–293.

G. F. H. Smith, F. N. Ashcroft, and G. T. Prior, Chabazite and associated minerals from County Antrim. Ibid., 1916, vol. 17, pp. 274–304.

F. N. Ashcroft, The natrolite occurrence near Kinbane (White Head), County Antrim. Ibid., 1916, vol. 17, pp. 305–308.

M. H. Hey[1] used some Antrim material in his studies on the zeolites. As far as our knowledge of the zeolite distribution in Antrim goes, however, the fact remains that little advance has been made since J. E. Portlock published his Report on the geology of Londonderry in 1843. Apart from a very brief mention in the Geological Survey Memoir on the area nothing whatever appears to have been written on the zeolites of the Garron plateau, with which the present work is concerned.

2. Geological environment.

Tertiary plateau-lavas, dominantly basaltic, cover an area of some 1500 square miles in the north-east of Ireland (fig. 1), resting for the most part upon sedimentary rocks of Mesozoic age. Although actually neither confined to the County of Antrim nor composed entirely of basalt the lava series is conveniently designated the Antrim basalts. The greatest known thickness of the lava pile is about two thousand feet, but the lavas have been deeply eroded and over most of the area the thickness preserved for study is much less than this. The constituent lava flows attain a maximum thickness of upwards of one hundred feet, but the average is of the order of about twenty feet. Evidence of eruption under subaerial conditions is afforded by the red lateritic weathering of the tops of many of the flows, by the absence of pillow-lavas, and by the existence in the lava succession of occasional beds bearing plant remains.

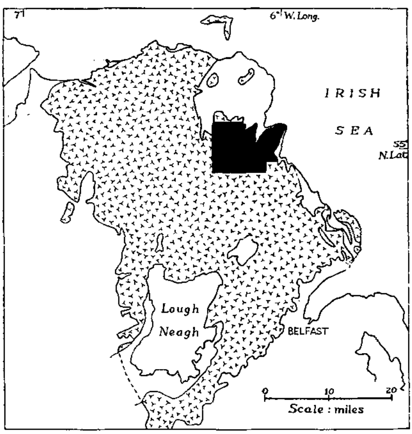

Fig. 1. Tertiary lavas of north-east Ireland (stippled); position of Garron plateau area (black).

In general, each lava flow possesses an amygdaloidal top and a thin amygdaloidal base, the latter commonly with pipe amygdales. Amygdales are often also present in the more massive interior of the flows. The cavities vary considerably in size, but are commonly an inch or more in diameter. It is the writer's experience that empty cavities are

[1] M. H. Hey, Studies on the zeolites. Min. Mag. 1932, vol. 23, pp. 51, 243; 1933, vol. 23, pp. 305, 421; 1934, vol. 23, pp. 483, 556; 1935, vol. 24, p. 99; 1936, vol. 24, p. 227.

exceptional; they almost always contain minerals of the zeolite group or their associates, particularly calcite.

Geology of the Garron plateau area.—The present work deals with the amygdale minerals in seventy square miles of lavas in the east of County Antrim, comprising the Garron plateau proper and adjoining regions to the west. This district was selected for detailed study for geological and geographical reasons.

The lavas within this area approach horizontality, although there is a slight prevailing dip towards the south. There are few faults. The geological structure is admirably reflected in the topography, in the flat plateau of Garron with average elevation of 1000 feet and bounded on the north-west, north, and east by steep, often precipitous escarpments, and in the long, flat-topped, wedge-shaped ridge of Lurigethan. Towards the north-west the land is rather higher, a consequence of the regional dip, rising to 1800 feet at Trostan.

Exposures are good in the escarpments, up to 1000 feet in thickness of lavas being available for study, but on the flat plateaux the rocks are concealed to a large extent by bog, and exposures of amygdaloidal basalt are largely confined to the water-courses.

Practically all the lavas in the area under consideration are olivine-basalts of rather uniform character, associated with subordinate picrite-basalts and olivine-poor basalts and mugearites. The lava succession has long been separated into two stratigraphical divisions, referred to as the Lower and Upper Basalts respectively, and separated by a thick zone of weathering, the lateritic iron ores and bauxites which were mined extensively in the past. Most workers are agreed that this interbasaltic zone of weathering represents a very considerable time-interval and lull in the eruption of basalts; the figure of one million years has recently been quoted by V. A. Eyles.[1]

Throughout the Garron area the Lower Basalts retain a uniform thickness of 450–500 feet. Individual flows may cover a wide extent; for example, a distinctive flow of basalt with large felspar phenocrysts rather more than midway up in the Lower Basalts may be traced laterally over a distance of at least eight miles. This wide lateral spread of individual flows and resulting comparative uniformity in the lava succession over a wide area deserves emphasis, as also does the uniformity in the composition of the lavas themselves.

[1] V. A. Eyles, Abstr. Proc. Geol. Soc. London, 1950, no. 1465, pp. 132–133.

3. Zeolites in the Garron plateau area.

The following are the zeolites found in the lavas of the Garron plateau area, arranged in order of relative abundance:

Chabazite.—Chabazite is ubiquitous. It occurs as distinct crystals ranging up to half an inch or so in size, and unlike the other zeolites never forms radiating aggregates. In optical character it is sometimes uniaxial, but more commonly biaxial with small 2V. The sign is negative when the mean refringence exceeds about 1·488, and is positive when lower. The birefringence is small, usually of the order of 0·003 or less. The mean refringence ranges from 1·483 to 1·495, and it is unrelated to the habit of the crystals. Some crystals are zoned, but the zoning has not been studied in detail.

