Supplement — Metamorphism in The Mona Complex

Introductory

A chapter dealing with this subject ought, as was stated in the Author's Preface, to have followed upon Chapter 7, but for certain difficulties which had not at that time been sufficiently overcome. It seems better, however, for it to be presented out of order (and with less time for consideration than I should have liked), than for it to be omitted altogether.<ref>As the Index was, already in paged-proof when this Supplement was written, no attempt has been made to index its subjects in detail.</ref>

The metamorphic phenomena have already been dealt with in Chapters 4 (*passim*)*, 7* (pp. 176–80, 198–205), 8 (pp. 206–31, *passim,* and 237–41), 10 (*passim,* but particularly on pp. 272–7, 292–4, 305, 320–1, 322–34, 347–8, 366–77, 385–6), and 41 (pp. 901–4, and especially 907–10)<ref>The conclusions reached in those chapters will be briefly recapitulated in this one, but for the evidence on which they are based the reader is requested to refer to the passages quoted.</ref>. The object of this supplement is, bringing them all together, to summarise and compare the metamorphic types as such, in order to obtain a clear static picture of the condition of the Complex; and then to deal with their ætiological relation, especially their relations to the tectonics.

The Mona Complex lends itself especially to this treatment on account of its remarkable range of crystallisation, almost every grade, from the lowest to the highest, being accessible within a space of less than 200 square miles; and also because we now have some knowledge of the connexion of its different metamorphic phases with the successive stages of the tectonics.

The reader is requested, however, to look upon this, not as an essay upon metamorphism in general, but merely as an attempt to present *that of the Mona Complex* in such a way as to render it readily available in the service of the growing science of metamorphic ætiology.

Comparative view of the metamorphic products

The products may be arranged in five groups, due respectively to metasomatism, thermo-metamorphism, dynamo-catamorphism, dynam-anamorphism, and dynamo-thermal anamorphism.

Metasomatism

Apart from what is usually understood by metamorphism, eight changes can be recognised which are essentially metasomatic. Silicification, Albitisation, Haematisation, Calcification, Dolomitisation, Manganisation, Serpentinisation, and De-Dolomitisation, have all been described as features of the Petrology. Here we need only call attention to their aggregate importance. This is considerable, for all of them (even in cases where the change itself has been but slight) affect large bodies of rock, and have contributed materially to the composition and condition of the Complex.

Thermo-metamorphism

The products comprise adinoles, epidosites, and many varieties of hornfels, with a textural range from crypto-crystalline to phenocrystalline rocks with porphyroblasts as much as seven millimetres in diameter. Let us compare the effects of the different kinds and sizes of intrusion.

The albitised dolerites of the south-west produce adinoles, with several varieties of compact hornfels, chiefly epidotic. The dolerites of the north produce an andalusite-hornfels with white and brown micas .25 mm. in diameter, iron-ores, and tourmaline. The dolerites are the only intrusions with chilled selvages. The albitic hornblende- and glaucophane-diorites of the Aethwy Region are surrounded by zones of quartz-albite rock with epidote, zoisite and garnet, which appears to have been a kind of adinole. The aureole of the serpentine-suite is composed of epidote-hornfels and actinolite-epidosite.

The great Coedana granite has an external aureole of crypto-crystalline hornfels composed of quartz, orthoclase, albite, white and brown mica, tourmaline, magnetite, ilmenite, and sphene, with occasional porphyroblasts of xanthophyllite and andalusite. Its great internal xenoliths are composed of phenocrystalline hornfelses, all rich in orthoclase, with albite, white and brown mica, amphiboles, epidotes, tourmaline, sphene, and iron-ores; the white-mica porphyroblasts attaining three millimetres, those of orthoclase seven millimetres in diameter, and the tourmaline prisms four millimetres in length. Here and there the granite is marginally greisenised.

With regard to the extent of alteration; the aureole of the northern dolerites (quite out of proportion to their size) is a quarter of a mile in width, while that on the southern margin of the peridotites has the same width and is a mile in length. At the termination of the Coedana granite its aureole is a mile and a half wide and is traceable for nearly two miles to the north-east<ref>The foliation rudely parallel to bedding in the Bodafon anticline (p. 204) may be older than the thermal action (pp. 907–8).</ref>; while some of its internal xenoliths exceed a mile in length.

Destruction of Aureoles— Owing to the subsequent effects of the regional dynamic metamorphism, we seldom, if ever, see the whole original extent of any of these aureoles. That of the peridotites of Holy Isle is now reduced to a few short strips on the northwestern side, where the waves of the great isoclinal folding broke full against it. Even the aureole of the Coedana granite has been destroyed in like manner along a considerable length of the (south-eastern) onset-side, and the granite attacked by the Pen-mynydd foliation. As for the Aethwy Region, only small cores of the intrusions remain in an unfoliated state, and mere skeletons of the aureoles have survived, so that the destruction in this case is almost complete. From the Complex as it is to-day, therefore, we obtain a very inadequate idea of the original importance of its thermo-metamorphism.

Dynamo-catamorphism

Let us begin, as is fitting, with the very lowest types. These we shall find in the breccias (a few of which are faintly compressed) of the final settlement-faulting. Unconnected with such faulting, and thus rather older, are certain other breccias, which are occasionally somewhat schistose. Older again, because *always* compressive, are the mylonites.. All these structures are merely local, and none of them are followed by any reconstruction. Autoclastic mélange, on the contrary, was followed by reconstruction, and is regional, for it occupies nearly 60 square miles.

Dynam-anamorphism

The manifold anamorphic products have been described in some detail in Chapters 4 and 10 as members of the several groups. Our present purpose is to convey, if possible, a comprehensive view of the anamorphism as such, to obtain which we will briefly compare the leading types with one another, and with certain well-known types in the Scottish Highlands. There are as yet no accepted standards of intensity; but rough ones may be found either in the dimensions of authigenitic minerals or the obliteration of original structures. In the Mona Complex, as we shall see below (pp. 946–7), the results obtained by the two methods do not agree; so we shall make use of the first one, considering mainly the dimensions and crystalline development of the micas and amphiboles.

In a few tracts, all of which are very small, such as parts of Gynfor, of the Llanddwyn Wedge, of the Eastern Pentraeth Inlier, and of the massive Church Bay Tuffs in the Western Region, anamorphism appears to be absent altogether.

Its very lowest developments are found in other parts of the Church Bay Tuffs aforesaid, and (much more extensively) in the Gwna mélange; wherein (though schistosity may be pronounced) true foliation is imparted only by extremely minute authigenitic flakes of chlorite or white mica. Yet even this stage includes types more advanced than those which we find in the well-known belt of intense cleavage along the south-eastern side of the 'Padarn ridge' of Carnarvonshire.

