25. *On the OCCURRENCE of SILURIAN [?] ROCKS in FORFARSHIRE and KINCARDINESHIRE along the EASTERN BORDER of the HIGHLANDS.*¹
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I. THE MODE OF OCCURRENCE OF THE ROCKS.

ALONG the south-eastern border of the Highlands, between Blairgowrie and Stenichaven, a remarkable group of rocks has been mapped in the course of the geological survey of that region. They occur as isolated lenticular strips, which intervene between the schistose rocks of the Highlands on the north-west and the boundary-fault that truncates the Old Red Sandstone on the south-east. The first and largest of these lenticular strips is about 20 miles long, extending almost from Cortachy in Forfarshire to about a mile beyond the Clattering Bridge in Kincardineshire. In the valley of the North Esk it is about $\frac{3}{4}$ mile broad, but elsewhere much narrower. The second lenticular mass begins at a point about a mile north of Drumtochty Castle, and stretches for 6 miles in a north-easterly direction to the Braes of Bervie. Part of a third strip is shown on the eastern margin of Sheet 66 of the 1-inch Geological Survey Map of Scotland, on the north side of the Highland Fault. The lenticular mode of occurrence of these rocks is due to the alternate approximation and recession of their northern margin from the great fault which everywhere forms their southern boundary.

II. THEIR LITHOLOGICAL CHARACTERS AND ORDER OF SUCCESSION.

Notwithstanding the mechanical deformation which these rocks have more or less undergone, we are still able to ascertain their original characters and mutual relations. They may be arranged in two divisions, namely:—(1) the Jasper and Green-Rock Series; and (2) the younger Margie Series.

Section in the North Esk River. (Fig. 1, p. 330.)

An almost complete section of the whole series is exposed in the North Esk, though parts are visible only when the river is low. Beginning at Gannochy Bridge, near Edzell, and proceeding northward, we traverse an almost continuous section of Old Red

¹ Communicated by permission of the Director of H.M. Geological Survey.

Conglomerate for about a mile, and thereafter the Lintrathen porphyrite. Immediately to the north of the latter igneous mass the rocks now to be described appear. The section is divisible into three parts.

The first and southernmost—about 400 yards long—is best seen when the river is low. The strata consist of sandstones or grits, reddish or pale brown on a weathered surface, but almost white in fresh fracture. Their milky-white aspect is due to the matrix being composed of carbonate of iron and lime, which effervesces briskly with acid. The pebbles in these grits may be seen by the eye, though at this locality they are rarely as big as peas. Some thin bands of white, grey, and chocolate-coloured shales are associated with these grits, which are sometimes cleaved. The characteristic feature of these shales, however, is the occurrence in them of original clastic micas, which serves to distinguish them from the Highland slates with which they were formerly grouped. Both shales and grits are seen to lie at all angles in the bed of the river, sometimes nearly vertical, sometimes almost horizontal. Local lines of shear or crush are frequently met with. Nevertheless a close examination of the section leads to the belief that the actual thickness of the strata is small.

At the northern end of this part of the section are two dykes of dolerite, probably of Tertiary age, and on the north side of the second dyke the curious pebbly limestone (Margie Limestone) was formerly noted by Lieut.-Col. Imrie. It is no longer visible, being now covered by river-gravel.

From the foregoing description it appears that the first part of the North Esk section exposes the members of the Margie Series, consisting of grits, shales, and a little band of pebbly limestone.

The second part of the North Esk section begins on the north side of the second dolerite-dyke just referred to, where a wall-like mass of rock crosses the river (see fig. 1, p. 330). The latter consists of a confused mass of jasper, calc-jasper, and Green Rock, which has obviously been subjected to intense dynamic action. The wall-like mass is followed by much deformed Green Rock, becoming more massive farther north, which, on examination, is found to be a crushed and decomposed basic igneous rock. Northward some thin bands of brittle red jasper are infolded with the igneous rock, and still farther up stream there is a considerable mass of jasper. On the sides of the rocky gorge the observer may note that the rocks are isoclinally folded, the limbs of the folds being nearly vertical; and it may further be seen that the increased thickness of the jasper is mainly due to repetition by folding. Moreover, the mode of occurrence of the jasper in the folds of the Green Rock shows that it is stratigraphically above that rock. Northward, some phyllite occurs, which, from the evidence in the gorge, is stratigraphically above the jasper. At the bend of the river, at the northern end of the Wood of the Burn, some interesting rocks appear, which will be described in the forthcoming Geological

Fig. 1.—Diagrammatic Section about the North Esk. (See Geol. Surv. 1-inch Map, Sheet 66.)

