NO. XXIV.—THE CLASSIFICATION OF THE POST-CARBONIFEROUS
INTRUSIVE IGNEOUS ROCKS OF THE WEST OF SCOTLAND. By
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I. INTRODUCTION.

No one studying the geological maps of Scotland, on whatever scale, can fail to be impressed by the enormous amount of igneous activity they disclose in the geological history of that country. The broad areas of pink or brown, indicating great lava plateaux, and the splashes and stripes of crimson, indicating intrusive rocks, are literally everywhere. Not only are the igneous rocks widely distributed in space, but also in time. Practically every formation up to the Permian supplies its quota. In the Archæan we have the great foundation of gneiss, with its inextricable tangle of acid and basic igneous rocks. The Dalradian schists and gneisses of the Grampians are everywhere penetrated by igneous masses now largely metamorphosed to massive epidiorites and hornblende schists. The Cambrian of the north-west Highlands contains an interesting complex of highly alkaline rocks, including borolanite and several other rare types. The Ordovician, Devonian, Carboniferous, and Permian in Scotland each exhibit a great series of extrusive and intrusive igneous rocks. Finally, after a long period of quiescence in the Mesozoic, an enormous outburst of igneous activity in the Tertiary gave rise to the great lava plateaux of the Western Isles.

This richness in material makes Scotland a petrographer's paradise. The amount of work that has been done, however, in spite of the labours of Zirkel, Allport, Judd, Geikie, Teall, Harker and others, is very little in comparison with the great amount that still remains for petrographers to do. "No adequate investigation," says Sir A. Geikie, referring to the Carboniferous plateau eruptions, "has yet been made of the chemical and microscopic characters of these various rocks, regarded as a great volcanic series belonging to a definite

geological age, though many of the individual rocks and the petrography of different districts have been more or less fully described.”¹ The same remark is applicable to the igneous rocks of many of the other formations, although in regard to some we are fortunate in possessing memoirs like that of Mr. Harker on “The Tertiary Igneous Rocks of Skye.”

The district about Glasgow and the West of Scotland generally is exceptionally favourable to the study of igneous petrology. The great lava plateaux of the Campsie, Kilpatrick, and Renfrewshire Hills are in close proximity. The Old Red Sandstone and Permian igneous rocks of Ayrshire, and the numerous, as yet unclassified sills and dykes, are practically virgin ground. In addition, there are the Tertiary volcanics of the Western Isles, and that favoured island of perennial petrological interest, Arran.

The ages of various groups of igneous rocks in Scotland are well defined up to the Carboniferous by their association with sediments of definite age. This is, of course, especially true of interbedded lavas. For intrusive rocks, however, the evidence may not be quite so conclusive. Nevertheless, it has been found possible, by means of several converging lines of evidence, to ascertain the place in time of several groups of intrusive rocks. A difficulty arises, however, when we come to intrusions piercing the younger Carboniferous rocks on account of the absence or fragmentary condition of all younger sediments. The lavas intercalated with those small patches of red sandstone overlying the Coal Measures in Ayrshire may be regarded with some probability as Permian. There remain, however, a great number of *intrusive* masses, later than the Carboniferous, whose exact age is still very uncertain. It is with these rocks that it is proposed to deal in this paper. It is hoped to show by the petrographical evidence that they fall into several well-defined groups, the respective ages of which may be determined with some degree of precision.

Although the use of age distinctions in the general classification of igneous rocks has fallen into disrepute, mainly owing to the criticisms of British petrologists, it is well to remember that, in strictly circumscribed areas, the igneous rocks of a

¹ “Ancient Volcanoes of Great Britain” (1897). Vol. i., p. 377.

particular age are often characterised by a distinct petrological facies. To take a particular case: while it is impossible to maintain that there is a world-wide classificatory difference between Carboniferous and Tertiary dolerites, yet within limited areas such differences may frequently be recognised, and are often very constant and peculiar. Moreover, when minuter petrological and chemical features are taken into account, these distinctions become much sharper, and constant differences may also be recognised between the igneous rocks of different parts of the same formation. While this principle is used in this paper, it is not maintained that single rock specimens can be assigned to their respective age groups on petrological examination alone. For example, it may not be possible to distinguish between the marginal facies of a late Palæozoic quartz-diorite sill and some of the Tertiary dykes, or between the analcite-free facies of the teschenite group and some of the coarser ophitic Tertiary dolerites. But if a small, representative suite of specimens from any particular occurrence is available, then there should not be much difficulty in assigning it to its particular age group.

