THE GEOLOGY OF THE HIGHLAND BORDER

FROM TAYSIDE TO NORANSIDE.

by

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SECTION IX.

GENERAL ACCOUNT of the SEQUENCE and STRUCTURES.

Having described the nature and arrangement of the different varieties of rocks and the major dislocations to which they have been subjected, it is now possible to consider the sequence and general structures along the Highland border. The rocks fall into three groups; the Dalradian phyllites, schistose grits, and quartzites; the Highland Border Rocks, graphitic shales and grits, probably including the serpentine-schalstein complex; and the Lower Old Red Sandstone sandstones, conglomerates, and lavas. Scanty evidence has been obtained of a discontinuity between the first and second named groups in the Prosen section and further to the north-east they are probably bounded by faults. The junction between the Old Red Sandstone rocks and those of the Highland Border Series is apparently a reversed fault, while the younger series lies with a strong unconformability on the Dalradian schists wherever the boundary is not a plane of dislocation. The two older groups having been implicated in the Caledonian folding movements, it is with the/
the structures of the Lower Old Red Sandstone rocks that this investigation is most concerned.

The lowest beds are the phyllite conglomerates of the upper Erich, (Pl. VIII., fig. 3.), which are overlain locally by other conglomerates of a more mixed Highland assemblage, by thin micaceous, red sandstones, and bedded, fine-grained tuffs. These pass upwards into a microporphyritic olivine-basalt seen on the Erich below Old Milton of Drimmie and in the outlier among the Dalradian schists in the Burn of Watersheal, which is proof of an originally much wider spread of lavas than remains to-day. What is possibly the same flow is exposed south of Balintore where, however, it is underlain by a porphyritic pyroxene-andesite not found in the other sections, but which may not have extended so far to the south-west. The succeeding beds as exposed appear to be fine-grained biotite-andesites with some conglomerate bands and occasionally beds of sandstone. The next outstanding horizon is formed by the Lintrathen type dacite which outcrops at Craighead and again at Pitewan, showing the repetition also found in the underlying acid andesites and due to the N. E. - S. W. fault, which runs/
runs from Craighall on the Erich to the neighbourhood of Balintore, the beds dipping to the south-east while the fault, which is a normal one, throws down to the north-west. The highest bed exposed is an olivine-basalt overlying the dacite.

The boundary of this northerly area of Lower Old Red Sandstone rocks starts from the neighbourhood of Bridge of Gally and can be traced with a general north-east direction to the valley of the R. Prosen, where it apparently fuses with the more northerly thrust described in Section VIII of this paper. While the mapping and also occasional references to the district in Sir A. Geikie's "Ancient Volcanoes of Great Britain" suggest that this junction is an unconformity, a detailed petrological examination of the rocks to the south has demonstrated an abrupt truncation of different members of the lower lava flow sequence which is only compatible with the presence of a line of fault. As brecciation of any kind is conspicuous by its absence, it is probable that we have here a normal fault with the downthrow to the south-east.

In the district between the two thrust planes the main structure is a syncline elongated parallel to the/
the lines of dislocation, and rising to the north-east. The lowest beds are sandstones underlying the dacite, exposed in the Isla section and again above the Prosen near Pearsie. While the dacite is in the main confined to the lower parts of the syncline in the north-east, it is again met with at Tamhingan near the Tay, where only a short distance separates it from a higher pyroxene-andesite group. The porphyritic biotite-andesite overlying the dacite is seen in the Isla section. The exposures of olivine-basalt associated with these two acid rocks are curiously irregular in their development, being seen in the north near Garlow, in the Isla gorge, near Fyall, and also north-east of Tamhingan. Above is the widespread conglomerate charged with boulders of highly acid volcanic rocks as well as basic ones. Towards the south-west the higher horizons show an increasing percentage of basic igneous rocks and intercalated among them is a group of microporphyritic pyroxene-andesites and olivine-basalts.

In the vicinity of the Erich a secondary anticlinal fold has been truncated by the dip fault already mentioned leaving a greater extent of lava outcrops on the upthrow side to the east while on the downthrow/
downthrow side the overlying conglomerates are exposed. These beds, which contain more basic igneous material than the underlying ones, constitute the highest group of rocks seen on the north side of the main Highland Boundary Fault. On the south side of that line the sequence opens with a group of porphyritic pyroxene-andesites capped by one or more flows of olivine-basalt. While to the south-west of the Isla these rocks are lost against the Boundary Fault, a small faulted area occurs south of Blairgowrie, and they reappear at Stenton on Tay. North of the Isla, for a large part of their outcrop they show a steep anticlinal fold between the main Strathmore syncline and the Highland Boundary Fault. Although they are lost against this fault yet again in the vicinity of the S. Esk they reappear in a somewhat attenuated form along the south side of the Den of Ogil, being there represented by olivine-basalt only.

The succeeding basic volcanic conglomerate can be traced for sixteen miles north-east of the Isla, and the sandstone which overlies it can be followed for an even greater distance, several quarries marking the outcrop.
outcrop. The highest conglomerate with quartzites and schistose grits gives rise to a ridge from the south of Blairgowrie to the Hill of Ogil, a distance of some twenty-five miles. These beds all dip south-east into the Strathmore syncline, the centre of which is occupied by a series of well-bedded, red sandstones, overlying the last mentioned conglomerate. The dips near the Highland Boundary Fault are about 70°; a mile-and-a-half away the dip is barely 40°. In the highest sandstones the dip approaches, but is rarely less than, 20°. As the strata on the opposite side of the syncline, often barely a mile to the south-east, are inclined at an angle of 5° - 10° the fold has a steeper limb on the west than on the east, as has been described from Kincardineshirc to the north.

It is unfortunate that there is no stratigraphical horizon on the north side of the main Highland Boundary Fault which can be compared directly with any on the south side, for there is thus a gap in the sequence reconstructed above. The highest lavas to the north are pyroxene-andesites as are the lowest ones/  

ones to the south of the fault, but the northern ones are microporphyritic while the southern ones are strongly porphyritic. The conglomerates on the north side contain acid as well as basic volcanic rocks, while those to the south are practically devoid of anything but basic rocks. As the lower conglomerate horizons on the north side are increasingly acid, the general trend in the direction of an increasingly higher content of basic igneous rock boulders is continuous across the fault line. The olivine-basalts associated with the pyroxene-andesites are similar on the opposite sides of the fault.

The only feature of the tectonics still calling for attention is the development of a series of strike faults with a general N. - S. orientation. The most important one, running from Craighall to Balintore has been mentioned already. There are others, apparently extending for much shorter distances, in the vicinity of Bridge of Gally, Lintrathen Loch, and the Knock of Cortachy. They are probably of later formation than the major S.W. - N.E. dislocations, and as they seem to be normal faults they may represent the phase/
phase of tensional relief subsequent to that of compression.

The interpretation of the major vertical variation is a comparatively straightforward one. The lowest conglomerates indicate the denudation of a region of Highland schists and over them spread flows of acid andesites together with a few olivine-basalts. The succeeding conglomerate represents the wastage of a district of volcanic rocks presumably overlying a Dal-radian schist floor, and the variety of igneous material must reflect a corresponding variety in the composition of the lava flows from which it was derived. Had the fragments come from one or more intrusions the ratio of pebbles of non-igneous country-rock to those of igneous origin would have been very much greater than is the case. It is not certain that these highly acid lavas were of Old Red Sandstone age, but if they occurred in Pre-Old Red Sandstone times it is curious that no fragments of them are present in the lower conglomerates.

The succeeding lava flows of andesites and basalts are associated with conglomerates in which the acid igneous rock content steadily diminishes, until in the/
the highest volcanic conglomerate only basic rocks are represented. The basic material in these boulder beds is closely akin to that of the intercalated lava flows from the northward continuation of which in all probability it was derived. On account both of this affinity between the lavas and the waterworn pebbles, and the general freshness of the material of these conglomerates, it is suggested that the later denudation of the basic igneous rocks indicates the removal of a group of flows poured out after the underlying acid volcanic rocks had been completely eroded away, and not that the processes of weathering had cut down to a horizon underlying that of the acid rocks. Practically conclusive evidence to this effect lies in the absence, so far as is known, of similar basic andesites from the lower conglomerates.

