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On zoned associations of antigorite, talc, actinolite, chlorite, and biotite in Unst, Shetland Islands.

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INTRODUCTION.—During my mapping for the Geological Survey in 1930 of the metamorphic rocks of western Unst, numerous small masses were encountered that were composed of a central part of talc followed outwards in order by zones of actinolite, chlorite, and biotite.[1] Whilst revisiting the island in 1933 I was able to examine these associations in detail and to collect abundant material for study. As in many cases the zones are made up of a single mineral and may be a foot or so in thickness, specimens of great beauty are obtainable. It must have been from occurrences similar to these in Unst that M. F. Heddle obtained his fine examples of the various minerals from the Hillswick area of the mainland of Shetland.

It is the purpose of this communication to describe these remarkable rocks and to discuss their genesis. It will be found that they are more complete developments of an association already known from certain contacts of serpentine and acid rocks, such as those of the Lizard in Cornwall and Shabani in Rhodesia. Further, they have a very close resemblance to the soapstone bodies of the Appalachian belt of the eastern United States. The study of the Unst occurrences throws light not only upon the origin of this particular assemblage

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[1] Summ. Progr. Geol. Surv. Gt. Brit., 1931, for 1930, part I, p. 67.

but also upon the general question of movement of material in metamorphism. In what follows, the masses showing this zoned arrangement are referred to as the zoned bodies.

The Country-rocks.

The zoned bodies occur in the tectonic unit that makes the western ridge of the island. This unit may be called the Valla Field block after its most conspicuous topographic feature, the high ridge of Valla Field. It is made up of a series of gneisses, mostly of sedimentary origin, with subordinate granitic and pegmatitic intrusions and permeations.

The gneisses comprise pelitic, semipelitic, and calcareous rocks that have had a long metamorphic history. There is evidence that the rocks of the whole block had been subjected to a metamorphism characterized by the production of garnet, staurolite, kyanite, and biotite in the pelitic members. After this episode, the southern portion of the block was affected by a superposed metamorphism in which these index minerals were no longer stable. They were broken down, and chlorite and chloritoid appeared in their place. Finally, the margins of the block, and certain restricted belts in the interior, were the seats of a further metamorphism associated with the dislocations limiting the block. This dislocation-metamorphism was characterized by the production of chlorite from the chloritoid of the second episode. The zoned bodies occur in areas of the gneisses that have been affected by the first metamorphism and in most cases by one or both of the succeeding. With the first metamorphic episode is associated an injection of acid igneous material, either in discrete sills and veins of granite and pegmatite or in more intimate forms that produce injection-rocks of various types.

It will be sufficient for the study of the zoned bodies to give an indication of the dominant types of gneisses found associated with them. Most of the bodies now occur amongst pelitic gneisses with conspicuous felspar blebs. These rocks recall certain similar types found in Scottish injection-complexes. They are traversed by innumerable sheets and irregular masses of pegmatitic material. The blebbed gneisses consist of biotite, muscovite, epidote, acid plagioclase, quartz, and iron oxide, and this association is stable throughout the metamorphic history of the block. Other zoned bodies are found in streaky gneisses with the same mineral composition as the blebbed gneisses; these streaky rocks are undoubtedly of injection-origin. A few zoned bodies are closely associated with thick granite sills, whilst others are intimately connected with a group of injection-rocks characterized by large felspar ovoids. Some are found in striped hornblendic granulites traversed by pegmatites. Finally, one occurrence—that of Burgar Stack, Burra Firth—has for dominant country-rock siliceous and hornblendic rocks, but even here pegmatites are numerous.

In the first place, therefore, the zoned bodies are associated with rocks in the formation of which acid igneous material has had a share.

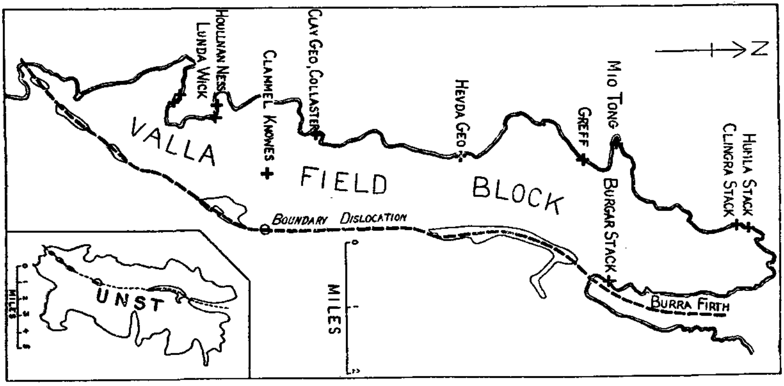

FIG. 1. Sketch-map showing the main localities of the zoned bodies in the Valla Field block, Unst.

The presence of acid injections during or soon after the production of the first metamorphism is in evidence throughout the block. The rocks of this metamorphism were most likely formed just on the margins of an injection-complex of some size; sillimanite has as yet been found only as inclusions within the garnet. In the second place, the zoned bodies are often found with hornblendic rocks of various types. As indicated in a later page, this association may be of importance in connexion with the early history of the bodies.

Field Relations of the Zoned Bodies.

The location of the larger zoned bodies within the Valla Field block is shown in fig. 1. Probably the best locality for these bodies is on the south-western shore of Lunda Wick, immediately east of Gorsendi Geo. Here purplish semipelitic and pelitic gneisses enclose a dozen or more masses. The most easterly mass (fig. 2) is the largest, being over 20 feet in diameter. The larger balls project above the wave-washed platform of gneiss, whilst one remarkable ball (fig. 3) lies 'loose' on the platform completely detached from its country-rock. As shown in the next section of this account, many of the masses are complete, that is, they exhibit an orderly sequence of zones arranged parallel with their present margins; such masses are separated from the gneiss of the country-rock by a sharply defined surface made by the smoothed outer skin of the outermost layer, biotite. The later movements have simply smoothed the outer surface without distortion of the zones. In other cases, however, the originally roughly spherical balls have been sheared out into lensed mixtures of the various constituents of the zones. For instance, a few yards westwards from the large easternmost ball, there is found a long narrow belt made up of lenticles of actinolite in biotite sheaths mixed with lenticles of gneiss, the whole being clearly a sheared-out biotite-actinolite body. Another excellent example of a distorted lensed mass is found near Gorsendi Geo; here talc, actinolite, and biotite are concerned (fig. 5 A).