II. LITERATURE.

It will be necessary here to review, as briefly as possible, some of the work already done in the petrology of the West of Scotland. These notices will be strictly confined to the range indicated by the title of this paper, namely, to the post-carboniferous intrusive igneous rocks of the West of Scotland. On account of the enormous increase of precision in classification afforded by the introduction of the microscope into petrology, it will be unnecessary here to refer to the many valuable memoirs of pre-microscopic days. Accordingly, our first reference is to be found in the classic pioneer paper of the late Dr. Sorby, "On the Microstructure of Crystals." In this paper the pitchstone of Arran is described at some length, mainly with regard to the enclosures and cavities in the porphyritic crystals.² Whilst petrological study was somewhat neglected in Britain during the ensuing years, it was taken up enthusiastically by Continental geologists, one of whom, Ferdinand Zirkel, paid

² *Q.J.G.S.*, vol. xiv. (1858), p. 476.

special attention to the rocks of Western Scotland. He described some of the Arran pitchstones in his "Microscopische Gesteinsstudien,"³ but his most important contribution is to be found in his "Geologische Skizzen von der Westküste Schottlands."⁴ Herein is described very fully the granites, "traps," and pitchstones of Arran, and many other of the igneous rocks within our range occurring in Mull, Iona, Staffa, and Skye. In the next year, 1872, Samuel Allport contributed two papers to the *Geological Magazine* on the pitchstones and felsites of Arran.⁵ These were followed in 1874 by his great paper on "The Microscopic Structure of British Carboniferous Dolerites," in which many Western Scottish rocks were described.⁶ Under the term "porphyritic dolerite" he described the well-known porphyritic essexite occurring on the hillside north of Lennox-town. The teschenites of the east of Glasgow are described as micaceous dolerites, and several of the quartz diabase sills are described under no particular name. From his descriptions the sills of Clauchland and Dippin in Arran are also probably teschenites.

In the same year Professor J. W. Judd began his researches on the Tertiary volcanic rocks of the Western Isles of Scotland.⁷ Since that time a number of memoirs on the same subject have appeared from his pen, all of which contain valuable additions to the petrology of Western Scotland. In 1883 appeared a paper on the Tachylytes of the Western Isles, with Professor G. A. J. Cole;⁸ in 1885, on "The Tertiary and Older Peridotites of Scotland";⁹ and, in 1886, on "The Gabbros, Dolerites, and Basalts of Tertiary Age in Scotland and Ireland."¹⁰ In 1888 appeared Dr. J. J. H. Teall's monumental work, "British Petrography," in which numerous Western Scottish rocks are described and figured. Dr. Teall first recognised the teschenitic affinities of the rock of the Necropolis Hill in Glasgow,¹¹ and

³ Sitz. Akad. Wiss. Wien., xlvii. (1863), pp. 260-262.

⁴ Zeitsch. d. deut. Geol. Gesell., xxiii. (1871), pp. 1-124.

⁵ *G.M.*, vol. ix. (1872), pp. 1-10; 536-545.

⁶ *Q.J.G.S.*, xxx. (1874), pp. 529-567.

⁷ *Q.J.G.S.*, xxx. (1874), pp. 220-302.

⁸ *Ibid.*, xxxix. (1883), pp. 444-465.

⁹ *Ibid.*, xli. (1885), pp. 354-418.

¹⁰ *Ibid.*, xlii. (1886), pp. 49-97.

¹¹ *Brit. Petrog.* (1888), p. 194.

also the well-marked differences between the Newer Palæozoic and Tertiary dykes of the South of Scotland and the North of England.¹² Professor Judd maintained the same distinction in his paper of 1889.¹³ A paper by the same author in 1893 described some of the Tertiary intrusions in the west of Arran.¹⁴ The presidential address by Sir A. Geikie to the Geological Society in 1892 gave many details of the rocks within the scope of this paper.¹⁵ From this point onward papers on Scottish petrology become too numerous to be mentioned individually. Only those of outstanding importance will be mentioned. In 1895 appeared Dr. Corstorphine's memoir on the eruptive rocks of the South of Arran.¹⁶ In 1897 appeared Sir A. Geikie's "Ancient Volcanoes of Great Britain," a book from which all workers in the igneous rocks of Scotland must start. It contains a most comprehensive and valuable survey of all pre-existing knowledge of the rocks dealt with in this paper. In 1897, too, appeared the Geological Survey Memoir on the Cowal District, in which Mr. Clough established the pre-Tertiary age of the great E.-W. dykes. Since 1900 Survey Memoirs and Annual Summaries of Progress have given a good deal of information, especially in the way of chemical analyses. The Memoirs on N. Arran and Bute (1903), on "The Tertiary Igneous Rocks of Skye" (1904), and "The Geology of the Small Isles" (1908) must be specially mentioned. The two latter districts lie somewhat outside our territorial range; and, moreover, have been so fully dealt with by Mr. Harker as to require very little attention in this paper, which deals more with the district within easy reach of Glasgow. In these *Transactions* may be mentioned two recent papers, one by Mr. P. MacNair "On the Dolerites of the Neighbourhood of Glasgow,"¹⁷ and by Mr. R. Boyle "On the Ultrabasic Rocks of the Lugar and Cumnock Districts."¹⁸

¹² Brit. Petrol. (1888), p. 206.

¹³ *Q.J.G.S.*, xlv. (1889), p. 209.

¹⁴ *Ibid.*, xlix. (1893), pp. 536-565.

¹⁵ *Q.J.G.S.*, xlviii. (1892). Proc., p. 60.

¹⁶ *Tscherm. Min. u. Petr. Mitth.*, xiv. (1895), pp. 443-470.

¹⁷ *Trans. Geol. Soc. Glasgow*, xiii., pp. 56-86.