A considerably higher grade is attained in what we have termed the Gwna Green-schist. Crystallisation must still be classed as low, for though authigenitic albite is beginning to appear, the ferro-magnesian constituent is still chlorite, the white micas are very small, and the granoblastic bands are crypto-crystalline. The quartzites are in a corresponding condition; and so are the limestones, for no calc-silicates have been found in them<ref>Their white micas (pp. 83, 85) ought, however, to be examined, as they may prove to be margarite. The method (p. 117) by which paragonite was determined would probably be successful, and is easy to carry out.</ref>. Basic igneous rocks, however, which lie among Gwna Green-schist, have become actinolitic-epidote-chlorite-schists with clear granoblastic albite, thus revealing that the grade is higher than the state of the more obdurate sedimentary matter would lead one to suppose. A curious feature of the Green-schist, which will be discussed further on, is the rapidity with which original clastic structures disappear, even when the new texture is merely crypto-crystalline. The type seems to be a special feature of the Mona Complex, for I do not remember it in the Scottish Highlands, unless perhaps in the rocks which are apt to occur a few yards above the Moine thrust-plane, between the mylonites and the ordinary flaggy Moine-schist.

The Church Bay Tuffs of Trwyn Bychan are at about the same stage as the foregoing; but, in the Skerries Grits and Amlwch Beds of the Northern Region, and in the New Harbour Beds of the Northern Inliers and the Western Region, we meet with a distinctly higher grade, for their authigenitic micas are larger, the grano-blastic matrix is beginning to be phenocrystalline, and their fissile bands can be described as mica-schist. Concurrently with which we find a rich development of actinolite in the spilitic lavas.

Still higher grades are met with in the Coeden beds and the southern part of the Western Region, which constitute (pp. 241, 909) the anamorphic maxima of Llanffiewyn and the West. Here the mica-schists have become lustrous and the amphibolised lavas foliated, while the peridotites are converted into talc-schist and the gabbros into fissile rocks with finely felted actinolite.

Even more intense is the anamorphic maximum of Holy Isle, wherein the micas commonly attain diameters exceeding 0.75 mm., and the matrix of the flaggy beds, where not fissile, has become saccharoidally granoblastic and phenocrystalline. Green biotite is here an essential mineral, while sphene and other accessories indicative of a high intensity are extremely abundant. As for the Plutonic Intrusions, they manifest, in their actinolitic, fissile, gabbro-schists, their talc-schists, and their fine developments of tremolite, fully as high a grade as would be expected from the condition of the sediments. To compare with a well-known type, the flaggy Soldier's Point beds recall strongly, so far as their crystalline condition is concerned, the flaggy Moine-schists of the tract which extends for several miles to the east of the Moine thrust-plane in Scotland.

The Penmynydd anamorphic maximum is fully equal in intensity to that of Holy Isle, its granoblastic schists being thoroughly saccharoid and phenocrystalline, while the micas of its fissile bands exceed one millimetre in diameter. Biotite, here brown instead of green, is frequent, and so is garnet, xanthophyllite is found here and there, sphene, rutile, and zircon are abundant as accessories, while porphyroblastic albites one millimetre in length occur in some bands. The basic rocks are represented entirely by amphibolitic schists whose crystals are often large, and prismatically well developed. Green-hornblende-schists occur in large masses, but glaucophane-schists, in masses even larger, are an especial feature. The quartz-schists are now completely reconstructed, and the limestones are full of high-temperature minerals. Survivals of original structures are extremely rare. This last feature, with the complete amphibolisation and perfect foliation of the basic rocks, may perhaps be regarded as indices of a still higher anamorphic intensity than that of Holy Isle. We shall presently see, however, that obliteration of original structures may not be a satisfactory measure of intensity, and we must remember that the basic rocks of Holy Isle would have become far more amphibolised and foliated than they did, but for their protective belt of hornfels. Comparing with Scottish standards, it seems to me now that the expression (p. 110) 'rocks immediately above the mylonites of the Moine thrust-plane' is misleading, for my recollection is that those rocks are much finer than typical Penmynydd mica-schist. The finer members of the zone correspond, I think, to the well-known flags that are usually found many hundreds of feet above the Moine thrust-plane, while the more highly crystalline members recall 'Moine-gneisses' that are common a good many miles to the east of the outcrop of that great thrust.

Anamorphism of the ancient floor

The Pebbles (pp. 169, 165–6), even without assuming that the visible Gneisses form a part of that floor, enable us to make rough comparison with the metamorphic types of the Bedded Succession. The fragments of schistose grits tell us of the existence of very low grades, comparable with those found in Gwna mélange, while the mica-schists indicate an intensity not very different from the maxima of the Penmynydd Zone and Holy Isle. The gneissose fragments, however, considerably exceed either of those maxima, and are not equalled except among the visible Gneisses. Here, also, therefore, there are signs of a wide range of crystallisation.

The Gneisses The only members of the Complex in any way resembling the basic gneisses are the intrusive diorites, and neither in phenomena of segregation or of foliation are they for a moment comparable. The basic gneisses are vastly more deep-seated.

From among the varieties of the foliated component of the Gneiss proper, only the fine hard siliceous bands resemble anything found in the Bedded Succession, and they form an insignificant proportion of the Gneiss. All the biotite-gneisses are composed of far larger felspars and micas than we meet with in the maxima either of Holy Isle or of the Penmynydd Zone; while the minerals of the limestone also point to more deep-seated conditions and a higher temperature. The garnets are much larger, while sillimanite and idocrase are found in no other member of the Complex. Comparisons of the gneissic developments with those of Scotland have already been made (pp. 133, 142–3).

Ætiology of the metamorphism

The metasomatising agencies

These are somewhat various, chemically similar products being sometimes the result of more than one agency. Three kinds of silicification can be distinguished. One of them is essentially volcanic, being the geyseritic process that has locally affected the Fydlyn and the Church Bay Tuffs. Of another, which converted most of the purer quartz-sands into quartzites, the cause is not yet known. These processes were (p. 166) pene-contemporaneous, but the great separation of quartz which accompanies the formation of the Gwna Green-schist, and is a special feature of the Mona Complex, is dynam-anamorphic, and thus of much later date. Of the albitisation, haematisation, and 'occasional calcification of the spilitic lavas and tuffs all that need be noted here is that they are pene-contemporaneous. That the jasperisation of the cherts took place not long after their formation is (p. 166) certain, and so it may be connected with the wide-spread haematisation of the lavas. The dolomitisation and manganisation of the Gwna limestones is manifestly pre-diastrophic, and as it waxes with vulcanism, it would seem to have some connexion therewith. The serpentinisation of the peridotites we know (pp. 107–9) to have preceded the major secondary folding, and may reasonably be ascribed to the liberation of heated waters during the unrest of the interval between the recumbent and the subsequent movements. But their calcification seems to have been later; while de-dolomitisation (pp. 106, 137) appears to be in each case connected with regional anamorphism.

Thus the pene-contemporaneous changes (in so far as their origin is known) can reasonably be ascribed to volcanic, the subsequent changes to dynamic action.

The thermal agencies

The thermo-metamorphism is always dependent upon the Plutonic Intrusions; for the thermal effects of the small albite-diabases of the spilitic-suite have not yet been identified, owing to the confusion due to deformation. The effect of the Coedana granite seems to have been somewhat metasomatic, potassium-solutions having, apparently, proceeded from it. The original foliation of the granite may be fluidal. It should not be forgotten that the thermo-metamorphism, though quite independent of the regional dynam-anamorphism, is, ultimately, of dynamic origin. For the intrusions upon which it depends, having all appeared in an interval of the great movements, are manifestly in some way dependent on those movements, and thus, indirectly, products of dynamic action.