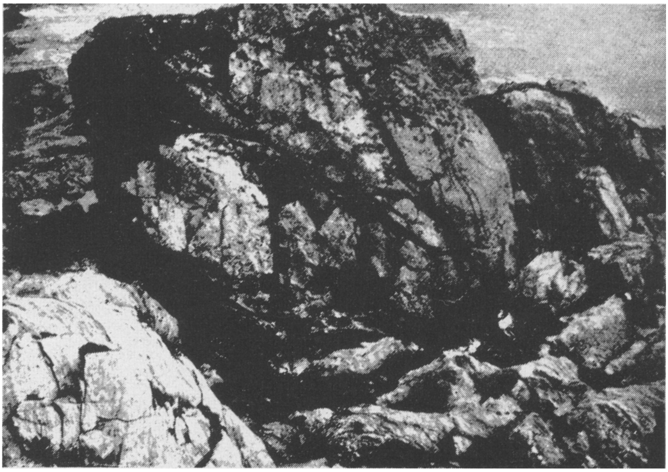

FIG. 2. Zoned body, 20 feet diameter: Lunda Wick.
(Compare fig. 5 H.)

On the opposite shore of Lunda Wick, along the southern coast of Houllnan Ness, dozens of small masses are encountered in flat-lying mixed hornblendic and pelitic gneisses. Here are found separate shear-streaks of biotite, chlorite, actinolite, and talc, but less distorted bodies are seen also, the largest being 2 yards across. Noteworthy at this locality is the occurrence of masses of actinolite, 2 feet across and 6 inches thick, made up of crystals radiating from a central plane (fig. 5 B). These nodules are almost always coated with a thick skin of biotite, but small nodules lacking this biotite skin have been noted as well.

Farther north, in Wick of Collaster, knots of bronzy-coloured biotite and nodules of radiating actinolite occur in blebbed gneiss. At Ness of Collaster, in the northern cliff of Clay Geo, some good examples of the zoned bodies and their deformed derivatives are well exposed (fig. 5 J). The chief country-rock is here striped hornblende-granulite traversed by innumerable thick pegmatites. Great shear-planes run through the country-rocks and have distorted the zoned bodies and in places disrupted them into lenticular fragments. The largest zoned body is mainly composed of a lens of white talc-schist, 4 yards wide by 10 yards long, which is sheathed by black mica with an irregular zone of actinolite between. Other smaller bodies show complete zoning, whilst, on the other hand, wisps of bronzy biotite and nests of actinolite occur throughout the cliff-section. It is clear that a group of originally spherical zoned bodies has been deformed by shearing.

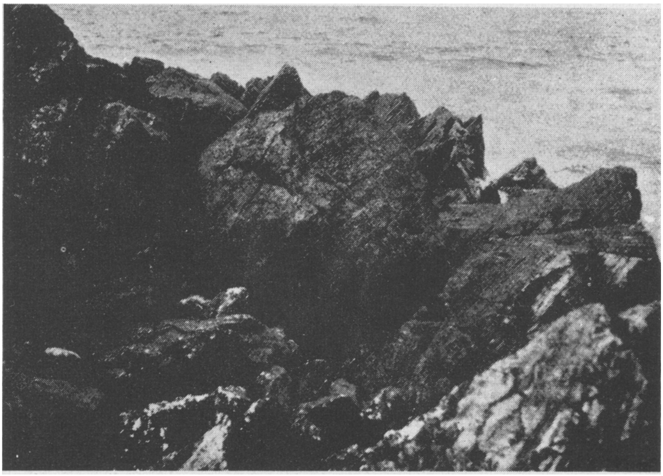

FIG. 3. 'Loose' ball, 12 feet diameter, on gneiss platform: Lunda Wick.

On the Valla Field ridge at Clammel Knowes (Clammel = Kleber = soapstone) there is an old quarry in soapstone. Relations to the country-rocks, felspar-blebbed gneisses succeeded by tourmaline-garnet-muscovite-biotite-gneiss, are not now visible.

North of Hevda Geo a few pods of radiating actinolite occur in coarse streaky garnet-mica-gneisses which are full of very coarse felspathic streaks and patches and, besides, are traversed by sheared pegmatites. These country-rocks are clearly injection-rocks.

The next occurrence to the north is found low down in the cliffs between Greff and Poindie ; it can be located west of the base of the great granite sill that makes the lower part of the Greff cliffs. The country-rocks consist of various flaggy semipelitic and pelitic schists and striped hornblendic granulites, traversed by sills of granite and in part permeated by acid materials. Conspicuous in this series of rocks is a layer of dense dull-green hornblendic rock, and it is with this rock that the zoned bodies are closely associated. These consist either of elongated balls of actinolite with biotite sheaths or else long lenses of talc-schist containing actinolite nodules and coated with a schistose mixture of talc and biotite. These masses are shreds of original zoned bodies.

Mio Tong, the point of the headland of Tonga, consists of many sheets of granite in hornblendic and micaceous schists. Between two of the granite sheets there is found a two-foot layer of bronzy-biotite rock containing balls of actinolite, whilst small radiating clumps of actinolite-prisms are not uncommon in several of the granite sheets.