¹⁸ *Ibid.*, xiii., pp. 202-223.

III. CLASSIFICATION.

Broadly speaking, the post-Carboniferous intrusive rocks fall into three main groups—

- (1) The great E.-W. dykes and their associated sills of quartz-diorite or dolerite. The age of these is almost certainly Permo-Carboniferous.
- (2) The alkalic group of teschenites and essexites, with their ultrabasic and other varieties—these seem to be connected with the Permian vulcanicity of Ayrshire.
- (3) The extremely varied group of intrusive rocks of undoubted Tertiary age—in our district occurring chiefly in the Island of Arran.

The minuter subdivision of these groups is set forth below. About three hundred rock-slides have been examined in the course of this work, including a fine collection of sections of igneous rocks from Ayrshire and Arran, for the kind loan of which I have to thank Mr. David Ferguson, F.R.G.S., Mem.Inst.M.E.

IV. THE QUARTZ-DIABASE DYKES AND SILLS.

One group of these rocks has been fully described in my paper on the "Geology and Petrology of the Igneous Intrusions of the Kilsyth-Croy District."¹⁹ They appear almost invariably as very long, massive, vertical-sided dykes, extending in an E.-W. direction, sometimes for many miles. With them are associated great sill or laccolite-like protrusions into the adjacent strata. These rocks are grey to black in colour, and of medium grain, although there occur sporadically towards the interior of the masses lighter coloured and much coarser types. The marginal facies is a dense black basaltic rock, sometimes porphyritic with small, glassy feldspars. Microscopically they are found to consist of an interlocking framework of labradorite and augite, with iron ores, in a groundmass of quartz and micropegmatite. In the more acidic, coarser grained rocks above mentioned the last-named constituents become very abundant. The average proportions of the essential constituents in the normal grey

¹⁹ *Geol. Mag.* (v.), vol. vi. (1909), pp. 299-309; 359-366.

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medium-grained rock, of which the great bulk of these intrusions is composed, are given below. These have been calculated from the "norm" of an analysis of the rock of Auchinstarry Quarry, Kilsyth.²⁰

	Per cent.
Plagioclase (chiefly labradorite), - - - - -	48
Pyroxene (augite and hypersthene), - - - - -	32
Quartz and micropegmatite, - - - - -	9
Iron ores, - - - - -	8
Water, CO ₂ , &c., (= alteration products), - - - - -	3
	<hr/> 100 <hr/>

The plagioclase is highly zonal, a medium labradorite forming the core of the crystal, and oligoclase the margin. Where adjacent to an area of micropegmatite, the felspar of the margin is often seen to be continuous with the feldspathic base of the micropegmatite. The pyroxene is a pale yellow to colourless augite, with the sahlitic striation parallel to the basal plane, which, in conjunction with simple twinning, gives rise to "herring-bone" structure. Occasionally it appears to take on the pleochroism and polarisation colours, but not the straight extinction, of hypersthene. Chemical analysis of the augites of similar rocks has shown in a number of cases that the mineral contains an abnormally large proportion of the hypersthene molecule.²¹ The phenomenon has been explained as a sub-microscopic intergrowth of the orthorhombic and monoclinic pyroxenes. The iron ore consists of an intergrowth of magnetite and ilmenite, or of the latter only. Quartz and micropegmatite, the latter varying in freshness and grain with the freshness and grain of the rock, fill up the interspaces. Numerous apatite needles penetrate all constituents, least in the pyroxene and most abundantly in the micropegmatite.

The usual type of structure is that termed subophitic by Professor W. W. Watts. In the most typical rocks early basic unzoned felspars may be found entirely enclosed in augite. Conversely, the later, highly zonal felspars occasionally enclose idiomorphic crystals of augite. This variation may frequently be found within the limits of a single slide, and may be

²⁰ See petrological part of above paper.

²¹ For petrological detail and references, see Kilsyth-Croy paper, *op. cit.*

explained as due to a continuous separation of felspar substance from the magma during its crystallisation, the separation of augite being episodal, beginning after the first crop of basic felspars, and ending before the crystallation of the later acidic felspars.

As pointed out in the paper on the Kilsyth-Croy intrusions, the normal quartz-diorite is a widely distributed type of igneous rock throughout the world, and exhibits a remarkably uniform chemical composition.

Age.—There is now a general consensus of opinion that these intrusions should be assigned to the late Palæozoic. They cut all strata to the Upper Coal Measures, but are not found in the Permian red sandstones of the West of Scotland. Mr. Clough found that the small N.W.-S.E. Tertiary dykes invariably cut the E.-W. dykes in the Cowal district.²² These observations were confirmed by Mr. Gunn in the Cumbræes.²³ Much additional evidence has been found during the recent work of the Geological Survey in Central Scotland.²⁴

Distribution.—The E.-W. dykes of Rowardennan, Vaulstield (Loch Long), Dumbarton, Blanehead, Dunoon, Lochgoilhead, Carrick, and Bishopbriggs belong to this group, as well as the intrusions of Kilsyth, Croy, Stirling, Milngavie, and the large mass to the south-east of Old Cumnock.