Thomsonite.—Thomsonite is usually closely associated with chabazite, but is rather less common. It characteristically forms compact aggregates of small acicular or bladed crystals, often hemispherical in form and with radiating structure, and commonly as a cavity-lining to the larger cavities. β varies from 1·515 to 1·530. The more or less hemispherical aggregates often show concentric zoning, with lower refringence near the cavity-wall.

The variety 'sphaerostilbite' is less common, forming a distinct second generation, as described from Golden, Colorado, by H. B. Patton.[1] but not differing appreciably in optical properties from the more normal thomsonite with which it is associated, despite the different age and appearance. It typically occurs as non-compact aggregates of very delicate crystals.

Levyne.—Levyne is very widespread, nearly always as thin tabular crystals with (0001) prominent, and invariably penetrant-twinned. Sheaf-like aggregates are found occasionally. In optical character it is uniaxial negative, with ω normally in the range 1·499 to 1·505. The birefringence is about 0·005.

A very interesting and characteristic feature, shown by at least half of all the crystals in the area is the alteration to a fibrous mineral with satiny lustre, the fibres lying normal to (0001) of the levyne. This mineral is believed to be uniaxial with negative sign and refractive indices ϵ 1·491–2, ω 1·495. W. Cross and W. F. Hillebrand[2] recorded a fibrous mineral from Golden, Colorado, closely associated with levyne; how closely is not stated, and there is no mention of it occurring as an

[1] H. B. Patton, Bull. Geol. Soc. Amer., 1900, vol. 11, pp. 461–474.

[2] W. Cross and W. F. Hillebrand, Bull. U.S. Geol. Surv., 1885, no. 20, vol. 3, pp. 231–257.

overgrowth. Their analysis of the fibrous mineral proved to be almost identical with that of levyne from the same locality. They concluded, 'it cannot be referred to any definite species from present data'.

Analcime.—Analcime is quite abundant in the area, mostly as single crystals which may exceed an inch in diameter, but occasionally in the form of radiating aggregates. The crystals are always of simple habit, (211) being the only form observed. The mineral is never isotropic, and possesses a birefringence of up to about 0·003. The mean refringence is near 1·487.

Natrolite, mesolite, and scolecite.—These three minerals very commonly occur together as tufts of delicate hair-like crystals. They have crystallized in the order listed, mesolite continuing the growth of natrolite at the extremity of the crystals, and scolecite forming a thin overgrowth on the mesolite. Mesolite is almost isotropic, with mean refringence of about 1·504. Scolecite has an appreciable birefringence, with α 1·507, β 1·519, and an extinction of about 16°. In addition to the delicate tufts natrolite is not uncommonly found in the form of compact aggregates of stouter crystals. In the Garron area natrolite is inconspicuous in amount when compared with analcime; on the other hand, in certain other parts of Antrim the converse is true.

Other minerals.—Phillipsite is found at a considerable number of localities, but is seldom abundant or conspicuous. It forms both single crystals and radiating aggregates. Stilbite and heulandite have also been met with in the course of the work, but neither is common. In one or two places the latter has been found as a granular layer on chabazite and calcite. Of the non-zeolites, calcite is very common throughout the area. Aragonite is rare, and quartz has not been observed. Apophyllite has been found at one locality.

Order of crystallization.—Levyne is believed to be the earliest zeolite. Certainly whenever it is associated with chabazite or thomsonite in the same cavity it precedes them, but its relationship to phillipsite, which definitely precedes chabazite, is uncertain. Chabazite and thomsonite are very closely associated, sometimes the one being the earlier, sometimes the other, and in all probability their periods of crystallization overlapped. The habit of thomsonite which has been called 'sphaerostilbite' constitutes a distinct generation appreciably later than chabazite. Stilbite and heulandite, when they occur, are later than chabazite.

An important feature, which will be referred to again when the origin of the minerals is considered, is that analcime crystallized later than the levyne-thomsonite-chabazite assemblage. At a few localities analcime is followed by a sugar-grained aggregate of chabazite of low (i.e., simple) habit, representing a distinct generation of chabazite in the same way that the variety 'sphaerostilbite' represents a distinct generation of thomsonite. The latest zeolites in the sequence appear to be natrolite, mesolite, and scolecite. Of the non-zeolites, calcite may either precede or follow the zeolites. Apophyllite, in the single locality at which it has been found, is later than thomsonite and analcime.

4. Chabazite crystal habits.

Chabazite is a trigonal mineral with the axial ratio $a : c = 1 : 1{\cdot}086$. Twinning may take place on two laws, namely contact twinning on $(10\bar{1}1)$ and interpenetration twinning on (0001). The crystals show a considerable range of habit, from the simple, untwinned unit rhombohedron to the complex-twinned varieties, phacolite and herschelite. Different habits may be recognized, based on the relative development of some half-dozen different forms and the incidence and nature of the twinning. These cannot be regarded as completely unrelated habit elements as, to take an example, when $s(02\bar{2}1)$ is present it is usually accompanied by $e(01\bar{1}2)$, vicinal faces on $r(10\bar{1}1)$, and interpenetration twinning on (0001). It is this interrelation of elements that has enabled a habit series to be recognized; as a result of the examination of many thousands of crystals it appears certain that there is a continuous gradation between two extremes, and that all, or practically all, chabazite crystals may be arranged in this simple habit series.