Survey memoir on that district. Beyond the bend for 250 yards, the river flows over Green Rock with numerous small vertical in-folds of jasper.

The dominant member of the series displayed in the second or central part of the North Esk section is a more or less crushed basic igneous rock, to which the name Green Rock has been applied, owing to the persistent green colour produced by deformation. Jasper and jaspersy phyllite are so constantly associated with these igneous rocks that the name Jasper and Green-Rock Series seems appropriate. It may here be noted that neither in the North Esk section, nor at any other locality in that region, is the base of this series visible; indeed, there can be little doubt that denudation has exposed only the top of what may possibly be a complicated series of igneous rocks.

The third part of the section in the North Esk begins at a point about 250 yards above the sharp bend already mentioned. Immediately to the north of the Green Rock is a coarse green conglomerate, made up of the underlying igneous materials, together with numerous small fragments of red jasper. The conglomerate is traversed by small planes of movement, and a more persistent movement-plane occurs at its base, where calcareous material has accumulated. The upward succession can be studied only when the river is low. Next in order comes a green grit, which heralds the beginning of the Margie Grits. As we ascend in the series the pebbles in these grits become smaller and the proportion of cementing-material becomes

greater, till a fairly thick band of shale is reached, which is followed by chocolate-coloured and dark-grey shale, the latter containing some carbonaceous material. Northward appears the band of pebbly limestone, which was formerly quarried here. A small band of dark shale runs through the quarry, being the highest visible member of the Margie Series in this section. Still farther north the limestone is repeated by folding, with a persistent dip to the north-west; but the strata are there inverted, for the shale-bands reappear, though in reverse order. Here the third part of this interesting section ends, for the shales are in conjunction with the slates of the Highland Series.

The many excellent sections north-east of the North Esk add little to our knowledge of the succession of these rocks. Moreover, with one notable exception, no fossils have been found in them, and it therefore became necessary to determine accurately their lithological characters, a summary of which is now given.

The Margie Series.

A characteristic feature of the whole group is the presence, often in considerable quantity, of white and brown clastic mica. Where the grits are much crushed there is some difficulty in recognizing them. The occurrence of these micas is, however, of importance, as they serve to distinguish the cleaved Margie Shale from the Highland Slate, in which, so far as this district is concerned, no such micas have been detected.

The pebbles in the grits consist of quartz and felspar, the former predominating. The felspar-pebbles consist almost entirely of oligoclase; this, where the rock is not decomposed, possesses the remarkable freshness that is known to characterize the oligoclase of the metamorphic series. This felspar abounds in the adjacent Highland rocks, and probably has been derived from them. The quartz-pebbles may have been obtained from the quartz-segregations so abundant in the Highland Schists.

As already indicated, the green conglomerate at the base of the Margie Series is composed of the detritus of the green igneous rock (Jasper and Green-Rock Series) and contains abundant pebbles, indeed, in places, boulders of that rock. Fragments of jasper are met with in the outcrop in the North Esk, but not in the exposure in the Kirkton Burn, about a mile to the north-east. Some of the larger boulders so closely resemble the basic lamprophyres met with in the Highlands that it was supposed they might be derived from that source; but more recent investigation has shown that a similar rock occurs among the Green Rocks, though this special type is not known in the North Esk district. The origin and local character of the green conglomerate is obvious, and attention has been drawn to the probable local origin of the pebbles in the grits. The carbonate-cement in the grits is probably also of local origin, for it may have been derived from the lime and iron set free by the decomposition of the basic igneous rocks (the Green Rocks).

The Jasper and Green-Rock Series.

The highest known member of this series consists of rather fine-grained sandstones, which, in a little stream near Brawliemuir, are infolded with the originally underlying shale. They differ from the Margie Grits, owing to the abundance of microcline in some parts of them, which has not yet been detected in these grits. Microcline is very rare in the Highland rocks near this locality, so that these sandstones have probably had a less local origin than the Margie Grits. This conclusion is strengthened by the nature of the underlying grey slaty shale, which has always a deceptively crystalline aspect. Thin microscopic sections of the latter rock show that it is less crystalline than many shales of the Coal-Measures; its finely crystalline aspect is due to the fact that it is built up mainly of minute clastic micas, embedded in a matrix of decomposed micaceous material, in which movement would take place with great facility. The clastic micas are so extremely small as to make it certain that the materials were laid down on the sea-floor near the edge of the zone of sedimentation, or on an area where deposition proceeded with extreme slowness.