The highest conglomerate with its scanty igneous content and its abundant quartzites and schistose grits suggests the almost complete removal of the lava cap with the re-exposure of the Dalradian basement. The upward passage of the conglomerates into sandstones is in keeping with the increasing distance of the area from/
from the shore-line and the diminishing speed and erosive power of the rivers, which would attend the subsidence of the area of deposition and the extensive denudation of the hinterland.

An interpretation of this kind demands substantial evidence of contemporaneous erosion. The removal of so great a mass of material to form extensive conglomerates is indeed shown by the incomplete sequences which to no small degree rendered difficult the mapping and interpretation of the rocks. Certain exposures reveal eroded surfaces — at, for example, the old quarry south of the Knock (Cortachy), (Pl. II., fig. 3.), where a massive conglomerate rests on an uneven floor of dacite. A closely similar phenomenon is exposed at the north end of Tamhingan near Dunkeld.

On the other hand a search among the boulders of conglomerates at the same or at slightly higher horizons has yielded good results and enabled broken sequences to be reconstructed and compared with more complete ones. A few examples will serve to illustrate this.

At the Hill of Ascreavie the lavas above the dacite are missing, but in the overlying conglomerate occur/
occur pebbles of a fairly coarse olivine-basalt identical with that which occupies the corresponding position in the Fyall section. In Aucharrock Wood the dacite is exposed, and in the conglomerate above are pebbles of a porphyritic biotite-andesite similar in every way to that which in the Isla section lies a little above the dacite. North of Meams Hill the dacite is exposed but there are no overlying lavas. In Meams Quarry, however, the most striking feature of the conglomerate, which is high up in the sequence, is the huge roughly angular masses of porphyritic biotite-andesite. In the Knock quarry, Cortachy, the dacite is exposed, and in the overlying conglomerate the same rock occurs as a boulder. Pebbles of the porphyritic biotite-andesite, while not conspicuous in this bed, are common in the conglomerate fringing the south side of the Den of Ogil, at a horizon which is a little lower in the sequence than that at the Knock quarry — which is worthy of note as the biotite-andesite overlies dacite. Pebbles of the biotite-andesite occur in the conglomerate at the top of the Reekie Linn, while the same rock is present in its proper position a little downstream.
downstream. Two miles to the north, on the other side of the syncline, the dacite is exposed in the bed of the Melgam Water, but the andesite is missing, so that the pebbles may have travelled from the denuded outcrop to the north. The biotite-andesite appears at the surface north of the Loch of Clunie in its proper place in the sequence. To the south of the loch, fragments of the same andesite are present in a conglomerate at a higher horizon at Craigiewallace. At Dunmore and at Craig of Stenton further south, the biotite-andesite occurs only as pebbles in a conglomerate overlying the dacite. Below the Foghouse, Craighall, on the Ericht, both the dacite and the andesite are present as pebbles in a conglomerate.

No volcanic necks have been found anywhere and as so many of the exposures in the area are strike sections there is available little evidence to show from what direction the lava flows came. In the micro-porphyritic olivine-basalt associated with the lowest lava group — the mica-andesites — there are present amygdules as large as hens' eggs, one end of which is hemispherooidal while the other is tapered to a very fine edge/
edge, approximately parallel with the surface of the flow. On the assumption that the walls of the cavities bounded originally approximately spherical vapour bubbles, the distortion of which by the flow of the surrounding mass would be most marked in the parts last consolidated, and also that those portions of the flow most distant from the focus of dispersion would solidify earliest, the hemispherical ends of the vesicles must represent the "forward" direction of the flow. The amygdules present their rounded ends towards a direction 125° Magnetic, so that it would appear reasonable to assume the orifice or orifices from which the lava came lay to the W. N. W. If this is true for the entire group of acid andesites, in Perthshire and Forfarshire, they fall into line with those of Kincardineshire where, from a comparison of the lavas on both sides of the northern continuation of the Strathmore syncline, R. Campbell advocated a Highland source for the more acid rock types.

With regard to the source of the stratigraphically higher pyroxene-andesites and olivine-basalts there is no evidence within the area, but compared with the corresponding groups in Kincardineshire there is a marked attenuation towards the west, suggestive of an eastern origin for the lavas.

COMPARISON with the LOWER OLD RED SANDSTONE SEQUENCE in KINCARDINESHIRE.

In Kincardineshire R. Campbell has established a sequence for the Lower Old Red Sandstone rocks with which it is useful to compare that derived from the Perthshire and Forfarshire ones. He divides the sequence into five groups named Dunnottar, Crawton, Arbuthnott, Garvock, and Strathmore respectively. The conglomerates show a main threefold subdivision, a lower Highland one, a middle volcanic one, and an upper Highland one, a general variation which holds good also in the southern area.

Near the base of the Crawton Group, he records a dacite of the Lintrathen type, succeeded by a porphyritic biotite-hornblende-andesite, which is in turn overlain by a conglomerate containing a high percentage of strongly acid volcanic rocks. As this succession only occurs at one horizon in Kincardineshire and at one in Forfarshire it seems reasonable to regard them as representing the same stratigraphical horizon. Below it, in both areas, there is an essentially Highland conglomerate, which belongs to the Dunnottar Group.

With/

With this conglomerate there is on the western side of the Strathmore syncline in Kincardineshire towards the Highland Boundary Fault only a limited exposure of an acid andesite, but in Forfarshire there is between 3,000 - 4,000 feet of strata, mainly compact acid andesites, below the dacite horizon, and most of this apparently should be considered as belonging to the Dunnottar Group. In both districts there is a porphyritic augite-andesite near the base of the division.

Above the Crawton Group, which in the southern area may be taken to include the dacite, the porphyritic biotite-andesite, together with some olivine-basalts and the overlying acid volcanic conglomerate, the next subdivision of the Kincardineshire rocks is the Arbuthnott Group, characterised by a wide spread of pyroxene-andesites and olivine-basalts on the southern limb of the syncline and a volcanic conglomerate on the northern one. In Perthshire there is a similar series of pyroxene-andesites, olivine-basalts and a basic volcanic conglomerate partially represented on each side of the Highland Boundary Fault, which taken together would seem to be closely equivalent to the/
the Arbuthnott Group.

The succeeding Garvock Group in Kincardineshire consists of sandstones and Highland conglomerates associated in the eastern limb of the syncline with basaltic lavas. In Perthshire and Forfarshire there are sandstones and Highland conglomerates but lava flows are absent. The Strathmore Group of flagstones and sandstones appears to be similar in both districts.

While no fossils have been found in the Old Red Sandstone rocks along the northern limb of the Strathmore syncline, a fairly numerous plant assemblage comes from the quarries at Myreriggs, two-and-a-quarter miles south-east of Blairgowrie. In a well-bedded series of fine grey sandstones occur many fragments of stems and branches of Psilophyton princeps, less commonly portions of the stems of Psilophyton robustus and of Arthrostigma gracile. The strata have a gentle north-westerly dip and appear to be about a thousand feet below the highest beds along the centre of the synclinal axis. From this axis northward the first thousand feet of strata have been referred to the red Strathmore Sandstone Group, while below lies the quartzite conglomerate provisionally placed in the Garvock/
Garvock Group, and which would thus appear to be at the same horizon as the plant-bearing grey sandstones. This is strictly in accordance with the fact that in Kincardineshire abundant fossil plants characterise the Garvock Group, while no organic remains have been recorded from the succeeding division.

In his book on "The Geology and Scenery of the Grampians", P. Macnair places these plant-bearing beds near the summit of the (Lower) Old Red Sandstone series, and, in order to account for their proximity to certain "basal conglomerates" in the Ericht, invokes the aid of a strike fault, illustrated in the section shown on p. 16. In the first place the "basal conglomerates" are the quartzite conglomerates of the Garvock Group, at least sixteen thousand feet above the local basement of the Lower Old Red Sandstone Series. Secondly the steady upward succession from these conglomerates into red sandstones, with a diminishing dip towards the south-east, can be demonstrated in the Ericht and in many other exposures. Thirdly, if his section/

** Ibid, p. 9.
section is drawn to scale, the centre of the Strathmore synclinal axis is shown to be $2\frac{1}{2}$ miles south-east of Blairgowrie while it is only half-a-mile away in that direction, and the fault is placed half-a-mile south-east of Blairgowrie and yet shown to truncate beds along the north-west limb of the fold. The only field exposures where anything suggestive of a fault is to be seen are about a mile to the south-east of the axis, where what may be a dip fault has tilted up some of the sandstones. Other sandstones not far away show little signs of any disturbance.