The simplest crystals show the unit rhombohedron, $r(10\bar{1}1)$, alone, commonly with the faces curved and stepped, and twinning on r is very common. Tracing the habit series in the direction of increasing complexity, interpenetration twinning on (0001) first appears, the twin individuals being of unequal size at first, and the curvature and stepping of the faces and the twinning on r are no longer found. The next change is the partial replacement of r by vicinal faces, which appear as striations parallel to the terminal edges of the unit rhombohedron, and faces of other forms then appear, $s(02\bar{2}1)$, $e(01\bar{1}2)$, and sometimes $a(11\bar{2}0)$. Usually s precedes e. The relative size of the twin individuals also becomes more uniform. Continuing, the relative sizes of s and e, both normally present at this stage, gradually increase and a, if present, becomes very prominent, r at the same time decreasing in size and importance. The vicinal faces in the zone re become better developed, and $t(11\bar{2}3)$ usually appears at this stage and may become prominent.

Soon after the appearance of t the well-defined shape of the crystals becomes lost and the faces of *r*, *e*, and *t* become broken up into innumerable minute facets in oscillatory combination; *a* (when present) and to a lesser extent *s* resist this tendency to break up and persist as discrete faces. The crystals assume the overall shape of a flat hexagonal pyramid, the 'pyramid' faces being composed either of *t* or of *r* and *e* in oscillatory combination. Crystals of this habit have long been termed 'phacolite' in reference to their lenticular shape, and although the term has been used at times in a wider sense it seems desirable to limit the term, as here, to the complex-twinned habit with *r* and *e* represented by minute facets in oscillatory combination rather than as discrete faces or, alternatively, to crystals in which *t* is the predominant form.

The final habit of the series would appear to be that which is marked by the appearance of *c*(0001) on crystals of phacolite habit; and the rare variety 'herschelite', with *c* and *s* as practically the only forms present, is probably the most extreme habit. In the Antrim basalts chabazite is the most common and characteristic zeolite, and crystals of all the above habits, with the exception of typical herschelite, are abundantly represented.

Chabazite habit notation.—For the purpose of recording chabazite habit data a simple descriptive notation has been developed in which the crystals are classified into six habits, defined as follows:

Habit 1.—*r* alone. No interpenetration twinning. Commonly present: simple twinning on *r* and stepping and curvature of the faces.

Habit 2.—*r* alone, without vicinal faces. Interpenetrant-twinned.

Habit 3.—*r* dominant but normally striated by vicinal faces, and other forms present (*s*, *e*, and sometimes *a*). Interpenetrant-twinned.

Habit 4.—*r* subordinate, and other forms (*e*, *s*, *a*, *t*, and vicinal faces in the zone *re*) dominant. Interpenetrant-twinned. Forms represented by discrete faces.

Habit 5 (phacolite habit).—Crystals with overall lenticular shape, complex interpenetration twinning with *r*, *e*, and *t* as minute facets in oscillatory combination, or alternatively crystals with *t* prominent. *a* may or may not be present; *s* always present.

Habit 6 (herschelite habit).—Characterized by the presence of *c*(0001). Not represented in the Garron area.

The above habits are illustrated by the drawings of fig. 2. Some drawings are idealized; particularly is this true of habit 4 in which marked irregularities of growth are usually present. It has been decided to refer to the more complex crystals as possessing 'higher' habits, and the more simple crystals as 'lower' habits.