The probable deep-water origin of this grey shale is confirmed by the fact that it overlies a bed of jasper, in which my colleague Mr. Peach detected circular bodies resembling the radiolaria in the cherts of the Southern Uplands. Only at one place, however, have radiolaria been detected in the jaspery chert, notwithstanding its great development in this region. Though the jasper is rarely sheared, it is usually much shattered, the lines of fracture being filled with quartz, which is always more coarsely crystalline than that in the jasper, and it is usually free from the iron-oxide to which the colour of the jasper is due. In places the jasper passes upward into a jaspery phyllite with a lower silica-percentage, and occasionally this phyllite appears to replace the jasper. Being softer, the phyllite is almost always sheared. In a few instances, however, even the jasper is 'milled,' as in the little stream near Brawliemuir. Though the red jasper is the type commonly met with in these areas, patches of green chert appear about the North Esk, where they are seen to be part of one and the same set of cherts, the difference in colour being due to the comparative absence of iron-oxide.

In several cases the silica-percentage of these cherts and jaspers has been ascertained, the results being given below:—

SiO ₂ = 88.85.	Typical red jasper, North Esk; the most abundant type.
SiO ₂ = 71.50.	Jaspery phyllite, North Esk; fairly abundant in many localities.
SiO ₂ = 93.30.	Pale jasper, finely milled, Burn of Brawliemuir; milling exceptional.
SiO ₂ = 93.85.	Mullion Island chert; rarely if ever sheared. (Quoted for comparison.)

The mode of occurrence of this jasper leaves no doubt as to its sedimentary origin; but the evidence that it was originally a radio-

larian ooze is by no means so satisfactory as one could wish. Still, if we compare the hand-specimens and microscopic sections with those of the cherts from the Southern Uplands, where the latter are somewhat altered, little doubt can be entertained that the cherts in these widely-separated regions had a common origin.

As already indicated, the term Green Rock is applied to a variable series of basic igneous rocks, usually green, a coloration due to the presence of a green mineral, which is often chlorite. In many places, however, it is a more or less distinctly green material, generally isotropic, which may be conveniently named viridite. The rocks vary considerably in texture, and to a less extent in mineralogical composition, and, with one local exception, the variation in ultimate chemical composition is small. The most abundant rock is an ophitic dolerite, in which the original basic mineral was augite. Indeed this type differs from the central part of a broad dolerite-dyke of Tertiary age solely in the fact that the latter contains more iron-ore than the Green Rock. The variation in the coarser varieties consists mainly in the partial replacement of augite by original brown hornblende and brown mica. This change is often accompanied by a slight difference in structure, the type containing these two minerals being not so markedly ophitic.

The coarseness of texture suggests that these rocks are probably intrusive. Indeed, in many cases it is clear that the igneous rock becomes more fine-grained at its point of junction with the jasper; but there is still a considerable residuum of fine material too decomposed to enable us to say confidently that it is only the quickly-cooled edge of an intrusion, and not part of a lava-flow. The junction-line with the jasper is often incrusched, and notwithstanding decomposition, it is evident that the upper surface of the igneous mass was not originally slaggy or uneven. The jasper has not been found filling cracks or fissures in the igneous rocks, as recorded in the case of the radiolarian chert in the Southern Uplands.

In several localities curious augen-shaped cavities in these basic rocks have been observed, suggestive of a coarse vesicular structure. These are so numerous at one locality near Brawliemuir, that a specimen showing one of these cavities was sliced in order to ascertain its character. This section (5570) showed that the hollow was formed at the intersection of two crush-planes, where the lime set free by crushing had been accumulated, and this being dissolved out afterwards, a cavity has been left.

Close to the locality just mentioned some pale-green and white igneous rocks are met with, which contain much more felspar than the normal Green Rock, and seem to have possessed an original flow-structure. They are more suggestive of a lava-flow, but they are so crushed and decomposed that it is impossible to determine precisely their original characters.

The Green Rocks, as a whole, seem to consist of a series of sills of ophitic dolerite, varying slightly in mineral composition and structure, and rarely continuous for any great distance. The fine-grained material is probably the quickly-cooled edge of these sills

repeated by rapid folding, though it is quite possible that some true basic lavas may also be present. The crushed and decomposed acid rock near Brawliemuir may, as already suggested, have been originally a lava. It must, however, be borne in mind that, owing largely to repetition by folding, no rock much below the horizon of the jasper is ever exposed.