V. THE ALKALIC GROUP.

Since the publication of the British Petrography a group of basic rocks of highly alkalic nature has been recognised in the South of Scotland. They comprise teschenites and essexites, which pass gradually by an increase in basicity to picrites of the Inchcolm type, and by a decrease in alkalinity to olivine gabbros and dolerites which are, however, more alkalic than the ordinary types. This group is characterised by the association of original analcite, with plagioclase, orthoclase (probably a soda-bearing variety), purplish titaniferous augite, and

²² Geol. of Cowal (1897), p. 139, 140, 156.

²³ Sir A. Geikie, "Ancient Volcanoes of Great Britain" (1897), vol. i., p. 407.

²⁴ A general summary of opinions as to age is given in *G.M.* (v.), vol. vi. (1909), p. 303.

occasionally a green ægerine-augite, olivine, a deep red-brown barkevicitic amphibole, biotite, and ilmenite. Nepheline has been observed by Lacroix in the beautiful porphyritic essexite of Crawfordjohn.²⁵

These rocks occur as large and small sills, although in general smaller than the quartz-diabase intrusions. They are not associated with E.-W. dykes, and rarely with dykes of any particular direction or magnitude.

Teschenites.—In hand-specimens these are medium to fine grained, grey to black rocks, in which olivine, augite, and biotite may frequently be recognised. Analcite is abundant as large white, grey, or pink patches studded with small crystals and flakes of the darker minerals. A very distinctive rock is one containing plagioclase, analcite, augite, and olivine, in which the augite appears prominently as lustrous black idiomorphic crystals, occasionally reaching 1 inch in diameter. Good examples of this type are found on the slope of the Campsie Fells north of Lennoxtown, at Crawfordjohn in Lanarkshire, and at Lugar.²⁶

Microscopically the teschenites consist of plagioclase and analcite, with augite, olivine, biotite, hornblende, and ilmenite. The felspar is highly zonal, the central parts giving the extinction angles of medium labradorite. Its relation to the augite is generally subophitic. Untwinned felspar occurs interstitially in subordinate amount. Some of the latter is probably soda-orthoclase, or even anorthoclase, but not sufficient evidence has been obtained on this point. The augite is the purplish titaniferous and soda-bearing variety. The colour deepens towards the margin; and occasionally a crystal purple coloured in the interior changes gradually to pale green on the margin, especially if it abuts on an area of analcite. The latter sometimes contains a few small deep green crystals of ægerine. The olivine is generally in rather rounded crystals, and is very fresh. When alteration has proceeded to any extent the product is a deeply coloured green serpentine. Analcite occupies all the interspaces. Its freshness varies with the freshness of

²⁵ Comptes Rendus (1900), p. 1273.

²⁶ In a recent survey of the Dalmellington district, another occurrence was found as a small intrusion in the Permian vent of Carclout, 1 mile south-west of Patna.—G. W. T., Sept., 1909.

the rock, but in the larger areas it becomes turbid with a brown dust towards the margins. Radial zeolites and calcite are the ultimate products of its decomposition. It is generally charged with a great number of apatite needles, together with small flakes of biotite, crystals of deep red-brown barkevicite, ægerine, and occasionally a detached crystal of plagioclase, olivine, and augite. The enclosed plagioclases occasionally present ill-defined boundaries to the analcite, as if some corrosion of the former had taken place. This is probably due to the pneumatolytic replacement of the felspar by the analcite,²⁷ but this is a very local phenomenon. As a rule, the plagioclase presents quite sharp boundaries to the analcite.

The above facts leave practically no doubt that the analcite is a primary constituent of the rock, and has been the last to crystallise. The latter process may have been so drawn out as to include the pneumatolytic changes due to the rock "stewing in a concentrated solution of sodium carbonate," as expressed by Messrs. Bailey and Grabham.²⁸ Although Lacroix states that he has found nepheline in the Crawfordjohn rock, this mineral has not yet been recorded in the other teschenites and essexites of South Scotland, and there is no evidence whatever that the analcite is secondary after nepheline.²⁹

Distribution.—Probably the most typical locality for teschenites and their associated rocks in the West of Scotland is that of Lugar, which is described in more detail later. These rocks also occur amongst the sills intrusive in the Coal Measures near Dalmellington, in the east of Glasgow (Necropolis Hill), and at Cathcart, Ardrossan, Saltcoats, Troon, and Stewarton.

Picrite and other Rocks associated with Teschenite.—This group will be best treated by describing the remarkable variations occurring in the Lugar sill. This intrusion, which is about 140 feet thick, and has been injected into the Millstone Grit series, is magnificently dissected by the Bellow and Glenmuir Waters, so that practically every foot of its thickness may be

²⁷ Bailey and Grabham, *G.M.* (v.), vol. vi. (1909), p. 256.

²⁸ *Ibid.*, p. 253.