Catamorphic agencies

The great autoclastic mélange, which bears every mark of excessive shearing stress, is the work of thrusting in connexion with ternary and tessary folding, proceeding at levels where, for a time, the load was insufficient to induce recrystallisation, conditions which recurred with the buckling of successive recumbent folds. The other catamorphic processes all appear to belong to late stages of successive readjustment.

Dynamical origin of the regional anamorphism

That the regional anamorphism of the Mona Complex is of dynamic origin has been tacitly assumed throughout this work, and many phenomena pointing to that view hale been described in various connexions, but no attempt has been made at a systematic demonstration of the thesis. This is hardly legitimate, for although the dynamical theory of metamorphism is rapidly gaining general acceptance, many phenomena, are very imperfectly understood. Moreover, for the reasons given on p. 934, the Complex presents unusual advantages for the study of anamorphic aetiology. It is desirable, therefore, to consider the evidence.

General considerations — To begin with: no other *vera causa* is put forward. As for plutonic influence: the regional anamorphism is conspicuously independent of the plutonic intrusions. It develops to a maximum whether they are present or not; and their thermal products are of a totally different character, foliation disappearing as we penetrate the aureoles; while those aureoles are to a considerable extent destroyed by its development. If we postulate a general thermal condition of the planet which no longer obtains, we shall be met by the facts that crystalline schistosity is not the original state of any of the rocks, and that their original states do not indicate thermal conditions differing appreciably from those which obtain in the world to-day. Their sediments point to ordinary atmospheric processes; their fossils prove that the temperature of the ocean could not have been too high for the maintenance of life, while their volcanic rocks tell us that the earth-crust had arrived at much the same condition as that in which it still remains.<ref>The Pre-Cambrian age of so many crystalline schists often tempts one to suppose that special facilities for metamorphism must have prevailed in those times. A suggestion of Leith and Mead that the metamorphic cycle is not quite compensating, so that, though the *causes* of metamorphism have been the same in all ages, there has been a gradual accumulation of metamorphic products, may perhaps throw light on this. But it is uncertain yet whether the apparent excess of Pre-Cambrian over later metamorphism be not an illusion, and speculation on the subject is probably premature still, as we now *see* it to have been some 50 years ago.</ref>

On the other hand, no sooner do we step upon the soil of the Complex than we are confronted by signs of disturbance, of whose magnitude and all-pervading character we have attempted to convey some idea in Chapter 7; while in scarcely two square miles out of some 200 shall we fail to meet with some degree of anamorphism. The coincidence is so marked that it may well be held to place the burden of proof upon any who would deny the dynam-anamorphic theory, and might be held to constitute a demonstration but for one circumstance, which is that the conspicuous, external marks of disturbance, instead of waxing with waxing metamorphism, tend rather to become somewhat less conspicuous. To take a concrete example. The origin of the great breccia-like mélange of Gynfor is now manifest: but to ascribe to the very same process a sparkling, saccharoid schist from the heart of the Penmynydd Zone is to make an assertion that ealls for demonstration. If then, the theory be sound, we need to show that the tendency of dynamic agency in the Complex was to effect a progressive change in the nature of the process, and, after a certain stage had been attained, to develop structures which mask its initial character.

Evidence in the Bedded Succession — Let us, if at the cost of some repetition, review the principal successive stages. Where, as in parts of the Gynfor mélange, the harder autoclasts are approximately iso-diametral, it is evident that, however great the disruption, compressive shearing is at a minimum. A shearing component, however, is already present, for the fissile matrix displays, under the microscope, a lenticular structure. At this stage, authigenitic minerals have not, as yet, been detected with certainty.

The truth is that to say where catainorphism ends and anamorphism begins is almost impossible, for not only are the first microlithic germs of authigenitic minerals ultra-microscopic (so far, at any rate, as the powers usually employed in petrological instruments are concerned), but the same rock is frequently catamorphic as regards its coarser and anamorphic as regards its finer components. Cores of massive grit or deformed spilitic ellipsoids in autoclastic mélange often show no sign of internal recrystallisation while the schistose films that sweep round them are full of authigenitic flakes.

Now the stage at which such flakes begin to appear is, for our present purpose, of the utmost significance. It is the stage, found even in Gynfor, but far better developed in other districts, where the harder autoclasts begin to assume a lenticular form, and where we find undulose extinction, deformation of grains, and all the allied phenomena which are described on pp. 65–6, 193–5. The first signs of anamorphism thus appear concurrently with those of excessive shearing stress. There is no evidence whatever of any other agency, and it is abundantly clear that the crystallisation is due to a transformation of a portion of the mechanical energy into chemical readjustments.

Further: as deformation increases, not only do the new mineral flakes of lepidoblastic seams increase in size; but the original minerals within the lenticular autoclasts begin to lose their outlines, and then to recrystallise as elements of nemablastic mosaic. The orientation of both lepidoblastic and of nemablastic foliation is parallel to the direction of deformation as indicated by the major axes of the lenticular autoclasts, thus indicating that the direction of growth of new mineral elements, which determines the folial planes is also determined by the direction of the shearing stresses.

Up to this point we have been considering autoclastic mélange, and the product. is still, at one and the same time, both catamorphic and anamorphic. But, as we have shown on p. 69, there is an unbroken transition from this type into that which we have called the Gwna Green-schist, wherein catamorphism begins to be subordinate to anamorphism. The general structure is still lenticular, but distinct autoclastic lenticular cores of grit or spilite have disappeared, though, in the less altered portions of the belt, a few epiclastic grains of quartz are often to be found under the microscope. These are then absorbed, and with them disappears the last trace of the original textures of the rock. With them also disappear the last direct signs of mechanical stress, though an indirect sign thereof persists almost throughout the whole width of the belt, in the undulose extinction of the elements of the mosaic, which is intensely nemablastic. The basic igneous rocks, however (always so highly susceptible), have by this time lost every sign of catamorphism, and have developed clear granoblastic albite and needles of actinolite. Yet the foliation of all these products is one with that of the lepidoblastic seams of the mélange, and it is certain that the agency is the same in both cases; and can therefore be no other than shearing stress. We thus establish our thesis that this agent has developed crystalline foliation to such a degree as to completely mask the character of the initial stage of its own work.

But there is a final stage: that of the Penmynydd Zone, wherein, as we pass to it from Gwna Green-schist, undulose extinction disappears, and with it the last- trace of catamorphism. Nemablastic texture also vanishes, though lenticular structure, doubtless a legacy (for we cannot call it a trace) of deformation, still remains. There has taken place a rise (p. 124) to a far higher crystalline grade of intensity. The micas and amphiboles are large and well-developed, while new minerals of high temperature (such as brown mica, garnet, *&c., &c.*), have appeared, and the rocks are now true holo-crystalline schists. Yet it is certain (p. 124) that their foliation and crystallisation are as thoroughly one with those of Gwna Green-schist as are those of the latter with those of Gwna-mélange; and consequently that the agency at work (for there is not the slightest evidence of any other, but rather the contrary<ref>The phenomena described on p. 127 prevent our ascribing the Penmynydd metamorphism to expansion set up by direct thermal action. Moreover, if stress had been set up in that way, the orthoclase of the inner parts of the hornfels aureole would surely have been destroyed.</ref>), is the same in all three cases. It follows that the phenomena of the Penmynydd Zone, and thus the maximum anamorphism of the Middle and Aethwy Regions and the Pentraeth Inliers (which is exceeded only by the Gneisses), must be ascribed solely to dynamic agencies.

