

PETROLOGICAL STUDIES
of the
LAVAS AND ASSOCIATED ROCKS
of the
ARTHUR'S SEAT VOLCANO.

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ABSTRACT.

Arthur's Seat is the remains of a dissected Lower Carboniferous volcano, from which were erupted a series of basaltic rocks representative of the province to which it belongs. The rocks occur as lavas, intrusions and tuffs, and include basalts of Dalmeny, Jedburgh, Dunsapie, Craiglockhart and Markle types, in addition to mugearite. The Dunsapie basalts have been subdivided into Normal Dunsapie and Feldspathic Dunsapie types.

The volcano has been remapped on a scale of 15 inches to 1 mile, and a few minor departures from the 6-inch Geological Survey map have been recorded. These include changes in the numbering and classification of some of the lavas, an alteration to the position of a fault, and slight adjustment of a vent boundary.

The petrographic characters of the various volcanic rocks have been described in detail, with modal and chemical analyses. Particular attention has been given to the augite phenocrysts of Craiglockhart basalt, and a method of cutting serial sections through single crystals has been devised. Evidence indicates that the augites have been corroded, and then have regrown prior to eruption.

The parental magma of the volcano was probably
of/

of a composition very similar to that of Normal Dunsapie basalt. Markle and Craiglockhart types were produced as complementary differentiates of the parental liquid by a process of gravity differentiation, in which sinking of ferromagnesian crystals, particularly augites, played an important part.

The Dalmeny and Jedburgh basalts, which have strong chemical resemblances, probably represent only slightly differentiated parental magma. Some sinking of olivine may have occurred in the pre-eruptive history of these microporphyritic types, and transfer of feldspar components by volatiles and establishment of a composition gradient under gravity may also have had some effect in producing the slight differences in composition which have been noted. The less pyroxenic Dalmeny and Jedburgh rocks are ophitic, and their plagioclase crystals show a well developed flow structure which passes through the ophitic augites. In such cases it is inferred that the augite did not crystallise until a late stage in the crystallisation history of the lava.

Concentrations of soda-rich volatiles produced intense albitisation in the Markle basalts and the mugearites. It is considered that the mugearites of Arthur's Seat initially crystallised as Jedburgh type, and were altered/

NORMAL DUNSAPIE

FELDSPATHIC DUNSAPIE

MARKLE

Lava XIII

Lava XII

Lava XI

Lava X

MUGEARITE

Dunsaapie Mugarite

Lava IX

Lava VIII

Lava VII

Markle Lava

Upper Ash

Markle Lava

CRAIGLOCKHART

Whinny Hill Intrusion

Lava VI

Lava V

Lava IV

Lava III

Lion's Head Basalt

Jedburgh Lava and dykes in Vent

Dunsaapie Hill and Lion's Haunch Basalts

Felspathic Dunsaapie Lava in Vent

Mugarite Lava in Vent

Markle Dyke

Lion's Head Basalt

Jedburgh Lava and dykes in Vent

Dunsaapie Hill and Lion's Haunch Basalts

Felspathic Dunsaapie Lava in Vent

Mugarite Lava in Vent

Markle Dyke

DALMENY

Pulpit Rock

Lava II/A

Upper Ash of Dry Dam

Lava II

Lower Ash of Dry Dam

Lava I

Ash

Craiglockhart Dyke

Sumson's Ribs Intrusion

Sumson's Ribs Lavae

Felspathic Dunsaapie Lava in Vent

Mugarite Lava in Vent

Markle Dyke

NORMAL DUNSAPIE

ASH

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

Lava I

ROCK TYPE. WHINNY HILL SERIES. DUNSAPIE. WESTERN LIONS HEAD VENT.

WESTERN LIONS HEAD VENT.

LIONS HAUNCH VENT. OTHER ROCKS

The Eruptive History of the Arthur's Seat Volcano.
(to accompany abstract)

Duddingston Basalt
General Craig
Dikes
St Leonards Craigs

altered to their present state during the deuteritic stage.

The magma chamber believed to have underlain the volcano was charged with parental magma at least twice during the period of activity. The first and last eruptions were of Dunsapie basalt; the albitised products appeared at a fairly late stage. (see Table summarising Eruptive History).

A macroscopic method of fabric analysis has been evolved, and fabric analyses of representative specimens made. Both linear and planar fabrics, and sometimes both, have been shown to occur.

I. INTRODUCTION

The imposing hill known as Arthur's Seat rises within the confines of Holyrood Park, well within the boundaries of the City of Edinburgh. The highest peak, the Lion's Head (822 feet), is only a little over a mile from the "Heart of Midlothian". The impressive aspect of the Hill has been ably described by the famous Edinburgh geologist Charles Maclaren (1839, p.1) "Arthur's Seat for grandeur and picturesque effect, is worth all the temples and monuments of London and Paris put together".

In view of its eminence and geographical position, it is not surprising that the Hill has for very many centuries figured in the affairs of men. Its slopes were tilled as cultivation terraces long before Edinburgh existed; traces of these remain today on the eastern slopes of the Lion's Haunch, and near the base of the Haggis Knowe. Between the summits of the Lion's Head and the Lion's Haunch are remains of walls which were once fortifications, and date from a very early period. In medieval times a chapel was built near the mouth of the Dry Dam; the ruins of this ancient building still stand.

In 1745 Arthur's Seat enjoyed brief military importance, for the Jacobite Army was encamped near/

near Duddingston, and Prince Charles Stuart reviewed his troops from the south-eastern slopes of the Hill. Grimmer events appear to have occurred on Dunsapie; the former name of this prominence was Gallows Hill.

The columnar basalt of the Lion's Head has been worn smooth by the feet of the countless thousands who have ascended the hill to enjoy the spectacular view; it is recorded that here royalty encountered geology when Queen Victoria and Prince Albert met Professor Geikie on the summit.

Hugh Miller (1863) quoted from Thomas Campbell's poem "The Queen of the North" with reference to Arthur's Seat as follows:

"Ever musing here beside the Druid's Stone,
Where British Arthur built his airy throne".

Presumably the columnar nature of the Lion's Head basalt reminded Campbell of Stonehenge! However, it seems unlikely that the name "Arthur's Seat" is connected in any way with the legendary King. The writer is indebted to Dr. A. Lamont for the information that the "Arthur" in Arthur's Seat is almost certainly a corruption of the Gaelic "àrda", the nominative plural of "àrd", meaning high, and applied to rocks, among other things. In much of the geological literature of the nineteenth century/

century, reference is made to "Arthur Seat", and it seems likely that the modern use of the possessive case is a further corruption.

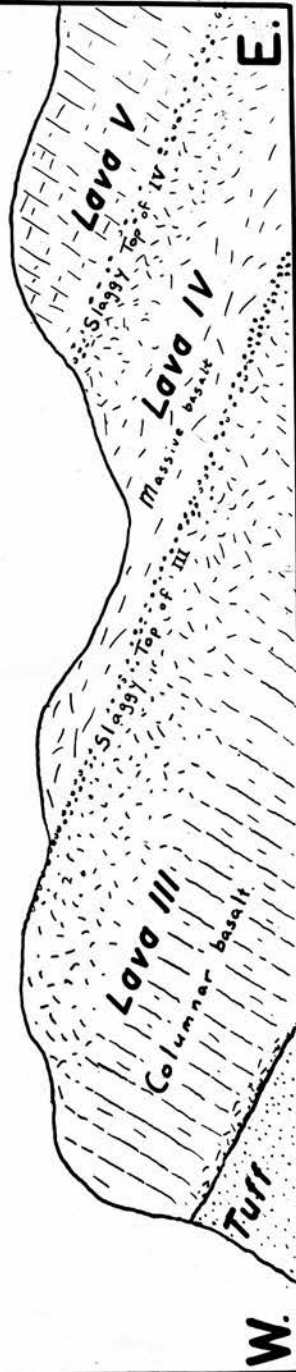
Arthur's Seat consists of the dissected remains of a Lower Carboniferous volcano from which lavas, tuffs and agglomerate were erupted in Calciferous Sandstone times. The Lion's Head and the Lion's Haunch - two adjoining hills - mark the sites of two main vents. The Lion's Head is the older; its early period of activity being followed by the formation and subsequent enlargement of the Lion's Haunch. A third, smaller, vent, referred to here as the Western vent, is probably the oldest of the three.

To the north of the main vents occur basaltic lavas (Flows I-XIII), intrusions and tuffs which form the succession of rocks known, for convenience, as the Whinny Hill Series. The southern margin of the vents is flanked by a great thickness of tuffs, with only a few interbedded lavas. These form the Duddingston Series.

Since the cessation of volcanic activity and burial of the igneous rocks, the whole succession of volcanics and sedimentaries has been tilted to the east at an angle of about 20° , excepting the northern part of the Whinny Hill, where local tilting to the north-east has/

FIG. 1

SECTION THROUGH SOUTHERN PART OF WHINNY HILL



has occurred. Erosion, and in particular the scouring effect of the Pleistocene ice, has removed the sedimentary cover, and exposed the volcanic rocks to reveal a comprehensive section through the volcano. The earliest products are well exposed, and it is unlikely that important effusion of flows younger than the highest lavas at present visible ever occurred.

The general easterly dip of the rocks has resulted in a "scarp and dip-slope" topography over most of the Whinny Hill. Interbedded tuff is generally insignificant between flows higher than Lava III. The more massive and sometimes columnar central parts of the lavas resist weathering more strongly than the slaggy upper parts, some of which have been differentially eroded back. This is well shown by Lava V of the Whinny Hill Series. The scarp where this flow is best exposed contains the slaggy top of Lava IV near its middle (Fig. I).

Good exposures exist of most of the Whinny Hill lavas, particularly the lower members, which can be traced along their strike from the vents for a distance of nearly half a mile northwards, until they are cut off by two faults. Probable extensions of some of these flows are to be found in the Calton Hill, about a mile north-west of the main vents, and separated from the Whinny Hill Series by St. Margaret's and Calton Faults.

II. History/

II. HISTORY OF RESEARCH

The rocks within Holyrood Park have been objects of study since the early years of British Geology. As far as can be ascertained, the earliest work in which these rocks are mentioned dates from 1619, when Stephen Atkinson gave an account of the gold mines of Scotland. In this he referred to "Lapis Haematite" in the Park (p. 84).

It is of interest to note that the first paper dealing solely with Arthur's Seat which the present writer has been able to discover is one by Hutton (1789), "Of certain Natural Appearances of the Ground on the Hill of Arthur's Seat". Despite its title, this paper is not in fact geological, but is instead a description by the versatile Hutton of curious strips of dead turf on various parts of the Hill, which were neither sheep tracks nor footpaths. He ascribed the withering of the turf to the action of either electricity or insects. In the third volume of Hutton's "Theory of the Earth", (edited by Sir A. Geikie and published in 1899) the Hill is mentioned as being of volcanic origin. This must have been written prior to Hutton's death in 1797.

The earliest recorded geological description of Arthur's Seat is that of Townson (1799, pp. 210 - 215). His remarks on Arthur's Seat contain mention of "the large pentagonal/

pentagonal and hexagonal prisms" of Samson's Ribs. He recorded the occurrence of feldspar and "basaltic hornblende" in this rock, and noted prehnite in cracks. The limestone bands above the Loch Craig did not escape his notice - nor did the olivine crystals in the Giral Craig. He pointed out that chains of rock similar to those near Duddingston Loch occur on the other side of the Hill - this is the first suggestion of possible correlation of the rocks north and south of the vents, and probably served as a basis for Boué's work more than two decades later.

Townson referred to the agglomerate of the vents as breccia, and noted the differences between the basalts of the Lion's Head and the Lion's Haunch. The Lion's Head basalt he correctly recognised as identical with that of the Castle Rock. No less shrewd is his statement that the rock of the Long Row differs from that of Salisbury Craigs, but is the same as that "near Duddeston Loch" - presumably the Loch Craig. In his description of the Whinny Hill rocks he noted the occurrence of vegetable impressions in the ashy sandstone above Lava II, beneath St. Anthony's Chapel, and the limestone inclusions in a higher flow, probably Lava III.

Sir James Hall's paper "Experiments on Whinstone and/
and/

and Lava" (1805) is of particular interest in view of the controversy which raged at the time between the Wernerian and Huttonian schools over the origin of igneous rocks. Hall fused a number of rock specimens, among them two from Arthur's Seat. From his description of the outcrops from which he collected these two specimens, one was probably a piece of Samson's Ribs basalt, and the other of the Duddingston intrusion. He found that his rocks fused completely and cooled to a black glass; by reheating and very slow cooling, he was able to convert the glass back to a crystalline rock.