Still farther north very good developments of derivatives of the zoned bodies are seen on Clingra Stack and Humla Stack at the base of the Herma Ness cliffs.[1] The section shows fine-grained hornblendic and biotitic schists and coarser felspathic gneisses invaded by sills of granite. In much of the schist there is a development of large ovoid felspars, presumably due to injection-processes. Lenses of actinolite, sheathed with biotite, and elongated masses of biotite-talc-schist are closely associated with a thick granite sheet making the landward slope of Clingra Stack. Wisps and very elongated drawn-out layers of similar material occur at many levels in the main cliff of augened and ovoid rocks opposite Humla Stack.

The last locality for the zoned bodies is on the west coast of Burra

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[1] In visiting this locality, it is advisable to obtain the guidance of a local man, such as the bird-watcher of the skua sanctuary on Herma Ness, for the descent of the cliff.

Firth immediately north of Burgar Stack. The country-rocks consist of massive felspathic and siliceous granulites, with subordinate semipelitic and pelitic intercalations, and rare belts of hornblende-felspar-gneiss. Pegmatite veins, and stringers and permeations of acid igneous material, are abundant. In the cliff north of the cove in which is Burgar Stack, there is a band, some 20 feet thick, of coarse hornblende-felspar-gneiss cut up by shear-planes into lenticular masses coated with biotite-hornblende-schist. Elongated masses of talc-schist, wisps of bronzy biotite, and nodules of actinolite occur in the lensed gneiss. Measurements of some of the talc lenses are 12 feet long by 5 feet thick, 10 by 1, and 10 by 3 feet; while actinolite nodules reach a length of a foot.

FIG. 4. Zoned body weathered out on shore: Lunda Wick. (Compare fig. 5 c.)

From this consideration of the country-rocks and field-relations of the zoned bodies it may be concluded:

i. The zoned bodies occur in a series of rocks in which acid injections and permeations are abundant.

ii. They are often associated with hornblendic rocks of various types.

iii. Two types of zoned body are separable; the first consists of the undistorted zoned type, with complete zones arranged parallel with their present margins; the second type is formed by wisps and lenses of the materials of the zones produced by the shearing-out of the originally undistorted type.

Description of the Zoned Bodies.

Details of the Zoning.—Piecing together the evidence supplied by the complete and the relatively undisturbed zoned bodies we are led to the conclusion that these in their most complex form have the following zonal arrangement (fig. 5) from within outwards:

antigorite, talc, actinolite, chlorite, biotite.

Though the chlorite zone may be absent in some examples, the order given never varies. Representative samples of the evidence are illustrated in Sketches C, D, E, F, G of fig. 5. Sketch C of this figure shows one of the best preserved balls; it is spherical and has an interior of talc-rock, followed by a complete zone of actinolite 3 inches in thickness and then a rim of biotite 2 inches thick (fig. 4). The chlorite zone, as already mentioned, is not always present, but a perfect example is shown in fig. 5 G. From these more complex forms we may pass to the simpler actinolite-biotite associations, as illustrated in fig. 5 B. Here crystals of actinolite radiate from a median plane to form a lens-shaped nodule which is surrounded by a biotite sheath. In some examples, e.g. fig. 5 E, there is a central portion of talc-rock with prisms of actinolite. This type may indicate, as discussed below, that the process giving rise to the zoned talc-actinolite-biotite bodies has gone a step nearer finality in the actinolite-biotite bodies. It is worth noting in this connexion that the actinolite-biotite bodies are all small, all less than 2 feet in length and most of them less than 9 inches. Examples of the distorted bodies are figured in fig. 5 A, H, and J. Fig. 5 H is of the biggest ball at Lund (fig. 2). The main part of the occurrence is a central portion, 20 feet in diameter, which has an antigorite core and talc-rock margin. Around this comes a sheath of talc-schist in which are nodules of actinolite and wisps of biotite. Portions of the margins of the talc-schist are coated with a thick skin of biotite. The whole phenomenon is that to be expected from the shearing-out of an originally undistorted and complete zoned body.

Mineralogy of the Zones.

Antigorite Zone.—Rocks containing abundant antigorite and coming from the central part of the largest ball at Lund are grey-green in