The succession of the rocks in these lenticular patches that intervene locally between the Highland Schists and the Old Red Sandstone is tabulated below in descending order:—

MARGIE SERIES.	{	1. Grey shale.
		2. Pebbly limestone, lenticular, 1 to 5 (?) feet thick; quarried at all known outcrops.
		3. Dark carbonaceous, grey, chocolate-coloured, and white shales; about 20 feet thick.
		4. Pebbly grits, with carbonate-of-iron cement, becoming coarser towards the base; about 120 feet thick in the North Esk section.
		5. Green conglomerate, occurring locally about 30 feet thick in the North Esk section.
JASPER AND GREEN-ROCK SERIES.	{	1. Fine grit with microcline-pebbles.
		2. Fine shale, always cleaved, with a pseudocrystalline aspect.
		3. Jasper (altered radiolarian chert?), 6 feet thick in the North Esk section; at certain localities it seems to be replaced by jaspersy phyllite.
		4. Green Rocks, mainly lenticular sills of ophitic dolerite, though some lava-flows may also be present; upper part only visible.

III. THE AGE OF THE TWO SERIES.

Attention has already been drawn to the local character of the deposits forming the Margie Series. The nature of the chert and fine shale associated with it points on the other hand to oceanic conditions of sedimentation, and suggests a wide distribution.

When I had completed the survey of the North Esk region, a series of uncrushed specimens and a section showing the geological structure of the area were examined by Mr. Peach, who at once recognized the resemblance of the Jasper and Green-Rock Series to the radiolarian cherts and volcanic rocks of Arenig age in the Southern Uplands, and the similarity of the geological relations in the two regions. Subsequently, most of the sections in the North Esk region were visited by Mr. Horne, who was equally impressed with the resemblance in the field, notwithstanding the deformation of the rocks along the Highland Border.

At a later date Mr. Peach and Mr. Horne showed me certain typical sections of the radiolarian chert and Arenig igneous rocks in the neighbourhood of Sanquhar, where the junction between the two is of two distinct types. In the first, the chert rests on an uneven surface of the pillow lava, cracks and fissures in the latter being filled by chert: no similar junction has yet been detected along that portion of the Highland Border which I have examined. In the second type, the junction of the chert and igneous rock is perfectly even, and resembles that seen in the northern area of Forfarshire and Kincardineshire. In the latter region, the mechanical deformation which

the rocks have undergone gives them the appearance of an older series ; but notwithstanding this fact, there is strong presumptive evidence that the cherts and green igneous rocks in the Southern Uplands and along the Highland Border are of the same age (Arenig).

Attention must now be directed to the question of the age of the Margie Series. The green conglomerate, as already indicated (pp. 330, 331), proves conclusively that these sediments are younger than the Jasper and Green-Rock Series. On the other hand, it is beyond doubt that the Old Red Conglomerate has not shared in the powerful movements that affected the Margie Grits. The relative age of the two is, however, placed beyond dispute by the fact that, in the area south-west of the North Esk, the Old Red Conglomerate passes unconformably over the upturned edges of the Margie Grits. The latter are, therefore, presumably of Silurian [?] age, though younger than Arenig time.

IV. THE NATURE OF THE NORTHERN BOUNDARY OF THE SILURIAN [?] ROCKS.

Having established the order of succession of these rocks, and determined their age as far as possible, we will now consider their relation to the Highland Series.

Between the Highland rocks on the one hand, and the Jasper and Green Rocks on the other, are several small lenticular patches of the Margie Series which are shown on the Geological Survey Map (Sheet 66) and lettered *b*. These are five in number, and occur at the following localities :—(1) North Esk ; (2) Kirkton ; (3) Crichtie Burn ; (4) Clattering Bridge Quarry ; and (5) Burnieshaig Quarry, north of Drumtochty Castle. The phenomena observed on the margins of these patches are so important as to justify me in entering into the following details :—

(1) The North Esk.—On referring to the description already given (p. 331) of the northern outcrop of the Margie Series in this section, it will be seen that there is a marked inversion of the strata near their northern limit. On the northern face of the old quarry the Margie Limestone, dark shale, and chocolate-coloured shale are repeated in reverse order with a north-westerly dip (see fig. 1, p. 330). It is clear that the beds north of the quarry are arranged in descending order, although from the apparent dip we might at first conclude that there is an ascending sequence. It is further evident that there can be no natural sequence between the chocolate-coloured shale at the northern limit of the Margie Series and the Highland Slate a few yards to the north, for no representative of the Margie Grits occurs here. And as there is no ordinary fault-rock present, it is most probable, in view of the great deformation of the strata, that the junction is a thrust-plane. But even supposing that this inversion could not be proved, the lithological evidence would demonstrate the fact that there is no true upward succession from the sheared Margie Shale, with its

original clastic micas, to the finely crystalline slate in which no trace of clastic mica has been found anywhere in this district. Briefly, it may be stated that at the junction of the Margie Series and Highland rocks we find the deceptive appearance of a stratigraphical sequence, accompanied by intense shearing of the softer rocks, so characteristic of the more important planes of overthrust in the North-western Highlands.