To group the higher sandstones and conglomerates along the northern limb of the Strathmore fold with the Garvock beds is to regard as contemporaneous two lithologically different rock types. In so doing, however, we have again a parallelism with the same stratigraphical group in Kincardineshire, for there the conditions which favoured the formation of a Highland conglomerate to the north-west apparently precluded the deposition of the sandy limestone, which in Forfarshire and Kincardineshire occupies a position near the top of the Garvock Group on the south-eastern limb.
limb of the fold. To explain this limitation of the sandy limestone to the south-east of the synclinal axis by the presence of a long strike fault would demand considerable field evidence at present entirely lacking.

The application of Campbell's subdivisions to the Perthshire and Forfarshire Lower Old Red Sandstone Series does no violence to the natural grouping of the rocks and thus avoids any further addition to stratigraphical nomenclature. On the following table the thickness of the two sets of groups can be compared.
<table>
<thead>
<tr>
<th>Sequence in Perth and Forfar.</th>
<th>Kincardine.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartzite Conglom. 2200ft. 3500ft. 4000ft.</td>
<td>Garvock Group.</td>
</tr>
<tr>
<td>Sandstone 1300ft.</td>
<td></td>
</tr>
<tr>
<td>Basic Volc. Conglom. 2200ft.</td>
<td>Arbuthnott</td>
</tr>
<tr>
<td>Pyroxene-Andesites 1100ft. 7200ft.+ 5000ft.</td>
<td></td>
</tr>
<tr>
<td>Pyroxene-Andesites 900ft.</td>
<td></td>
</tr>
<tr>
<td>Biotite-Andesite 600ft. 3400ft. 1600ft.</td>
<td></td>
</tr>
<tr>
<td>Dacite 800ft.</td>
<td></td>
</tr>
<tr>
<td>Biotite-Andesite 4000ft.</td>
<td>Dunnottar Group.</td>
</tr>
<tr>
<td>Highland Conglom. 4700ft.+ 6900ft.</td>
<td></td>
</tr>
<tr>
<td>Augite-Andesite 700ft.</td>
<td></td>
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<tr>
<td>* Break in sequence owing to Highland Boundary Thrust.</td>
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</tbody>
</table>
The MAGNITUDE of the THRUSTS.

From a consideration of the average thickness of the different groups it is possible to obtain some idea of the magnitude of the major dislocations which have affected the rocks. The sequence on both sides of the more northerly thrust plane contains stratigraphical horizons common to both, from the comparison of which it would appear that in the vicinity of Balintore the vertical displacement is fully five thousand feet. Near Derryhill it seems to be about three thousand five hundred feet, while further south at Parkneuk the dislocation is nearly four thousand feet.

In attempting to estimate the displacement of the more southerly thrust plane, where it is not complicated by the presence of rocks of the Serpentine Belt, only a minimum value can be given owing to the unknown extent of the gap in the sequence already mentioned. The fact that such a hiatus exists is significant probably of the importance of the movement. Near Stenton on Tay the vertical displacement is over three thousand five hundred feet; north-east of the Loch of Clunie it is seven thousand feet; in the Erich/
Ericht at Blairgowrie it is over five thousand feet; near Fyall Mill it may be nine thousand feet; in the Isla it is fully seven thousand five hundred feet, and at Kimlune it is over seven thousand feet.

The average value for the vertical displacement in this important fault zone is thus over seven thousand feet. The low figure from Stenton is due to the presence, to the east, of a second fault with its upthrow side to the west, so that for comparison with the displacement along the Highland border elsewhere the values at Stenton ought to have added to them the amount of the downthrow of this subsidiary fault, which it has not been possible to obtain so far. That the northern thrust is the less important of the two is further emphasised by the fact that the average extent of its displacement is four thousand five hundred feet. Therefore, on account of its greater vertical displacement and its striking continuity from south-west to north-east, the southern thrust is considered to be the main line of dislocation, the Highland Boundary Fault.
SECTION X.

INTRUSIONS.

A. Field Occurrence.

The district is similar to others in Scotland where a wealth of superficial volcanic rocks is accompanied by intrusions on a very small scale. The re-mapping of the Lintrathen type dacite as a lava flow has removed from the map the most considerable "intrusion". Only one sill remains, that at Corriefodly near Bridge of Cally, the rest of the rocks being in the form of rather narrow dykes.

On the banks of the R. Arde, immediately upstream from Bridge of Cally, is exposed a series of schistose grits standing almost vertically with their strike direction E.N.E. On the left bank upstream, below the grounds of Corriefodly, the lowest exposures are of a conglomerate containing an almost exclusively Highland assemblage of boulders, which presumably rests on a floor of schistose grits although the contact is not visible. Overlying the conglomerate are thin-bedded sandstones and mudstones, and along their bedding-planes has been intruded a dolerite, its outcrop making/
making a steep cliff face among the trees for a distance of about a hundred yards, (Pl. IX., fig. 1.). Above this scarp no further exposures were found. The dolerite, which is characterised by very irregular jointing, is often vesicular and is veined with calcite. It exhibits locally transgressive junctions on a small scale among the sandstones and contains fragments of the same rock, but the most convincing evidence of its intrusive nature lies in the contact alteration of the underlying sediments which have been indurated to such an extent that they resist weathering almost better than the sill itself, and project boldly for fully two feet in some cases beyond the eroded unaltered sandstones below.

The previous mapping of the sill on Sheet 56 of the Geological Survey of Scotland shows its extension on the south bank of the Ardle. No exposures of igneous rock indubitably in situ were found, but one small Knob, which may be a boulder, occurring in the west bank of the small tributary burn immediately east of the old Cattle Market, yielded a dolerite identical with that of the sill. In the higher reaches of the "Cairns"/
"Cairns" burn, another tributary of the Ardle, thin-beded red mudstones, sandstones, and tuffs were found. For three hundred and fifty yards downstream there are no exposures, and finally, just before the Ardle is reached, the Highland conglomerate, described from the opposite bank of the main river, forms steep banks for some seventy yards. It is unfortunate that the intervening stretch, where one would expect to locate the sill, is covered thickly with glacial sands and gravels.

Before describing the field disposition of the majority of the dykes, that at the extreme northeastern end of the area calls for mention on account of its distinctly different lithological characters. Below the west gate of Auchnacree, in the stream bed which forms a deep gully running south-eastwards, is exposed a narrow (6 feet) dyke of igneous rock, truncating a group of bedded Lower Old Red Sandstone tuffs. A little to the south-west, what is apparently the same dyke rises through Margie Grits, and still further in the same direction it is occasionally exposed among Lower Old Red Sandstone rocks in the bed of the Noran Water below Glenley.

The most extensive development of dyke rocks follows/
follows very closely the Highland Boundary Fault from Tayside to Noranside. In practically every exposure of the serpentine belt there is a dolerite dyke, and in many cases the chilling of the latter against the former is so obvious as to render unnecessary the use of a lens. The dykes have a general S. W. - N. E. orientation, and with one exception, that at Pictfield, keep to the northerly limb of the Strathmore syncline. It is possible, however, that the scanty record of such rocks from the level portions of Strathmore reflects rather the presence of widespread sands and gravel than the absence of intrusions. The dykes, which generally show good columnar jointing, are usually single, but sometimes two run alongside each other a little distance apart. They show violent transgression with regard to the country rock, truncating sandstones, conglomerates, and lavas with equal ease, and seem to follow rather the main line of steep folding and dislocations. As certain of the dykes rise through the Strathmore Sandstones, some if not all of them must be of post Lower Old Red Sandstone age. They are a remarkably uniform assemblage petrographically and belong to the group of "East-and-West Dykes" so well developed throughout the Central/
Central Valley of Scotland, which are now usually regarded as of late Carboniferous age. A summary of the evidence with regard to the age of these dykes is given on pp. 150 - 151 of the Glasgow District Memoir (1925).