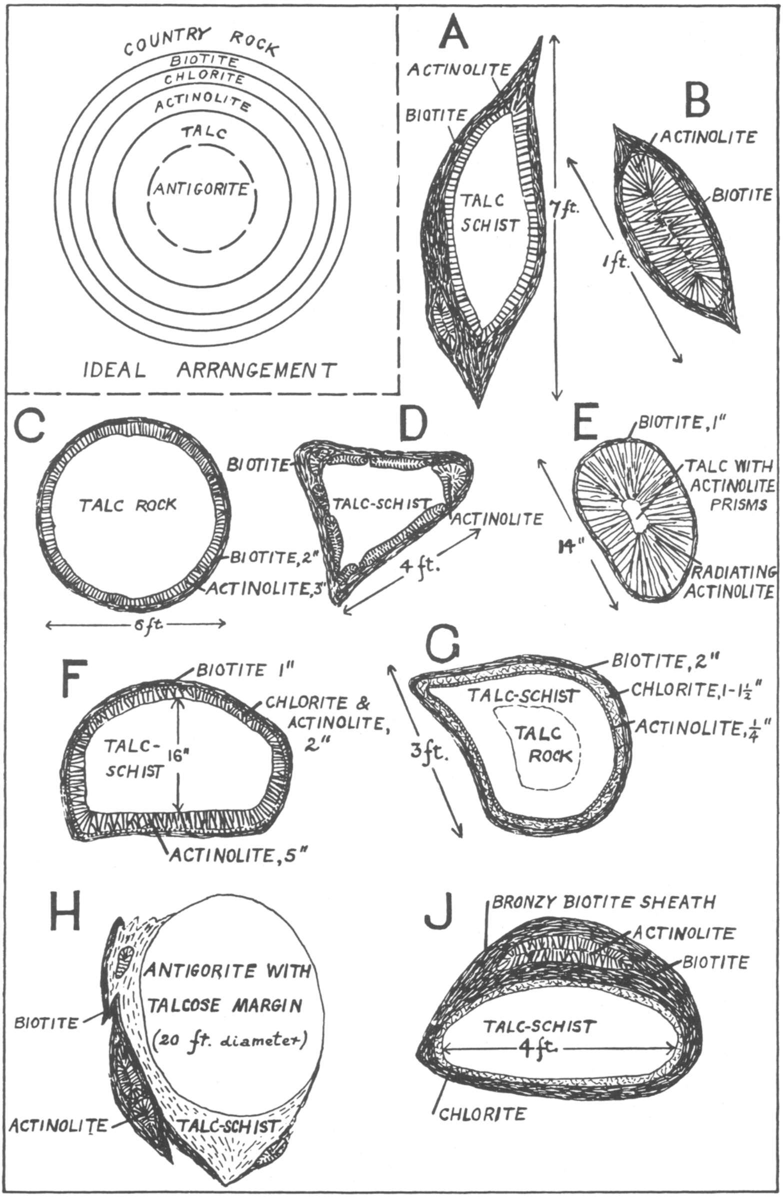

FIG. 5. Sketches of zoned bodies: Unst.

colour and fine in grain. They are seen in slice to be composed mainly of antigorite, with subordinate talc, scanty carbonate, and a few grains of iron oxide. The antigorite forms colourless plates and lamellae. The elongation of the blades is positive. The mineral is optically negative with 2V small, α along the blades 1·576. In some parts of the slice talc is abundant as colourless wisps and patches. Carbonate is also sporadic in occurrence and forms irregular patches of granules; the mineral effervesces in cold dilute acid. Black iron oxide, in collections of shapeless grains, is not common.

Talc Zone.—Rocks of the talc zone are either massive talc-rocks or foliated talc-schists. They are white or pale greenish in colour. In slice, the talc-rock is seen to be made up almost entirely of talc in a confused aggregation of wisps and flakes in which are occasional larger plates. Small grains of iron oxide are scattered evenly throughout the slice. A dusky carbonate is fairly abundant. Small nests of chlorite are not rare; it is lamellar twinned, optically positive with small optic axial angle, and faintly pleochroic from yellow to green. In the talc-schists, talc with quite subordinate chlorite, and rare iron oxide and carbonate, occur in a foliated association. The largest zoned body at Lund shows a 2-inch vein of coarsely crystalline green talc and brownish dolomite.

The portion of the talc zone immediately adjacent to the succeeding actinolite zone shows the incoming of amphibole as pale greenish flattened prisms up to an inch in length. A rock typical of this border portion has in slice large flakes of talc as its main constituent. In this occur slender colourless actinolite prisms, patches of colourless lamellar-twinned chlorite, and many small plates of a phlogopitic mica, with a strong pleochroism, brassy brown to colourless, and γ 1·594.

Actinolite Zone.—A typical member of this zone is in hand-specimen a bright-green rock made up of interlacing and subradiate crystals of actinolite that may reach a length of 3 inches. Slices of such rocks show actinolite as practically the sole component; sometimes a few small interspaces between the actinolite prisms are filled with talc or chlorite, the latter occasionally in ripidolitic forms.

The amount of talc present naturally increases at the border of the zone towards the talc zone. Similarly, at the border to the chlorite zone, when this is present, chlorite becomes an important constituent. When the chlorite zone as such is absent, a passage to the biotite zone is provided by the presence of biotite and chlorite, or of biotite alone, in the interspaces between the actinolites. The mica occurring with chlorite has a yellow to deep brown pleochroism, and γ 1·619; that occurring alone has a yellow to greenish-brown pleochroism, and γ 1·609.

In all these rocks the actinolite forms long prismatic crystals with poor terminations. In thin sections it is colourless or pale green. Determinations with the universal stage gave 2V 82°, $\gamma : c = 15°$; by the immersion method with light from a Zeiss sodium lamp, β 1·632. These values are consistent for an actinolite having 5–6 % FeO, according to the curves given by Winchell.[1]

Chlorite Zone.—Passage rocks from the actinolite to the chlorite zone have already been noted. The main part of the chlorite zone is formed by large plates of deep-green chlorite with the following characters: very faint pleochroism, colourless to pale greenish; optical sign positive with small optic axial angle; α 1·595. The mineral is a pennine. In addition to the chlorite there may be in some rocks a very small quantity of talc or actinolite and, in a few, sparse collections of iron-ore grains or pellets of rutile.

Biotite Zone.—The biotite zone is made up of a rock which must surely be one of the most remarkable in existence. In many cases the zone consists entirely of a biotite with the following properties: pleochroism yellow to light chestnut-brown, γ 1·621. The mica here occurs as large plates with a poorly expressed alignment. In the more foliated type of biotite sheath, the mineral shows a different pleochroism, almost colourless to pale yellow-brown, and γ 1·614.

The nature of the margins of the biotite zone against the country-rock is a subject of importance. One type of margin is clean-cut and consists of the smoothed outer surface of the biotite sheath itself. The actual separation surface is usually plastered with a bronze-coloured biotite with γ 1·627, cleavage flakes in oils being deep brassy-yellow. In other examples there appears to be a passage into the country-rock. One such passage rock shows a biotite similar in optical properties to that making the main part of the zone (γ 1·621), but between the biotite plates occur shapeless grains of oligoclase. The amount of felspar increases towards the country-rock side until a normal oligoclase-biotite-gneiss is reached. In another passage-rock, the transitional portion is formed of biotite and muscovite, with abundant epidote. Such a rock differs from the country-rock adjacent to the occurrence only in the absence of plagioclase. These

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[1] A. N. Winchell, Elements of optical mineralogy. 1927, pt. 2, p. 211.

passage rocks are of importance in the consideration of the genesis of the zoned bodies.

Comparison with similar associations in Shetland and elsewhere.