In the same year (1805) the first chemical analysis of a basalt from the Arthur's Seat volcano appeared. The rock, a specimen from the Calton Hill, was analysed by Kennedy. Yet another publication of this year of Trafalgar was Jameson's "A mineralogical Description of the County of Dumfries". In this he briefly described the rocks of Holyrood Park (pp. 169 - 170), referring Salisbury Craigs to "the coal formation". He stated that the summit of Arthur's Seat, being unstratified, belonged to the "recent floetz-trap formation". Jameson's is the only published Neptunist interpretation of Arthur's Seat encountered by the present writer.

In 1811 Allan gave a fairly detailed description of Salisbury Craigs, and also made brief mention of St. Leonard's/

St. Leonard's Craigs and Hunter's Bog. A few other papers appeared in the next few years; Hall (1815) discussed the "dilluvial phenomena" of Edinburgh, and described how Arthur's Seat had resisted the "floods". Many more papers on "dilluvial" effects were to appear before and even after Agassiz recognised the work of ice at nearby Blackford Hill in 1840.

Jameson (1819) and Necker (1821) recorded some notes, but the next work of importance was that of Boué (circa 1821), who included a description of Arthur's Seat in his celebrated "Essai Géologique sur l'Écosse". His writings are comparable with Townson's in detail and importance, and thus form the second noteworthy account of the geology of the Hill. Boué correlated the Dasses and Long Row north of the vents with the Giral Craig and Loch Craig to the south, thus adding weight to Townson's earlier views regarding these features.

Three publications containing mention of the volcano appeared in the next twelve years; the authors were Playfair (1822, pp. 300 - 301), von Oeynhausen and von Dechen (1830) and Rhind (1833). Playfair added an important detail to existing descriptions by his recognition of one of the sandstone beds that are interbedded with the volcanic rocks of the Haunch vent.

The year 1834 is probably the most important
of/

of the nineteenth century in the history of research upon Arthur's Seat. Early in the year Charles Maclaren published the first systematic description and interpretation of the rocks in a series of articles in the "Scotsman" then, as now, the leading newspaper of Scotland. In December of the same year the first meeting of the Edinburgh Geological Society was held in Robertson's Tavern, Milne's Square. At this first meeting the subject for discussion was "To examine the evidence for Arthur Seat being of volcanic origin". The Society came to the conclusion that the hill was indeed volcanic, and in later years of the nineteenth century, its fellows carried out much detailed investigation upon the rocks.

Maclaren, in the years following the journalistic début of his researches, revised and extended them, and eventually they were published in book form in 1839. Very little escaped his acute observation. Today, reading his descriptions is rendered rather difficult because the place names used by him for various topographic features of the volcano differ from those used by later writers, and now in common use. For example, he referred to the Dasses as "Bog Craig", and the Long Row as "Well Craig". Perhaps because of this, some of his observations appear to have escaped later workers; for instance, he noted two distinct types of basalt in the/

the Dasses, and described briefly (and correctly) their petrographic differences (p. 4). The existence of these two types was lost sight of until their rediscovery by Oertel (1952) in the course of structural investigations well over a century later.

Although some details of Maclaren's interpretations have been disproved by later workers, nothing can detract from the value of his detailed descriptions. The main difference between his interpretation and that of Peach (1910) lay in his conception of a long period of quiescence preceding the activity which produced the Lion's Haunch basalt (p. 34). In a second edition of his book (1866, p. 47) Maclaren stated that he had altered his opinion, and no longer considered that there had been two clearly separated eruptive periods. However, Geikie (1861) had already accepted the earlier view, and in spite of opposition from Judd (1875), it was not until the 1910 work of Peach that the idea of a single more or less continuous eruptive period became universally accepted.

The acuteness of Maclaren's observation is well exemplified by his description of the rock of the cliff above St. Anthony's Chapel (p. 34). This passage also shows his appreciation of the importance of gas as a constituent of lava. "The amygdaloid found above the columnar/

columnar basalt, is apparently the same rock in an altered form. The upper part of the basalt assumes a grey colour; the columns subdivide into small concretions; which, at a short distance above the basalt, present cells filled with spar. By degrees the cells diminish, the base takes a redder tint, and passes into the chocolate-coloured basalt. At some places, however, the distinction between the rocks is more sharply defined; and they are perhaps the produce of successive eruptions of the same matter, under circumstances somewhat different, such as a greater or smaller pressure, or a more or less abundant impregnation of gaseous substances."

Cunningham (1838 and 1839, pp. 51 - 62)

published a brief general description of Arthur's Seat, Salisbury Craigs and Calton Hill. He paid particular attention to St. Leonard's Craigs (p. 51), and described in detail the contacts of the igneous rock with the underlying sandstone. In addition to noting the indurated nature of the sandstone near the contact, he recorded differences between the marginal facies of the sill and the porphyritic central portion.

By the 1840's, Arthur's Seat was very definitely "on the geological map". A model was constructed, and a description of it published by Wright (1842). Mention of the volcano became commonplace in general geological books/

books of the time; among these may be listed those of Rhind (1842) and Nicol (1844). Attention began to be given to particular details. Milne (1846) described striations in the gully between Samson's Ribs and the Lion's Haunch hill, exposed during the construction of the Queen's Drive. (Presumably the striae of which he wrote are those still exposed on the roche moutonnée preserved in the wall of the Queen's Drive above Samson's Ribs.) In 1851 Fleming gave an account of certain markings on the Dasses, and in 1857 the same writer recorded his views of the structure of the area. He incorrectly extended the Calton Hill south to Samson's Ribs, including St. Leonard's Craigs in this prolongation. Fleming's contributions were concluded by the posthumous publication of his book "Lithology of Edinburgh" (1859) in which brief mention was made of Arthur's Seat.

Chambers (1857) published an account of the glacial phenomena of the Hill, and in the same year results of the earliest geophysical experiments were given by James. These consisted of measurements of deflection of a plumb-line, and James calculated from his results that the mean specific gravity of the rocks of Arthur's Seat was 2.75. One year later (1858) McBain recorded the discovery of a tooth of *Rhizodus* in the beds below St. Anthony's Chapel. The/

The first detailed work by the Geological Survey on Arthur's Seat was that of Archibald Geikie, whose results were published in the first edition of the Edinburgh Memoir (1861). Geikie's work did not differ essentially from that of Maclaren, and he accepted the earlier writer's opinion that there were two eruptive periods, agreeing with a conjecture of Forbes that the younger rocks were Tertiary (p. 123). Geikie's description and diagram of the exposures near the junction of the Loch Craig and Lion's Haunch are extremely detailed. Among the important features of his work was the elucidation of the structural relationship of Calton Hill to the rocks of Holyrood Park. He showed that the Calton rocks were faulted portions of the Arthur's Seat lavas.

Hugh Miller (1863) referred to Arthur's Seat, and described "Hutton's Rock" - an outcrop in front of the largest quarry wrought in the Salisbury Craigs, where the teschenite has been veined and partly replaced by haematite. Miller explained the preservation of this rock, despite the quarrying operations, as having been due to the intervention of Hutton, who was fascinated by the exposure.

Particular aspects of Arthur's Seat continued to receive attention, and Haswell (1864) commented upon the denudation of the Hill. The second edition of Maclaren's "Geology/

"Geology of Fife and the Lothians" published in 1866, has already been referred to. Other notes by the same writer, mentioning glaciation of Arthur's Seat, appeared in 1869. The commencement of regular publications by the Edinburgh Geological Society in the later years of the century tended to stimulate interest in the volcano. Excavations for drainage and building foundations, and boreholes for water were recorded, and a number of short papers appeared. The first of these was by Taylor, who published a description of excavations near Salisbury Craigs in the second volume of the Society's Transactions (1874).

Judd (1875) had studied the Hill for some time, and published his results in a detailed paper. He reached the conclusion that only one eruptive period was represented, independently of Maclaren - who had stated this, but without reasons, on p. 47 of the second edition of his book in 1866. Judd (p. 140) pictured the Lion's Haunch mass as part of a lava stream "which had flowed down the side of a cone", and explained the tongue which extends downwards from this mass as having been caused by the lava filling a crevice in the underlying agglomerate. Later writers have not agreed with this, but have confirmed his views as to the single period of volcanic activity.

One remark made by Judd is of particular interest, in view of the coming development of petrological research in Britain. On p. 134 he stated "no geologist has succeeded in pointing out any distinctions whatever, either in their petrographic characters or their state of preservation, between the lavas of the basal and upper portions of Arthur's Seat respectively". Neglect of petrographic study of these rocks since the start made by early workers such as Boué and Maclaren was not to continue for long; in fact, microscopic examination of them had commenced before publication of Judd's paper.

In 1870 the Lion's Head basalt had been mentioned by Zirkel in a publication dealing with the microscopic structure of basaltic rocks, and in 1874 Allport had published his work "On the microscopic Structure and Composition of British Carboniferous Dolerites". Allport included in his work brief petrographic descriptions of the rocks of the Long Row, Haggis Knowe, vicinity of St. Anthony's Chapel, Heriot Mount (part of St. Leonard's Craigs), and the Dasses. His description of the rock of Salisbury Craigs was more detailed. One of the most important of Allport's contributions was his recognition that no essential differences existed between Carboniferous basalts and those of Tertiary age.

Some remarks by Taylor (1878) were followed in the same year by an important paper by Bonney, who criticised Judd's views on the history of the volcano. Bonney was disposed to support the hypothesis of two eruptive periods, and considered Samson's Ribs, usually regarded as intrusive, to be part of a lava. However, in spite of these unacceptable views, Bonney's paper is of considerable importance in the history of Arthur's Seat research for it contains the first reasonably detailed petrographic description of an Arthur's Seat basalt - that of Samson's Ribs. He also described the Lion's Haunch and Duddingston basalts, and showed that their differences were sufficient to render very unlikely their suggested correlation by Maclaren. Petrographic resemblances between the Giral Craig and the Dasses did not impress him; perhaps because he may have studied the more feldspathic of the two Dasses rocks.

The next paper of importance was by Henderson (1880). This writer summarised and compared the views of Maclaren, Geikie, Judd and Bonney, and gave his own. He did not agree with previous workers that a contact existed between the Loch Craig and the Lion's Haunch basalts but believed that they graded into each other, being portions of a single sheet of basalt. Henderson considered/

considered that no neck existed in Arthur's Seat, and that all the rocks belonged to a series of interbedded flows, intrusions and layers of agglomerate (pp. 232 - 244, and section 3, facing p. 231). No other geologists have ever supported this interpretation of Henderson's; moreover, the sharp contact between the Loch Craig and Lion's Haunch was noted by Peach (1910) and is still exposed (see Plate II). However, Henderson's paper is of considerable value, as his descriptions are very detailed, and some of his observations corrected earlier erroneous views. He was the first to note that the crag on which St. Anthony's Chapel stands was not separated from the cliff east of the chapel by a fault, as Maclaren had suggested.

Two papers by Taylor appeared in 1880. One, entitled "Notes on the Petrology of Arthur's Seat" was an attempt to reply to Bonney's remarks on an earlier paper of Taylor's (1878). Bonney had criticised Taylor's petrology, remarking that the meaning was not always clear. In his later paper Taylor attempted to clarify and enlarge his earlier work, but much of the meaning still remains obscure. Apparently he considered it likely that many of the Arthur's Seat "lavas" had never been "red-hot", and challenged their "directly igneous" origin. He suggested a "hydrothermal agency/

agency" for the origin of many of the materials of the Hill. Taylor's other paper, dealing with "Crag Structure on Southern Slopes of Queen's Park" is also by no means clear, and does not appear to have contributed materially to knowledge of the area.

Archibald Geikie included a description of the basalt of the Long Row in an important paper on the Carboniferous volcanic rocks of the Forth Basin (1880). In 1888 two more of the Arthur's Seat rocks were described, in Teall's "British Petrography". These were the Lion's Haunch basalt (p. 188) and that of Dunsapie Hill (pp. 188 - 189).

Henderson (1883) described a bore-hole sunk through the Abbeyhill Shales near the Calton Hill, and in 1888 Taylor recorded the exposures in a trench dug near Holyrood Palace. More temporary exposures were described by Henderson in the same year.

In 1897 Geikie's monumental work "Ancient Volcanoes of Great Britain" appeared. This contains numerous references to Arthur's Seat; on p. 378 of Volume I is recorded the occurrence of rocks of Jedburgh type in the Whinny Hill. However, Geikie paid no attention to the work of Judd, and retained his earlier view (1861) of two eruptive periods. The later he now ascribed to the Permian/

Permian, correlating it with volcanic activity in Ayrshire.