²⁹ Since this was written, nepheline has been recorded in the Cathcart teschenite, the Lennoxtown essexite, and a weathered theralite from Barshaw, near Paisley. Flett and Bailey, *Summ. Prog. Geol. Survey* for 1908, p. 44.—G. W. T., Sept., 1909.

examined. Starting at the upper margin, we first encounter a dense black basaltic marginal facies passing gradually into a perfectly typical teschenite. Proceeding downwards, the proportion of the coloured minerals relative to analcite and felspar gradually increases, the rock becomes slightly finer-grained, and the augite, olivine, and hornblende take on idiomorphic forms, so that the structure of the rock becomes like that of a lamprophyre. In fact, the composition and structure at this point are identical with that of the rock known as camptonite. It is noteworthy that whole sills, like that of Cathcart—in fact, most of the smaller alkalic sills and dykes—are composed of this camptonitic variety. The thick dyke crossing the Lugar Water between Old Cumnock and Lugar is a typical example. Still passing downwards in the sill, the felspar gradually fails and finally disappears, leaving a rock composed of augite, olivine, hornblende, biotite, and ilmenite embedded in a groundmass of analcite. The coloured minerals are perfectly idiomorphic, and the rock is identical with the monchiquites of Rosenbusch. Now the analcite begins to fail, and in the centre of the sill disappears entirely, leaving a beautiful rock consisting mainly of olivine in all stages of alteration to green, blue, yellow, and colourless serpentine, purple augite, deep red hornblende and biotite, and ilmenite. This rock is identical with the picrites of Inchcolm and Barnton, and makes up the greater part of the Lugar sill. Passing now to the lower margin, we find the same changes in the reverse order, until at the actual margin teschenite, with its basaltic marginal facies, is found. Specific gravities of selected specimens taken from various parts of the sill show a regular variation from top to bottom. The following table gives the specific gravities, arranged in that order:—

Upper part.	{	Teschenite, coarse, with very abundant analcite (R1044), ³⁰	2.64.
		normal (R1046), - - - -	2.70.
		camptonitic variety (R1054), - - - -	2.98
		monchiquitic variety (R1048), - - - -	2.99.
Central		Picrite (R1049) - - - -	3.01
Lower part.	{	Teschenite, camptonitic variety (R1051), - - - -	2.81
		normal (R1052), - - - -	2.77

The picrite occupies approximately five-eighths of the total

³⁰ The numbers given in brackets are those of specimens in the collection of the Geological Department, Glasgow University.

thickness, the upper margin of teschenite, &c., one-quarter, and the lower one-eighth. The lower margin of the picrite is rather sharply marked off from the underlying teschenite.

In his valuable and comprehensive paper on the Lugar intrusions, Mr. R. Boyle has recognised the transition from picrite to teschenite, and has described the intermediate rocks as doleritic picrite, olivine dolerite, and olivine basalt.³¹

The phenomena described above are perhaps best explained as a simple case of gravity differentiation. The original magma was a rather basic teschenite, and was intruded in a highly heated and liquid condition. The sudden cooling at the contacts produced layers of teschenite with sharp margins of basalt, both at top and bottom, thoroughly insulating the still highly liquid interior. In this the heavier minerals sank as they formed into the lower strata of the magma, until increasing viscosity checked this movement. The greater the degree and duration of liquidity the more thoroughly would this density stratification take place. In a later stage of crystallisation, if viscosity had not become too great, the feldspars, as they crystallised, would tend to rise through the magma. This would explain the formation near the top of the sill of a rock very rich in feldspar and analcite (specific gravity 2.64), which bears the same relation to teschenite as nepheline syenite does to theralite. The very irregular and local distribution of this type of rock may be then explained as due to the obstruction caused by increasing viscosity and the clouds of new minerals being formed, preventing the regular stratification exhibited in the lower parts of the sill. The greater thickness of the upper layer of teschenite is easily explained on this hypothesis, for the upper layer consists of the contact plus a certain thickness of acidic teschenite due to the draining away of the heavier minerals into the monchiquite and picrite strata, whereas the lower teschenite consists of the contact layer only.

That such gravity differentiation is *a priori* possible, and has occurred in many magmas, has been amply proved by Daly.³² The explanation has also been applied with great

³¹ *Trans. Geol. Soc. Glasgow*, xiii. (1908), pp. 202-223.

³² R. A. Daly, "Origin of Augite-Andesite," *Journ. Geol.*, vol. xvi. (1908), pp. 401-420.

success to the case of a highly olivinic ledge in the Palisade quartz-diorite sill, New Jersey.³³

The Lugar picrite is identical with those occurring at Inchcolm, Barnton, and Blackburn, in the East of Scotland. The Inchcolm rock is also associated with teschenite, which occurs on the margins of the sill.³⁴ The occurrence at Barnton, according to Sir A. Geikie, presents almost exactly the same appearances as the Lugar sill, the upper layer of dolerite (=teschenite) being much thicker than the lower.³⁵ Dr. Falconer has described a sill at Ardrossan in which transitions from picrite to hornblende and mica dolerites (=teschenites) occur.³⁶ Sir A. Geikie mentions a picrite similar to that of Inchcolm from Lethan Hill, near Waterside, in the Dalmellington district.³⁷

Essexites.—This group of rocks may be regarded as the granitic representative of the teschenites. They contain the same set of minerals, but the structure is hypidiomorphic, not diabasic as in the teschenites. The proportion of analcite, however, is distinctly smaller, but that of red hornblende and biotite larger. The plagioclases are long and lathy, and frequently have a sub-parallel arrangement. Augite and olivine, as a rule, do not occur in such large crystals as in the teschenites, although the augite occasionally occurs in large porphyritic crystals. Deeply coloured and idiomorphic red hornblende (barkevicite) and biotite are abundant in the essexites. Analcite generally occurs in small water-clear triangular areas between adjacent feldspars.