Chabazite habit study in the field.—It has been found that, in general,

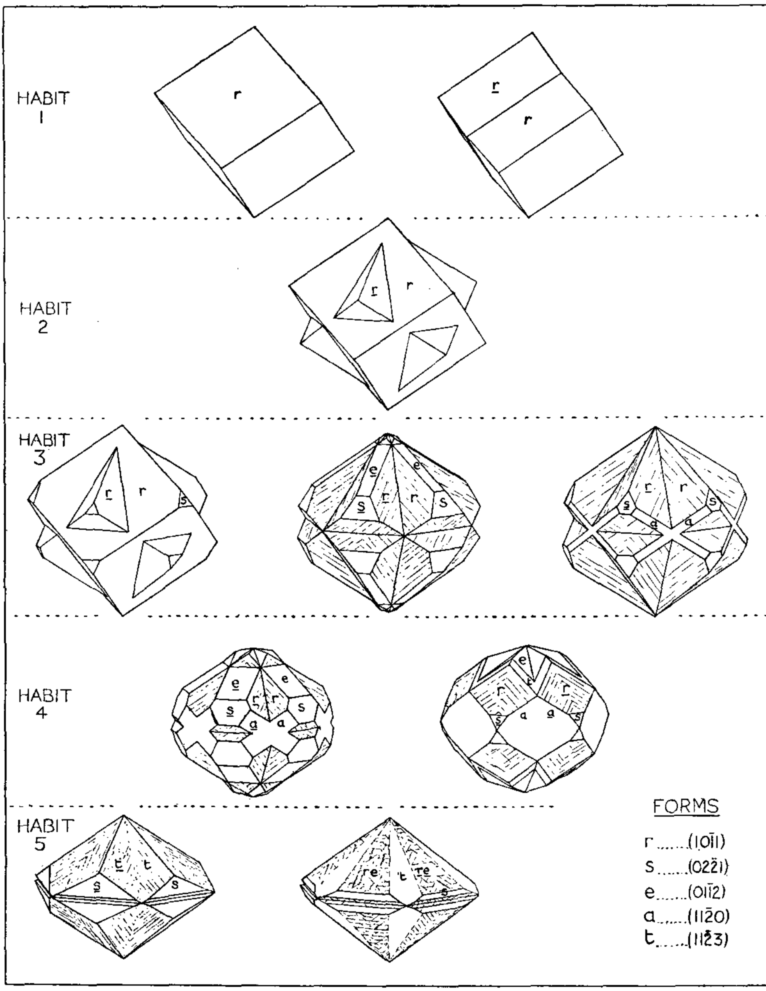

FIG. 2. Chabazite habits, illustrating the proposed habit notation.

the chabazite crystals in any one cavity all possess approximately the same habit, and further that, at a given locality, all the crystals will possess very nearly the same habit. The extent of such variation as does occur is illustrated by the diagrams of fig. 3, which embody the results of a study of the habit variation at four localities in County Antrim.

To illustrate the procedure, a quarry on the Collin Mountain in the south of Antrim may be considered (*a*, fig. 3). A large number of chabazite-bearing cavities were collected from the red amygdaloidal top of a flow and from the basal part and interior of the overlying flow. It was found that in no cavity did habit 1 occur alone; in 85 % 1 and 2 were present together, 1 being predominant in half of them, 2 in the other half; and in only 15 % of the cavities did habit 2 appear alone. In no case was any form other than $r(10\bar{1}1)$ seen. When habits 4 and 5 appear they are usually associated with a rather greater range of habit (*c*, fig. 3).

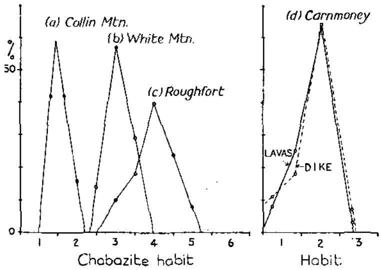

FIG. 3. Variation of chabazite habit at four localities in County Antrim.

Having established that crystals at a given locality show a limited variation in habit, the possibility arises of mapping the lateral and vertical distribution of habit in the lavas. Assuming the crystals are amenable for habit study such a three-dimensional picture of the habit distribution can be drawn only if the mineral is sufficiently widespread and if there are abundant exposures both laterally and vertically through an appreciable thickness of lavas. Further, the exact position of any locality in the lava series must be determinable, involving an accurate knowledge of the stratigraphy and structure of the lavas. In Antrim such geological conditions are perhaps realized only in the Garron plateau area, where chabazite is fortunately very abundant.

5. Chabazite habit distribution in the Garron plateau area.

It has been possible to recognize five chabazite habit assemblages for purposes of mapping, and these have been utilized on the map of the Garron plateau area (fig. 4). The 227 localities on which the habit zones on the map are based have been plotted to illustrate the degree of control achieved. The habit distribution is found to be extremely regular.

Habit 5, usually associated with lower habits (that is, habits 4, 3, and sometimes 2), occurs only towards the base of the lavas and has been found at six places: in the Bush valley, in Glen Ballyemon, in small patches near the Altmore Burn and Evish, and in larger expanses in the