Fig. 2.—Diagrammatic Section about Crichtie Burn, Fasque. (See Geol. Surv. 1-inch Map, Sheet 66.)

[The ground south-east of A is very obscure. In this and the following sections the lentilles of the Margie Series at the major thrust are enlarged, in order to make the details visible.]

(2) The Kirkton.—The sections about the Kirkton throw no light on the nature of the junction of the Margie rocks with those of the Highlands, and their discussion may for the present be postponed.

(3) Crichtie Burn, north of Fasque (fig. 2).—In this small lenticle the limestone has been quarried on both sides of the burn. On the south side of the eastern quarry, the dark shales of the limestone are in contact with the grey slaty shale of the Jasper Series, and both are greatly deformed. From our knowledge of the succession, it is evident that the junction of these two rocks cannot be a natural one, and as there is no trace of normal faulting here, it is probable that a thrust-plane intervenes, the beds on each side of it being intensely sheared. On the north side of the quarry, the beds are apparently inverted as in the North Esk; for, although the dip is northerly, the strata are arranged in descending order as follows:—

1. Limestone.
2. Dark shale.
3. Chocolate-coloured shale.
4. Fine Margie Grits.

These grits form the lower part of a small waterfall north of the quarry, where their whiteness is well marked, but it disappears about a yard above the fall. Here the grit is clearly seen to be part of the Highland Series, and it is further apparent that the sequence cannot be normal, for the

lower part of the Margie Grits is absent, and so too the whole of the underlying Jasper and Green-Rock Series. In view of the intense shearing of the rocks at the fall, it is probable that the Highland rocks are driven over the Margie Grits by means of a reversed fault.

Two points are especially well shown here. First, it is impossible to locate the exact junction of the two series; secondly, the crushing accompanying this movement extends only for a yard or two into the Highland Grits.

(4) The Clattering Bridge Quarry (fig. 3).—Regarding the section in this quarry, it may be sufficient to state that, as in the Crichtie Burn, the upper beds of the Margie Series are in contact with the Highland Series on the north side, and with the slaty shale and jasper on the south. Neither can be a natural junction, and there is no ordinary fault-rock present. The junction in both cases is marked by intense shearing, and both are probably thrust-planes. But we here see clearly for the first time that these two planes intersect at the top of the western end of the quarry, and that the more northerly plane cuts out the more southerly. The displacement along the margin of the Highland Series has been

Fig. 3.—*Diagrammatic Section across the Clattering Bridge limestone-quarry.*

produced by a major thrust, and that between the Margie Series and the Jasper, etc., by a minor thrust. The effect of the intersection of these two thrust-planes is that, on the slightly higher ground to the south-west, there is no outcrop of the Margie Series. It is only because the burn here has cut through the point of intersection of the two thrusts, that the wedge-shaped mass of the Margie Series contained between them is exposed. This is made perfectly clear in fig. 3, above. Further, we now begin to see the meaning of the fact that these quarries all lie in valleys; for in the valleys alone has denudation cut deep enough to expose the rocks between the two thrust-planes.

(5) The Burnieshaig Quarry (fig. 4, p. 338).—This old quarry, in the Margie Limestone, lies about a mile almost due north of Drumtochty Castle, and a small burn flows through it.

Here the limestone has been exposed by the denuding action of the burn, and is not seen on the higher ground above in the line of strike. The Margie Series forms the floor of the quarry, and the beds are intensely puckered or folded, though careful examination shows that the folds are of no great depth. The peculiarity of this quarry is, that we are able to make out that at the junctions of the different rock-groups the section varies every foot. This is essentially due to a slight south-westerly inclination of the folding, in consequence of which we slowly ascend in the Margie Series as we walk along the floor in the direction of the strike of the folding. The southern wall of the quarry consists of the slaty shale, with the addition of small patches of intensely sheared jasper.

Fig. 4.—*Diagrammatic Section across the Burnieshaig limestone-quarry.*

This additional variation in the rock next the Margie Series makes the hypothesis of a natural sequence still more improbable. No fault-rock is present, but the shearing at the junction of the two series is intense. Similar phenomena are seen at the northern face of the quarry, where first the shale and then the limestone are in contact with a Highland Grit. The intersection of the two thrusts can be clearly made out at both ends of the quarry, and the cause of the non-appearance of the Margie Series higher up along the hillside, in the direction of the strike, can be easily understood. As already stated (p. 337), the type of crushing associated with these thrust-planes does not extend for more than a yard or two into the Highland Grit.