In the Northern Region (p. 204) we can also pass from an auto-clastic mélange, without any folial break (p. 160, &c.), into feebly anamorphic rocks, and from them into the crystalline schists of the Llanfflewyn maximum. But instead of the Gwna Green-schist we find the massive though foliated Church Bay Tuffs; and the phenomena as a whole are less striking, for not only is the advance in crystallisation spread over a much wider belt, but the maximum attained is lower, so that the rate of change is far less rapid. The same is the case at the Garn and Fydlyn Inliers, but the maximum attained is lower still; very much lower, indeed, at Fydlyn. Nevertheless, the principle is precisely the same; the foliation is one with the structures in a catamorphic mélange. Moreover, in the Amlwch Beds, whose crystallisation is far advanced, we find that the foliation develops along and parallel to a system of minor thrusts (Figure 65). Foliation is also developed on the thrusts (Figure 142), which bisect and displace the hard pebbles of the Trwyn-bychan rocks. In the Skerries Grits, finally, we find an interesting confirmation. These rocks have (pp. 61–2), advanced to a degree of anamorphism which has produced in certain zones a chloritic mica-schist with needles of actinolite; and in such zones their boulders have been drawn out (Figure 3) into thin lenticular strips, whose major axes lie along the foliation, so that it is perfectly clear that the crystallisation is the work of the same agency that flattened out the boulders. In this region, therefore, the whole of the anamorphism is manifestly the work of dynamic action.

In the Western Region its relations to the Gwna mélange are again (p. 204) the same, though with a very feeble development on the northern side of the dense mass of the Church Bay Tuffs. Fortunately, there is no need to labour the point, for we have already seen (p. 198) that the foliation of the region is a development of the Valley thrust-planes, and is, accordingly, of dynamic origin.

Holy Isle differs from all the rest in that it is highly crystalline throughout. Yet, as the Valley thrust-planes constitute no hiatus, we seem justified in regarding it as a downward continuation of the phenomena of the Western Region. But were that not the case, there is independent evidence. In the bi-planic rocks of the South Stack Series, the foliation is parallel to the axial planes of the major folds, to which it is manifestly related. Now the burrow-castings of *Scolithus* are (Figure 103) deformed along this foliation, as well as driven somewhat out of their original position of verticality to the bedding. The castings of *Planolites* which occur in the more fissile beds are drawn out along the foliation, and so are the small pebbles in the Soldier's Point beds. In the Tre-Arddur Gap foliation is seen (Figure 63) to develop along minor thrusts, which break the folding. The circumstances were different, for in this region autoclastic mélange is absent and thrusting subordinate, pure unruptured folding being the rule. But it is as certain as in all the other regions that the crystalline anamorphism (which is a maximum, equalling that of the Penmynydd Zone) is of dynamic origin, and is a product of the folding.

Evidence in the Gneisses — Catamorphism is totally absent in this case, and though there is folding, its laws have not yet been discovered. Nevertheless, in the successive stages of development of the hornblende-gneiss (pp. 131–3) we meet with unequivocal proofs of deformation after consolidation, and of the development of a crystalline foliation parallel to the direction of deformation. Now, when the hornblendic and micaceous gneisses are seen together, the divisional planes are common to the two. It is a legitimate inference, therefore, that the foliation of the micaceous gneisses also is dependent upon and its direction determined by dynamic agencies. Nevertheless, differences from pure dynamic anamorphism can be observed. The permeation-granites, however intimate their union, do not appear to be themselves deformed. The sillimanite is manifestly due to thermal influence exerted by these granites; and its disposition is of an ambiguous nature, its needles manifesting an independence of the foliation-planes, and occasionally forming stellate groups. Yet the excessive intimacy of the granitic permeation implies conditions very different from those of normal intrusion; and certainly the gneissic textures are quite different from that of even the most crystalline hornfels in the Complex. While we must admit that an adequate theory of gneissic development , is not yet within the reach of geological science, we can discern that both dynamic and thermal agencies have played a part, and some such term as 'Dynamo-thermal anamorphism'<ref>'Thermo-dynamic' is excluded because of its well known use in physics.</ref> may perhaps be suggested.

Conclusion — It is thus not too much to say that the whole of the regional anamorphism of the Mona Complex can be demonstrated to be of dynamic origin. In that of the Gneisses dynamic has been in some way combined with direct thermal action. But in the whole of the remainder of the Complex none but dynamic agency can be admitted.

Foliation and folding

We have seen (pp. 907–8) that the regional metamorphism must be ascribed to the secondary, ternary, and tessary movements. The various dips and strikes of the foliation (pp. 201–5, (Figure 101)) are in harmony with this, indicating that the directions of growth of the principal foliation-minerals, such as micas, chlorites, and amphiboles, are intimately related to the varying directions of dynamical stress. They express, in fact, the 'reactions between the external stress exerted by folding and the internal stress exerted by the habits of growth of those minerals. In bi-planic rocks, the nature of this reaction is not difficult to understand. It is intelligible also (p. 902) in unfolded mono-planic rocks. In the case of rapidly folded mono-planic rocks we have (pp. 902–3) attempted an explanation. But the curious anomalies of the Aethwy Region (pp. 228–30) indicate that the reactions of a group of rocks crystallising under stress can be extremely complex; and it may be that satisfactory chemico-physical explanations will not be arrived at for some time to come.

Ætiology of the textures

The several types of crystallo-blastic texture have been enumerated on pp. 143–4, but without any discussion of the several stages of anamorphism at which they are produced.

The thermal action always gives rise to some grade of granoblastic texture, which has a wide range from crypto- to coarsely phenocrystalline, and at the latter stage, porphyroblastic (occasionally also poicilo- and diablastic) developments are not uncommon.

Dynamo-catamorphism pure and simple, while producing (in the nature of the case) no crystalline texture of its own, produces a great variety of residual structures; but these are of greater interest when recrystallisation has begun. Excluding the breccias of the final settlement-faults, almost the whole of the catamorphism of the Mona Complex has resulted in lenticular structure, which has a very wide range of scale.