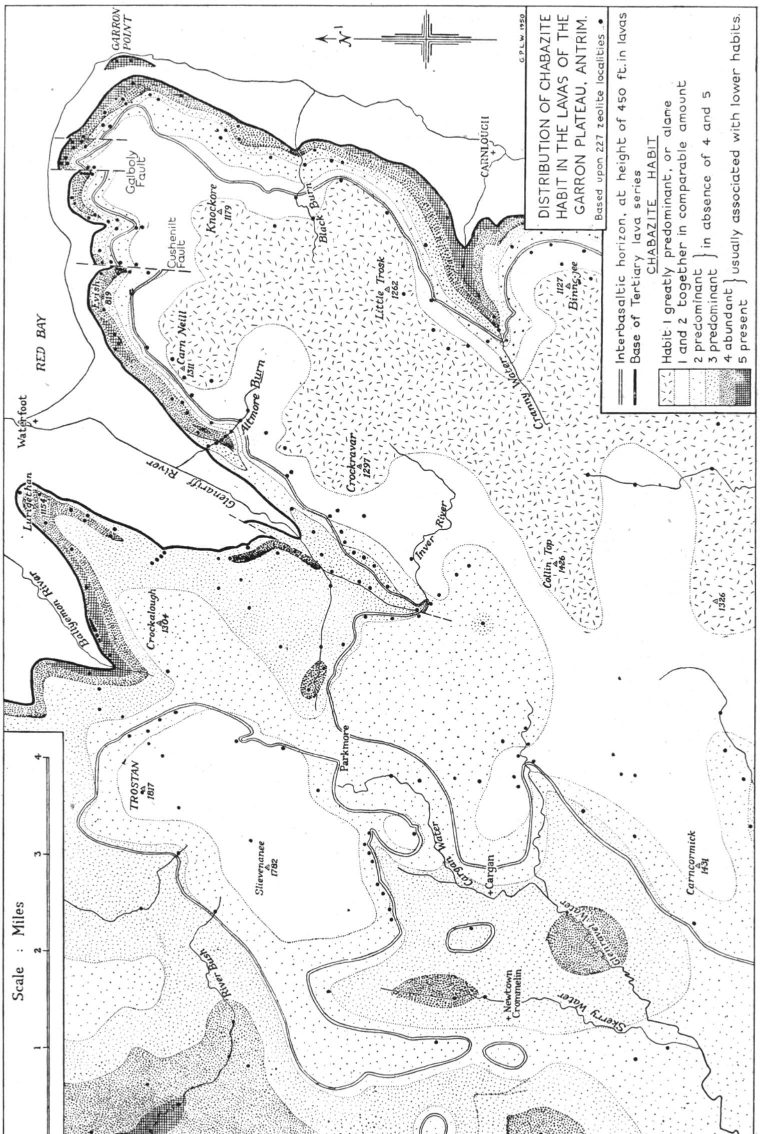

FIG. 4. Distribution of chabazite habits in the lavas of the Garron plateau, County Antrim.

vicinity of Garron Point and near Carnlough. At several of these places, notably near Altmore Burn, habit 5 is found in the middle of the Lower Basalts rather than at the base, an observation that assumes significance when the origin of the minerals is considered.

Habit 4, also usually associated with lower habits, is distributed in a zone enclosing the previous one, and naturally has rather wider extent; in fact in only a few places is habit 4 missing from the lower part of the lava series. The zone characterized by the presence of habit 4 is almost entirely confined to the lower 350 feet of the Lower Basalts, but probably reaches the interbasaltic horizon near Garron Point, and almost reaches it in the Cranny Water.

The third chabazite habit assemblage is characterized by the predominance of habit 3, usually associated with habit 2 in smaller amount, but without more than a very small amount of habit 4. Habit 3 falls into a continuous zone, probably nowhere exceeding a height of 550 feet in the lavas, but crossing the interbasaltic horizon north-west of Trostan, at Tuftarney Hill, near the Inver River, and in small areas near Garron Point and Cranny Water.

The next habit assemblage is characterized by the predominance of habit 2, often in the presence of minor amounts of habits 1 or 3. This habit again falls into a continuous zone and is usually located near the interbasaltic horizon, although locally entirely above or below it. The zone varies from fifty to several hundred feet in thickness.

The two remaining habit assemblages both contain an abundance of habit 1, either in association with habit 2, the two being in comparable amounts, or alone. Habit 1 occurs alone, or in association with a minor amount of 2 in a thick zone, the top of which is not exposed, forming the top of the Garron plateau proper. The isohabit surface forming the base of this zone has a marked regional easterly dip with respect to the lavas, being absent from the top of Trostan (900 feet up in the lavas) and the hills south of Cargan, coming in at a height of some 800 feet at Carn Neill, and reaching to a height of only 400 feet in the lavas, that is, below the interbasaltic horizon, north of Carnlough. The assemblage characterized by the association of habits 1 and 2 in comparable amount forms a continuous zone of variable and often considerable thickness between those of habits 3 and 1 alone respectively, and forms the tops of the principal hills in the west of the Garron area.

The chabazite habit data which have been collected are treated statistically in the diagrams of fig. 6, where the distribution of habits at nine different levels in the lavas has been plotted. It can be seen that habits 4 and 5 are practically confined to the lower 450 feet of lavas, and that habit 3 occurs mostly in this range, whereas habit 1 is mostly confined to the lavas above 450 feet in the succession. Habit 2 is slightly more abundant in the higher levels, but does not exhibit any very marked preferential distribution, a consequence of its presence in variable and often small amount in all, or nearly all of the habit assemblages recognized for mapping purposes.

Summing up, the habit shown by the chabazite varies but little at individual localities, and the habit assemblages which are found in the lavas fall into a number of well-defined zones. These zones have a rough stratigraphical distribution, but they are clearly superimposed upon the lava pile just as zones of regional or contact metamorphism characterized by certain mineral assemblages, or zones in a mineralized area such as Cornwall or Derbyshire and characterized by a certain gangue or ore mineral, are superimposed upon the country-rock.

Significance of habit distribution.—The genetic significance of this habit distribution is clear: the chabazite is entirely later than the 1000-feet or so of lavas in the Garron area. Further valuable evidence of genetic significance is derived from a study of the several faults which cut the lavas of the Garron plateau. Of these the Cushenilt and Galboly faults are magnificently exposed in the cliffs west of Garron Point, and each has a throw of rather more than 200 feet, which is readily demonstrated in the field. After careful study of the chabazite habits on either side of these faults and also of the smaller fault in the Inver Burn it has been established that the chabazite habit zones are faulted to the same extent as the lavas themselves. There is evidence, in the occurrence of chabazite (of lower habit than in the adjacent lavas) in the fault fractures, that the formation of chabazite did not entirely antedate the faulting, but the fact remains that the bulk of the chabazite must have preceded the faulting.