Olivine Gabbros and Dolerites.—By the gradual failure of analcite and the disappearance of hornblende and biotite the essexites pass into rocks composed of plagioclase, purple augite, olivine, and ilmenite, the structure remaining hypidiomorphic. The teschenites frequently show a similar transition, but the

³³ J. Volney Lewis, "Ann. Rpt. of State Geologist for 1907, Geol. Survey of New Jersey" (1908), p. 129.

³⁴ Campbell and Stenhouse, "Geology of Inchcolm." *Trans. Edinburgh Geol. Soc.*, ix. (1908), p. 121.

³⁵ "Ancient Volcanoes of Great Britain" (1897), vol. i., p. 450.

³⁶ *T.R.S.E.*, vol. xlv., pt. iii. (1907), pp. 601-609.

³⁷ "Ancient Volcanoes," vol. ii., p. 67. There are at least four other occurrences of picrite associated with teschenite amongst the sills of this district.—G. W. T., Sept., 1909.

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structure remains diabasic. There is no diminution, however, in the size of grain. These rocks have therefore the mineral composition of olivine gabbro and dolerite, but they would doubtless be found, on chemical analysis, to be richer in alkalis than normal gabbro or dolerite, although less rich than the essexites and teschenites. The transition to olivine gabbro and dolerite frequently takes place in the same mass. The rocks represent a portion of the magma locally poorer in alkalis than that giving rise to the essexites and teschenites. Occasionally a small area of clear analcite may be discovered wedged in between adjacent felspars.

Distribution.—The great sills of Craigie and Dundonald, in the north of Ayrshire, are essexites passing locally into olivine gabbros, as are also the sills of Benbeoch, Benquhat, and others in the Dalmellington district. The olivine dolerites are well represented by the sills at Quarrelton, near Paisley.

Age of the Alkalic Group.—This group is considered to be the hypabyssal or plutonic phase of the Permian vulcanicity of Western Scotland, for the following reasons:—

(1) They are intruded into all formations up to and including the Permian red sandstone of Ayrshire.

(2) They become more numerous as the Permian volcanic districts of the West of Scotland are approached. They are most numerous in the immediate neighbourhood of the areas in Central and Southern Ayrshire, where Permian volcanic necks and lavas are developed. They are occasionally found as plugs or as intrusions into the ash of a Permian neck; and at Howford Bridge, near Mauchline, they cut the Permian lavas also.

(3) The alkalic intrusions and the Permian lavas of Ayrshire are petrologically consanguineous. Both contain the same minerals, and the essential minerals have the same peculiarities in each. The lavas comprise types ranging from basic analcite basalt, through olivine basalt and limburgite, to almost pure augite-olivine-iron-ore rocks practically devoid of felspar, thus corresponding to the teschenite-picrite series of the alkalic group.

The alkalic group is probably slightly younger than the quartz-diorite dykes and sills. The latter do not occur within the Permian red sandstones, which are, however, cut by the

alkalic intrusions. On the East Coast, however, Messrs. Campbell and Stenhouse have recorded an E.-W. dyke of quartz-diorite cutting the teschenite and picrite of Inchcolm.³⁸ It is probable, therefore, that the two groups are nearly co-extensive both in time and space.

VI. THE TERTIARY INTRUSIONS.

This section will be limited to the discussion of those intrusions occurring in the western counties and the Clyde islands. Those of Skye, Mull, and the Small Isles have already been admirably dealt with by Mr. Harker.

The Tertiary intrusions of our district comprise a great variety of rocks ranging in composition from acid to basic. They are most typically developed in Arran, but great numbers of small dykes, with a fairly constant N.W.-S.E. trend, are to be found on the mainland. These cut the youngest sedimentary rocks known in this area, and are to be found piercing the earlier igneous rocks. They are thus relegated with a fair amount of certainty to the only known period of igneous activity subsequent to the Permian in the West of Scotland—the Tertiary.³⁹ The majority of the Tertiary intrusions of the West of Scotland have been so often and so well described that it is only necessary here to indicate as briefly as possible their main classificatory characteristics. They will be classified in order from acid to basic.

Granites.—In our district these occur only in Arran. They form the great circular boss in the north of that island, and their denudation has given rise to the picturesque Goatfell group of mountains. Petrographically they are biotite granites, containing quartz, orthoclase, oligoclase, and biotite, with frequent granophyric structures. The granite which forms part of the ring of intrusive rocks surrounding the great volcanic vent of central Arran contains hornblende, and, by a gradual increase in the proportion of that mineral, passes into quartz-diorite and diorite. The biotite-granites closely resemble the rocks of the Mourne Mountains of Ireland, whilst the horn-

³⁸ *Op. cit.*, p. 130.