In many cases the dyke rocks have been quarried extensively for the supply of road metal, and these undertakings have left available for inspection the contacts of the intrusions. In nearly every case the outstanding feature of the country rock walls, whether of sandstone or of conglomerate, is the marked development of smoothed and slickensided surfaces, showing that the dyke occupies a fracture plane, (Pl. IX., fig. 2.). That these fractures do not represent fault lines with any considerable vertical displacement is evidenced by the fairly close continuity of the bedding planes across the break and by the fact that convex portions of the one wall are found to be nearly opposite similar but concave parts on the other in certain cases. It is clear, however, from the generally steep inclination (60° - 90°) of the slickensides scoring that whatever movement there was took place in a nearly vertical direction. The actual directions of the scores have/
have been mapped but as yet they are too conflicting to yield results. The inclination of the dykes varies from the vertical to $30^\circ$ from it on either side.

B. Petrology.

The Corriefodly Sill.

The rock is porphyritic with large serpen-
inised olivines often nearly idiomorphic, and at other times resorbed. The serpentine is bright green in colour, fibrous in texture, and it retains the characteristic curved cracks of olivine. Closely associated with it are numerous small specks of black iron oxide. There are also many large tabular crystals of fresh plagioclase — zoned labradorite — which are in most cases devoid of resorption on the rim although they are occasionally spongy further in. Twinning on all three laws is sometimes seen, and there is a tendency for the crystals to develop in clusters.

The groundmass consists of smaller laths of labradorite which are moulded on clots of tiny granular augite. The interstices are occupied by dark glass with apatite needles, iron oxide microlites and rods. The last stage in the history of the rock apparently was the infilling of any cavities and possibly the re-
placement of/
of some of the glass by bright green chlorites, and a minute quantity of quartz.

Apart from the serpentinised olivine, the constituent minerals are absolutely fresh, (Pl. XX., fig. 1.).

The rock is a coarse-textured olivine-basalt.

The Auchnacree Dyke.

This rock is strongly porphyritic with large tabular plagioclase felspars usually with idiomorphic outlines, although inside they display bands of honeycomb structures and often contain inclusions of brownish glass. Although it is highly decomposed in every section examined, the felspar was most probably labradorite. Slightly less conspicuous in size and number are elongated, slightly resorbed, crystals now replaced by aggregates of chlorites and calcite, the general appearance of which suggests that they are pseudomorphs after hypersthene and possibly augite as well. Of smaller size and more scanty development are pseudo-morphs after olivine with the characteristic shapes and cracks still retained.
The groundmass consists of small stout felspar crystals, granular calcite probably after augite, iron oxide, and brownish-black glass with microlites. The general appearance of the rock recalls most strongly the porphyritic pyroxene-basalts of the Arbuthnott Group, but that we are dealing with an intrusion is shown by the narrow extent of the dyke and the marked chilling towards the contacts where the phenocrysts are small slender felspars set in a groundmass of glass with radiating aggregates of minute felspar needles, in many respects similar to the chilled edges of the dolerite dykes to be described next. The absence of fluidal arrangement of the minerals of this dyke is in contrast to the usual behaviour of those in lava flows, (Pl. XX., fig. 2.).

The rock appears to be a Porphyritic olivine-hypersthene-basalt with definite affinities with certain of the latest lavas of Lower Old Red Sandstone age, and it may well be the product of a late stage of that vulcanicity.
The N. E. – S. W. Dykes.

The dyke rocks are essentially aggregates of plagioclase, pyroxene, olivine, ilmenite, with quartz, apatite and a varying proportion of dark glassy residue.

The most abundant constituent is fresh, water-clear, tabular plagioclase. In coarse-grained rocks the crystals tend, where anything approaching idiomorphism is seen, to have a rather squat habit; in the finer-textured equivalents the felspar occurs as elongated slender laths. It is invariably strongly zoned, the major and central portions being labradorite while the surrounding parts are progressively more acid towards the rim. Twinning on the Carlsbad and Albite laws is prominently developed, and cross and stellate clusters are common. The felspar is on the whole remarkably free from inclusions. Some strings of rather oval or globular dark glass, obviously following cleavage planes, have been noted, together with apatite needles, although this last named mineral was most abundantly crystallised towards the close of the cooling history of the rocks. In addition some small interstitial areas of orthoclase are present.
The pyroxene is a very pale grey-green augite with well marked cleavage. Lamellar twinning is frequent but zoning and hour-glass structures are absent. Very occasionally a dark brownish resorption rim is seen, but on so small a scale that it was not possible to be certain that it is hornblende, although it is probably so. Orthorhombic pyroxene is very scantily represented.

Olivine, or rather its decomposition material, is of widespread occurrence in all the sections examined. It is in the form of rather small lozenges, often approaching idiomorphism and frequently displaying resorption bays, the periphery being marked with black iron oxide, which also occupies the characteristic ramifying cracks throughout the mineral. It is replaced by either fibrous green serpentine or pleochroic reddish-brown to green iddingsite.

Iron oxide is the most abundant accessory and appears in two distinct habits. In one it has the form of complex skeletal crystals, often of fairly large size; in the other it occurs as narrow rods. While the structures are most suggestive of ilmenite, the/
the oxide is magnetic and is regarded as titaniferous magnetite. Apatite is represented by tiny colourless acicular crystals.

Quartz occurs only interstitially or in ocelli, and in very small quantity. It is usually surrounded by greenish and brownish decomposition products in the interstices or by calcite or chlorites in the ocelli.

The mesostasis is of dark brownish glass bounded by idiomorphic felspars. Within it are numerous tiny rods of iron oxide, a few minute felspar laths, some augite microlites, and abundant apatite needles.

An examination of the coarse-textured rocks from the centre of the dykes throws light on their consolidation history and the structures produced, (Pl.XX., fig. 3.). The earliest formed mineral was olivine which, apart from irregularities due to subsequent resorption, presents idiomorphic outlines to all the other constituents, and upon which all the other minerals can be seen to be moulded. Then followed resorption of the crystals, but only to a slight extent. The next mineral to crystallise was iron oxide, skeletal forms not infrequently being embedded on the olivine.

Labradorite/
Labradorite came next in the sequence, followed closely by the pyroxene, for the commonest structure of all the dyke rocks is that most conveniently described as an hour-glass shaped felspar held between jaws of augite. The crystallisation of the augite came to an end before that of the plagioclase which often envelops rounded and idiomorphic edges of the pyroxene. The closing stages of cooling are represented by the formation of glassy mesostasis between the crystalline constituents, but during this time, and slightly before it, the long narrow rods of iron oxide were growing, for they are most widely developed in the glass and penetrate the surrounding plagioclase only to a very slight extent. In many cases they stop short against the pyroxene; in a few they penetrate it, but to an even less extent than in the case of the felspar. The coarse-grained rocks are thus non-porphyritic and strongly ophitic, with comparatively little interstitial mesostasis.

The portions of the dykes nearer the country rock show a progressively finer texture and an increasing percentage of glassy residue, which tends to emphasise the earlier-formed minerals, producing porphyritic structure, (Pl. XX., fig. 4.). The phenocrysts/
phenocrysts are either labradorites, with idiomorphism in the longer pair of sides and a dentate structure in the other two, or labradorite-augite clusters. Nearer the centre of the dyke these clusters show ophitic relationships between the felspar and the fairly large plates of augite, but towards the margin of the intrusion the plates of augite tend to be replaced by clots of granular or hypidiomorphic pyroxenes. With a greater amount of undifferentiated base the chance of finding different minerals in contact is correspondingly lessened, but nowhere was there any evidence of a variation in the order of crystallisation. The plagioclase phenocrysts, even in the finest textured "chilled edge", envelop augites, in a glassy matrix containing abundant small idiomorphic pyroxenes and skeletal titaniferous magnetite, and rather less widespread olivine.

Circular ocelli are frequently developed in the marginal portions of the dykes, and are bounded by tangentially disposed plagioclase. Where the infilling material is glassy mesostasis there is a general radiate arrangement of the microlites. In others, quartz has crystallised/
crystallised inwards from the bounding surfaces, developing regular faces, and the interstices are occupied by calcite in most cases, with or without an intervening layer of sheaf-like green chloritic material. The amount of free quartz present increases towards the margins of the dykes.