What is most likely a zoned association essentially similar to those of Unst occurs on the south bank of the Niddister Burn on Ness of Hillswick in the north mainland of Shetland. The present writer has not visited this locality, but the similarity is evident from the sketch of the field-relations given by F. Coles Phillips.[1] According to Phillips the country-rocks are gneisses with veins of reddish granite. If this Hillswick occurrence is a zoned body then serpentine is followed outwards by a 2-foot belt of anthophyllite, this by soapstone and then talc-schist against the country-rocks. Until the field-relations and metamorphic history of the country-rocks are better known it is impossible to decide whether this sequence is original or mechanical, but the occurrence is important because Heddle[2] has given analyses of serpentine, talc, anthophyllite, actinolite, chlorite, and biotite from this locality. From Heddle's notes on the mode of occurrence of the analysed minerals it is clear that they are closely associated in the field and, accordingly, the analyses may be employed in the discussion of the Unst phenomena. Phillips concludes that the anthophyllite and talc belts arise by the introduction of material, mainly silica, from the neighbouring intrusive veins. This origin of anthophyllite-schists has been characterized by A. Harker[3] as a 'quite gratuitous hypothesis'.

For somewhat analogous occurrences in the Lizard, transfer of material has been shown to occur by Sir John Flett.[4] Here, at the contact with igneous gneiss, serpentine is altered to a soft greenish rock consisting mainly of talc and tremolite, sometimes with anthophyllite and chlorite. Smaller inclusions in the gneiss are talc-tremolite-chlorite-schists. Flett concludes that two agencies have been in operation, an impregnation of the serpentine by hot vapours or liquids given off by the gneisses on cooling, and also mechanical shearing.

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[1] F. C. Phillips, The serpentines and associated rocks and minerals of the Shetland Islands. Quart. Journ. Geol. Soc. London, 1927, vol. 83, p. 642.

[2] M. F. Heddle, Min. Mag., 1879, vol. 3, p. 18; and The mineralogy of Scotland. Edinburgh, 1901, vol. 2.

[3] A. Harker, Metamorphism. London, 1932, p. 276.

[4] J. S. Flett, The geology of Lizard and Meneage. Mem. Geol. Surv. England and Wales, 1912, Explan. Sheet 359, pp. 141–142.

In his account of the Shabani asbestos deposits of Southern Rhodesia, F. E. Keep[1] considers that serpentine is there formed by the action of magmatic waters accompanying an intrusion of granite. In the later hydrothermal stage, talc-carbonate-rocks are produced, whilst actinolite-rock arises by a similar introduction of material from the acid rock. Keep gives references to several actinolite occurrences that, in their field-relations, support this explanation.

The celebrated Vermont talc deposits have been considered by J. L. Gillson[2] to be of replacement origin. Gillson believes that hot alkaline solutions, low in silica and towards the last rich in magnesia and carbon dioxide, have there replaced not only serpentine but even sedimentary gneisses. In the latter case it is supposed that the gneiss is converted into chlorite and amphibole and then these changed into talc. The time-sequence given by Gillson is tourmaline, quartz, biotite, apatite, actinolite, chlorite, dolomite, talc, magnetite, and pyrrhotine. From the accounts and discussion of these Appalachian soapstone and talc deposits recently given by H. H. Hess[3] it is obvious that they are practically identical with the Unst zoned bodies. Hess considers that dilute solutions, consisting simply of water and carbon dioxide and emanating from an acid intrusion, were responsible for the change of gabbro to amphibolite, and of ultrabasic rock to actinolite-rock, chlorite-actinolite-rock, and soapstone. These changes took place with falling temperature, the time-sequence of the minerals being hornblende, actinolite, chlorite, talc, and carbonate.

The Origin of the Unst Zoned Bodies.

If, following Harker, it is considered that no transfer of material has taken place, then the question of the original pre-metamorphism nature of the bodies must be examined. The present writer finds it difficult in this event to suggest what such bodies could have been. If they were of sedimentary origin, they must have been concretions of extraordinary size and of a remarkable zoned composition. If they

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[1] F. E. Keep, The geology of the Shabani mineral belt, Belingwe district. Bull. Geol. Surv. Southern Rhodesia, 1929, no. 12, pp. 78, 82, 104, 105, 106. [Min. Abstr., vol. 4, p. 181.]

[2] J. L. Gillson, Origin of the Vermont talc deposits. Econ. Geol., 1927, vol. 22, p. 246.

[3] H. H. Hess, Hydrothermal metamorphism of an ultrabasic intrusion at Schuyler, Virginia. Amer. Journ. Sci., 1933, ser. 5, vol. 26, p. 377; and The problem of serpentinization and the origin of certain chrysotile asbestos talc and soapstone deposits. Econ. Geol., 1933, vol. 28, p. 634. [M.A. 5-441.]

were of igneous parentage, they must have possessed some kind of gigantic orbicular or shelled structure. Further, whether they were originally sedimentary or igneous, they have on metamorphism preserved their primary compositional zoning and the arrangement of this zoning with respect to their present peripheries. All these possibilities and combinations of possibilities seem to the writer to be extremely unlikely.

It is suggested, therefore, that movement of material has taken place. The regular arrangement of the zones in relation to the present boundaries of the bodies clearly indicates this. What has been the nature of this transfer of material? A satisfactory answer to this question depends mainly on two points: the original composition of the unzoned body and the original limits of this. It is reasonable to hold that the bodies consisted originally of ultrabasic material, probably peridotitic in character. The existence of an antigoritic central portion, and the presence of so many magnesia-rich minerals in the assemblage, support this view. With regard to the second point, the original limits of this peridotitic ball, several aspects of the field-relations must be considered. The sharp boundary of the outermost layer, biotite, seen in most cases against the country-rocks suggests at first sight that here was the original limit of the peridotitic ball. But these bodies have been subjected in many instances to one or two later metamorphisms in which stress was a dominant factor, so that the sharp margins now found may be of mechanical type; slipping has taken place on the most likely surfaces. That such may be the case is indicated by the existence in a few localities of passage zones between the biotite layer and the country-rock. Where, then, was the original margin of the peridotite ball? This question cannot be definitely answered; all that can be done is to advance certain suggestions that have a bearing on the answer.