The relationship between chabazite habit zones and faults is best seen in the section, fig. 5 (upper part). This has been constructed from the data from 88 zeolite localities distributed along the northern escarpment of the Garron plateau proper, from the Inver River near its intersection with the interbasaltic horizon through Evish to Garron Point. Although clearly not on a vertical plane the error resulting from the localities lying on a sloping surface is probably negligible.

The conclusions reached after a study of the distribution of chabazite habits is that the bulk of the chabazite crystallized after the exposed lava pile had been erupted but before it was faulted. The possibility that the chabazite crystallized during the cooling of individual flows immediately after their eruption may be excluded at once as incapable of accounting for the observed habit distribution, and that the chabazite originated as a result of weathering by present-day percolating waters of meteoric origin may equally definitely be excluded, particularly in view of the faulting of the habit zones.

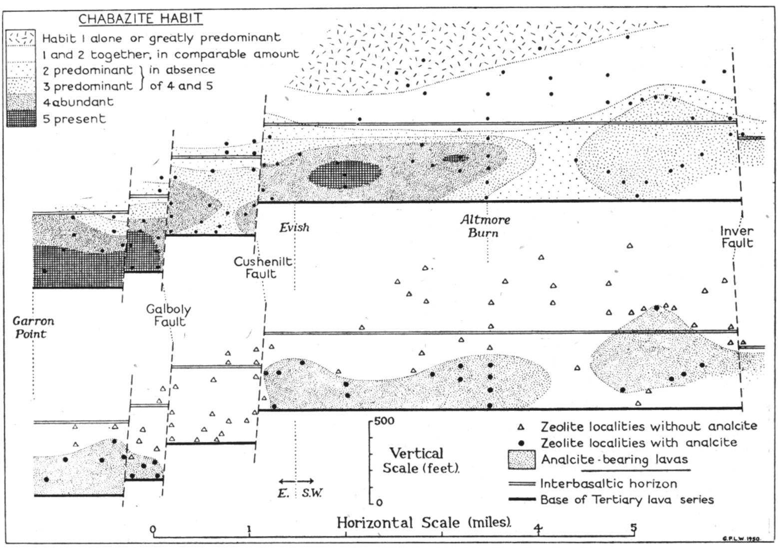

FIG. 5. Sections along the north escarpment of the Garron plateau showing distribution of chabazite habits (upper section) and analcime (lower section). Based on 88 zeolite localities.

Considering the reason for the observed habit distribution, variation of habit in crystalline substances can be related to the operation of a variety of factors, of which the temperature, rate of crystallization, and the presence and nature of impurities are perhaps the most important. The writer considers that the temperature of formation is most likely to have been the controlling factor in the development of the different habits in the case of the Garron chabazite, on account of the extreme regularity of the habit distribution.

It is tempting to regard chabazite of habit 5 as having been formed at the highest temperature, with the lower habits crystallizing at progressively lower temperatures. Supporting evidence is provided by the fact that, whenever two generations of chabazite can be distinguished, the later is always of lower habit than the earlier. The use of this as evidence of temperature control involves, of course, the not unreasonable assumption that the later chabazite formed at a lower temperature than the earlier. Temperature control of the habit is capable of accounting for the common association of habit 5 with lower habits.

6. Zeolite distribution in the Garron plateau area.

Chabazite is almost ubiquitous in the Garron plateau area and is evenly distributed throughout the lava series. Certain of the other

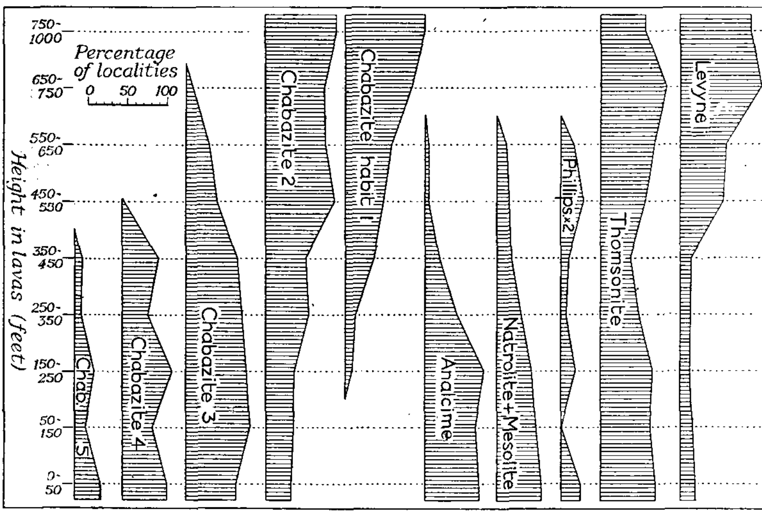

Fig. 6. Distribution of chabazite habits and zeolites at different levels in the lavas of the Garron plateau area. Graphs based on data from 243 zeolite localities.

zeolites, however, have restricted distribution in the lavas. To study the distribution of these minerals the records of the zeolites present at each of the 250 zeolite localities in the area have been analysed, and the percentage of localities in each of the nine arbitrary levels in the lava series at which the particular zeolite has been recorded is plotted on the diagram, fig. 6. It can be seen that analcime, natrolite, and mesolite (with scolecite) are mainly confined to the lower few hundred feet of lavas; levyne, on the other hand, is mainly confined to the upper levels. Thomsonite and phillipsite have also been plotted, but show little sign of any preferential distribution.