Thus these little lenticles of the Margie Series, on the north side of the Jasper and Green Rock, lie between a major and a minor thrust-plane. They are confined to the valleys, where alone denudation has succeeded in cutting deep enough to expose their apex. Only in the specially-deep valley of the North Esk is the whole succession of the Margie Series up to the limestone exposed. All along the hill-sides the minor thrust is always cut out by the major, before the former can reach the surface.

The Major Thrust.

The junction of the Highland Rocks with the Jasper and Green-Rock Series along the hillsides is more or less buried under Drift and other materials throughout the whole of the largest patch of the Silurian [?] rocks. But in the second, the evidence is fortunately more satisfactory. Between the limestone-quarry last described and the Bervie Water the course of the major thrust can, as a rule, be accurately traced. That the slaty shale, the jaspers, and the Green Rock are successively truncated by it as shown on the 1-inch Geological Survey map, is especially clear; for in several cases these bands can be followed to within a few feet of the Highland Grit, which can be traced persistently along the north side of the thrust.

In fig. 5 (p. 340) a reduced copy of a portion of the 6-inch field-map is given, in order to make this point perfectly clear: in no case is any fault-rock seen. It becomes obvious, therefore, that this major thrust is of great structural importance, and everywhere separates the great mass of crystalline (Highland) rocks to the north from the supposed Silurian rocks to the south, over which the crystalline rocks have been driven.

The Second Minor Thrust.

The junction of the southern outcrop of the Margie Series in the North Esk with the Jasper and Green-Rock Series is marked by a zone of intense shearing, described on p. 329 as a wall-like mass composed of lenticles.

In view of the evidence already given, this line of junction must also be a thrust-plane, for there is no ordinary fault-rock present, and the phenomena are totally unlike those of ordinary faulting. Though more important than the minor thrust-plane already described (see p. 337), it must also be a minor thrust, as it undoubtedly disappears on reaching the major thrust. Unfortunately, the exact place where the intersection takes place cannot be accurately fixed, for the ground is covered with thick Drift, as already stated.

V. THE POSITION OF THE MAJOR THRUST WITH REFERENCE TO THE HIGHLAND ROCKS.

As I have already stated (p. 335), in the area a little to the south-west of that here described, the Old Red Conglomerate rests horizontally upon the upturned edges of the sheared Margie Grits, and is totally unaffected by the movements that produced the shearing. But the conglomerate itself is in turn affected by the great Highland Fault, which throws that rock down to the south in some cases for several thousand feet. Now viewed on a fairly large scale, the position of these two great movements, though of totally different ages, is almost identical, and there must be some cause for this approximate identity of position. This position we believe to be fixed by the condition of the Highland rocks. It has been found that

Fig. 5.—Reduced copy of a portion of the 6-inch Geological Survey Map, Sheet 16 S. W. (Kincardineshire), showing the outcrop of the major and minor thrusts.

[In the above map is seen the contrast between the straight normal fault and the constantly curving overthrust.]

these rocks rapidly become less crystalline as we approach the position of these two great planes of disturbance. Close to these planes brown mica, of metamorphic origin, so abundant farther north, no longer occurs, and the only sign of alteration in the grits is the change in the elastic micas. Clearly if we could proceed a little farther in the direction of this decreasing crystallization, even this sign of alteration would be lost. The position, then, of the great planes of movement approximately coincides with the last trace of crystallization in the Highland rocks, which would be the position of least power of resistance to powerful earth-stresses coming from a south-easterly direction. Under the influence of such stresses the non-crystalline part of the Highland Series has snapped off from the crystalline and harder portion, and the latter has been forced over the

newer rocks composing the lenticles here described; just as the Lewisian gneiss has been forced over the Torridonian and Cambrian rocks in the North-western Highlands.

In the Southern Highland area, owing to the faintly marked crystalline character of the older rocks, an apparent order of succession has been produced that is far more deceptive than is usually the case in the Durness-Erribol area. Indeed, in the case of the North Esk section I was at first completely deceived by it, and it was only on mapping out the ground in minute detail that the deception was exposed.

Fig. 6.—*Enlargement of a portion of fig. 5, p. 340.*

[The complicated folding of the lenticle A of the Margie Series, seen in the former map (fig. 5, p. 340) between the major and minor thrusts, is well shown in the above enlargement.]