Anamorphism — Residual structures are still frequent, but are of course more so at low grades of reconstruction. They differ from those in purely catamorphic rocks in that crystalline union has now been brought about between the relict and the crystalloblastic matrix by which it is surrounded. Sometimes the relict is invaded by the mosaic in a succession of corrosion-bays, sometimes penetrated by the foliation-micas, while weathered relicts have been rejuvenated externally. Relicts of different kinds vary greatly in their powers of survival. Blasto-pelitic structure is, indeed, almost unknown, for pelitic rocks yield a fine lepidoblastic schist at the very earliest stages of recrystallisation. The next to succumb are the blasto-granitic, blast-ophitic, and blasto-porphyritic, because the chemical composition of igneous rocks lends itself to recrystallisation much more readily than does that of sedimentary rocks. The blasto-psammitic and blasto-psephitic structures display a surprising power of survival, being found even low down in the anamorphic horizon of Holy Isle. The conditions respectively favourable and hostile to them will be discussed below. Blasto-venous structures are exceptional, for as the separation of quartz is part of the anamorphic process, its incorporation may take place at several successive stages of that process.

Of the truly holocrystalline textures, the lepidoblastic is the first to develop, for it appears at the first stages of reconstruction in the fissile matrix of autoclastic mélange. The nemablastic texture first appears a trifle later, when crystallisation begins to invade the hard autoclasts, and, waxing, is especially characteristic of green-schist', wherein it attains a high degree of intensity. It is manifestly a product of the peculiar circumstances of the belt of passage from catamorphic to anamorphic conditions. The first appearance of granoblastic texture is also in the green-schist', as well as in the Trwyn-bychan rocks of the north, but it remains crypto-crystalline until we pass to the succeeding stage. It is beautifully developed in all the anamorphic maxima of the Island. The Penmynydd maximum differs from the others, however, in that lenticular foliation or flaser-structure is very common in its mica-schists, whereas it is rare in the mica-schists of Holy Isle and the west, a difference which will be discussed below. Porphyroblasts and other exceptional structures also belong mainly to the Penmynydd maxima; but the texture we have termed encarsioblastic is mainly developed in the anamorphic maximum of the low tectonic horizons of Holy Isle. The. textures of the Grneisses may perhaps be termed grano-blastic, lepidoblastic, and porphyroblastic, and they are frequently lenticular. But they are seldom wholly folial, they tend also to graduate into the granitoid, and must be regarded as special modifications due to dynamo-thermal conditions.

The two paths of intensification

Anamorphic intensification in the Mona Complex takes place along two paths or lines of development which are quite independent of each other; and which differ considerably both in mode of operation and in the kind of modification they produce. The metamorphism of the north and west culminates in the maximum of Holy Isle. That of the middle and Aethwy culminates in the Penmynydd maximum. Let us call them H. and P. respectively. Then we shall find:

1. That whereas true Green-schist' is quite subordinate in H., it is developed on a great scale in P.
2. That nemablastic texture and lenticular foliation, highly characteristic of P., are almost absent in H.
3. That whereas original structures (such as bedding, clastic grains, varioles, spilitic ellipsoids, &c.), survive even in the maximum of H., they are obliterated in P. before the maximum is reached.
4. That whereas the rate of intensification is gradual and steady in H., it is spasmodic in P. This might be expressed graphically. We should then find that the curve of intensification in H. would approximate to a straight line rising at a moderate angle. But that the curve in P. would be sigmoidal, rising at first very gently, then steepening very suddenly, and then rising again very gently to the maximum.<ref>I have not attempted to give a drawing of these curves here,

because, with our present knowledge, they could only be sketched in a very generalised way. I am not without hope, however, that the tectonic and other obstacles may be overcome to some extent before long, so that the curves might be drawn from at any rate approximate measurements.</ref>

5. But that the ranges are nearly equal, for the lowest term both in H. and P. is autoclastic mélange, and intensity differs but little in the two maxima.

It is clear that the cardinal difference is No. 4, so that if we can find an explanation of the rapid steepening of the curve, the other contrasts will also find an explanation. A partial one is given on pp. 126–7, but it does not account completely for the third contrast, the basic rocks involved in 'Green-schist' losing their original textures even more rapidly than do the sediments. The steepening is at the nemablastic belt. Why is that absent in H.? The reason would seem to be found in facies; for in H. we have the thick and almost homogeneous mass of the Church Bay Tuffs, which is absent in P. This dense mass offered great resistance to the destructive shearing which produces autoclastic mélange. That process, accordingly, checked in H., was allowed great freedom in P., leaving its marks in the nemablastic texture of the Green-schist, and in the lenticular foliation of the mica-schists even or the maximum. Combine this with the view put forward on pp. 198–200, and it will appear that whereas P. was imposed upon rocks that had already been catamorphically broken down by shearing stress, H. was imposed upon rocks that had been protected from this process. In the maximum of P. shearing is dominant: in that of H., unruptured folding is dominant. It thus appears that catamorphic destruction saps the stability of rocks, and prepares them to take on crystalloblastic textures. Accordingly, in H., the curve rises very steadily, and residual structures are able. to survive even in the maximum. In P., the curve rises very steeply, and relicts are obliterated even before the maximum is reached. Combine this again with the proposition (pp. 126–7) that highly susceptible felsitic material was presented to the P. maximum, and the series of curious contrasts between P. and H. receive what seems a satisfactory explanation.

Tectonics and anamorphism: a correlation

The regional anamorphism having thus been shown to be the work of dynamic agencies, what were those agencies, and what are we able to discern of the relations between them and their anamorphic results? There are two distinct series: those of the Ancient Floor and those of the remainder of the Complex.

Of the elder series, all we can say is that, as the Gneisses are visibly folded here and there, a connexion is to be assumed between this folding and their anamorphism. But we know far too little to be able, as yet, to correlate crystallisation with dynamics in this case.

With regard to the remainder of the Complex, it is of course manifest that the dynamic agencies in question are those which found their other form of expression in the remarkable structures described in Chapter 7. Here we can establish a correlation, for we have found (pp. 907–8) that the regional anamorphism is a work, not of the recumbent, but of the secondary, ternary, and tessary foldings; a correlation which finds confirmation in the principle that it is not free but frustrated movement which gives rise to molecular activity. Frustration, moreover, varied greatly in different parts of the geographical extent of each tectonic horizon as it was being buckled-up, and in different parts of them, accordingly, we find that different degrees of intensity were developed. In harmony with the same principle, too, we find in the Complex two types of anamorphism, differing somewhat according as the rocks had been previously protected from or exposed to catamorphic shearing, though intensity differs but little in their two maxima.

Upon the dynamical theory, we should expect not only that anamorphism would vary with power of impulse and with its frustration, but that, given equal dynamical conditions, it would prove to be a function of depth. And this, from purely geological considerations, we have found to be the case. Anamorphism has been shown ((Figure 101)B and pp. 237–41) to be completely independent both of stratigraphical horizon and geographical direction; but to be conditioned strictly by tectonic horizon. Wherever crystallisation waxes, wherever it heals up and replaces rupture, we are descending in tectonic horizon.