The distribution of analcime is particularly regular and interesting. The mineral has been recorded at 75 of the 120 localities in the lower

350 feet of lavas, and in only seven of the 120 or so localities above 350 feet. In the lower part of the basalts analcime is sufficiently abundant to enable a distribution map to be drawn (fig. 7). The areas in which analcime occurs have been stippled, and as in the chabazite habit distribution map, the position of the localities upon which the distribution of the stippling has been based are given to illustrate the degree of control achieved, which varies in different parts of the map. The lower

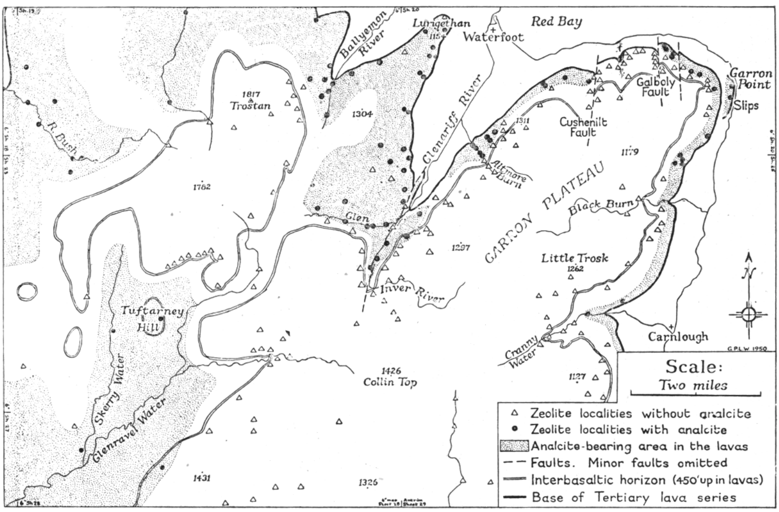

FIG. 7. Distribution of analcime in the lavas of the Garron plateau. Based on 228 zeolite localities.

section of fig. 5 can be used in conjunction with the map. The main points to notice are the confinement of analcime to an almost continuous zone in the lower part of the lava succession, and the fact that this zone is not a stratigraphical horizon such as might be expected were analcime confined to a certain type of lava. The analcime zone is clearly superimposed upon the lava pile, rising above the interbasaltic horizon at three places (south of Glenravel Water, at Tuftarney Hill, and north of the Inver Burn), being probably absent from the lavas at one point near the Altmore Burn, very thin in the vicinity of Carnlough, and definitely absent between the Cushenilt and Galboly faults.

The disappearance of the analcime zone between the faults is particularly significant, and can hardly be due to chance. It will be remembered that, although the bulk of the chabazite antedated the faulting, some chabazite has been deposited in fissures associated with the faults. As analcime is known to have succeeded chabazite it would be expected to have post-dated the faulting, and certainly the analcime zone shows no indication of having been faulted. However, analcime is not found in the fault fractures or in the immediate vicinity of the faults. It seems as though the conditions which obtained in the lavas near to the faults were inimical to the formation of analcime, and the suggested explanation is that the fault fractures provided a path for the escape of hot waters from the lower parts of the lavas, thus lowering their temperature in the vicinity of the faults to below that at which analcime was able to form.

It is not certain what were the factors controlling the distribution of levyne, which varies in amount inversely with the analcime, natrolite, mesolite, and scolecite. It seems very likely that the small content of levyne in the lower part of the lavas is due to its destruction or concealment by the later minerals, and in particular by analcime.

7. Origin of the zeolites.

Most workers are agreed that the zeolites in amygdaloidal rocks have derived their material from these rocks, from the felspars, or glass when present. Glass is absent from the lavas of the Garron plateau area, and the felspar is indicated as the most likely source of the materials which compose the zeolites. The chloritic minerals which are seen in thin sections of the lavas represent the hydration products of the other pyrogenetic minerals of the basalt. There is sometimes evidence of the enlargement of zeolite-bearing amygdales by corrosion of the adjacent basalt, but it is likely that the bulk of the zeolites in the cavities crystallized from material migrating from the surrounding rock.

It is generally agreed that the zeolites in lavas were formed at temperatures normally above 100° C. It would seem, then, that a source of hot water is required to account for the production of the zeolites in the Garron lavas. The most obvious source of heat is that supplied by the lavas themselves. However, the evidence of the distribution of chabazite habits and analcime shows that the zeolites, or at any rate the bulk of them, were formed not within individual flows as they cooled immediately after eruption but after a considerable thickness (at least 1000 feet) of lavas had accumulated.

On the eruption of a lava flow cooling takes place both upwards into the atmosphere and downwards into the subjacent rocks. There is therefore the possibility of the progressive accumulation of heat in the lava pile by a succession of small increments from each flow erupted.

However, the deep lateritic weathering of the tops of many of the flows shows that a considerable time interval often elapsed between the eruption of successive flows, and the interbasaltic horizon in particular represents a lull in the eruption of flows of considerable duration. In the circumstances it is probable that no appreciable accumulation of heat in the lavas could be expected by this means.