A last feature of the dyke rocks, arising from a study of them in thin section, is worthy of mention. The felspars are frequently broken across and rejoined rather imperfectly. The augite in many cases shows marked bending of the cleavage lamellae, with the production of wavy extinction. Both phenomena suggest dislocation and compression of the cooling magma, probably not unconnected with the movements evidenced by the slickensiding of the bounding walls of the intrusion.

From their mineral composition and textures, these rocks can best be described as olivine-tholeiites of the Salen Type, so abundantly represented among the dykes of Mull. An analysis of a good coarse-grained specimen is appended, and for comparison, one from Mull. The similarity is obvious.

### Chemical Analyses of Tholeiites

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<tr>
<td>CO₂</td>
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**A.** Dyke cutting Serpentine Belt at Kinaird on the Melgam Water, Lintrathen.

**B.** Dyke on short ¾-mile S.S.E. of Kintallen and 2½ miles N.N.W. of Salen, Mull. (p. 17 of the Mem. Geol. Survey of Scotland, "Mull, etc." 1924.)
The N. E. - S. W. dykes are a remarkably fresh group of rocks, and so is that of the Corriefodly sill. There is much in common between the two although the sill contains much more olivine. The felspars and the pyroxene are closely akin to each other, and the dark glassy mesostasis is identical to the development of the long streaks of black iron oxide, which penetrate the groundmass felspars only slightly. It is probable that they represent different manifestations of the same phase of vulcanicity. In their general development and characters, they show the closest resemblance to the intrusions of late Carboniferous times. If that be their age it is quite comprehensible why the Auchnacree dyke rock with its Lower Old Red Sandstone affinities should be so highly decomposed while they are so strikingly fresh.
NOTES on GLACIAL HISTORY.

The Pleistocene ice sheets have left many indications of their presence in the peculiarities of topographical relief seen in the northern districts of Perthshire and Forfarshire. The major evidence lies in the rounded features of every mountain and valley, and is too well known throughout Scottish highland areas to call for particular description. The less conspicuous traces of ice work in the form of roches moutonnées, glacial grooves, and striations were noted and considerable additions have been made to the number already recorded on the maps of the Geological Survey, (See Map 2.).

In the Dalradian Schist country, at altitudes generally over 1,000 feet above sea level, the striae are with a few exceptions orientated in a south-east direction parallel to the main river valleys. The exceptions occur in the south-west near the southern margin of the Highland rocks. In the Old Red Sandstone belt to the south, at altitudes from 850 - 500 feet, both striae and roches moutonnées occur, mainly on lava-form/
lava-form rocks although a few were located on conglomerates, (Pl. IX., fig. 3.). Their orientation varied from E. S. E. to E., but in two cases the direction was well north of east. In Strathmore the striae are either easterly or north-easterly, and on the north-western flanks of the Sidlaws, 400 feet higher up, the ice markings show the same easterly trend. The general interpretation of the striae would seem to be that the main Strathmore glacier moving, in its lower parts, towards the north-east had a more easterly direction forced upon it by the advance of powerful tributary ice streams coming from the Highland gathering grounds.

The transport of erratic blocks has left in exposed positions numerous large boulders to which in many cases local names and traditions have been attributed. It is probable that the many "Standing Stones", cairns, etc., which abound in the higher parts, reflect a prodigality of material which attracted the attention of the prehistoric architects. The blocks are almost invariably of Highland and metamorphic origin. The huge "Devil's Stone", below Cortachy Bridge, is a mass of synthetic gneiss. In the Isla above the Reekie Linn there are boulders of a speckled epidiorite more than/
than fourteen feet in diameter.

The most striking relics of glaciation, however, are associated with retreat phenomena. Terminal moraines occur in the upper reaches of most of the valleys in the schist country, barriers of rock debris stretching from side to side and breached only where the present stream passes through. There is a very well preserved terminal moraine in the valley of the S. Esk near Gella Bridge and another on the Back Water below Over Scithie. While variations exist, it is on the whole true that these moraines occur at 750 - 800 feet above sea level.

Drift extends over most of the area up to these altitudes but considerable differences in thickness have been noted. In the valleys of the Prosen and the Carity there is fully 130 feet of boulder clay, but the more common depth probably lies between 30 and 50 feet in more open situations along the north-western flank of Strathmore. On the schist country immediately north of the present Old Red Sandstone boundary it is usual to find drift along the river banks to a depth of over ten feet.

While an examination of the nature of the boulders in the drift would make a special investigation of/
of its own, it was noted that generally Highland material predominates along the Highland boundary, except towards the north in the Prosen and the S. Esk valleys where a fairly high proportion of Old Red Sandstone material occurs in a till overlying a Pre-Old Red Sandstone floor. This would indicate either the removal of an Old Red Sandstone outlier such as that which remains in the Burn of Watersheal or the encroachment of the Strathmore ice upon the higher ground along its northern margin. In keeping with the latter hypothesis is the occurrence of striae with a south-north orientation at Balloch (Ascreavie), a mile-and-a-half to the south-west.

As the ice sheets diminished in thickness, ridges of rock were uncovered and, along the exposed margins, torrents of melt-water found their way to lower levels, carving channels in the process and sweeping away morainic and other debris to be deposited in Kame-like mounds along their banks. Many such piles of irregularly bedded sands, gravels, and pebbles have been noted. There are several elongated hummocks parallel to, but above, the present bed of the Carity, (Pl. XI., fig. 3.). Much more conspicuous masses occur higher/
higher up the same stream east of Auldallan, where the most striking marginal drainage channel in the district debouches on to an old lake bed. At Dykends, Glenisla, the road cuts through a good example of a Kame parallel to the valley of the Back Water, and near Bellaty is another lying alongside the Isla. Between Alyth and Blairgowrie, and parallel to the north-western flank of Strathmore, are long mounds of a similar character and presumably associated with drainage streams, which were forced to keep to the slopes above the central depression by the presence of ice. The best example in the neighbourhood is that south of Pictfield. In the valley of the Erichth there is a long gravel mound, roughly parallel to the stream about a mile-and-a-half above Craighall Bridge. Further to the south-west there is an elongated gravel pile at Concaigie, a little west of the Loch of Clunie. It is at right angles to the Lunan Burn there and was probably associated with a tributary stream coming down the valley from the Craig of Clunie to the south.

The marginal drainage channels with a general parallelism to the fringe of the Grampians form a striking group of valleys linking together the main/
main glens. In some cases they contain diminutive streamlets, in others except for an artificial drainage ditch they are dry. They are generally accompanied by a group of topographic features which may be described briefly. To the south-west these valleys terminate high up on the left banks of some of the principal rivers coming from the Highlands. The dry valleys may be simple, or they may have feeders, or they may occur in groups at different levels. To the north-east each system passes into a triangular shaped depression in the course of a less important Highland river, commonly occupied by sand and gravel banks. Beyond the hollow another dry channel leads in a north-easterly direction to the next Highland valley. It is suggested that this arrangement of surface features, which is duplicated several times between the Tay and the N. Esk, may be interpreted in the following way. For the first part of the dry valleys to be operative, the major river valley to the south-east must have been filled with ice to a height slightly greater than that of the overflows, by means of which the melt-water followed a north-easterly direction seeking an opportunity to flow down into Strathmore, but prevented by the ice sheet lying there, (Pl. XIII., fig. 3.). When/
When the water encountered the remains of a smaller Highland valley, the glacier occupying which had retreated north-westward, a small lake was formed in which sediment carried by the stream from the south-west and the other one from the north-west was deposited. If the Strathmore ice was about the same height above sea level as that in the major Highland valleys, or even fifty feet less in some cases, the water in the small lake would be enabled to flow still further to the north-east until it reached a south-west flowing stream which entered Strathmore beyond the ice margin. At Glenley on the Noran Water there are two dry valleys, one about 700 feet and the other a little lower, which unite a short distance to the north-east forming a well rounded, fairly broad valley till the Cruick Water coming down from the Highlands is reached. If the gap there were barred by Strathmore ice to a height of 700 feet a small lake would be formed, the overflow of which would pass north-eastward along the fine dry valley, below Trusta, to the alluvial flats which indicate an old loch at Balfield (400 feet), through which the present West Water flows to join the N. Esk.
Above the left bank of the S. Esk at Cortachy there are two sets of overflows with tributaries, one set passing north of the Knock Hill at 700 feet, and the other along the south side at 650 feet, (Pl. XII., fig. 1.). At present, what drainage there is joins the White Burn, a Highland stream, and plunging through a steep pile of sands and gravels at Newmill of Inshewan descends to Strathmore. A barrier at 650 feet, however, would divert this drainage through the Den of Ogil — now a reservoir — to feed into the Noran Water about a mile downstream from Glenley.