'Depth', however, needs to be understood in a special sense. It is not (pp. 909–10) to be measured by the whole of the cover that was eventually imposed by the sum total of the successive recumbent foldings; but strictly and only by the cover overlying any given tectonic horizon, at the time when it was undergoing recrystallisation. For there is geological evidence (p. 909) that the secondary and subsequent foldings were not confined to a single episode, but that each recumbent fold was driven together under a moving weight, while the one above it was developing. So that each new tectonic horizon underwent anamorphism in connexion only with its own buckling and compression. Further, when the process recurred, the effects already produced lower down were not affected. Thus: when the Rhoscolyn and Holyhead recumbent folds were crystallising, the Bodorgan recumbent fold does not seem to have existed. When the Bodorgan fold began to crystallise, the crystallisation of the two lower folds does not seem to have been intensified. Accordingly we obtain a Metamorphic Succession (p. 241), wherein we encounter the surprising and apparently anomalous phenomenon that, after having risen from an horizon of maximum to one of minimum anamorphism, we begin again with another horizon of maximum and rise once more to one of minimum, and yet the law of depth is never violated. In other words, each tectonic horizon seems capable, as we descend through it, of repeating a portion of the metamorphic cycle.

The metamorphism in space and time

Its geographical extent

Unless we make the incredible assumption that metamorphism was universal in the earth-crust, it is clear that limits to the Mona Complex, considered as a tract of crystallisation, must have existed somewhere or other, outside which its rocks escaped from changes of the kind. There is a natural tendency in the mind to look for those limits at the confines of the Island; and it happens that certain phenomena of the two coasts that are approximately strike-sections lend themselves to this expectation. For on the north and on the Menai (Figure 101)B we find anamorphic minima, suggesting that we have reached the limits of the crystalline area. Both cases are illusory. High grades as well as low grades occur along the Menai shores, and extend even further to the south-east than do the low ones. In the north, metamorphism is considerably higher on the islet of the Middle Mouse than it is on the sea-cliffs of Gynfor, showing that after sinking to a minimum, intensity is rising again beyond the confines of Anglesey, which might, indeed, have been expected, from the magnitude of the Carmel Head thrust-plane. Moreover, we meet with anamorphic minima at intervals (Figure 101)B all across the Island. In fact, as was remarked on p. 240, anamorphism is quite independent of geographical direction. Further, the pebbles of crystalline schists in the Cambrian rocks of the Harlech anticline, which are suspected to have come from an easterly direction, show that we have not reached a limit even there. We have, indeed, as yet no clue whatever to the extent of the metamorphic area.

The peculiar distribution of the metamorphism is of more than local interest, for it raises the question as to whether we ever see the limits of any of our British metamorphic areas, even along such a line as the south-eastern border of the Scottish Highlands. This memoir is not, of course, the place for discussion of those districts. But attention may be invited to the following consideration. Suppose that the Berw faulting had never taken place, and that, consequently, the Aethwy Region, with its high grade of anamor-phism, had remained buried beneath Carboniferous and Ordovician rocks. Ignorant of that, but noting the gradual eastward waning of crystallisation in the Middle Region till it nearly dies away along the south-eastern margin of that region, how easily we might have persuaded ourselves that we had found the true south-eastern limit of the whole of the metamorphic area. And we should have been utterly mistaken! The lesson of the Mona Complex in this particular is that to reach a narrow belt of no metamorphism is not enough. Before we can assign geographic limits to any tract of regional metamorphism we must trace the stratigraphical horizons affected by it out into some tract of considerable width wherein they are unaffected, wherein, moreover, the signs of shearing stress have also died away, and the tectonics are of a different order.

Its chronology

We are now able to expand the brief summary which was given on p. 205.

The oldest process of which we can detect any traces is the dynam-anamorphism of the rocks of the Ancient Floor; for the abyssal dynamo-thermal process (wherewith dedolomitisation seems to have been connected) appears to have been subsequent.

After a long interval, the next change is the geyseritic silicification of the Fydlyn rocks, and then came the quartzitisation, jasperisation, albitisation, hamatisation, calcification, dolomitisation, and manganisation of the several varied members of the Gwna Group. Then the Church Bay Tuffs were locally silicified, the spilites of the New Harbour Group albitised, and (probably) the Holyhead Quartzite quartzitised. All these metasomatic processes were pene-contemporaneous.

The first real metamorphism of the Bedded Succession was that which was induced by the Rhoscolyn and Holyhead Recumbent Folding. Slight though it seems to have been, there is reason to think that it brought the rocks into a more susceptible condition.

It was followed by the production of a succession of thermal aureoles, first those of the peridotites and their associates, then those of the diorites, and finally the extensive aureole (and intense crystallisation of the xenoliths) of the Coedana granite; not long after which came the serpentinisation of tfie peridotites.

We then enter upon the successive stages of the great regional dynam-anatnorphism, which is due to the secondary, ternary, and tessary movements. The earliest known to us is that due to the buckling of the Rhoscolyn and Holyhead recumbent folds, which appear to have been buckled both together, as their foliation seems to be one and the same. This gave us the maximum of Holy Isle, and apparently also that of Llanfflewyn, with the whole of the crystallisation of the Northern Inliers and the Northern Region. Then followed the Valley thrusting and the development of the foliation of the Western Region. The precise order of events is now difficult to be sure of, but in any case the Bodorgan recumbent folding must have taken place about or probably after that time. Its final buckling does not seem to have taken place until (p. 200) a higher recumbent fold had rolled over it, but that buckling developed the Penmynydd anamor-phism. Then followed the catamorphic mylonites and faintly schistose breccias, and finally the settlement-fault-breccias, some of which may even be later than a portion of the great erosion. But even these are to be regarded as of Pre-Cambrian age.

Recapitulation

Five different agencies of change, Metasomatism, Thermo-Metamorphism, Dynamo-Catamorphism, Dynam-Anamorphism, and Dynamo-Thermal Anamorphism, contributed to bring the rocks of the Mona Complex into the condition in which they were left at the dawn of Cambrian time. The term 'Regional' ought perhaps to be applied to the result of all combined, but the most influential, without which none of the others would have produced a regional effect, is undoubtedly the fourth. The pene-contemporaneous changes, being apparently due to the volcanic agencies, may be regarded (p. 898) as connected, ultimately, with geosynclinal or vertical movement. All the subsequent changes are directly or indirectly connected with tangential movement. It is thus interesting to note that the whole of the long and varied series of transformations is traceable, in the last resort, to dynamic impulse of one sort or another.

Summarising their effects, it may be said that complete absence of anamorphism is confined to very small portions of the Complex, that tracts of low, moderate, and high intensity are approximately equal to each other in extent, and that its maxima are of about the same intensity as that of large tracts of 'Moine-gneiss' type in the Scottish Highlands. Then we find a hiatus in intensification, for the gneissic anamorphism is isolated, so that we miss the types across which we pass as we approach a Scottish tract of granitisation; but the intensity attained is equal to that of the Scottish tracts in question.

The regional anamorphism can be correlated with the secondary and subordinate foldings, and varies greatly both in intensity and in character, according to local circumstances. Though dependent upon depth, it was able to recur as soon as similar conditions recurred in the course of the recumbent holding. Thus we obtain a metamorphic succession, and can begin to trace out an order in time. We have, as yet, no clue to the extent of the area affected. But, within that area, the geographical distribution of the crystalline intensity is due to the combined effects of the metamorphic succession, of the major secondary folding of the Complex itself, of the great movements of Paleozoic and later time, and of repeated denudation.