Two papers on the Calton Hill, by Henderson and Goodchild respectively, appeared in 1899. In 1904 notes by Traquair on fish remains collected from the beds below Salisbury Craigs were published. The remains were identified as portions of *Holoptychius nobilissimus*, proving beyond all doubt that the strata underlying the Craigs belong to the Upper Old Red Sandstone. Goodchild (1905) noted the haematite of Arthur's Seat, and advanced the hypothesis that iron and magnesium had permeated down from a supposed former cover of New Red Sandstone. However, most of the iron ores of the Arthur's Seat rocks are undoubtedly of volcanic origin, and Goodchild's view has not been supported.

Bailey and Grabham (1909) contributed a most important account of the albitisation of plagioclase crystals, and used many of the Markle basalts of the Whinny Hill and the Calton Hill to illustrate their views. Their paper is the first record of minutely detailed microscopic examination of any of the Arthur's Seat rocks, and it also contains the first description of the considerable deuteric alteration which has affected many of the lavas and intrusions of the volcano.

In/

In 1910 the second edition of the Edinburgh Memoir was published. Arthur's Seat had been remapped by Peach, and his results were contained in the Memoir. His detailed and accurate account of the Hill, and his elucidation of the relations of the various rocks, laid a firm foundation for future study. Peach's account of the Geology of Arthur's Seat was published separately as a guide to the Hill in 1911, with a second edition in 1921. Flett, who had provided petrographic descriptions of many of the basalts for in the Memoir, wrote a brief petrological appendix for the 1921 edition of the "Guide".

T. Cuthbert Day (1912) described contacts of the upper surfaces of the Long Row and the Loch Craig basalts. He considered that in each case the overlying sediment was indurated, and postulated that the igneous rocks were parts of a sill, not of a flow. Day's view has not found acceptance, for it is generally considered that the slight induration of the sediment near its contacts with the basalt results from the effects of residual heat of the lava.

Campbell (1914, p. 248) noted the presence of petrified plant remains in the agglomerate of the Lion's Head vent, in a paper which was to be the last dealing with the volcano for some years. The next publications, in 1923, are separate descriptions by Day and Bailey of phenomena/

phenomena exhibited by St. Leonard's Craigs and Giral Craigs. Bailey discussed explosive phenomena, and showed that the sill which formed the features was composite, and had been intruded under shallow cover. His account was amplified, some new observations made, and a detailed petrographic description of the St. Leonard's rocks carried out by MacGregor (1936).

A book on the volcano was published by Day (1933). In this, Day described the details of the Hill in a way suitable for both the interested layman and the experienced geologist. Much of the book is based on Peach's 1910 account, but Day also included observations of his own on topics such as his earlier work on the Long Row and the St. Leonard's sill, as well as a considerable number of photographs illustrating details of the volcano.

Hans Cloos's methods of structural investigation were applied to some of the rocks of Arthur's Seat by Oertel (1952) while he was temporarily attached to the staff of the Grant Institute of Geology in 1950. Oertel studied in considerable detail the Dasses, Lion's Haunch, and Dunsapie Hill, and in less detail Samson's Ribs, Giral Craig and the Duddingston basalt. He rediscovered solely by structural observations in the field the two distinct rocks noted by Maclaren (1839) which constitute the Dasses, and discussed the/
the/

the possibility that the Lion's Haunch basalt had formed part of a lava lake. On Oertel's suggestion Rutledge (1952) carried out a detailed petrographic study of the Dasses, and recorded descriptions of the two basalts.

The present study was commenced in 1950 largely as a result of Day's great interest in the volcano. Shortly before his death Day had analysed a number of the Arthur's Seat rocks, collected by his friend and colleague Stenhouse. These analyses were left in the care of Dr. Robert Campbell, who generously made them available to the writer. Day's analyses are included in the Petrochemistry section of this thesis (Table VII).

An attempt by the writer to continue structural investigations by the methods used by Oertel resulted, after collaboration with Dr. D. B. McIntyre, in the publication of a paper dealing with structural nomenclature (Clark and McIntyre, 1951 A), and the other describing a new method of fabric analysis, in which three typical rocks from Arthur's Seat were used as examples (Clark and McIntyre, 1951 B). Structural and petrographic methods have been combined in a study of the microporphyritic basalts, which resulted in the publication of a paper dealing with the significance of ophitic texture in several of the Whinny Hill lavas (Clark, 1952). These papers are included/

included in this thesis.

In the course of the present study most of the volcano has been remapped (Fig. 6), and petrological and structural examination made of the rocks of the Hill. The work accomplished is recorded in the pages that follow.

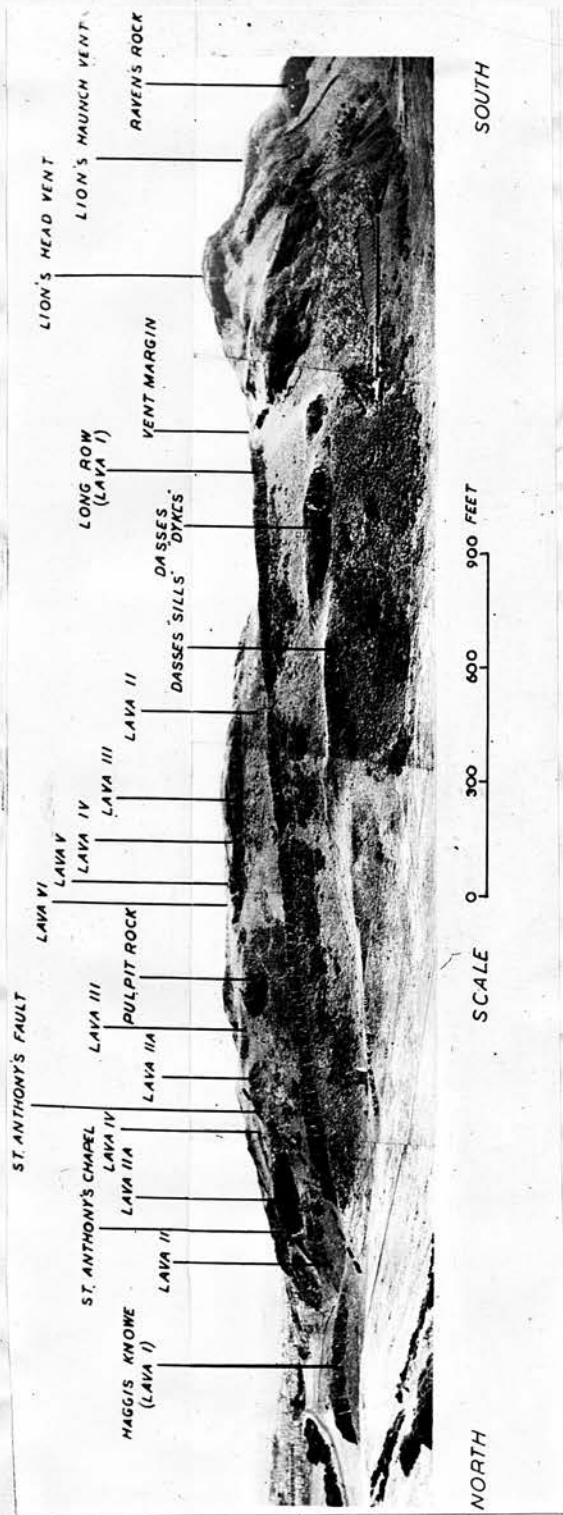


Fig. 2

View of the Vents and the Whinny Hill as seen from the vicinity of the Camstone Quarries. The scale refers to distances measured along the outcrop of the Long Row. Other photographs of features of the volcano are contained in Plates I-XII.

III. FIELD RELATIONSThe Whinny Hill Series and the Duddingston Series.Lava I

The earliest lava of the Whinny Hill Series (the rocks north of the Lion's Haunch and Lion's Head vents) is referred to as Lava I. It is the lava flow which forms the Long Row, of which the northern end has been downfaulted by St. Anthony's Fault to form a detached knoll, the Haggis Knowe. The Long Row is stratigraphically identical with and petrographically very similar to the Loch Craig, the lowest member of the Duddingston Series, but the two are separated by the vents. The Long Row is clearly truncated by the margin of the Lion's Head vent, while to the south the junctions of the Loch Craig with both the basalt and the agglomerate of the Lion's Haunch are exposed (Plate II, figs. 1 and 2). Lava I was probably originally a continuous sheet which was broken through, first by the Lion's Head, then by the Lion's Haunch vents. Throughout its exposure the rock is a basalt of Dunsapie type, and it has characteristics which enable it to be distinguished readily from all other basalts of Arthur's Seat.

Day (1912, pp. 40 - 48) advanced the hypothesis that/

that the Long Row and the Loch Craig were not extrusive, but were portions of a sill intruded under shallow cover. He based his interpretation mainly upon the indurated character of certain bedded sediments which he found in contact with the upper surface of the basalt. However, these sediments usually fill crevices, and are generally regarded as having been deposited immediately after consolidation of the crust of the lava, and to have been baked by the residual heat of the flow (Peach, 1910, p. 58). Day's view that the basalt was intrusive has not found support.

After the extrusion of Lava I the bed known as the lower ash of the Dry Dam (Peach, 1910, p. 59) was built up. It is nearly 100 feet thick, and is a tuff with numerous epiclastic intercalations. Two limestone bands which outcrop near St. Anthony's Well are especially prominent. Fossils, including plant remains, have been found in these sedimentary beds of the Dry Dam. A conspicuous limestone band also occurs above the Loch Craig, south of the vents.

Lava II

The next volcanic episode in the area was the emission of Lava II, a basalt flow of Craiglockhart type, which is poorly exposed between the vents and Pulpit Rock, on the east wall of the Dry Dam. So unsatisfactory are/

are the exposures, which are masked by scree, that difficulty was experienced in obtaining unweathered specimens of this basalt for petrographic study. However, on several occasions fresh rock was found to have been exposed by gullying in the steep wall of the Dry Dam after heavy showers of rain. The lower of the two flows of Craiglockhart type beneath St. Anthony's Chapel, north of St. Anthony's Fault, is probably a continuation of Lava II. The lava beneath the Chapel is extremely brecciated, and contains masses of sediment.

Blocks of basalt of Dunsapie and Craiglockhart types are numerous in the agglomerate of the Western vent; no other types were found in this vent. The Dunsapie basalt has been further identified as that peculiar to Lava I. Lavas I and II may have originated from this vent; alternatively, the vent may have merely broken through them.

Below St. Anthony's Chapel the second lava is overlain by fossiliferous bedded tuff about two feet in thickness, which in turn is overlain by a thick flow of basalt that has plicated the sediments into small folds, with axes trending roughly east-west. As Peach remarked (1910, p. 60) this folding indicates that the succeeding lava flowed in a northerly direction. Peach lists the fossils/

fossils found in this tuff as a tooth of Rhizodus (Traquair, 1908, p. 689), Calamites, Stigmaria, Elonichthys Striatus and Callopristodus pectinatus. A tuff band overlying Lava II south of St. Anthony's Fault extends almost to the edge of the vent. Both in thickness and in coarseness of its materials this band shows a steady increase as it is followed southwards.

Lava IIA

The upper lava at St. Anthony's Chapel, which overlies the fossiliferous tuff, is of Craiglockhart type, and is remarkable for its extremely varied nature. Near its base it has a massive columnar portion, on which the chapel ruins stand. Near the foot of the cliff above the chapel, this part can be clearly distinguished, but here the columns are small and apparently horizontal, in contrast with the vertical disposition of the columnar structure beneath the chapel. The columns which protrude through the turf immediately south of the ruins are inclined towards the north at various angles.

The columnar basalt in the cliff passes upwards into less massive, highly jointed basalt, which in turn grades into a brecciated rock practically indistinguishable from pyroclastic material (Pl. IV, figs. 1 and 2). The change is extremely gradual, and is probably the result of gas release/

release from the lava at a late stage in its cooling history. The escaping gas shattered the partially consolidated rock, perhaps locally producing fire-fountaining. Fissures so formed have been filled in with scoriaceous material produced by the pyro-explosions. In several places within the flow, bands of slaggy basalt with elongated aligned vesicles have been shattered by the escaping gas, and blocks have been rotated so that the vesicles of adjacent blocks are now aligned in different directions. The unusual disposition of the columns described above may have resulted from cooling proceeding from certain dominant foci of gas escape.

The upper Craiglockhart flow is traceable across St. Anthony's Fault as far as Pulpit Rock, but does not appear south of this feature. It was mapped by Peach as Lava III, but is in fact not part of the Lava III shown on the 6 inch Survey map south of Pulpit Rock. The third flow in the succession between Pulpit Rock and the vents is of Dalmeny and not of Craiglockhart type. Immediately north of Pulpit Rock, the Dalmeny flow is seen to overlies the Craiglockhart lava. To make the minimum departure from Peach's numbering, the second Craiglockhart flow is referred to here as Lava IIA, and the Dalmeny as Lava III (Fig. 2, p. 23).

Pulpit/

Pulpit Rock.(Pl.V , Fig. 1).