There is, moreover, another deception even more difficult to detect. Owing to the slightly crystalline condition of the Highland rocks we seem to see a perfectly gradual transition, through the greatly crushed newer rocks of these lenticles into the highly crystalline schists of the Southern Highlands. In reality, however, no such transition exists. Under the microscope the clastic micas can be recognized in nearly all the newer sedimentary rocks, even when close to the thrust-plane. No such clastic micas have ever been detected even in the least altered Highland rocks.

The facts and inferences set forth in the foregoing pages have a very important bearing on a matter of controversy. In the area here

discussed the rocks affected by what is commonly known as regional metamorphism have been driven over a newer series by a movement of pre-Old Red Sandstone age, and no similar movements have since taken place in this area. But on the margins of crystalline areas in other countries similar movements have taken place as late even as Tertiary times, and in such areas a Tertiary age has been claimed for the regional crystallization. In view of our experience both in the Northern and Southern Highlands, it seems not unreasonable to suggest that movements similar to those here described may have occurred along the slightly crystalline margin of the areas affected by regional metamorphism. Whatever may be the age of the beds overridden by the crystalline schistose rocks, there will appear to be a passage from the newer into the older, and the crystallization of both will seem to be somewhat later than the age of the beds so overridden. As in the case of the area here described, the transition from one series to the other may be deceptive.

VI. THE MECHANICAL DEFORMATION OF THE SILURIAN [?] ROCKS.

I cannot conclude the account of the phenomena seen in these lenticles without some notice of their bearing on the vexed question of the origin of crystalline schists. Great as is the crushing and shearing in these lenticles, it has nowhere resulted in the production of a crystalline schist, and not a particle of new brown mica has been met with anywhere. The total length of outcrop of more or less basic igneous rock is about 10 miles. No hornblende-schist ever occurs in it. Indeed, it would be difficult to find an area which seems to show so conclusively that mechanical deformation alone does not produce crystalline schists. The structures in the sheared grits are in the main identical with those seen in the Torridon Sandstone of the North-western Highlands,¹ and in the Boulder-Conglomerate found by my colleague, Mr. G. W. Lamplugh, in the Isle of Man.²

VII. SUMMARY OF RESULTS.

The results of the examination of the remarkable group of rocks described in this paper, which intervene between the Highland Schists and the Old Red Sandstone in Forfarshire and Kincardineshire, may be summarized as follows:—

- (i) They may be arranged in two divisions—(a) the Jasper and Green-Rock Series, and (b) the Margie Series. The former is most probably of Arenig age, and the latter is of later date, though undoubtedly of pre-Old Red Sandstone age.
- (ii) Both groups of rock have been much deformed, the shearing being most persistent along the junction of the Highland rocks with the northern margins of the supposed Silurian rocks.

¹ Quart. Journ. Geol. Soc. vol. xliv (1888) pp. 431 *et seqq.*

² *Ibid.* vol. li (1895) p. 563.

- (iii) The appearance of an upward succession at this line of junction is always deceptive, the boundary being marked by a great line of displacement or overthrust which has been proved to extend for many miles.
- (iv) The apparent passage from the non-crystalline newer rocks (Silurian?) into the Highland schistose series is equally deceptive.
- (v) The crushing accompanying this thrust never extends more than a few yards into the Highland Series, owing to the induration of the rocks of that series by previous metamorphism.
- (vi) The position of the major thrust truncating the so-called Silurian rocks on the north and that of the later great boundary-fault skirting the Old Red Sandstone have been determined by the outer limit of the great aureole of crystallization of which the South-eastern Highlands form a part. The harder crystalline schists to the north-west have snapped off, under the influence of enormous pressure, from the softer portions now covered by newer rocks to the south-east.
- (vii) Though the rocks have been much sheared, they have not been changed into crystalline schists. In particular, the sheared basic igneous rocks are never altered to hornblende-schists.

DISCUSSION.

SIR ARCHIBALD GEIKIE stated that he had had occasion to examine the Author's evidence with him on the ground, and had no hesitation in agreeing with the conclusion arrived at by Mr. Peach and Mr. Horne that the series of jaspers and igneous rocks wedged in along the Kincardineshire border of the Highlands, between the metamorphic rocks and the Old Red Sandstone, bear the closest resemblance to the Arenig Group of the Southern Uplands, and are in all probability of the same age. The Author, however, had detected in that region a younger group of strata (Margie), which may belong to some later part of the Silurian System. The Arenig Group had been detected at other places along the Highland Border: by Mr. Clough between the Tay and Loch Lomond, and more recently by Mr. Gunn in the Island of Arran. Though the speaker had gone over the ground with the Author, he had not been able to detect any section showing indications of such a thrust-plane as the mapping would appear to require. Nor in the tracts farther to the south-west had it been practicable to draw any hard-and-fast line, between the Arenig Group and the metamorphosed clastic rocks of the Highlands to the north of them. It is possible that, while a thrust-plane may be shown by the mapping to exist in Kincardineshire, there may be no such break in the tract between Callander and Loch Lomond. In Arran, too, it has been found impossible to trace a definite boundary between the Arenig Group and the contiguous schists.