In the discussion of the possible transfers in the production of the Unst bodies, one may conveniently use the analyses by Heddle, early though they are, of the constituent minerals of the Ness of Hillswick occurrence. In the table below, these analyses are given, together with two analyses of the Unst country-rocks. It may be objected that the Hillswick minerals are possibly not of the same composition as those of Unst and may not have had an entirely comparable origin. If this objection is sustained, then it may be pointed out that the minerals of the zones are sufficiently well characterized and sufficiently different from each other in composition for their average values to be used in this discussion. Whether Heddle's compositions or the theoretical compositions are used, the conclusions concerning the general trends of the transfer are the same. The data listed in the table are shown in fig. 6, where Heddle's compositions of the minerals are plotted in the order in which they make up the Unst zoned bodies, the innermost zone, serpentine, being at the top and the outermost, biotite, at the bottom. The compositions of the Unst country-rocks from analyses by Mr. B. E. Dixon, H.M. Geological Survey, are shown below the biotite.

Compositions of the Minerals of the Zones.

	SiO_2.	Al_2O_3.	Fe_2O_3 +FeO.	CaO.	MgO.	K_2O.	Na_2O.	H_2O.
Serpentine	41·46	0·01	3·58	—	41·76	—	—	12·43
Talc	60·89	4·14	1·24	—	28·09	—	—	4·72
Actinolite	55·00	1·51	4·45	10·38	23·31	1·12	1·10	2·90
Chlorite	39·81	11·43	7·97	2·80	25·64	1·20	3·15	7·91
Biotite	39·80	14·19	14·17	0·10	18·32	8·43	2·11	2·52
Blebbed gneiss ...	64·46	14·60	6·55	3·50	2·78	3·31	2·62	0·71
Staurolite-kyanite-garnet-gneiss ...	55·79	25·17	9·60	0·68	1·93	3·00	1·12	1·39

Inspection of the table and of fig. 6 leads to certain indications of the course of the movement of material. Let it be assumed for the present that the margin of the peridotite or serpentine ball was situated at the *outer* margin of the biotite zone. First, it is clear that magnesia and water have left the ball. It may be recalled that in the case of the Lizard serpentine-gneiss contact, Flett (loc. cit., pp. 143–144) has shown that magnesia-rich solutions have given rise to pseudophite from the alkali-felspar of the adjacent rock; a soapstone with 31·08 % MgO replaces granite. Second, it seems likely that silica has been introduced into the ball, but has been concentrated in the interior layers. The serpentine centre and the chlorite and biotite outer layers have the same silica percentages, whilst the intervening zones show greatly increased percentages with a maximum at the talc zone. It could be suggested, however, that no influx of silica has taken place, but that talc and magnesite were produced by the reaction of introduced carbon dioxide and the serpentine centre. If this has been so then the magnesite has been almost entirely removed, for examination of slices shows that carbonate occurs only sporadically and in small quantity in the talc zone and, except for rare and thin dolomite-talc veins, appears to be calcite. An analysis of the Hillswick soapstone given by Phillips (loc. cit., p. 643) shows no carbonate. It is preferable, therefore, to consider that an introduction of silica has taken place, perhaps accompanied by some carbon dioxide. Third, lime has also been introduced and has collected almost entirely in the actinolite zone. The most remarkable point about the movements of these components is the formation of the silica maximum in the talc zone and the accumulation of practically all the imported lime in the actinolite zone. Continuing the assumption that the outer margin of the ball was at the outer margin of the biotite zone, then in the formation of the chlorite and biotite zones there has been an introduction of alumina, iron oxides, and alkalis into these zones, pari passu with the outflow of magnesia and water.

The alternative assumption that the original outer margin of the peridotite ball was not at the outer margin of the biotite zone must now be considered. The other positions that appear possible are at the *inner* margin of the biotite zone or slightly farther in so as to include a narrow portion of the chlorite zone when this is present. We have already noted that there is a certain amount of evidence in favour of regarding the country-rock, blebbed gneiss, as influenced by injection-metamorphism, so that any suggestions with respect to the original nature of the country-rock are difficult to make. In the production of similar blebbed gneisses in certain injection-complexes, a transfer of silica, lime, and soda, or of oligoclasic material, has been considered likely.[1] In order to proceed with this discussion, let us assume, therefore, that the original country-rock had the composition of the blebbed gneiss less a certain amount of silica, soda, and lime. Except for alumina, it might have had a composition like that of the staurolite-kyanite-garnet-gneiss, another country-rock of the zoned bodies. To produce the biotite zone from such a forerunner of the blebbed gneiss requires an addition of magnesia, iron oxides, and alkalis, and an outflow of silica and lime. Except for the field-fact that the biotite zone never exceeds 9 inches in thickness whilst the actinolite zone may be 2 feet thick and the talc zone a dozen feet or

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[1] V. M. Goldschmidt, Die Injektionsmetamorphose im Stavanger-Gebeit. Vidensk.-Selsk. Skrift. Kristiania, 1921, for 1920, no. 10.

T. Vogt, Sulitelmafeltets geologi og petrografi. Norges Geol. Undersök., 1927, no. 121, p. 491.

H. H. Read, The igneous and metamorphic history of Cromar, Deeside, Aberdeenshire. Trans. Roy. Soc. Edinburgh, 1927, vol. 55, p. 317; and The geology of central Sutherland. Mem. Geol. Surv. Scotland, 1931.

more, it could be suggested that this outflowing lime and silica passed into the balls to form the actinolite and talc zones. It is preferable, however, to consider the lime and silica of these zones as coming in the main from outside the biotite zone.