The Pulpit Rock is a plug-like mass of Craiglockhart basalt, flaring upwards, with deep fissures filled with tuff in its upper portion. It was mapped by Peach as intrusive; this interpretation is evidenced in several places by the exposure of nearly vertical contacts of the vesicular margin of the Pulpit Rock basalt with the ash of the Dry Dam. The basalt of Pulpit Rock is strongly columnar and the columns, vertical near the top, when followed downwards turn gradually until they become radial and nearly horizontal, which strongly suggests that they were formed by cooling proceeding from the vertical walls of an approximately circular "pipe". It is likely that Pulpit Rock is the filling of a flank orifice from which Lava IIA was extruded.

Lava III

Emission of Lava IIA was followed by the extrusion of Lava III, the only flow of Dalmeny type amongst the Arthur's Seat rocks. The only other occurrence of this type of basalt in the volcano is the Lion's Head intrusion. This is the cup-shaped mass which is believed to seal the Lion's Head vent. Petrographically it is very similar to Lava III - particularly to the basalt at the/

the southern end of the outcrops of the flow. It is probable that the vent was sealed immediately after the extrusion of the flow, by material of the same magmatic composition.

The contacts of Lava III with the basalt of Pulpit Rock are not clearly exposed, but a small outcrop of the flow is visible above the intrusion, and the lava is apparently very thin at this point. At its most northerly extremity immediately north of Pulpit Rock, the Dalmeny flow overlies the basalt of Lava IIA. Still further to the north, Lava IV, which for most of its length overlies Lava III, appears to rest directly upon IIA. These facts suggest that the flank orifice now marked by Pulpit Rock was in existence before the extrusion of Lava III, and formed a slight elevation on the northern slope of the cone. Lava III was dammed up behind this feature, and was probably diverted to the east and west, except for a small quantity of its basalt, which flowed over the obstruction to produce the single outcrop visible to the north of Pulpit Rock.

Lavas IV, V, and VI.

Lava IV is a basalt of Jedburgh type, and may be traced from the vents north over the whole length of Whinny Hill to St. Margaret's Loch. About 200 feet southeast/

southeast of Pulpit Rock a patch of coarsely porphyritic basalt of Craiglockhart type occurs in the outcrop of Lava IV. Its relations with the Jedburgh basalt are discussed later (p. 33).

Lava IV is followed by two more flows of Jedburgh basalt, which are petrographically indistinguishable in the field. The presence of a more or less continuous band of slag indicates the location of the top of Lava IV, but Flow V has a clearly defined top only north of St. Anthony's Fault. South of the fault exposures are masked by turf extending to the point where the relations of the Jedburgh lavas have been complicated by the mass of basalt referred to here as the Whinny Hill Intrusion.

Lava V has an average thickness of about 20 feet with little variation, and is characterised by the presence of columnar structure, generally poorly developed, and faint flow banding. The banding usually conforms to the general easterly dip of the Arthur's Seat rocks. Lava VI is considerably thicker than V, being about 80 feet from base to top. It is not so noticeably columnar as Lava V, and displays platy jointing rather than flow banding. This jointing, like the banding in V, frequently dips to the east, but in one locality immediately south of the depression known as Samson's Grave the platy jointing shows/

shows crude anticlinal structure, with one limb dipping steeply to the west.

St. Anthony's Fault

The horizontal displacement of outcrops of Lavas IV to IX, and the N.W. - S.E. strike of the northern parts of these flows, shows that St. Anthony's Fault does not curve to the south-east as indicated on the 6 inch Geological Survey Map, but instead passes almost due east across Whinny Hill. The northern parts of the outcrops of Lavas V and VI are downfaulted by the western part of this fault, which appears to die out in Lava VI. The eastern part strikes north-east across Whinny Hill and may be traced as far as the Queen's Drive; the western end of this part of the fault overlaps the eastern extremity of the other part, but is offset to the south by about 100 feet (see Map). Samson's Grave lies on the line of the eastern part of St. Anthony's Fault. The "Grave" is a natural hollow about 50 feet in diameter, completely enclosed by higher ground, and is probably a result of the removal by ice of basalt, principally of Lava VI, shattered during the fault movements. Even in the wettest weather, water does not lie in the hollow for any length of time; apparently it drains down into the shatter-zone of the fault and reappears as seepages at lower levels along/

along the outcrop of the fault. The abnormal disposition of the platy jointing of Lava VI near Samson's Grave may have resulted from the movements along the fault plane.

The eastern continuation of St. Anthony's Fault offsets the northern parts of the higher lavas of Whinny Hill (Nos. V, VI, VII, VIII and IX) to the west. The downfaulted northern portions of these flows are disposed with some difference in dip from that of their southern counterparts. The dip north of the fault is slightly east of north, in contrast with the general easterly dip south of the fault. This difference in dip is clearly demonstrated by the way in which the westwards-facing scarps on the north face of the hill maintain their northerly trend in spite of the considerable declivity of this face of the hill. On the south face of Whinny Hill the trend of the scarps curves towards the east as elevation decreases, as is to be expected of strata with an easterly dip.

Thus it is apparent that downfaulting to the north along the line of St. Anthony's Fault has been accompanied by tilting towards the north, and it is probable that the fault is a reverse one. It seems likely that the block between the Calton and St. Anthony's Faults/

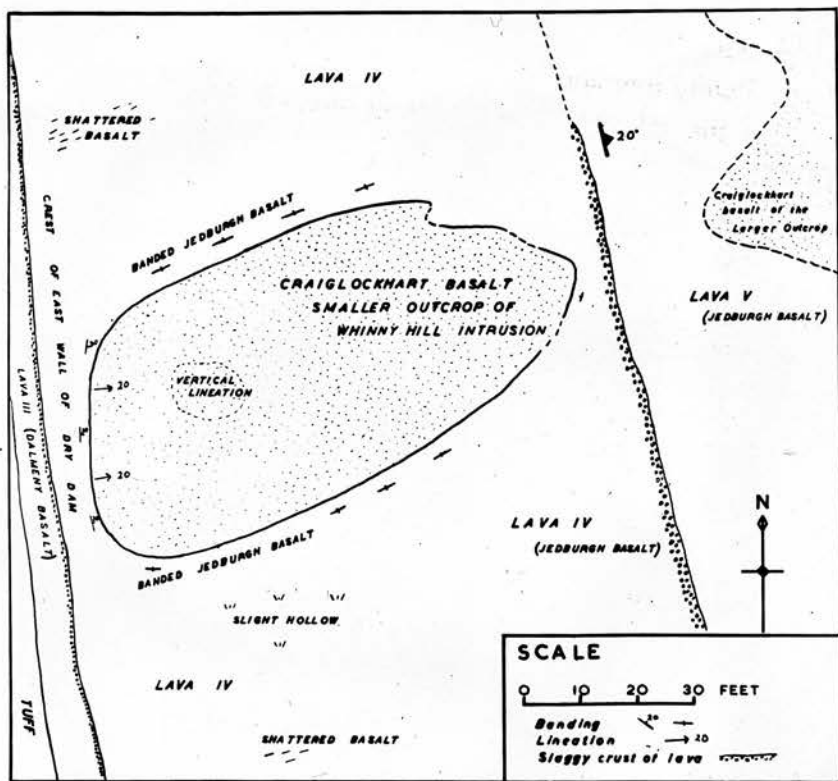


FIG. 3

THE VICINITY OF THE SMALLER OUTCROP
OF THE WHINNY HILL INTRUSION.

Faults has been tilted towards the considerably down-thrown Calton rocks.

The Whinny Hill Intrusion.

Associated with the Jedburgh lavas IV, V and VI of the Whinny Hill are two masses of coarsely porphyritic basalt of Craiglockhart type, at slightly different levels, but petrographically indistinguishable from each other. For reasons that will appear in the following pages, both these masses are regarded by the writer as having been parts of the same intrusive body, referred to here as the Whinny Hill Intrusion.

The smaller of the outcrops occurs in Lava IV (see Fig. 3), and was noted by Peach (1910, p. 61). He had classed all the Jedburgh flows as finely porphyritic Craiglockhart basalt, but referred to the actual Craiglockhart rock of the smaller outcrop as "a clearly defined layer [which] can be recognised by the large size of its porphyritic constituents".

The larger mass, which is associated with Lavas V and VI, was tentatively mapped by Peach (p. 61) as intrusive into the lavas, because of absence of slaggy character at the top and bottom of the sheet, and because of its considerable thickness compared with its lateral extent.

The/

The two outcrops are discussed separately in the following pages.

The Smaller Outcrop.

The outcrop of the smaller mass is roughly triangular, with a north-south base-line of about 30 feet, situated a few feet east of the crest of the wall of the Dry Dam, 300 feet south-east of Pulpit Rock. Its apex, 90 feet distant in an easterly direction, is only a few feet below the top of Lava IV and it is completely surrounded in horizontal outcrop by the Jedburgh basalt of this fourth flow. The phenocrysts, particularly the augites, have resisted weathering more effectively than has the groundmass, so that on weathered surfaces these large dark coloured crystals stand out conspicuously against the lighter groundmass (Plate VII, Fig. 1). This gives the rock a "plum pudding" appearance, and enables it to be readily distinguished in the field from the relatively even-grained Jedburgh basalt.

Although Peach states that the passage between the two rocks is not abrupt, the field exposures today show probably better than those in 1910, that the contact is sharp. However, neither rock is chilled against the other. Over most of its outcrop exposures of Lava IV are poor, though sufficient to show that columnar structure is not well-developed in this flow. Near the exposure of Craiglockhart/

Craiglockhart basalt, however, columnar structure is remarkably strong in the Jedburgh rock, and the columns pass up almost vertically and are continued into the porphyritic rock. Where their lower portions are exposed, immediately above Lava III on the wall of the Dry Dam, they are seen to curve slightly outwards away from the centre of the Craiglockhart outcrop. The continuity of the columns through both types of basalt, together with the lack of chilling of one type against the other, shows conclusively that both rocks were in contact in their cooling stages.

There is no trace of any layering. In thin section it is apparent that the extreme margin of the Craiglockhart basalt sometimes has fewer phenocrysts than are to be found in the rest of the outcrop. In some slices from marginal areas small patches reminiscent of the Jedburgh basalt of Lava IV can be recognised in the groundmass of the porphyritic rock. On the other hand, xenoliths of Craiglockhart basalt have not been found in the Jedburgh lava and mixing does not appear to have occurred. The absence of layering, fingering and mixing suggests that one of the two basalts was at least partially consolidated when the other was emplaced, and the xenolithic patches of Jedburgh basalt within the porphyritic rock indicate that the Craiglockhart/

Craiglockhart magma intruded the Jedburgh basalt when the latter had partially solidified; i.e. the Jedburgh lava is very slightly the older of the two rocks.

This sequence is supported by the comparative scarcity of phenocrysts in the Craiglockhart basalt near its margins. The writer sees no reason to doubt that the phenocrysts of Craiglockhart basalt existed prior to eruption of the liquid in which they are contained. If this is so, it may be supposed that the large crystals lagged behind the front of the advancing magma, in which case the earliest intruded portions - those now marginal - would be expected to contain relatively few phenocrysts.

Evidence as to the manner of emplacement of the Craiglockhart material is afforded by study of the structures both in it and in the surrounding Jedburgh lava (see Fig. 3). Everywhere near the Craiglockhart exposure the Jedburgh basalt exhibits a clearly defined banding. The rock has been shown to possess a strongly developed planar arrangement of its platy feldspar crystals (see p.201) parallel to this banding, which itself probably results from selective weathering parallel to the planar fabric. The banding is everywhere parallel to the contact of the Craiglockhart and Jedburgh basalts. On the western edge (the base of the triangular outcrop) it is nearly horizontal/

horizontal, but along both the longer margins it is practically vertical. From 10 to 20 feet both to the north and south of the outcrop the banding is absent, and instead vertical east-west shatter planes are exposed in a few places. Erosion has removed much of the shattered material, so that the porphyritic outcrop is now bounded first, on all sides, by the banded basalt, and then, further out to the north and south, by slight hollows. These hollows pass in turn into the usual outcrops of Lava IV, which are characterised by rather irregular jointing.

The banding in the Jedburgh basalt around the intrusive material may be explained in the light of the crystallisation sequence of Lava IV. (see p. 116). The ophitic augite of this flow crystallised at a very late stage, after the plagioclase had nearly completed crystallisation. Immediately before the solidification of the pyroxene the plagioclase and olivine crystals were in a liquid of mainly pyroxenic composition, with components of analcite and deuteritic constituents. Probably the Craiglockhart magma, rafting its large ferromagnesian crystals along, intruded the lava after the latter had ceased flowing, but before crystallisation of its augites had proceeded far. The pressure of the intruding basalt caused flowage of the lava, then principally a mass of plagioclase plates/

plates in a pyroxene lubricant. It may be conjectured that the movement so produced was sufficient to align the feldspar plates into parallelism in a direction perpendicular to the direction of the pressure responsible for the movement.