An alternative is to invoke the agency of heated waters rising from depth. This would be more plausible were there abundant faults in the Garron area to provide a passage for these waters; as it is, there is very little fracturing. The lavas of the Garron area are cut by a number of dikes with north-west trend, part of the great British Tertiary dike swarm, and the field evidence suggests that most of these dikes are later than most of the exposed lavas. It is possible that the dikes added a considerable amount of heat to the lava pile when intruded into it, and they may have caused an appreciable rise in the geoisotherms, already higher than in non-volcanic regions. However, the density of the swarm is not very great in the Garron area, there being probably no more than two or three dikes to the mile across the strike, and it seems unlikely that the heat from the dikes could have been adequate to give rise to such a widespread development of zeolites. It is perhaps possible that dolerite sills intruded into the Mesozoic or earlier sedimentary rocks below the lavas may have contributed, but no sills are present in the several feet of sedimentary rocks exposed in the district.

A further possibility is that the source of heat lies in the reactions producing the zeolites. The hydration of the felspars to zeolites is probably an exothermic reaction; so is the hydration of the olivines and pyroxenes. It is suggested that the heating up of the lava pile by dikes and other intrusions, by regional uprise of deep-seated waters, or by conduction of heat downwards from later erupted lavas initiated the reactions in the pyrogenetic minerals of the basalts and that, once started, sufficient heat was generated by these reactions to maintain them and to heat up the lavas further, the reactions perhaps coming to an end only when all the available water was used up.

This conception of self-generation of heat in the lava pile appears capable of accounting for certain features in the distribution of chabazite habits and zeolites that would be difficult to explain otherwise. If heat were generated throughout the lava pile there would be loss of heat upwards both by conduction and by migration of heated waters. As it is unlikely that a state of thermal equilibrium would be attained, which would involve the raising of the temperature in all the underlying rocks to more than that in the lavas, there would probably always be a certain amount of conduction of heat downwards from the lavas as well as upwards. Under such conditions the maximum temperature in the lava pile would be attained in the lower part but not quite at the base, and there would be a slight decrease in temperature from there to the base of the lavas. Upwards from the maximum there would be at first a slow falling-off in temperature becoming more rapid upwards. There is evidence from the distribution of chabazite habits and analcime that, assuming temperature to be the controlling factor, the maximum temperature was reached somewhere between the base of the lavas and a height of about 300 feet.

8. Implications of the work.

Mineralogists have always recognized that crystals of the same mineral often exhibit a considerable range of habit, yet the rapid progress in mineralogy of the last century has not advanced appreciably the knowledge of the significance of these various habits. In the present work an attempt is made to approach the question by studying the spatial distribution of habit shown by a mineral in a selected area of lavas, and the resulting chabazite habit map (fig. 5) is perhaps the first of its kind yet produced. The distribution is surprisingly regular, so much so as to suggest that the isohabits bounding the habit zones were parallel to geoisotherms and that the habit was controlled primarily by the temperature of formation of the mineral.

In addition to the crystallographic significance of the study of habit distribution the work has an important bearing on the age of the zeolitization, and enables a relative chronological sequence of events to be recognized. In the Garron area 1000 feet of lavas are exposed, comprising perhaps forty to fifty distinct flows, the accumulation of which must have taken at least several millions of years. The chabazite zones are superimposed upon the lavas, and the chabazite is thus indicated as having crystallized after the eruption of this lava pile. Towards the end of the period of chabazite formation the lavas were faulted, and at some subsequent period analcime and the fibrous zeolites natrolite, mesolite, and scolecite were formed. Finally, erosion carved out the present-day topography, the valleys being excavated not only through the lavas but also through the zeolite zones.

Unfortunately the time scale arrived at is purely relative, and it is not certain at what part of the Tertiary period the zeolitization and faulting took place. However, it seems to be significant that the newer Tertiary basalts of the Columbia plateau and the Hawaiian Islands contain zeolites only exceptionally. It may be that the process of zeolitization is a very slow one, and that these lavas are not of sufficient antiquity to have allowed the process to have taken place on a large scale. If, as is suggested here, the hydration of the pyrogenetic minerals of the basalts to zeolites and chlorites is capable of generating sufficient heat to maintain the reactions once initiated, and to account thus for the zeolitization, it is probable that the rise in temperature of the lavas to a sufficiently high level would require the presence of a considerable cover of lavas or other rocks, and that a very long period of time would be required before the reactions could get under way. The hot springs in certain volcanic areas, excluding those associated with volcanoes of central type, may represent the surface manifestation of present-day zeolitization below the surface.

In the Garron area the faulting took place more or less in the middle of the period of zeolitization. This has been demonstrated only in the case of several faults and the work requires to be extended to a wider area before any far-reaching conclusions can be drawn, but it may be that the Garron faults were formed at the time of the break-up of the great North Atlantic lava plateaux. One possible application of the work is the dating of faults and the grouping of faults into time groups, and, taking into account the relationship between the inclination of lava flows which have been tilted subsequent to their eruption and the zeolitization, it may be possible to gain an insight into the post-volcanic history of the lava plateaux. Another application of the methods described in this paper is the location, under favourable circumstances, of faults the exact position of which is uncertain. A third possibility is that continued study of chabazite habit distribution, coupled with experimental work, might provide a means of enabling estimates to be made of the original thickness of the lava pile in selected areas.

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