The questions involved in this paper are of the utmost interest and importance, both as regards the structure and history of the

Scottish Highlands, and with reference to theoretical questions in tectonic geology and metamorphism. If anywhere the Arenig Group really shades off without a break into the Highland Schists, we are at once led to enquire how much of these schists must be of Palæozoic age. But even if we claim that the boundaries of the group are everywhere actual lines of dislocation, we have to admit that the thrust-planes and metamorphism which have affected it, and which cannot easily be separated from those of the general mass of the Highlands, must be at least of post-Arenig age. And in that case we are naturally driven to ask how far the tectonic arrangement and crystalline condition of the Highland rocks have been determined or modified by movements that must be assigned to some date between the period of the Arenig Group and that of the Lower Old Red Sandstone. Having had opportunities of studying the rocks on the ground with each of the members of the Survey—Mr. Gunn, Mr. Clough, and the Author of this paper—who had surveyed the several areas in which they are developed, Sir Archibald could bear witness to the patience and skill with which the mapping had been carried out. If perfect agreement had not been reached in the interpretation of the phenomena, this difference of opinion only served to indicate the difficulty of the problems and the diversity of form under which they present themselves in the various districts. The speaker was inclined to believe that the key to the solution of these problems was most likely to be found in the North of Ireland, where, in the County of Tyrone, rocks which, there could hardly be any doubt, are a continuation of the Silurian Series wedged in along the Scottish Highland Border, expand over a broad stretch of country, and have been laid open in many natural and artificial exposures. They include sedimentary rocks among which are cherts and jaspers like those of the Arenig Group, and also red shales and pale grits and limestones, which may represent the Author's Margie Series. But their most remarkable feature is the great development of their igneous masses, which comprise ellipsoidal lavas, fine tuffs, and coarse agglomerates, together with intrusive sheets and bosses. These rocks require to be carefully mapped in detail, and their boundaries with the Londonderry Schists on the one side, and the Palæozoic formations on the other, must be closely traced. This task will not only tend to clear up an obscure chapter in Irish geology, but may help to remove some of the difficulties which still stand in the way of a satisfactory interpretation of the geological history of the structure and metamorphism of the Highlands of Scotland.

Mr. MAER, being interested in the relationship of the schists of the Highlands to the Palæozoic sediments, wished to call attention to certain slates which the late Hugh Miller, in his '*Cruise of the Betsy*' 7th ed. (1869), p. 257, stated, on the authority of Dr. Emslie, were graptolite-bearing. The late Prof. Nicholson had made a cursory examination of these slates, and judged that they distinctly possessed the characters of graptolite-bearing slates. He (the speaker) urged that these slates should be re-examined.

Prof. BONNEY expressed his sense of the value of the Author's paper, which was quite in accordance with the speaker's own experience. He had himself seen greenstones reduced to a condition apparently as fissile as some of those on the table, and the bringing together in apparent sequence and in a narrow zone of rocks differing much in age, reminded him of one or two cases in the Alps, where it was often extremely difficult to fix the exact position of a thrust-plane because of the crushing in its vicinity. This, he had observed, always produced very great effects near the junction of two rocks differing much in hardness. The crushing near a fault had often misled observers into supposing a transition to exist from crystalline schists into phyllites. The difficulty was caused by the fact that in the former the minerals were reduced in size, and there might also be a minute secondary development of mica; while in the latter much minute mica (supposing the rock argillaceous) was produced as a consequence of the pressure. So on the one side there was a 'levelling-down,' on the other a 'levelling-up,' which occasionally made the two rocks very like one another. He thought it highly probable that Palæozoic rocks would occur in lenticles in the Central Highlands—indeed he believed that the late Dr. Hicks had identified Torridon Sandstone. Mesozoic rocks occurred in that way in the Alps; and he was more sanguine than Sir Archibald Geikie that in such cases the newer rocks would be identified with certainty.

The PRESIDENT and Mr. R. D. OLDHAM also spoke, and the AUTHOR replied.