To choose between the two positions of the outer limit of the original peridotite ball is a difficult task. Hess,[1] in describing the talc deposit of the Mineral Products Company, Chester, Vermont—a deposit presenting very close similarities to the Unst zoned bodies—states that the biotite sheath represents approximately the original contact of the ultrabasic with the country-rock. In a later page, however, whilst presumably referring to the same type of deposit, he considers biotite to be a 'hybrid mineral; instead of being composed of elements derived from the ultrabasic as are the minerals of the characteristic series, it derives its potassium from the acid intrusive and its magnesium from the ultrabasic' (loc. cit., p. 646). The well-established production [2] of biotite in amphibolites in injection-com-

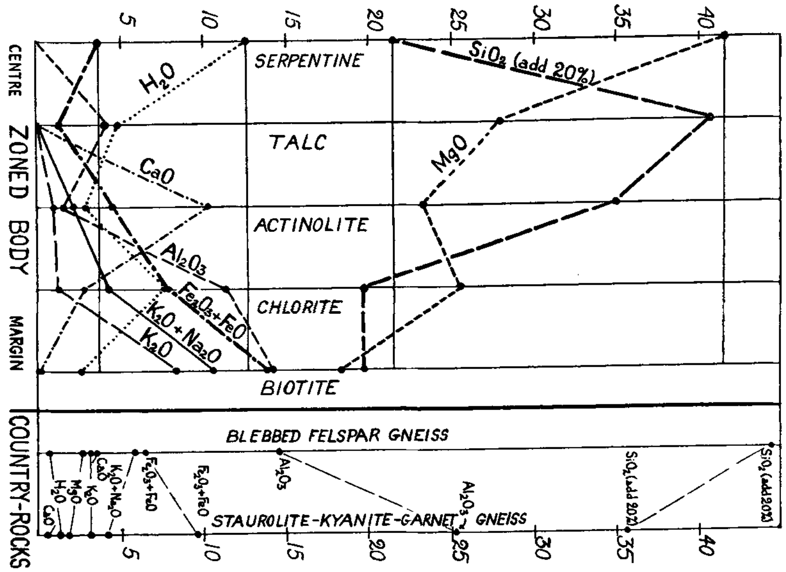

FIG. 6. Graph of suggested chemical compositions of the zones of the zoned bodies; and analyses of the country-rocks.

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[1] H. H. Hess, Econ. Geol., 1933, vol. 28, pp. 643–644.

[2] References are given in H. H. Read, Trans. Roy. Soc. Edinburgh, 1927, vol. 55, p. 346.

plexes has a bearing on this discussion of the original outer limits of the balls.

On account of the existence of transitions between the biotite zone and the country-rocks the present writer prefers to consider the biotite zone as belonging to the country-rock side of the original junction. If this were so, and assuming as reasonable from the field-evidence that no change in volume took place in the original ball during the transfer, then the following movements of material have taken place:

1. Magnesia leaves the peridotite ball and is concentrated in the immediately adjacent layer of the country-rock to help form the biotite zone.
2. Silica enters the ball, and is concentrated in the interior zones, forming a maximum in the talc zone.
3. Lime enters the ball, and is concentrated almost entirely within the actinolite zone.
4. Alumina enters the ball, and is concentrated in the chlorite zone.
5. Soda enters the ball and, from Heddle's analyses, is found in the chlorite and actinolite zones.
6. Iron oxides and potash are concentrated in the biotite zone. In this case, the iron oxides may have been turned out of the ball, but potash cannot have been.
7. Water leaves the ball.
8. Some carbon dioxide may enter the ball at some period to form with lime the sporadic carbonates of the talc zone.

The zones of the Unst zoned bodies therefore arise as follows:

Antigorite zone, with MgO and H_2O maxima, is a relic of the original peridotite body, modified, of course, by stress metamorphism.

Talc zone, with SiO_2 maximum, is formed by the inflow of SiO_2 and expulsion of MgO and H_2O from the peridotite body.

Actinolite zone, with CaO maximum, is formed by inflow of SiO_2 and CaO and outflow of MgO and H_2O.

Chlorite zone, with Al_2O_3 maximum, is formed by inflow of Al_2O_3 and expulsion of MgO and H_2O.

Biotite zone arises from the country-rock, by inflow of MgO, K_2O, and possibly iron oxides, with outflow of SiO_2, CaO, and Al_2O_3.

A few of the many points that arise from the contemplation of this complex mechanism may be examined. In the Appalachians, the mineral time-sequence—actinolite, chlorite, talc, and carbonate—has been demonstrated for innumerable deposits over a great area. Such a time-succession takes place with falling temperature. At a high temperature, actinolite will be the first mineral to form, and at any lower temperature the appropriate member of the succession will be produced. Thus, in the production of the Appalachian associations, the sequence of events is first the high-temperature alteration of the peridotite ball to actinolite; as the temperature falls the actinolite is replaced by chlorite, and at the lowest temperature by talc and carbonate.

When an attempt is made to explain the Unst zoned bodies on the Appalachian basis, great difficulties are encountered. Three features of the Unst bodies may be recalled: first, talc occurs always in an interior position; second, extremely narrow zones of actinolite and chlorite (e.g. in fig. 5 C, F, G, H) continue completely round large balls; and third, most of the smallest balls consist only of actinolite and biotite. From these features it appears extremely unlikely to the present writer that the peridotite ball has been completely made over into actinolite, then an *outer* margin converted into chlorite, and then the *interior* changed into talc, leaving unreplaced a very narrow but continuous zone of actinolite of uniform thickness, and, further, that this has happened in several distinct balls. Finally, if the Appalachian sequence was valid for Unst, the smallest bodies remained unchanged as the temperature fell, whilst the interiors of the larger bodies were altered. If the minerals of the Unst balls are not of simultaneous formation, then it could be suggested on the field-evidence that the time-sequence was talc, actinolite, chlorite, the whole of a ball having been made over into talc, then the outer portion of the talc made into actinolite, and then the outer portion of the actinolite made into chlorite. Though in some thin sections there is some evidence of a small degree of replacement of actinolite by talc at certain talc-actinolite zone margins, it must be remembered that these bodies have suffered two metamorphisms at least. The individual zones are of sufficient thickness and purity to show that transfer of material has taken place on a considerable scale; such transfers become remarkably complex if the zones are held to be of successive formation; it is sufficient in this connexion to point out how involved the movement of lime must have been if the zones were formed one after the other. In the writer's opinion, the field and microscope evidence shows that the minerals of the different zones were of simultaneous formation.