East of Lintrathen Loch there is a dry valley, associated with fairly broad alluvial flats, and running north-east to Kirkton of Kingoldrum at a height of about 600 feet. The present drainage from it turns right back upon its course there and flows south-west to join the Isla, but a barrier at 650 feet would have diverted the water still further north-eastward to discharge into the Loch of Kinnordy — now almost completely dried up.

Above the Alyth Burn near Bamff House are two dry valleys (650 feet and 640 feet) which join to form a broad rounded valley running north-east along the Serpentine/
Serptine Belt to the Achrannie Burn, a tributary of the Isla.

There is a conspicuous notch on the north-east bank of the Erich, north of Drimmie Wood, and truncating a lava with the formation of the cliff called the Craigies. Closer inspection shows this to be an overflow channel (780 feet) with a second a little to the south (750 feet) which join and then pass across the Moor of Drimmie to the Alyth Burn beyond. The fine deep dry valley known as the Den of the Welton is 850 feet above sea level at its south-western end and runs along the Highland Boundary Fault to the Alyth Burn.

Finally mention must be made of the finest dry valley system located, lying to the north of the series just described. Immediately to the north of Lintrathen Loch is a sheet of sand and gravel forming the floor of a valley which is somewhat broken by elongated hummocks and mounds terminating southwards in a broad barrier some fifty feet high, and composed of roughly bedded yellow sands with occasional layers of boulders, probably banked up against the Strathmore ice, (Pl. X., figs. 1 and 2.). Its base is about 680 feet above sea level. Round the margins of this tract are/
are traces of old terraces, and the general characteristics are those of an old lake. It was fed by the Quharity Burn coming from the north and it probably received in addition the Melgam Water, which now discharges into Lintrathen Loch, but which may have passed to the more northerly basin by one or other of the three hollows below Wester Coul Farm. The outlet of the lake, the water of which stood at an altitude of about 800 feet, was at its north-eastern corner below Craig of Auldallan, from which it is proposed to name this old loch. A striking deep valley, with steep but rounded sides and a spread of gravel and boulders across its floor, (Pl. X., fig. 3.), runs eastwards for two miles along the southern margin of the Dalradian schists, and debouches on to a second alluvial flat with gravel mounds and terraced margins, 680 feet above sea level, (Pl. XI., fig. 1.). The outlet of this loch, the Loch of Ascreavie, was not at its extreme eastern end but at its south-eastern corner where it overflowed across a ledge of dacite and cut back the gorge now known as Carity Den, (Pl. XI., fig. 2.), the waters then going eastward to join the Prosen. The speed of the floods passing/
passing from the Loch of Auldallan to the Loch of Ascreavie is evidenced by the deeply incised channel, and by the fact that the detritus was swept to the far eastern end of the lower loch, where now lie great piles of sand and gravel.

It is worthy of note that the dry valley systems, of which a few have been described, lie to the north-east of each major Highland Valley, a circumstance in keeping with the fact that the melting of snow and ice would be more marked along the south-facing slopes of the valleys. At certain places, the west banks of the Highland rivers are occupied by great piles of sand and gravel heaped against the side of the valley and often showing cone scree etc., examples being the Heuchs o’ Mause on the Erich, (Pl. XIII., fig. 1.), and also on the Burn of Kilry, west of Kilry. In all probability they represent material swept down by the late glacial floods and deposited wherever a widening of the channel demanded a diminution of the load.

The last and lowest marginal drainage channel of importance is now marked by the chain of shallow lochs, (Pl. XII., fig. 3.), separated by stretches/
stretches of bog or irregular areas of sand and gravel, which extends from the Loch of the Lowes, less than a mile distant from the Tay, through Butterstone, Clunie, (Pl. XII., fig. 2.), and Marlee Lochs — the last-named being seven-and-a-half miles E. N. E. of the Tay — eventually draining into the Isla, which joins the Tay at Cargill. The distance from the Loch of the Lowes down the Tay to Cargill is ten miles; the drainage of the lochs follows a course of fifteen miles.

We can gain some idea of the thickness of the Strathmore ice sheet, during the halt in its retreat indicated by the main marginal drainage channels, by a comparison of the level of their intakes with the present altitude of the floor of Strathmore opposite to them.

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<tr>
<td>S. Esk</td>
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<td>Alyth Burn</td>
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<tr>
<td>Erich</td>
<td>780</td>
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The ice apparently thickened from north to south, the increment being of the order 1: 465, although the actual surface was nearly horizontal. The latest drainage system through the lochs shows that the ice barrier sloped downwards in a northerly direction, the gradient being 1: 235, and that the corresponding thickening to the south was as 1: 222, more than double that during the earlier stages of retreat. It is possible that in the first case the edge of the ice sheet lay well to the north, while in the second there was a steep terminal slope somewhere in the vicinity of Blairgowrie.

The disappearance of the ice sheets left the river systems to re-establish themselves on an area the topography of which doubtless had been modified profoundly. While in their upper courses the streams probably followed ice-deepened ancient valleys cut in the schists, in the area to the south new channels had to be carved through Old Red Sandstone rocks. The shortest route to the floor of Strathmore demanded rock-cutting in the direction of dip, and, while in some cases this was done, in others there is deflection of the/
The Recent History of the Loch of Lintrathen.

Scale 2 ins = 1 mile.

1870

Lintrathen

1927

Lintrathen

Melgam Water

Inzium Burn

Auchen Flat

Melgam Water

Inzium Burn

Roads, Paths
the rivers for varying distances along the strike of the more resistant outcrops.

The general disposition of the outcrops at right angles to the principal drainage direction probably produced the ponding evidenced in different localities where alluvial flats indicate the earlier existence of lakes. The work performed by the considerable head of water thus conserved is shown in the deep and narrow gorges found downstream from the old lake beds, e.g. Craighall Gorge, (Pl. V., fig. 2.), Keith Falls, (Pl. V., fig. 3.), on the Erich; Reekie Linn, (Pl. IV., fig. 2.), Slug of Achrannie, on the Isla; together with others on the Prosen and S. Esk.

Lintrathen Loch, (Pl. XIII., fig. 2.), is a sheet of water on the Melgam drainage system, dammed behind a resistant mass of dacite. The erosion of its outlet channel had in 1870 lowered the water level and drained the basin to half its earlier superficial extent. The reason why it had not shared the fate of complete drainage suffered by the others is apparently either because it was the site of an earlier lake, the outlet of which was at its southern end, or because ice/
ice action had deepened that end. The Post-Glacial overflow was towards the south-east, through the Melgam gorge below Lintrathen Church, and when this was cut sufficiently low to drain the northern half of the loch, the south-western deeper basin remained untapped, separated from the exposed river channel by a belt of marsh nine hundred feet across. The most recent phase in the history of this interesting loch has been its reinstatement over the original extent by the erection of a dam across the Melgam Water overflow by the Water Commissioners of the City of Dundee.
SUMMARY.

1. The Highland Border Series.

The rocks previously mapped as Margie Grits have been examined microscopically and are shown to resemble very closely those from other localities. In the R. Prosen there has been found a new group of fine grits, black shales, and chert, which are devoid of fossils but probably belong to the older Black Shale-Jasper Series.

2. The Lower Old Red Sandstone.

A petrological examination of the lava-form rocks has shown them to belong to various subdivisions of the andesite and basalt families. The well-known "Lintrathen porphyry" is found to be a dacite and also a lava flow with a wide-spread occurrence at one stratigraphical horizon.