Cooling would have proceeded more rapidly in the lava distant from the intrusion, and must have been progressively slower in localities nearer to it. Extremely slow cooling in the immediate vicinity of the intrusion could have produced the columnar structure noted earlier, and the curvature of the columns away from the porphyritic outcrop is consistent with this hypothesis. At some distance from the intrusion more rapid cooling in the Jedburgh basalt could have caused the shattering which is present, which would have tended to be parallel to the vertically arranged plagioclase plates. Still further from the Craiglockhart rock, at a distance where no rearrangement of the feldspars had occurred, relatively rapid cooling would favour the production of the less regular jointing that is usual in this flow.

The shape of the intrusion of Craiglockhart basalt is not clearly shown by the surface outcrop, which is horizontal; the wall of the Dry Dam has not been eroded back sufficiently for the relations of the intruding basalt with the bottom of the flow to be seen. However, a linear arrangement of the phenocrysts has been found in several parts/

parts of the outcrop, and it is significant that, while at the western edge the lineation is nearly horizontal (parallel to the nearly horizontal plane of contact), towards the centre vertical lineation has been found.

The banding and shattering in the lava around the contact suggest that considerable pressure was exerted upon the partially consolidated Jedburgh basalt during emplacement of the porphyritic magma. It is unlikely that this could have accompanied auto-intrusion similar to that described by Kennedy (1933) near Kilmacolm. In addition, the fact that this is the sole outcrop of Craiglockhart basalt in Lava IV is against the hypothesis that the flow is composite, for in such a case one would expect to find a layer of Craiglockhart basalt of appreciable lateral extent instead of one small triangular patch. It is extremely likely that the Jedburgh Lava IV flowed in a northerly direction from the Lion's Haunch vent, but the north-south extent of the outcrop of Craiglockhart basalt in Lava IV is negligible.

Thus the available evidence suggests that the Craiglockhart patch is the outcrop of the filling of an orifice, of a pipe-like nature. Much if not all of the Craiglockhart basalt which occurs at a higher level in association with Lavas V and VI may have been emplaced through/

through this conduit. The surface of the smaller outcrop is suggestive of a pipe inclined to the east rather than vertical, and the relatively flat contact at the western margin may indicate local penetration into the upper part of Lava IV.

The Larger Outcrop.

The petrographically identical basalt which occurs at a higher level, associated with Lavas V and VI, was tentatively interpreted by Peach as intrusive (1910, p. 61). The relationship of this rock to the Jedburgh lavas can best be described by reference to the succession in the southern part of the Whinny Hill, which is as follows:

Markle Lava (Flow VII)
 Slaggy top of Jedburgh basalt.
 Jedburgh basalt with mainly euhedral augite.
 Craiglockhart basalt
 Jedburgh basalt with euhedral to slightly sub-ophitic augite.
 Slaggy top of Lava IV.
 Lava IV, Jedburgh basalt with ophitic augite.
 Slaggy top of Lava III
 Lava III, Dalmeny basalt.

Studied by itself, this suggests that Lava IV is overlain by a composite lava flow, comparable with that described by Kennedy (1931), and that the basalt mapped as Lavas V and VI form the upper and lower portions of a single lava, with a centre of different composition.

However/

However, the outcrop of Craiglockhart basalt terminates about 1300 feet north of the vent margin, and no further traces of it are to be found over the northern 1500 feet of the Whinny Hill. North of St. Anthony's Fault the slaggy top of Lava IV is overlain by about 20 feet of Jedburgh basalt identical with that which occurs at the same horizon at the south end of the hill. This basalt north of the fault passes up into a slaggy layer which appears to be the upper surface of a flow, and this is overlain by a third Jedburgh flow of considerable thickness, which is in turn overlain by a flow of Markle basalt.

Hence at the north end of the Hill there are three distinct flows of Jedburgh type basalt and these have petrographic similarities with rocks at the southern part of the hill; Lava IV, and the basalts above and below the Craiglockhart outcrop respectively. This suggests that the three flows at present recognisable north of St. Anthony's Fault originally extended over the whole length of Whinny Hill, and that the southern parts of the upper two were separated by the intrusion of the Craiglockhart basalt.

The contacts between the Craiglockhart and Jedburgh basalts are poorly exposed, as the area is largely covered by turf. However, in one locality 450 feet north/

north of the vent margin, the junction of Lava V and the porphyritic rock is visible. This contact is described in detail on p. 118, and here it is sufficient to state that the junction appears to be nearly horizontal, with slight but noticeable layering. Petrographic evidence (p. 119) suggests that the Jedburgh basalt was partially consolidated when contact with the Craiglockhart basalt occurred, as was the case with the smaller Craiglockhart outcrop.

The Craiglockhart basalt has resisted erosion more effectively than has much of the Jedburgh, which is sometimes brecciated near the junctions with the intrusion. No signs of shattering are visible in the porphyritic rock, which is remarkable for its massive non-columnar appearance. The outcrop of its upper surface is remarkably straight in contrast with the lobate outcrop of the lower surface. Almost horizontal lineation (when allowance has been made for the easterly dip of the Whinny Hill Series) has been found over much of the outcrop. These facts, together with the way in which the Craiglockhart body thins both to the north and to the south, are suggestive of an irregular sheet.

However, Lavas IV, V and VI, together with the outcrops of Craiglockhart basalt associated with them, may all/

all be grouped together as one composite eruptive episode. Probably the three Jedburgh lavas were extruded from the Lion's Haunch vent (Jedburgh lavas and dykes also occur in this vent) in fairly quick succession, and it may be that none of these had fully consolidated before Craiglockhart basalt was "quietly" erupted from flank fissures such as that now exposed in Lava IV. This material passed up through Lava IV, then probably more nearly consolidated than its successors, and spread out as a sheet-like body within the higher flows. It is of interest to note that the specific gravity of the Craiglockhart basalt is 3.01, which is appreciably higher than that of Lava V (2.89), and this may perhaps explain the lobes of the heavier basalt which have apparently protruded downwards into Lava V.

Lavas of Markle Basalt and Mugearite.

Lavas VII, VIII and IX (Markle).

The lowest flow of Markle type overlies Lava VI, and is accordingly referred to here as Lava VII. For the Markle and Mugearite lavas, the numbering in this description departs from that used by Peach (1910). The flow numbered VII by Peach is shown on the 1910 6 inch geological map as occurring only at the northern end of the Whinny/

Whinny Hill. This outcrop of lava seems to be merely the northern continuation - slightly offset by St. Anthony's Fault - of the Markle flow immediately overlying the uppermost Jedburgh lava (VI) on the main part of the hill. These Markle outcrops north and south of the Fault have been correlated, and numbered as Lava VII.

In the field the Markle lavas present a sharp contrast to the earlier flows, as, unlike the Jedburgh and Dalmeny lavas, they are characterised by very irregular upper surfaces, shattered and vesicular, reminiscent of aa lava. On their weathered surfaces the large white feldspar phenocrysts are often conspicuous.

Exposures of flows overlying Lava VII are generally poor, as they outcrop on the "dip slope" of Whinny Hill. The present writer considers that only two flows of Markle type overlie Lava VII; they are mapped by the writer as Lavas VIII and IX. This conclusion was reached after study of aerial photographs in addition to field observations. However, it is possible that the higher exposures of Whinny Hill were less obscured at the time of Peach's survey in 1910, and that more Markle lavas are present. The number is not important from a petrological viewpoint, and does not significantly affect interpretation of the eruptive history of the volcano to any extent.

The/

The Markle basalts of the Whinny Hill are probably of the same age as the two poorly exposed flows of Markle type which interrupt the upper ash of the Duddingston Series. (Lavas II, III, IV, V and VI of the Whinny Hill are not represented in the Duddingston Series, although fragments of Craiglockhart, Jedburgh and Dalmeny basalts occur in the ash as well as Dunsapie and Markle types).

Lavas X, XI and XII (Mugearite).

Lava X is the first flow of mugearite in the Whinny Hill Series; it is also the highest flow of this series which occurs in the confines of the King's Park. The ground outside the north-east part of the park has been closely built up since 1910, and hence remapping in the Scone Gardens area has not been practicable. However, in St. Margaret's Locomotive Yards the succession of three flows of mugearite noted by Peach (1910, p. 62) is still visible.

The mugearite lava east of Dunsapie Hill is the highest visible member of the Duddingston Series. It was thought by Peach (p. 63) to be of slightly earlier date than the Whinny Hill mugearites, but Oertel (1952, p.365) considered that it was probably coeval with these. The writer agrees with Peach, for it appears to occupy a structural/

structural position slightly lower than the lowest of the Whinny Hill mugearites. Petrographic evidence supports this view, for the Dunsapie mugearite contains numerous plagioclase phenocrysts, and hence may be termed a mugearite with Markle affinities.

Lava XIII (Markle).

The uppermost mugearite flow in St. Margaret's Locomotive Yards is overlain by a flow of basalt of Markle type. The top of this lava (Lava XIII) is obscured by drift; it is the highest member of the Whinny Hill Series, and is the youngest member of the Arthur's Seat rocks exposed outside the vents. No trace of any younger volcanics has been found in the course of the present study.

The Vents.

The Western Vent.

The outcrop of the western vent has the shape of an elongated mound about 700 feet in length and 200 in breadth, and is elevated above the general dip slope of the Salisbury Craigs sill, between the Cat Nick and Camstone Quarries. Peach (1910, p. 20) notes that at its eastern extremity it contains numerous fragments of Upper Old Red Sandstone, through which it cuts. Note has already been made (p. 25) of the petrographic characters of/

of the basalts in the agglomerate of this vent. The induration of this agglomerate was noted by Peach, who ascribed it to the heat of the Salisbury Craigs intrusion. This explanation of the induration may be correct but it is not necessarily so, for much of the agglomerate in the Lion's Haunch vent, similarly indurated - was probably baked by hot gases rising within the vent itself. However, the view that the western vent existed prior to intrusion of the Salisbury Craigs sill is favoured by the absence of blocks of teschenite in the agglomerate of the vent.

The Lion's Head Vent.

No amplification of Peach's description of the margins of this vent is necessary. The agglomerate contains fragments of Craiglockhart and Dalmeny basalts, and numerous pieces of the Dunsapie basalt of Lava I, but as Peach pointed out, no trace of Markle type has been found in it. In addition to the dykes of Dalmeny basalt which cut the agglomerate and unite upwards passing into the Lion's Head intrusion, a small dyke of Craiglockhart rock outcrops near the northern margin of the vent, and another of Jedburgh type is present near the Guttet Haddie.

An interesting observation was made by Dr. Campbell (1914, p. 248), who discovered plant remains in the agglomerate of the Lion's Head vent. The remains were of/

of vegetation which had not been derived from pre-existing rocks; this suggests that there were periods of quiescence in the history of the Head vent.

The Lion's Haunch Vent.

This is by far the largest and most complex of the three vents. It outcrops over about 1/6 of a square mile, and its rocks consist of agglomerate, lavas, intrusions and bands of sandstone.

Peach (1910, pp. 66 - 71) has described this vent in considerable detail. His views have been summarised by Oertel (1952), who has questioned certain details of Peach's interpretation. No useful purpose would be served by repeating much of Peach's description here. In general the writer is in agreement with Peach's main conclusions, but he feels it desirable to record certain new evidence that has come to light in the course of the present study.

Peach considered that the Lion's Haunch vent came into operation at a slightly later date than that of the Lion's Head, "and was drilled partly alongside and partly within the limits of the original orifice". He noted that the constituents of the older neck, including the Lion's Head intrusion, have supplied material for the agglomerate of the younger vent. This point is of considerable/

considerable importance, for, as petrographic evidence (p. 113) suggests strongly that the Lion's Head Intrusion was emplaced directly after the effusion of Lava III, and this sealed the older vent, the Haunch vent is a likely source for all higher lavas of the Arthur's Seat volcano.

The lavas and intrusions of the vent may be divided for descriptive purposes into four main groups.

- (1) The flows and intrusions in the south-west portion of the vent; these include the Samson's Ribs and Raven's Rock masses.
- (2) The lavas and associated rocks exposed in the Queen's Drive between the Loch Craig and the eastern end of the upper part of Samson's Ribs.
- (3) The lavas exposed in the northern and north-eastern portions of the vent.
- (4) The Lion's Haunch and Dunsapie Hill intrusions.