General and regional ætiology

Signs are not lacking that the study of metamorphism is on the point of making a fresh advance, comparable in importance to that which ensued, some 35 years since, upon the application of the dynamical theory.. In the hands of

Leith and Mead, Van Elise, Adams, Harker, and others, the implications of that theory are being unrolled, and a number of chemico-physical principles are beginning to be applied.

Among them we find such subjects as the chemical stability of minerals under given conditions, and the question of chemical equilibrium as expressed by mineral groups in rocks; the effects of minute quantities of solvents, and their behaviour above the critical temperature. Others concern the nature of the flow of solids, the strengths of minerals, the modifications of shearing stress on low horizons, and the true nature of solidity'. One of the most curious is the internal mechanical stress exerted by crystalline growth, in virtue of which a rock undergoing anamorphism plays not merely a passive but an active part. Especial attention may be drawn to the remarkable results obtained by Roberts-Austen on molecular activity in solids under quite moderate temperatures and pressures, results which seem to have been hardly appreciated as yet in their application to geology. For what, in such case, must be the chemical activity at high temperatures and pressures, especially high shearing pressures. It is to be noted, however, that most of these principles are but imperfectly understood, so that they cannot yet be applied *a priori.* Now, temperature and stress are admittedly the governing conditions. Can we, then, hope to apply chemico-physical principles with success to any given region until we have determined the true nature and chronology of the tectonics, the peculiar meaning and chronology of depth', the varying character and intensity of stress on different tectonic horizons and in different places, the relative ages of the intrusions, with many other local circumstances; and have correlated the metamorphic with all these phenomena? For general application of the principles, *a priori,* do we not need to have determined the said relations in a considerable number of regions? In other words; chemico-physical theory, while full of illuminating suggestion, continually infusing fresh life into research, cannot, considered as a whole, outrun precise geological knowledge of particular metamorphic areas. Such knowledge we have begun to reach out after in the particular case of the Mona Complex. And, as is but too patent in the foregoing pages, we have found it by no means easy to achieve, and very far from having been achieved. Our concept, even of this Complex, will, without doubt, be greatly corrected and expanded,

'Yet all experience is an arch, wherethrough

Gleams that untravelled world, whose margin fades

For ever and for ever when we move'.

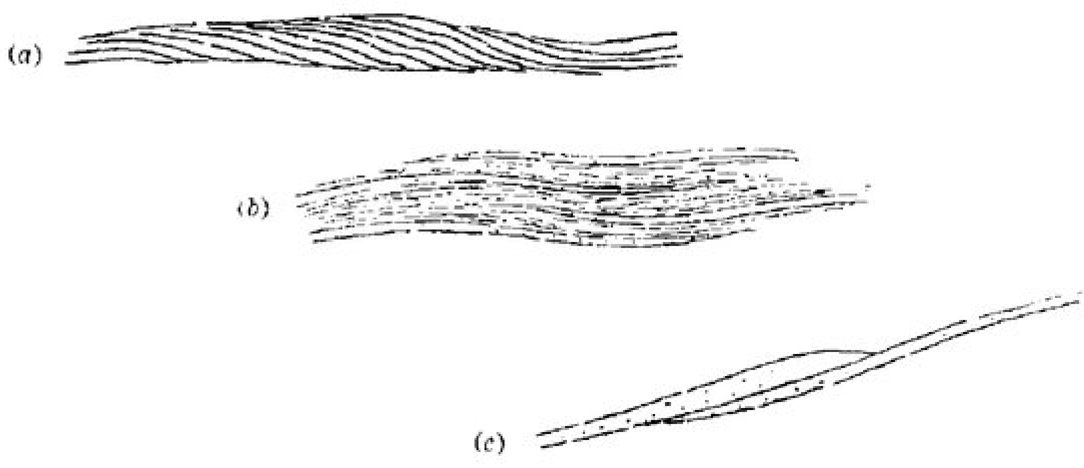


FIG. 65.--STRUCTURES IN THE AMLWCH BEDS.

(Figure 65) Structures in the Amlwch Beds. (a) West-south-west of Graig-ddu. (b) Porth-y-gwartheg. (c) About 250 yards west-north-west of 'Cave', Bull Bay.

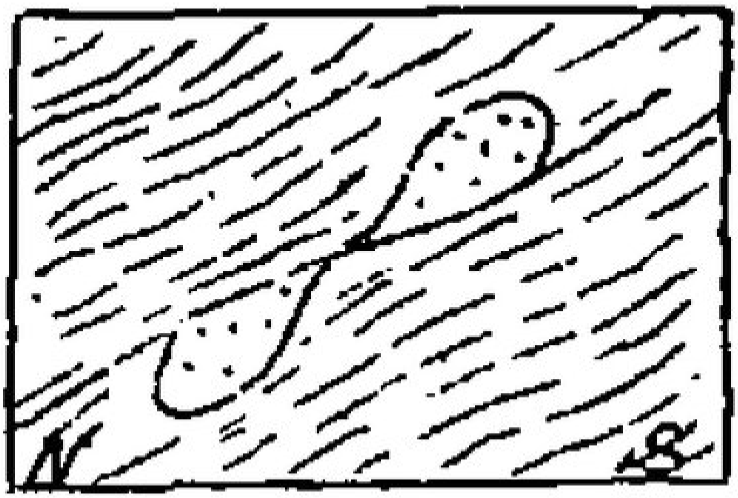


FIG. 142.

QUARTZITE PEBBLE BISECTED ALONG FOLIATION OF TUFFS.

(Figure 142) Quartzite pebble bisected along foliation of tuffs. Trwyn Bychan.

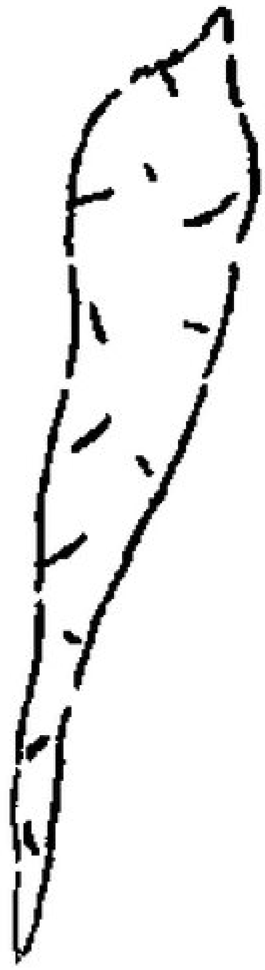


FIG. 3.

(Figure 3) Deformed boulder. 8 inches long. The Skerries.

FIG. 103.
DEFLECTION OF
SCOLITHUS PIPES.

(Figure 103) Deflection of the Scolithus pipes.