An investigation of the conglomerates has shown their reliability as stratigraphical indices, and a definite rhythmic variation in their composition has been demonstrated, upon which an interpretation of the conditions of their accumulation can be based.

The tuffs and sandstones show a closely similar variation in composition.
3. **The Upper Old Red Sandstone.**

What may be a remnant of Upper Old Red Sandstone sediments has been found among the Margie Grits near Auchnacree.

4. **The Serpentine Belt.**

The rocks of the belt contain the remains of three types of ultrabasic igneous rock, HARZBURGITE, SERPENTINE-PEGMATITE, and DUNITE, and probably represent one plutonic intrusion; together with a smaller quantity of highly decomposed tuffs resembling schalsteins.

5. **Intrusions.**

Most of the intrusive igneous rocks are N.E.-S.W. dykes of tholeiitic character, identical with the Salen type tholeiite from Mull. One sill near Bridge of Cally is probably associated with these rocks, representing a slightly different phase of the volcanicity which may be of Carboniferous age. The dyke at Auchnacree is a pyroxene-basalt and may be connected with the igneous activity of Old Red Sandstone times.

6. **Sequence.**

A stratigraphical sequence of the Lower Old Red Sandstone rocks has been worked out on the field evidence/
evidence, and it has been found that the order and grouping is similar to that derived from the Kincardineshire rocks by R. Campbell. The nomenclature of that author is therefore employed.

7. Tectonics.

The investigation has revealed the existence of a major Highland thrust with a minor one to the north, both of them being steeply inclined upthrusts from the north-west. Estimates of their magnitude are given. Beyond is a normal fault with its downthrow to the south-east. The rocks of the serpentine belt are bounded both to the south-east and to the north-west by planes of dislocation, evidence of contact metamorphism by the serpentine on the country rock being absent. The serpentine-schalstein complex is therefore thought to be older than the Lower Old Red Sandstone. There is a second group of dislocations—dip faults—cutting the Highland Boundary area in a direction N.N.E. - S.S.W.

The Old Red Sandstone rocks lie in synclines elongated approximately parallel to the major thrust and fault lines, and in the north-westerly area overlie/
overlie immediately a denuded Dalradian schist floor. In the middle and more easterly areas anticlinal folds occur in close proximity to the main Highland Boundary Thrust.

The glaciation of the region has left extensive relics. New striae and roches moutonnées are recorded and various kames are noted. A series of marginal drainage channels has been mapped along the fringes of the Grampians, parallel to the main valley of Strathmore, and the possibility of their inter-communication in some cases discussed. Associated with these are certain lakes, but there are many others, at intervals along the course of the present river systems, of probably later date, when the melting snows followed the shortest route to Strathmore and cut deep gorges through the conglomerate ridges.
Fig. 1. Marginal Drainage Channel north-west of Glenley with outcrops of Margie Grits along hillside to the left.

Fig. 2. Cliff of microporphyritic biotite-andesites on left bank of R. Ericht below Old Milton of Drimmie.

Fig. 3. Folded microporphyritic biotite-andesite immediately north of dolomite-fault-breccia on the Alyth Burn downstream from Craighead.
Fig. 1. The Devil's Punchbowl on the R. Isla. The waterfall is cut through Lintrathen type dacite. Below the distant crooked tree on the right, the dark shadow marks the hollow where the tuff has been eroded from between the dacite and the overlying olivine-basalt.

Fig. 2. A closer view of the same outcrop. The tuff is immediately above T on the photograph. D = dacite; B = basalt.

Fig. 3. Old Quarry south of the Knock, Cortachy, with conglomerate overlying an eroded floor of Lintrathen type dacite, the line of junction being marked in black.
Plate II.

1.

2.

3.
Fig. 1. Old Quarry South of the Knock, Cortachy. Conglomerate overlying eroded dacite floor. To the right above the hammer is a large rounded boulder of dacite.

Fig. 2. Tamhingan near Dunkeld. The hill consists of Lintrathen type dacite. The Highland Boundary Thrust runs through the loch, and the camera was standing on Dalradian schistose grits.

Fig. 3. The Isla gorge below the Rekie Linn, with cliffs of Lintrathen type dacite on the left bank.
Fig. 1. The Isla gorge below the Reekie Linn, with cliffs of porphyritic biotite-andesite on the left bank.

Fig. 2. The Reekie Linn on the R. Isla, the water falling over a ledge of microporphyritic olivine-andesite.

Fig. 3. The top of the Reekie Linn, with the ledge of microporphyritic olivine-andesite, showing platy jointing.
PLATE V.

Fig. 1. Basement conglomerate of phyllite and vein quartz fragments in Lower Old Red Sandstone outlier at Strone House on the R. Ardle.

Fig. 2. Gorge on the R. Ericht cut through Lower Old Red Sandstone conglomerates along a line of fault at Craighall.

Fig. 3. Quartzite conglomerate on the R. Ericht at the Keith near Blairgowrie. The erosion of the constituent pebbles often gives rise to the formation of potholes.
Fig. 1. Outcrop of serpentine on the R. South Esk immediately above Cortachy Bridge.

Fig. 2. Serpentine exposure on the Carity Burn, which beyond the right angle bend in the foreground flows along the junction of the serpentine with the most northerly infaulted area of Lower Old Red Sandstone mudstones.

Fig. 3. Serpentine exposure on the Carity, as above, but showing a great knob of pegmatitic serpentine (P).
Fig. 1. Carity Den section. Uptilted Lower Old Red Sandstone mudstones immediately to the south of the serpentine shown in Plate VI., fig. 2. This is the most northerly infaulted area of sediments in the serpentine belt.

Fig. 2. Carity Den section. Lower Old Red Sandstone conglomerate faulted into dolomitic serpentine-fault-breccia (F).

Fig. 3. Highland Boundary Fault in the Isla. To the left of the line are highly disturbed sandstones; to the right a tholeiite dyke.
Plate VII.

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3.
Fig.1. Limestone Bank Quarry south-east of Loch of Clunie. Tholeiite dyke cutting calcareous fault-breccia along the Highland Boundary Fault. The large slickensided surface is possibly associated with the injection of the dyke, but above the spade on the left the shear-planes of the breccia can be seen to lie at a lower angle from the horizontal and most probably follow the main plane of the original dislocation.

Fig.2. Fault on the right bank of the R. Ardle above Bridge of Cally. The hammer lies on Dalradian schists, the branch follows the line of fault, and the foreground is occupied by a Lower Old Red Sandstone "Highland" conglomerate.

Fig.3. Infaulted Lower Old Red Sandstone outlier at Strone House on the R. Ardle. The cliff at the back consists of vertical phyllites, to the left can be seen a local basement conglomerate of phyllite fragments, and to the right under the trees is a small outcrop of a microporphyritic biotite-andesite.
Fig. 1. Olivine-basalt sill at Corriefodly on the left bank of the R. Arde. The hornfelsed underlying sediments stand out as a ridge high up among the trees at the back.

Fig. 2. Tholeiite dyke at Westfield, Blairgowrie. Most of the igneous rock has been quarried away but a small patch remains in the bottom right corner. The slickensided walls of Lower Old Red Sandstone conglomerate can be seen towards the middle.

Fig. 3. Near Dunmore above Stenton on Tay. Roches moutonnées of andesite.
Fig. 1. View north-east from the Knock of Formal to Cat Law with the Gorge of Auldallan forming the V on the horizon and the alluvial flats of the old Loch of Auldallan in the central portion of the photograph.

Fig. 2. Gravel mounds and alluvial flats of the Loch of Auldallan with the outlet through the gorge to the left beyond the two trees.

Fig. 3. The north-eastern end of the Auldallan gorge — a dry valley with a gravelly bottom. It is here that it debouches on to the flats of the old Loch of A screavie.
Fig. 1. View from Kame at north-east end of Auldallan gorge to the old basin of the Loch of Ascreavie. Traces of terraces can be seen on the right. The wooded ridge in the central and right background is the outcrop of Lintrathen type dacite. The outflow was by the Carity Den, marked with the arrow.

Fig. 2. Carity Den, a dry valley with rocky walls of Lintrathen type dacite.