³⁹ "Ancient Volcanoes of Great Britain" (1907), vol. i., p. 408.

blende-bearing varieties are similar to the Tertiary granites of Skye and Mull.⁴⁰

Quartz-Porphyrries and Felsites.—These rocks, too, are found only in Arran, and have been described by Zirkel, Allport, Judd, Teall, and Harker. The quartz-porphyrries are very uniform in type. They usually have a grey, yellow, or white crypto- or micro-crystalline groundmass with numerous phenocrysts of quartz, sanidine, and oligoclase. The felsites have the same groundmass, but phenocrysts are rare or absent. Spherulitic varieties have been found at various places in Arran.

Pitchstones.—These well-known rocks have been so often described that it is unnecessary here to treat them at length. A comprehensive account, with a bibliography, may be found in the Geological Survey Memoir on N. Arran, S. Bute, &c. The commonest variety is a nearly colourless glass full of beautiful feathery green microlites, also containing phenocrysts of quartz, plagioclase, orthoclase, augite, and magnetite. Some varieties are beautifully spherulitic. As a whole, their affinities are with the dacite and andesitic glasses rather than the rhyolitic.

Trachytes.—A few trachytic dykes have been found in Argyllshire.⁴¹ These are pale brown, fine-grained rocks occurring as thin dykes with spherulitic margins. They consist of lathy orthoclase, with scales of biotite, altered pyroxene, and a few granules of magnetite. The spherulites of the margin are enclosed in a pale brown glass.

Gabbros.—Typical gabbros have been described by Mr. Harker from the plutonic girdle of the great volcanic vent of central Arran. These are medium-grained rocks, consisting of labradorite and augite in subophitic relations, with iron ores. Olivine does not occur. Specimens containing a large amount of orthorhombic pyroxene have been obtained near Glenloig Farm. Petrographically these are norites. A quartz-hyperite containing plagioclase, augite, bronzite, quartz, brown and green hornblende, with interstitial patches of micropegmatite, has been described from Creag-nan-Mult.

⁴⁰ Harker, "Geol. of N. Arran, S. Bute," &c. Mem. of Geol. Survey (1903), pp. 104-106.

⁴¹ Memoirs of Geol. Survey, "Geol. of Cowal" (1897), pp. 166-171; "Geol. of Mid-Argyll" (1905), p. 121.

Teschenites.—The great sill at Dippin, in the south of Arran, is composed of a rock identical with the Permian teschenites above described. From Allport's description, the Clauchland sill also appears to be a teschenite.⁴² These rocks are considered to be of Tertiary age by the Geological Survey officers.⁴³ They are intrusive into the so-called Triassic sandstones of Arran. These sandstones rest unconformably on the Carboniferous, and derived Carboniferous fossils have been found in a pebbly band near the Cock of Arran. The youngest rocks underlying them are Lower Coal Measures. This evidence is, of course, not decisive as to their Triassic age. The latter correlation is based on the discovery of marls associated with Rhætic beds in the central volcanic vent, identical with the marls forming the upper part of the red beds in the south of Arran.⁴⁴ The resemblance of these sandstones to the lower false-bedded sandstones of Ballochmyle is admitted. According to Mr. D. Ferguson, who has recently made an extensive survey of the Ayrshire Coalfield, there has been continuous sedimentation from the red sandstones of the Upper Coal Measures to the red sandstones of the Mauchline basin, unless the intercalated lavas be considered a break.⁴⁵ But these are interleaved with sediment, and enclose masses of sandstone as if the lava had rolled along a soft sea-floor. The Mauchline sandstones might even be considered as the highest part of the Upper Coal Measures. It is possible, therefore, that these intrusions will ultimately be classed with the Permian teschenites above described. Whatever the age of the red sandstones of Ayrshire and Arran, for the present the teschenites intrusive in the red rocks of Arran must be doubtfully classed as Tertiary until more decisive evidence as to their age is obtained. It is noteworthy that teschenites have not yet been found in any of the other Tertiary volcanic districts of Scotland or Ireland.

Andesitic Dolerites (Augite Andesites).—This group comprises the more acid types among the basic Tertiary dykes. These dykes are usually thin, short, and conform to a general

⁴² *Q.J.G.S.*, xxx. (1874), p. 563.

⁴³ *Geol. Sur. Mem.* "Geol. of N. Arran and S. Bute" (1903), p. 112.

⁴⁴ *Geol. Sur. Mem.* "Geol. of N. Arran and S. Bute" (1903), p. 67.

⁴⁵ Unpublished paper on the "Ayrshire Coalfield," read to the Glasgow University Geological Society; and oral communications.