If this were so, then the production of the zones can be considered as a kind of 'aureole-effect', conditions varying from margin to centre of the ball. The formation of each zone depends upon the physical and especially upon the chemical factors operative at any given position within the ball. In this 'aureole' the inner part of the ball corresponds to the outer part of the normal contact-aureole; in this inner part the physical conditions of temperature and pressure were suitable for talc formation when combined with the chemical factors, inflow of silica and outflow of magnesia, and similarly for the other monomineralic zones. The anomalous position of the chlorite zone in the Unst balls when compared with the Appalachian bodies is not anomalous when it is considered as chemically controlled by the supply of alumina from the outside.

Perhaps the most remarkable result of the interchanges of material is the virtual spacing of the introduced oxides, silica in advance of lime, lime in advance of alumina. I do not wish to conclude that silica as such passed more rapidly into the ball than lime as such, but the final adjustments of whatever transitional compounds were formed have been to cause these spaced maxima. This spacing recalls the interesting account given by F. D. Adams[1] of the transfusion of material between two bricks, one magnesite and the other dolomitic magnesite and mill-scale (largely Fe_3O_4) when burnt in a laboratory kiln. Silica and alumina have accumulated in the magnesite brick farthest from the contact, whilst lime 'has been carried through the substance of the brick and been deposited in progressively larger amounts in it as the distance from the contact increases, rising . . . to 6·3 % . . . beyond which the alteration ceases and the lime falls at once to 2·4 % which is the lime content of the unaltered brick' (loc. cit., p. 158). Further, there is produced a concentration of ferric oxide and magnesia near the contact of the two bricks. Such a spacing out of oxides recalls in type that of the Unst bodies; especially interesting is the comparable behaviour of lime in the two cases. J. W. Greig[2] has described a similar type of concentration in silica bricks used in the roofs of open-hearth steel furnaces. Such bricks become zoned, with an outside portion corresponding in composition to the original brick, followed by a zone in which there is a

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[1] F. D. Adams, The transfusion of matter from one solid to another under the influence of heat. Canadian Journal of Research, 1930, vol. 2, p. 153.

[2] J. W. Greig, On liquid immiscibility in the system FeO–Fe_2O_3–Al_2O_3–SiO_2. Amer. Journ. Sci., 1927, ser. 5, vol. 14, pp. 483–484.

concentration of lime and alumina, and then by a zone much higher in iron oxide.

The transfusion of the oxides into the peridotite balls of Unst is undoubtedly connected with the injection of acid material into the country-rocks. The evidence for such an acid injection-process has already been outlined. The various types of injection-rocks—blebbed gneisses, gneisses with felspar ovoids, permeation-gneisses and the like—and the ubiquitous pegmatitic and granitic intrusions are all characteristic of injection-complexes. The country-rocks have been soaked in juices which it is reasonable to believe were the same as those concerned in the production of similar injection-complexes, such as those of Stavanger, Cromar, central Sutherland, and elsewhere, that have been chemically studied. Such fluids, composed of silica, soda, lime, and probably alumina, have entered the peridotite ball, travelled into it at various speeds or become fixed at various positions, and so have brought about the zonal arrangement of the minerals formed; at the same time, magnesia has left the ball and, with the help of alkalis of injection-origin, has reacted with the country-rock to form the biotite zone.

Summary of the History of the Unst Zoned Bodies.

We are now in a position to consider the whole history of the zoned bodies.

(1) Their original rocks were most likely small intrusions of ultrabasic character of the geosynclinal phase;[1] they were as usual associated with basic intrusions typical of this phase and with what were most probably basic tuffs.

(2) The movement phase now began. The resulting metamorphism culminated in the production of the garnet-staurolite-kyanite-gneisses in the pelitic rocks of the area; at the same time the basic and ultrabasic intrusions of the geosynclinal phase were separated into small bodies, lens-shaped in the case of the basic rocks, more spherical with the ultrabasic rocks. The basic tuffs were converted into striped hornblendic schists and granulites, the basic rocks into amphibolites and the ultrabasic rocks into serpentine.

(3) In the later stages of this high-grade metamorphism, the country-rocks were permeated by acid materials and invaded by granite and pegmatite. Fluids of this injection-period entered the ultrabasic masses and formed the zonally arranged layers of the

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[1] H. H. Read, Trans. Roy. Soc. Edinburgh, 1927, vol. 55, p. 351.

zoned bodies. Material displaced from these reacted with the country-rock and the injection-fluids to give the biotite zone.

(4) One or two metamorphisms, both marked by great stress and moderate temperature, later affected the rocks of the region. One result was in most cases to pare away the transitional zone between the biotite zone and the country-rock and to form a sharp boundary marked by the development of bronzy biotite. In other cases, the zoned bodies were distorted or even sheared into elongated masses made up of wisps of the minerals of the various zones. When we reflect how vulnerable bodies of this nature enclosed in sedimentary gneisses of high grade must have been, we must be astonished at the perfection of preservation in so many instances of the zoned character.

The writer wishes to emphasize one aspect of this communication, namely, that in injection-metamorphism movement of material takes place on a considerable scale. This conclusion had already been reached by the study of sedimentary hosts in injection-complexes; this account of similar transfers in connexion with an ultrabasic host leads to the same result but uses more spectacular subjects.

Finally, I desire to express my thanks to Mr. I. S. Double, of the Geological Department, University of Liverpool, for help in the field, and to Dr. W. Q. Kennedy, of H.M. Geological Survey, for constructive criticism.