(1) The lavas which outcrop in the Powderhouse (south-west) corner of the vent may be studied in the section above the Queen's Drive at the western extremity of Samson's Ribs, where they are disposed with a steep dip towards the central part of the vent, probably as a result of subsidence within the vent. The lowest flow exposed probably overlies the agglomerate that fills the extreme western corner of the vent, at the foot of the Raven's Rock. The basalt of this flow is highly brecciated and its slaggy upper surface is overlain by about a foot/

foot of reddish tuffaceous sandstone - one of several such bands exposed within the Lion's Haunch vent.

The sediment is overlain by a lava of considerable thickness, with a slaggy upper surface, and is in turn followed by at least one further flow. The highest lava has an amygdaloidal upper portion, which is overlain by agglomerate. The higher levels of this agglomerate contain numerous fragments of Markle basalt very similar to that of Lavas VII - IX of the Whinny Hill Series.

Petrographic study of the lavas near Powderhouse Corner has shown that they are of Dunsapie type, and are very similar to but not identical with the basalt of the main mass of Samson's Ribs. Both the lavas and the intrusion contain a higher proportion of large plagioclase phenocrysts than most of the Dunsapie basalts of Arthur's Seat; the groundmass of the effusive rock is generally distinctly more feldspathic than that of the intrusion. The fact that a tongue of the Samson's Ribs mass intrudes the agglomerate above the lavas shows that the intrusion followed eruption of the lavas. However, the petrographic similarity between the two suggests that this part of the vent was the focus of uprise of the Dunsapie magma which formed these lavas, probably very early in the history of the Haunch vent.

When/

When the Samson's Ribs lavas, as they may be termed, are traced northwestwards along their strike, the exposures become poor. However, the flows are terminated abruptly by a fault, which trends about east-west and by which rocks to the north are relatively downthrown. The fault is filled with gouge, and erosion along the line of the fault has produced a noticeable depression which can be traced eastwards in the vent (see map). The lava is separated by the fault from agglomerate, apparently identical with that overlying the highest lava.

Immediately north-west of the fault the agglomerate passes laterally into a relatively fine-grained basalt of Jedburgh type. The basalt has engulfed blocks of agglomerate along a nearly vertical zone of contact, and is itself highly brecciated (Pl. XI, Fig 1), probably as a result of the faulting. Hence it is difficult to trace precisely where the agglomerate ends and the intrusive basalt commences. The Jedburgh basalt extends for a considerable distance northwards, as a narrow band of very splintery even-grained rock, and forms much of the face of the almost vertical cliff of the Raven's Rock. As the disposition of the roughly bedded agglomerate in this western part of the vent is not so steep as that of the lavas in the south-west corner, the vertical Jedburgh basalt is/

is probably a dyke-like intrusion, more or less parallel to the vent margin, from which it is not far distant.

Several other small intrusions are present in the vicinity of the Raven's Rock. These are mostly of Jedburgh basalt. Their upper limits are overlain by the considerable mass of agglomerate which makes up the bulk of the Nether Hill, west of the Lion's Haunch intrusion. High up in this agglomerate, only a few feet from the western crest of Nether Hill, is a small dyke. This has a central portion of Markle basalt - in the margins, however, plagioclase phenocrysts are less abundant than in the rock near the centre.

(2) The lavas exposed in the Queen's Drive between the Loch Craig and the eastern end of Samson's Ribs are not of Dunsapie type, as recorded by Peach (1910, p. 68). The flow nearer to the Samson's Ribs mass is of somewhat albitised Jedburgh type. It is the lower of the two, as the dip is to the north-east in this locality. It overlies a thin band of tuffaceous sandstone, and is followed by a considerable thickness of agglomerate. The higher flow is of greater thickness, and although in granularity it is comparable with the lower flow, the much greater degree of albitisation renders this rock petrographically similar to the mugearites of the Whinny Hill Series.

The/

The material within the vent in the vicinity of these flows has been displaced by a number of faults of small throw, which duplicate the outcrops of the lavas. However, these flows were very probably at a higher level within the vent than the Samson's Ribs lavas.

A short distance north-east of the mugearite lava occur the junctions of Girnall Craig and Loch Craig with the vent. The basalt of Girnall Craig is not exposed near the vent, but the Loch Craig (Lava I) may be followed north-westwards above the Queen's Drive to its junction with a tongue of the Lion's Haunch basalt. The contacts of the lava with the agglomerate are exposed further to the west; the vent appears to have moulded itself around some of the resistant basalt of the flow in this locality.

(3) The lavas which outcrop on the north-west and northern portions of the vent are generally poorly exposed. However, the lowest of these flows is probably now better exposed than when they were mapped by Peach in 1910. It outcrops above a band of fine agglomerate at the head of the Dry Dam, and petrographically is of Craiglockhart type. It is probably part of Lava II of the Whinny Hill Series, and should not be included within the vent. A very slight alteration to Peach's mapping of the vent boundary at this locality is sufficient to place this lava and the/

the underlying fine agglomerate, which is probably the lower ash of the Dry Dam, outside the margin.

The top of this flow is not exposed; it is likely that the first Dunsapie lava within the Haunch vent, which outcrops about 500 feet further to the east, overlies agglomerate. Outcrops of higher lavas are few, and the number of flows cannot be estimated. From the position of these lavas in the vent, it is likely that they represent upwellings of basalt within the crater at a fairly late stage in the eruptive cycle of the Haunch vent.

The lava outcrop recorded by Peach between the Lion's Head and Lion's Haunch intrusions has not been found. The exposures in this area are all of agglomerate which contains numerous fragments of Dalmeny basalt, and sedimentary intercalations.

(4) The Lion's Haunch and Dunsapie intrusions are well exposed. Some aspects of the former are discussed in a later section (p. 165); the main conclusions of Oertel (1952, p. 365) with regard to these masses are that they represent a lava lake and a marginal intrusion respectively. However, certain features of the lower portions of the Lion's Haunch intrusion require comment at this stage. Where the tongue of Lion's Haunch basalt on the south side of the hill cuts the Loch Craig, the ground-mass/

mass of the intrusion is extremely fine-grained near the junction, indicating that the intrusion was chilled against the lava. The contact plane dips steeply to the north, but the almost flat lineations in the basalt of the Lion's Haunch tongue suggest that the tongue is a dyke-like apophysis of the main mass of the intrusion and not part of the pipe through which the higher basalt was emplaced, as considered by Oertel (1952, p. 374).

Feach (1910, p. 67) mentions that a mass of porphyritic basalt resembling a dyke intrusion outcrops above the Queen's Drive between the two lava flows east of Samson's Ribs. However, he considers it probable that the mass is merely a large block in the agglomerate. Petrographic study has shown that the basalt resembles closely that of the Lion's Haunch intrusion, which almost certainly post-dates the agglomerate in this vicinity. Hence the mass is probably another dyke from the main intrusion.

Other Rocks of Arthur's Seat.

The Dasses , St. Leonard's Craig and Giraln Craig.

The Dasses outcrop about 100 feet below the Long Row, forming a number of crags which project from the scarp above the Hunters' Bog. The series of crags extends north from the vents to within about 300 feet of St. Anthony's/

Anthony's Fault. St. Leonard's Craig, downfaulted by St. Leonard's Fault, extends as an elevated feature from near the western margin of Samson's Ribs westwards as far as Jeannie Dean's Cottage, then northwards to St. John's Hill, outside the confines of the Park. Girnal Craig occurs below the Loch Craig; its stratigraphic relations with the extrusive basalt correspond to those of the Dasses with the Long Row lava.

All three of these features are believed to have been originally a continuous sheet of intrusive basalt emplaced in a single episode (see Peach, 1910, p. 72). The sill which forms St. Leonard's Craigs was shown to be composite by Bailey (1923, pp. 223 - 229), and later MacGregor (1936, pp. 317 - 331) gave a detailed petrographic description of the two constituent types - rocks with Dunsapie and mugearite affinities respectively. Both Bailey and MacGregor considered that intrusion had taken place under shallow cover.

In a recent paper Oertel (1952, pp. 366-370) discussed the structure of the Dasses and pointed out that two types of intrusion had occurred; first a basalt allied to Markle type (Rutledge, 1952, p. 381) had been broken through by a second basalt, of Dunsapie type. The later basalt formed a series of partly transgressive domes, referred/

referred to by Oertel as "the Dasses dykes".

The Duddingston Basalt.

The basalt of Dunsapie type outcropping near the eastern margin of Duddingston Loch is clearly intrusive, for it truncates the sediments overlying the Loch Craig basalt (Peach, 1910, p. 72). This occurrence was one of those studied by Oertel (1952, p. 374), who considered it to be an intrusion on the flanks of the volcano.

The Basalt near Samson's Ribs.

A small outcrop of basalt occurs a short distance to the west of Samson's Ribs. This rock was mentioned by MacGregor (1936, p. 318), who considered from petrographic evidence that it did not belong either to Samson's Ribs or the nearby St. Leonard's rock. Petrographic examination made during the course of the present study has shown that the basalt of this outcrop resembles closely that of Lava I. The rock is probably a down-faulted portion of this flow.

TABLE I.

Classification of Basaltic rocks present in Arthur's Seat.

<u>Macroporphyritic Basalts.</u>	
Type	Macroporphyritic crystals of
Craiglockhart	Augite, Olivine
Dunsapie	Feldspar, Augite, Olivine
Normal Dunsapie	Proportion of Feldspar phenocrysts is not more than twice that of porphyritic augite and olivine.
Feldspathic Dunsapie	Proportion of Feldspar phenocrysts exceeds twice that of porphyritic augite and olivine.

<u>Microporphyritic Basalts.</u>	
Type	Microporphyritic crystals of
Dalmeny	Olivine
Jedburgh	Feldspar, Olivine

Mugearite.

Consists of oligoclase feldspar and ferromagnesian minerals.

IV. PETROGRAPHIC DESCRIPTIONS.

Most of the rocks of the Arthur's Seat volcano are basaltic. Classification of the Scottish Carboniferous basalts has long been based upon the nature and size of the porphyritic constituents. This system was first introduced by Hatch (see Geikie, 1892, p. 129) and amplified by Watts (Geikie, 1897, p. 417). MacGregor (1928) revised the classification, and his version has been adopted in this investigation. In Table I the essential features of the different types are listed, and Table II (facing p. 59) shows the grouping of the various individual flows and intrusions of Arthur's Seat according to the classification.

In his paper MacGregor (p. 349) drew attention to the fact that transitional types are frequently encountered. Certain of the Arthur's Seat rocks may perhaps be regarded as transitional between Dunsapie and Markle, for they have a much greater proportion of feldspar phenocrysts relative to those of augite and olivine than the type Dunsapie basalt. For this reason it has been found convenient to classify as "Feldspathic Dunsapie" basalts all those rocks of Dunsapie type in which the modal proportion of large feldspar phenocrysts exceeds twice that of the total porphyritic augite and olivine combined.

Most of the Arthur's Seat rocks are black in hand/

TABLE II.

Arrangement of Arthur's Seat rocks according to classification of Table I.

Basalts.

Type	Extrusive	Intrusive
Craiglockhart	Lavas II, IIA.	Pulpit Rock, Whinny Hill Intrusion, Dyke in Lion's Head vent.
Normal Dunsapie	Lava I	Lion's Haunch, Dunsapie Hill.
Feldspathic Dunsapie	Samson's Ribs lavas. Lava in north side of Lion's Haunch vent ("Lion's Haunch Lava").	Samson's Ribs, Dasses, St. Leonard's Craigs, Girmal Craig, Dudding- ston basalt.
Markle	Lavas VII, VIII, IX and XIII.	Dyke in Lion's Haunch vent.
Dalmeny	Lava III	Lion's Head.
Jedburgh	Lavas IV, V and VI. Lava in south side of Lion's Haunch vent (Queen's Drive Jedburgh lava).	Raven's Rock dykes.
Mugearite	Lavas X, XI, XII. Lavas east of Dun- sapie Hill. Lava in south side of Lion's Haunch vent (Queen's Drive Mug- earite lava).	Marginal facies of St. Leonard's sill.

hand specimen, and weather to a dull orange colour. The porphyritic constituents become more conspicuous on weathered surfaces. When deuteric alteration has played an important part in the late cooling history of the rock, as in the Markle basalts, mugearites, and some of Dunsapie type, the colour of fresh exposures is grey or brown. The larger feldspar crystals of such rocks are usually conspicuously white.

Basalts of Dunsapie type.

Dunsapie basalts are characterised by the presence of numerous macroporphyritic crystals of plagioclase, augite and olivine, which are set in a groundmass consisting mainly of plagioclase, augite and iron ore.

The plagioclase phenocrysts generally range in composition from bytownite to labradorite, but sometimes possess a more sodic rim. They vary in size considerably, reaching a maximum length of about 6mm, and are usually subhedral. Some are tabular in shape, but others have almost equal width and thickness. In the crystals examined on the Universal Stage, twinning according to Albite, Carlsbad, combined Albite-Carlsbad, and Aclin or Complex Manebach-Ala laws was determined.