N.W.-S.E. direction. The commonest variety, seen in thin section, shows a mesh of rather short, lathy feldspars, with interstitial granular augite, embedded in a usually abundant groundmass of light-coloured glass, which is, however, frequently darkened by diffused magnetite dust. Rather rarely the ophitic relation occurs between feldspar and augite. Large, glassy plagioclases are the only porphyritic constituents. These are medium labradorites, usually beautifully zoned with inclusions of groundmass (see Plate XIX., Fig. 5). The glassy groundmass is sometimes patchy, and in the Eskdalemuir dyke described by Sir A. Geikie,⁴⁶ also in some of the Cowal dykes,⁴⁷ the glass has segregated into a thick central band, in which a curious arrangement of vitreous prisms, with thin sheaths of more lithoidal material, is seen. Tachylytic selvages are common in the Cowal dykes of this type.

Most of the Tertiary dykes of Ayrshire belong to this group, as, *e.g.*, the rather lengthy one near Coylton. They are also found in Arran, Bute, the Cumbraes, and Argyllshire. The Tertiary lavas of Ben Hiant, in Ardnamurchan, described by Professor Judd under the name of "younger augite andesite," belong to this group, as do also the andesitic dolerites of the Cleveland, Acklington, and Tynemouth dykes in the North of England.⁴⁸

Olivine Dolerites and Basalts.—These comprise dykes of considerably more basic character than the preceding group. The prevailing type is a fine-grained but holocrystalline rock, consisting of a groundmass of plagioclase ophitically enclosed in small plates of brown or purplish augite. Irregular grains of iron ore, and olivine in small grains or porphyritic crystals, are abundant. Other phenocrysts are rare, and, in contradistinction to the andesitic dolerites, a glassy or cryptocrystalline groundmass is also rare. Tachylytic selvages, however, are rather common.

By far the greater number of the small N.W.-S.E. dykes belong to this group. They occur in Arran, the Cumbraes, and the Cowal district in the greatest profusion. Many of the

⁴⁶ "Ancient Volcanoes of Great Britain" (1897), vol. ii., pp. 127, 133.

⁴⁷ "Geol. of Cowal" (1897), p. 133.

⁴⁸ Teall, *Q.J.G.S.*, xl. (1884), p. 209. Also Brit. Petrog. (1888), p. 200.

dykes of the Ayrshire and Renfrewshire coast belong here. A typical example is the Deil's Dyke, near the Heads of Ayr. This is a coarse-grained ophitic olivine dolerite, with porphyritic olivine and felspar.

Conclusion.—Here must conclude this necessarily imperfect survey of the post-Carboniferous igneous rocks of the West of Scotland. Many gaps in our knowledge must be filled before any classification can be said to be complete. It is hoped that the one adopted in this paper, imperfect and provisional as it is, will prove useful, at least in correlating and exhibiting in one view our present-day knowledge of these most interesting series of igneous rocks.

EXPLANATION OF PLATE.

Fig. 1.—Teschenite (camptonitic variety), old quarry near the Castle, Cathcart. Ord. light, $\times 21$.

Idiomorphic augite, olivine, hornblende, biotite, iron ores, and plagioclase in a groundmass of analcite. Panidiomorphic structure. Note area of analcite in centre of field pierced and bridged by augite in all directions. Olivine can be seen just above the central patch of analcite. Flakes of biotite occur here and there; but the hornblende, although abundant in small crystals, is not well seen.

Fig. 2.—Teschenite (camptonitic variety), upper part of picrite sill, near Bellow Bridge, Lugar. Ord. light, $\times 21$.

Same minerals and structure as in fig. 1, but the rock is coarser, and contains even less felspar. Fresh olivine in the centre and on extreme left of field. Hornblende well seen at the bottom of the field, and also to the left of the central olivine. Biotite on extreme right. Augite in numerous small granules. The light-coloured groundmass is plagioclase and analcite, the latter in excess.

Fig. 3.—Hornblende picrite (Inchcolm type), Bellow Water, Lugar. Ord. light, $\times 11$.

Hornblende (centre of field) enclosing olivine. Olivine, almost completely serpentinised, comprises most of the remainder of the field, and is especially well seen at the top right-hand corner. Augite, in numerous small granules, scattered over the field. Titaniferous iron ore associated with the hornblende.

Fig. 4.—Essexite (analcite-bearing), Craigie sill, 170 yards south of Harpercroft. Ord. light, $\times 21$.

Olivine, augite, plagioclase, biotite, and hornblende with analcite. Structure thoroughly hypidiomorphic. Augite in centre of field. Numerous long lathy plagioclase crystals. Highly-refractive olivines towards top of field. An area of analcite, showing part

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

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of its crystalline form, is seen to the left of the field. It is bordered with biotite, and encloses numerous idiomorphic crystals of augite.

I am indebted to Mr. David Ferguson for the negative from which this photograph was prepared.

Fig. 5.—Andesitic basalt, Tertiary dyke, foreshore near Birchpoint, Corrie, Arran. Ord. light, $\times 21$.

Groundmass of plagioclase and augite in ophitic relations, with much dark-coloured glassy matrix (black in the field, and hardly distinguishable from magnetite). The only phenocrysts are well-shaped plagioclases, usually zoned both mechanically and chemically.

Fig. 6.—Olivine basalt, Tertiary dyke, Invercloy, Brodick, Arran. Ord. light, $\times 21$.

A rather coarse-grained rock, consisting of plagioclase and augite in ophitic relations, with numerous large phenocrysts of serpentinised olivine.