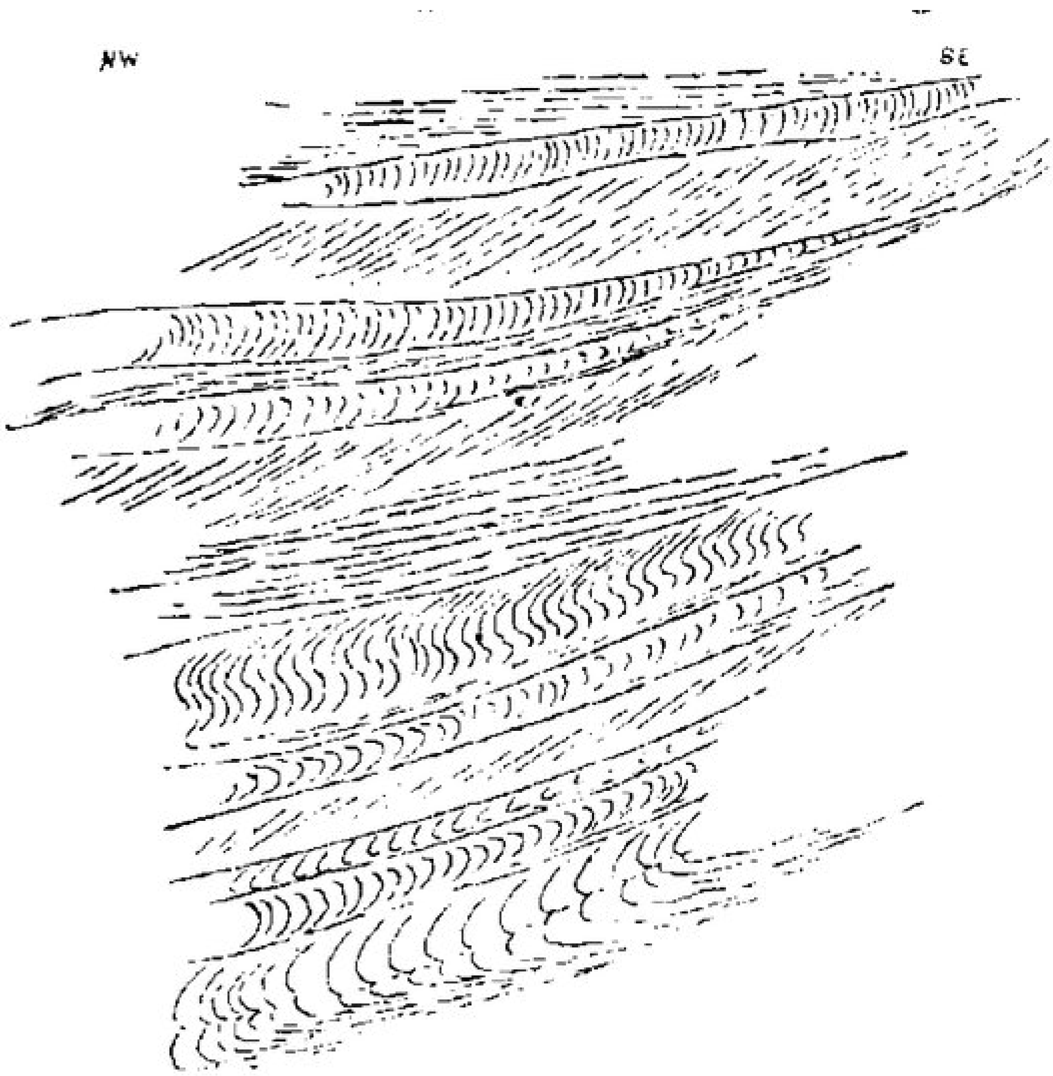
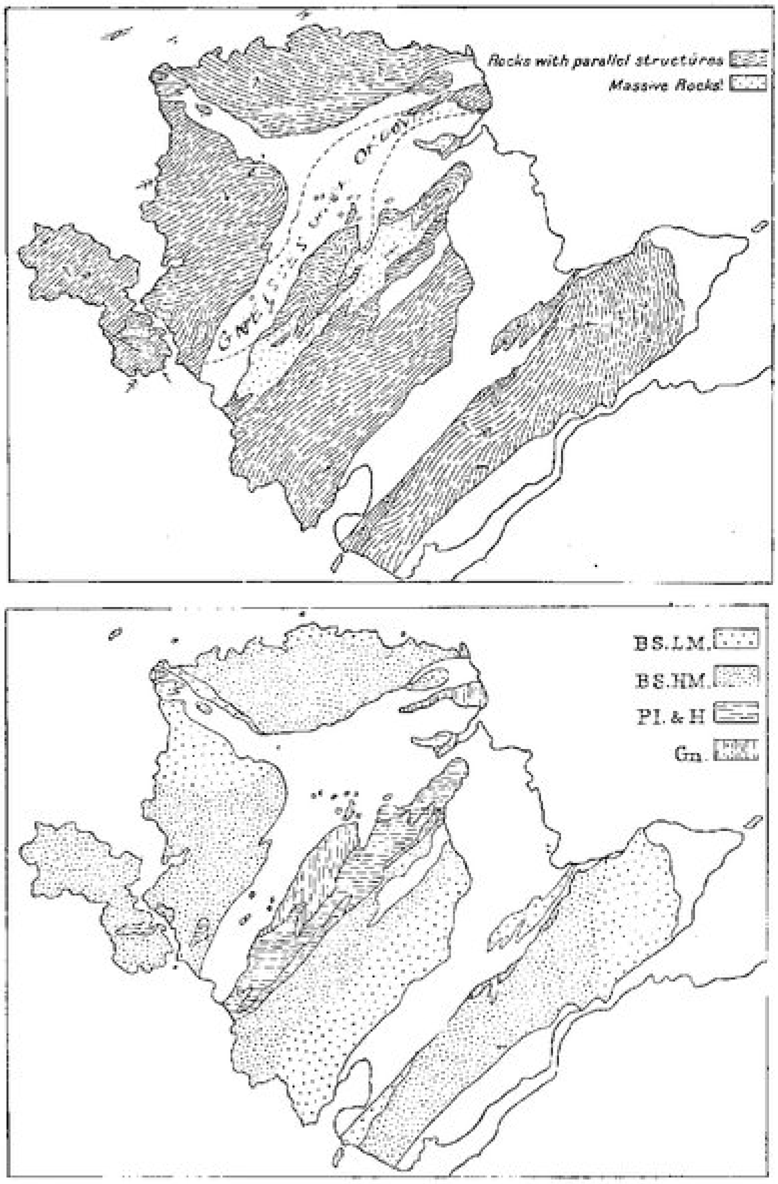


FIG. 63.

(Figure 63) Minor thrusts in the Tre-Ardour Zone. Foot of crag, south-east of Gareg-fawr. Height about nine inches.



(Figure 101) a. Chart showing the general directions of strike and other structures in the Mona Complex. Scale: 1 inch = 6 miles. 101B Chart showing the distribution of the metamorphism in the Mona Complex. Scale: 1 inch = 6 miles. BS. LM. = Bedded Succession, Low Metamorphism. BS. HM. = Bedded Succession. High Metamorphism. PI. & H. = Plutonic Intrusions and Hornfels. Gn. Gneisses. Note: To bring out the waxings and wanings. delicate gradations of stipple would be required that could not he applied to a small-scale chart. The chart here given ignores all gradation, and minor complications, but shows at a glance the general distribution of the metamorphism.