The large augite crystals vary considerably in appearance though not in composition. They are pale brown/

brown in colour and frequently have slightly darker outer rims. $2V$ averages 52° and $Z \wedge c$ 40° ; $\alpha = 1.682$, $\beta = 1.692$ and $\gamma = 1.707$. These figures show that composition of the augite approximates to Ca 42, Mg 42, Fe 16 (Hess, 1949). However, sometimes the outer portions of the phenocrysts are slightly purplish, which indicates that titanium is also present. Very slight pleochroism is common with Z rather more yellow than the X and Y directions. The crystals are usually subhedral, but both euhedral and anhedral outlines are often seen; the latter is often a result of corrosion. They reach a maximum length of about 8 mm, but most are between 1 and 3 mm, and are stumpy prismatic in shape.

The olivine phenocrysts are invariably less abundant than those of either feldspar or pyroxene. In some lavas and intrusions they have been completely altered, and only pseudomorphs remain, but frequently alteration has been slight, occurring only along cracks in the crystals, and around their margins. $2V$ is about 90° , indicating that the mineral is a magnesian chrysolite, Fo₈₆. Euhedral shape is not uncommon, but some are subhedral and others have been corroded.

Almost all the Dunsapie basalts of Arthur's Seat contain glomeroporphyritic aggregates of large crystals, which resemble xenolithic fragments of basic plutonic/

TABLE III.

Modes of Basalts of Normal Dunsapie Type.

(All modes were measured with the Hurlbut Electric Counter using sections cut from specimens used for chemical analysis. The chemical analyses are given in Table VII.). Facing p. .).

		A	B	C
Phenocrysts	{ Plagioclase	2.0	21.0	18.0
	{ Augite	2.2	9.4	11.2
	{ Olivine	4.1	6.7	9.7
Groundmass	{ Plagioclase	48.1	30.8	33.3
	{ Augite	16.3	12.4	13.7
	{ Olivine	4.9	3.6	4.3
	{ Iron ore	9.8	7.9	5.1
	{ Chlorite, analcite, calcite, apatite etc.	12.6	8.2	4.7

A. Lava I, Haggis Knowe.

B. Lion's Haunch basalt, northern escarpment.

C. Dunsapie Hill basalt (Type rock) near middle of eastern shore of Dunsapie Loch.

plutonic rocks such as olivine-gabbro, anorthosite, pyroxenite and others. The petrogenetic significance both of these and of the corroded phenocrysts is discussed later (p.134).

The groundmass of the Dunsapie basalts differs considerably in granularity in different flows and intrusion, but within each individual mass remains fairly constant (with the notable exception of Lava I). All contain plagioclase, mainly labradorite, as the chief constituent, with pyroxene, subordinate olivine and iron ore, mostly titaniferous magnetite. Apatite, analcite and chlorite are present as accessories in almost all Dunsapie basalts. Others occasionally encountered include biotite and picotite.

I. Basalts of Normal Dunsapie Type.

Extrusions

Lava I

Intrusions

Lion's Haunch basalt
Dunsapie Hill

A. Extrusive basalts of Normal Dunsapie Type.

(i) Lava I, represented by the Long Row, Haggis Knowe and Loch Craig.

This basalt is characterised by the comparatively small numbers of its phenocrysts (see mode, Table III), and by the presence of quartz in many olivine pseudomorphs. These features are sufficiently rare in other Arthur's Seat Dunsapie rocks to enable fragments of the basalt in Lava/

Lava I to be recognised with comparative certainty no matter where they occur.

The plagioclase phenocrysts usually have rounded and embayed outlines, as a result of corrosion. Zoning is common, and frequently a zone of inclusions separates the interior portion from a thin outer layer of later growth. Similar inclusions also occur along cleavage planes throughout the crystals, sometimes to so marked a degree as to produce a schiller appearance. In such cases thicker inclusions occur along the 010 cleavage than along the 001. The inclusions consist for the most part of magnetite, with some haematite, and occasional crystals of augite, apatite, chlorite and calcite. Some of the haematite, chlorite and calcite was probably formed by alteration of earlier ferromagnesian minerals.

The cores of some of the zoned plagioclase crystals are as calcic as An₈₀ (bytownite), but the greater part of each phenocryst has a composition of An₆₀₋₇₀ (basic labradorite). The outer zone of later growth is about An₅₅, and occasionally is even less calcic. Alteration is generally slight; the most common alteration is calcite. In some sections, particularly of the Loch Craig, some of the plagioclase crystals have been slightly albitised.

Corrosion/

Corrosion is particularly marked in the augite phenocrysts of Lava I, which as a result rarely display any crystal faces. Their length varies from 0.5 to 4 mm or more. Like the plagioclase phenocrysts, the augite also contain distinct inner and outer regions, separated by a zone of inclusions. The inner portion is pale brown in colour, and is usually free from inclusions. The outer zone is appreciably darker, and contains abundant inclusions of groundmass minerals. Sometimes the included minerals are quite large, and consist of a group of crystals - usually plagioclase, iron ore and chlorite or analcite occupying a former cavity within the pyroxene (Pl.XIII, fig.4). These inclusions are more common in the augites of Craiglockhart basalt than in those of Dunsapie type, and their origin is discussed on pp.80-81. In some localities, particularly parts of the Haggis Knowe and Loch Craig, the augite crystals have been completely altered to chlorite.

Large pseudomorphs after olivine are fairly numerous and sometimes exceed 6 mm in length. No unaltered olivine has been found in any specimen from Lava I. The alteration minerals include bowlingite, chrysotile, antigorite, calcite and quartz. The serpentinous minerals appear to have been the first alteration products, and/

and have themselves been frequently replaced by silica and carbonate. Embayments and rounded outlines characterise the pseudomorphs, showing that corrosion of olivine occurred at some stage in the crystallisation history of the lava.

The groundmass contains much labradorite, An₅₀₋₆₀, in the form of small subhedral and euhedral crystals, many of which are slightly zoned. Next in quantitative order of importance is augite, which differs texturally in different parts of the flow. In the Loch Craig, and in the Long Row from the vents to a point about 900 feet north of the vent margin, the augite is sub-ophitic, but from this point northwards to the Haggis Knowe it becomes less markedly ophitic, and many subhedral crystals are present. In the groundmass of the rock of the Haggis Knowe, augite occurs mainly as small subhedral and euhedral grains.

The groundmass of the basalt with ophitic augite contains more plagioclase and less augite than that in which the augite is euhedral. The significance of this textural and composition variation has also been observed in other rocks of Arthur's Seat, and is discussed elsewhere (pp. 108-122).

Circular or ellipsoidal aggregates of very small radially disposed prismatic augite crystals occur throughout Lava I, sometimes in fairly large numbers. They have been/

been produced by reaction of the basaltic magma with xenocrysts of quartz. In some sections the centres of the original quartz grains are visible (Pl. XIII, Fig. 2), showing that sometimes solidification of the rock ensued before reaction had been completed. In these sections the quartz is seen to be surrounded first by a zone of radially arranged fibrous chloritic material, and then by the radial augite prisms.

Development of augite by reaction of a basic magma with quartz xenoliths has been described by Campbell, Day and Stenhouse (1934, p. 166) in rocks from the Braefoot Sill. Radial aggregates of augites that have formed in this way are rare in the other Arthur's Seat rocks, but they have been found by the writer in considerable numbers in the Dalmeny basalt of the plug forming the Castle Rock, Edinburgh.

Small pseudomorphs after olivine occur sporadically in the groundmass, the alteration minerals being the same as those found in the larger pseudomorphs. Iron ore, mainly magnetite with some haematite is a plentiful accessory. Slender needles of apatite are numerous, and cloudy analcite has been replaced by pale green chlorite, which also replaces augite in some sections. Patches of carbonate are occasionally present; some of these result from/

from alteration of augite.

Amygdales are not numerous, except near the slaggy top of the lava. They are usually spherical, and are filled with chlorite, haematite, calcite and quartz. Bands of jasper are fairly common, filling cracks, and occasionally large drusy cavities contain crystals of calcite and quartz.

B. Intrusive basalts of Normal Dunsapie Type.

(i) The Lion's Haunch basalt.

The Lion's Haunch basalt has been described and figured in several petrological works including those of Teall (1888, p. 188) and Harker (1902, p. 204). The most detailed description is that by Flett (1910, p. 317). The rock is remarkable for the extremely fine-grained partly glassy character of its groundmass, for the large number of its phenocrysts, for plentiful "basic xenoliths", and for the manner in which many of its phenocrysts have broken into fragments.

The plagioclase phenocrysts are on average slightly larger than those of Lava I, and rarely display corroded outlines. In composition they range from An70-80 at their centres to outer portions which are considerably less calcic, about An55-65. They are usually subhedral, and contain plentiful inclusions. Sometimes corrosion cavities in the crystals are filled with/

with groundmass material. Other crevices which also contain groundmass material originate from mechanical causes - the crystals have broken along cleavages, and fragments have floated away. Sometimes this breakage has progressed so far that the original phenocryst now consists of a number of completely separated rectangular fragments, many of which have not moved far, and are still almost in optical continuity with each other (Pl. XIV, F₄).

The augite phenocrysts are frequently subhedral. Evidence of corrosion is less striking than in those of Lava I, but the cavities, rounded corners and embayments seen in certain crystals show that some resorption has taken place. A narrow outer zone, slightly darker than the fawn coloured cores of the crystals, contains inclusions of groundmass minerals. The augites do not display the shattering along cleavages noted in the plagioclase phenocrysts, but some are broken across, and a single large crystal has sometimes produced two or more smaller phenocrysts (Pl. XIV, F₂). This process of multiplication of phenocrysts by "fission" has been noted by MacGregor (1932, pp. 329 - 333). The mechanical disruption of phenocrysts in the Lion's Haunch basalt suggests that stress was considerable during some stage of the emplacement of the magma.

Phenocrysts of and pseudomorphs after olivine are generally/

generally subhedral, though some are euhedral, and others slightly corroded. Many crystals are only slightly altered, but some have been completely serpentinitised. Serpentinous minerals form the bulk of the alteration products, though occasionally quartz and carbonate are present. Glass enclosures which contain microlites of augite and plagioclase and skeletal growths of iron ore are present in many of the phenocrysts. Some chlorophaeite has been noted in cavities in the large olivines, which also occasionally enclose accessory picrotite.*

Xenoliths of sub-volcanic types are numerous, and few sections of Lion's Haunch basalt fail to show one or more of these. Some are quite large, one measuring 30 mm by 20 mm in section, and consisting of augite, plagioclase and olivine. Another comprises a large crystal of olivine poikilolitically enclosing tabular plagioclase crystals. Others are almost wholly of plagioclase or augite, and resemble anorthosites and pyroxenites respectively.

The fine-grained groundmass of the Lion's Haunch basalt is composed of small tabular crystals of plagioclase (laths in section), which average 0.05 mm in length, and/

* Personal communication from Dr. Campbell.

and have a composition of about An₅₀₋₆₀. Numerous very small crystals of pale fawn coloured augite are present; these are often euhedral, and frequently enclosed by plagioclase. The few olivines of the groundmass are usually completely serpentinised. Iron ore is present, and consists of small equidimensional crystals of magnetite, sporadic layer crystals and branching skeletal growths in brown glass, of which there is a little present. Needles of apatite are numerous.

Chlorophaeite occurring in amygdales in this rock was noted by Campbell and Lunn (1925, p. 440). Amygdales are on the whole not numerous; other minerals which they contain are iron ore and calcite. Occasional quartz xenocrysts altering to augite have been found; these are very sporadic.

(ii) Dunsapie Hill.

This feature is the type locality for Dunsapie basalt. The phenocrysts resemble closely those of the Lion's Haunch in numbers, size, degree of euhedral development and possession of inclusions. However, plutonic xenoliths are less numerous, and shattered phenocrysts have not been observed.

The groundmass is coarser in granularity than that of the Lion's Haunch - this is the most striking difference/

difference between the two rocks. The augites, frequently euhedral, are often enclosed in the groundmass plagioclase crystals. In this respect they resemble their smaller counterparts in the Lion's Haunch rock. Many of the small olivine crystals have unaltered cores, unlike those of the Lion's Haunch basalt. A certain amount of cloudy analcite is present, and occasional flakes of biotite occur. Some analcitisations of plagioclase has taken place, and chlorite and chlorophaeite occur in the groundmass and in amygdales. The type Dunsapie rock never has the clean unaltered appearance of the Lion's Haunch basalt.

A few pegmatitoid veins occur in the basalt of Dunsapie Hill. These were first discovered by Oertel, although he did not record them in his paper (1952). They consist of large crystals of feldspar and augite, with prominent iron ore and long apatites.