Fig. 3. View north-east across the Carity Burn valley. The hillock marked K is the dacite outcrop at the Knock, Cortachy. Beyond are Dalradian Schist hills. To the left along the banks of the Carity are Kames.
PLATE XII.

Fig. 1. View north-east along dry valley on south side of the Knock, Cortachy.

Fig. 2. Loch of Clunie. View from east side showing Dalradian Schist mass of Benachally beyond.

Fig. 3. View from hill to south-west of Loch of Clunie, showing the line of the lochs linked up with marshes and sand-banks. In the foreground is the Loch of Clunie, beyond is Marlee Loch.
PLATE XIII.

Fig. 1. Gravel and sand piles at Heuchs o' Mause on the R. Erich, above Blairgowrie.

Fig. 2. The Loch of Lintrathen from the Knock of Formal.

Fig. 3. View across Strathmore from the summit of the Heuchs o’ Mause, Blairgowrie.
Fig. 1. **Lintrathen type Dacite.** In the centre a large phenocryst of quartz showing marked resorption. On either side are crystals of oligoclase, while above are several flakes of biotite. The groundmass consists of small fragments of quartz, strips of plagioclase and accessory iron oxide and apatite set in a glass and together showing fluidal arrangement.

X 30. **Quarry beside Lintrathen Loch.**

Fig. 2. **Lintrathen type Dacite.** Phenocrysts of quartz and biotite, the latter with inclusions of apatite, set in a glassy groundmass possessing good spherulitic structure.

X 30. **Hill Quarry beside Lintrathen Loch.**

Fig. 3. **Porphyritic Biotite-Andesite.** Numerous phenocrysts of oligoclase-andesine with tabular habit occur to the right. On the left is a large crystal of biotite showing crumpling of the lamellae. The elongated light area is composed of pale green chlorites. Apatite inclusions are present. The groundmass consists of small stout laths of oligoclase, clear apatite, iron oxide, and brownish glass.

X 30. **Isla Gorge, right bank, downstream from Reekie Linn.**
PLATE XV.

Fig. 1. Microporphyritic Biotite-Andesite. A flake of biotite replaced by black iron oxide is seen in the upper part of the field, scattered throughout which are smaller elongated crystals of oligoclase-andesine. The groundmass consists of small felspar laths, biotite, some granular augite, and iron oxide. The dark appearance of the rock is due to the biotite of the groundmass having been replaced by black iron oxide which has tended to spread throughout.

X 30. Burn of Drimmie near Rannagulzion.

Fig. 2. Non-porphyritic Biotite-Andesite. A very fine-textured rock composed of tiny oligoclase laths, flakes of biotite, and granular calcite probably after augite. There is abundant acicular apatite. The irregular patches of iron oxide seen in the upper half of the field may represent original clots of biotite and are of frequent occurrence.

X 30. Quarry south-west of Wester Derry.

Fig. 3. Porphyritic Andesine-Pyroxene-Andesite. Near the top is a phenocryst of fresh andesine; to the right is one of hypersthene showing strong transverse cracks and a resorbed rim. The groundmass consists of andesine, augite, apatite, iron oxide, and glass—showing typical hyalopilitic structure.

**PLATE XVI.**

**Fig. 1.** Porphyritic Labradorite-Pyroxene-Andesite. Numerous phenocrysts of labradorite with abundant glass inclusions. To the left is a smaller hypersthene, to the right an augite. The groundmass is hyalopilitic containing tiny laths of andesine, pyroxene, apatite, and iron oxide.

X 30. Road floor east of Lintrathen, near Wardend.

**Fig. 2.** Microporphyritic Pyroxene-Andesite. Abundant small crystals of hypersthene set in a groundmass of laths of andesine and small prisms of both monoclinic and ortho-rhombic pyroxene. The structure is closely akin to pilotaxitic.

X 30. Gauldswell Quarry, Bamff.

**Fig. 3.** Microporphyritic Olivine-Andesite. At the bottom is a good idiomorphic serpentinised olivine. Other smaller ones are of frequent occurrence. The groundmass consists of laths of andesine and small prisms of augite, and fluxion structure is well developed. The accessories are iron oxide and apatite.

X 30. Top of Reekie Linn, R. Isla.
Fig. 1. Porphyritic Olivine-Hypersthene-Basalt. In the top left hand quadrant is a resorbed tabular labradorite phenocryst, and near it is a good almost idiomorphic serpentinised olivine. The bottom right hand quadrant is occupied by two or three bastite pseudomorphs after hypersthene, growing together. The groundmass consists of small but stout laths of labradorite, the remains of probably both hypersthene and augite, apatite and iron oxide. Some of the black represents glass.

X 30. Lornty Burn, Milton of Drumlochy.

Fig. 2. Porphyritic Olivine-Basalt. Large idiomorphic serpentine pseudomorphs after olivine, and smaller elongated crystals of labradorite, set in a groundmass of labradorite laths, granular calcite after augite, and a little olivine. Iron oxide, apatite, and dark glass fill in the interstices. The rock is exceedingly decomposed but is one of the best examples available.

X 30. Burn of Watersheal, Nether Drumhead.

Fig. 3. Microporphyritic Olivine-Basalt. Small porphyritic serpentinised olivines approaching idiomorphism, set in a groundmass of tiny labradorite laths and granular augite, together with apatite, iron oxide, and some glass. Good fluidal banding is seen.

X 30. Burn of Watersheal outlier.
Plate XVII.

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Fig. 1. Porphyrritic Olivine-Enstatite-Serpentine (Harzburgite).
Unaltered enstatite, with strong cleavage, embedded in mesh (olivine) serpentine. Near the top to the right is a crystal of picotite.

X 30. Bogside – Bamff ridge, north-west of Alyth.

Fig. 2. Pegmatitic Serpentine.
Fibrous serpentine after enstatite.

X 30. Carity Burn.

Fig. 3. Dunite Serpentine.
Serpentine after olivine, with black iron oxide occupying the mesh-lines.

X 30. South of Craig, north of Alyth.
Plate XVIII.

1.

2.

3.
Fig. 1. Schalstein. Silicified rock containing igneous fragments and iron oxide, showing "aschen" structure.


Fig. 2. Schalstein. Similar to Fig. 1 above, but with some quartz grains.


Fig. 3. Chert. Chert with rhombs of carbonates and specks of black iron oxide.

X 30. R. Prosen above Prosenhaugh.
PLATE XX.

Fig. 1. **Olivine-Basalt.**
In the centre is a serpentinised olivine, surrounded by tabular crystals of labradorite. The groundmass consists of laths of labradorite and small prisms and granules of augite. The remainder of the field is occupied by dark glass and iron oxide. Long streaks of black iron oxide are of common occurrence throughout.


Fig. 2. **Olivine-Hypersthene-Basalt.**
To the left is a bastite pseudomorph after porphyritic hypersthene, and at the bottom is a phenocryst of labradorite. The groundmass consists of small felspar crystals, and some granular calcite probably after augite. The residue is dark glass.

X 30.  Dyke in stream west of Auchnacree.

Fig. 3. **Tholeiite.**  Coarse-textured from centre of dyke. Large tabular labradorites in sub-ophitic to ophitic relationship to the augite occupy most of the field. To the left is a small lozenge-shaped serpentinised olivine on which is moulded black iron oxide. Both are surrounded in part by plagioclase and in part by augite.

X 30.  Hill of Ogil, Quarry on south side.

Fig. 4. **Tholeiite.**  Porphyritic "chilled edge" of dyke. Elongated crystals of labradorite with smaller augites partially embedded in them, set in a dark glassy base containing a felt of smaller plagioclase laths, granular augite, and some iron oxide.

X 30.  R. Isla, right bank, near Wester Campsie.
Sketch Map showing Glacial and Drainage Features along the Highland Border.

Present Rivers & Lakes, in Black.
Past Rivers & Lakes in Blue.
Gorges in continuous Red Lines; Marginal Drainage Channels in Broken Red Lines.

- Strips
  - Rocks Fossil Beds
  - Sands & Gravel

Scale 1 in. = 1 mile

Heights = Feet
Geological Map of the Highland Border in Perth and Forfar. Scale 1 inch = 1 mile.