2. Basalts of Feldspathic Dunsapie Type.

These are more plentiful in the Arthur's Seat rocks than basalts of Normal Dunsapie type, and contain a greater proportion of porphyritic feldspar. The modal proportion of feldspar phenocrysts exceeds that of augite and olivine by more than two to one.

Extrusions/

Facing p. 71.

TABLE IV.

Modes of Basalts of Feldspathic Dunsapie Type.

	A	B	C	
Phenocrysts	Plagioclase	18.3	16.7	16.7
	Augite	2.1	2.2	4.9
	Olivine	4.3	1.5	1.1
Groundmass	Plagioclase	41.3	41.2	39.6
	Augite	12.0	19.0	12.2
	Olivine	2.4	5.1	3.1
	Iron ore	12.1	8.3	6.3
	Chlorite, anal- cite, calcite, apatite etc....	7.5	6.0	16.1

- A. Lava in the north side of Lion's Haunch vent.
- B. Samson's Ribs intrusion, near base of exposure.
- C. St. Leonard's sill, Kaim Head 200 feet east of Jeannie Dean's Cottage.

Extrusions

Samson's Ribs lavas
Lion's Haunch lava

Intrusions

Samson's Ribs intrusion.
St. Leonard's sill, central portion
Dasses
Girnal Craig.
Duddingston plug.

A. Extrusive Basalts of Feldspathic Dunsapie Type.

(i) Samson's Ribs Lavas.

These flows are all very similar petrographically. The most noticeable constituent is phenocrystic plagioclase which is usually altered. The alteration varies; most commonly albitisation has affected the more calcic centres of the crystals, but has left outer zones, and patches within the crystal, entirely unaltered. This results in patchy extinction, and also gives a patchy appearance when the slide is viewed in ordinary light, for the albitised patches are cloudy, mainly owing to the growth of tiny flakes of sericite. Sometimes sericitisation has been intense, even though traces of albitisation may be almost absent. Some crystals of plagioclase have been largely altered to carbonate; in others, small patches of chlorite have been observed.

The plagioclase phenocrysts are usually sub-hedral, and show few signs of corroded outlines. The plagioclase of the groundmass is almost entirely unaltered, and consists of small tabular crystals often showing fairly well/

well developed flow structure.

Ferromagnesian phenocrysts have usually been completely altered, and are represented only by pseudomorphs. Many of these pseudomorphs have good olivine shapes; others resemble augite in form. When only pseudomorphs remain of former ferromagnesian phenocrysts, augite and olivine in the groundmass have invariably been completely altered to serpentine, chlorite, carbonate and iron ore.

In one locality—in an upper flow a few feet south of the fault which terminates the outcrops of Samson's Ribs lavas to the north — the reddish basalt with conspicuous white feldspar phenocrysts forming the major part of the outcrop of these flows passes gradually vertically and laterally into reddish brown basalt which appears in the field to be non-porphyrific. The reason for the apparent lack of phenocrysts is that this latter rock is much less altered, though still part of the same flow. Its feldspars are entirely unaltered, and so lack the conspicuous white appearance so characteristic of albitised plagioclase particularly on weathered surfaces. The augite too is unaltered, both the phenocrysts and that in the groundmass. The augite phenocrysts are subhedral and uncorroded. In the groundmass small euhedral and subhedral/

subhedral augite crystals are abundant, many being enclosed within groundmass feldspar.

(ii) The Lion's Haunch Lava.

The extrusive basalt which outcrops within the vent north of the Lion's Haunch intrusion is chiefly remarkable for its high iron-oxide content (see Table IV+V). Much of this is deuteritic, for the olivine pseudomorphs are sometimes completely composed of iron ore. Silica (usually quartz) and calcite form the other pseudomorphing minerals. The quartz frequently displays a "pseudocleavage", sometimes very strongly developed, and aligned in the direction of the c axis of the former olivine. The identification of this mineral as quartz was confirmed by the method of Gilbert and Turner (1949), using the universal stage. The "cleavage" was found to be caused by the presence within the quartz of minute inclusions, mainly iron ore, arranged in parallel planes. It is probable that an olivine alteration sequence similar to that of Lava I occurred in the deuteritic stages of this flow, and that the olivines were first replaced by serpentinous minerals, including bowlingite. Some of the deuteritic iron oxide was deposited along the cleavages of the bowlingite, forming a planar arrangement of very small grains which was retained in the quartz when this mineral/

mineral replaced the bowlingite (Plate XVI, fig 3).

B. Intrusive Basalts of Feldspathic Dunsapie Type.

(i) Samson's Ribs Intrusion.

The basalt of the Samson's Ribs mass is almost identical with the relatively unaltered part of the Samson's Ribs lava near the fault (p. 72), except that the groundmass contains more analcite, and the plagioclase phenocrysts are sometimes partly altered. Analcitisation is the most common form of alteration of the plagioclase crystals, but some are slightly albitised, and others contain small patches of sericite, chlorite and carbonate. Many contain numerous inclusions of groundmass minerals, mainly along cleavage cracks. Corroded outlines are exceptional.

The augite phenocrysts are very sporadic, and are not corroded. They contain a few included groundmass crystals, mainly occurring in the outer portions of the oikocrysts. The pale fawn centres pass gradually into slightly darker rims without evidence of intervening corrosion, in contrast with the augites of Lava I, where the colour change is abrupt.

No fresh olivine has been found in the Samson's Ribs basalt, but a distinctive alteration product is characteristic/

characteristic of its pseudomorphs. This is probably a variety of bowlingite with much more intense pleochroism (X = yellowish-brown, Z = green) than has been found in olivine pseudomorphs of other basalts.

Some cloudy analcite and chlorite are to be seen in the groundmass of most sections of the Samson's Ribs basalt, and prehnite is abundant as a crevice filling. The groundmass of the fingers of basalt which penetrate upwards into the agglomerate of the Lion's Haunch vent from the main mass of the Samson's Ribs intrusion consists of small crystals of plagioclase, augite, iron ore, apatite, and a dark brown glass. Amygdales of clear analcite and chlorite are conspicuous.

(ii) The Dasses, St. Leonard's Craig and Giral Craig.

The porphyritic basalt of St. Leonard's Craig has been described by MacGregor (1936, pp. 322 - 324) and that of the Dasses by Rutledge (1952, pp. 379 - 388). Petrographically the rocks of all three features have many points in common, but possess individual characteristics which enable them to be distinguished from each other. Both St. Leonard's sill and the Dasses are composite, but one facies of each of these intrusions has been described as basalt related to Dunsapie type by MacGregor (loc. cit) and Rutledge (loc. cit).

All/

All the rock of the Giral Craig is Dunsapie basalt.

The augite phenocrysts of all the rocks have an important feature in common with those of the Samson's Ribs basalt; they have not undergone the complicated history of large augite crystals of many other Arthur's Seat basalts. The rims are more distinctly reddish purple than usual; they are frequently euhedral, and sporadic inclusions are restricted to the rims.

The composite nature of St. Leonard's Craig has been emphasised by Bailey (1923) and MacGregor (1936). The sill forming the Craigs has non-porphyrific margins of an intensely albitised rock resembling mugearite, and a porphyritic centre. The latter, which is considered to have intruded the "mugearite" while this was still unconsolidated, contains much analcite, and was classed by MacGregor as an analcite-rich alkali-basalt allied to Dunsapie type. The considerable development of analcite, both in the groundmass and replacing plagioclase, is a distinctive feature of the porphyritic St. Leonard's rock. Another characteristic is the presence of flakes of biotite in greater abundance than in any other Arthur's Seat rock studied by the writer.

The plagioclase phenocrysts frequently possess extremely corroded cores, and contain very numerous inclusions/

inclusions. They are more noticeably zoned, with cores of about An70-80 and rims which may be as sodic as An₁₀.

The Dasses, as described by Oertel and by Rutledge, consist of sills of altered basalt allied to Markle type, cut while still unconsolidated by dyke-like bodies of Dunsapie basalt. The modal analyses made by Rutledge show that the sills contain more plagioclase phenocrysts than do the dykes. Patches of albitised basalt are also present in the dykes, and probably represent localised deuteric activity. The groundmass of the Dasses "dykes" is relatively coarse-grained, and contains sub-ophitic and ophitic augite.

The Giral Craig basalt is less altered than that of either St. Leonard's or the Dasses, although both plagioclase and augite show some chloritisation, and the olivines have been completely replaced by serpentine and carbonate. The groundmass augite is rather smaller than that of the Dasses.

(iii) The Duddingston Basalt.

The basalt of the Duddingston intrusion has strong resemblances to that of Giral Craig, to which it is geographically close. It is almost entirely unaltered, and contains fresh olivine. Its ferromagnesian phenocrysts/

Facing p. 78.

TABLE V.

Modes of Basalts of Craiglockhart Type.

	A	B	
Phenocrysts	Augite.....	10.7	16.0
	Olivine.....	5.3	9.8
	Plagioclase.....	37.2	40.3
Groundmass	Augite.....	24.4	16.7
	Olivine	7.8	7.2
	Iron ore.....	8.4	6.6
	Chlorite, calcite, analcite, apatite etc.....	6.2	3.4

A. Lava IIA, near St. Anthony's Chapel.

B. Whinny Hill intrusion, smaller outcrop.

phenocrysts are slightly more abundant than those of Giraln Craig.

Basalts of Craiglockhart Type.

Extrusions.

Lavas II and IIA

Intrusions.

Dyke in Lion's Head vent.
Pulpit Rock.
The Whinny Hill Intrusion.

Craiglockhart basalts are characterised by abundant large phenocrysts of augite and olivine. They are represented in Arthur's Seat by Lavas II and IIA of the Whinny Hill Series, and by the Pulpit Rock and the Whinny Hill intrusion. As with Dunsapie basalts, each of these bodies possesses minor characteristic features of its own which frequently permit recognition in thin section.

The fawn-coloured phenocrysts have a similar composition to those in Dunsapie basalts. They differ in that they have been affected by corrosion to a considerably more marked degree. Deep embayments, channels and cavities filled with groundmass minerals are very common (Pl. XVIII, Fig. 1). Many of the augites are composed of two distinct zones - an inner paler portion, free from inclusions, and an outer slightly darker area, containing inclusions, often so numerous that this zone assumes a honeycomb appearance. These zones have already been noted/

noted in the augites of Dunsapie basalt (p.63), but the outer zones of those in the Craiglockhart rock are generally much larger. The inner zone usually possesses a rounded shape suggestive of a corroded crystal outline, and has a sharp contact against the darker outer zone. Often included minerals, particularly grains of iron ore, are particularly numerous along the outer side of the junction. Sometimes the two zones interdigitate.

MacGregor (1932, p. 329 - 330) has described a honeycombed corroded augite phenocryst in Dunsapie basalt from Renfrewshire. He considered that the corrosion resulted from the crystal having been in contact, after growth, with magma under different conditions of temperature and pressure. The crystal figured by MacGregor does not show the two zones present in many of the augite phenocrysts of Arthur's Seat basalts, and its cavities may all be sections of channels and deep embayments. It probably corresponds to the inner part of the Arthur's Seat augites.

The full history of the complex augites of the Craiglockhart basalts of Arthur's Seat is probably as follows:-

1. Growth of large augite crystals prior to eruption of magma.
2. Movement/

2. Movement of crystal until it came into contact with magma of a composition such that the augite was no longer in equilibrium with the surrounding liquid.

3. Corrosion, causing embayment and honeycombing.

4. Change in conditions, producing return to equilibrium with surrounding liquid, and allowing regrowth on honeycombed skeleton. During this regrowth magma may have been trapped within the crystal.

5. Final growth during consolidation of ground-mass of rock after eruption of magma.

Inclusions in these crystals therefore fall into two classes.

(a) Those formed by crystallisation of trapped magma. Some fairly large included plagioclase crystals belonging to this class exactly fit parts of the boundaries of the more or less spherical cavities within the augite. They are often associated with crystals of iron ore, apatite, chlorite and analcite, but any pyroxene components present in the trapped liquid must generally have added to the growth of the large crystal until it was exhausted, for only rarely are small augite crystals present as inclusions. After crystallisation of the plagioclase and iron ore within the phenocryst had been completed, any cavity remaining was filled with secondary minerals; most of the inclusions have some chlorite or analcite/

analcite associated with the other minerals.

(b) Those crystallising outside the augite, but being later engulfed by continuing growth of the phenocryst. These are found near the margins of the crystal, and are mainly euhedral or subhedral feldspars and small magnetites.

All augite phenocrysts need not necessarily have passed through all the stages described above. For example, some which have corroded centres, but only a narrow outer zone, may not have undergone stage 4, probably because eruption occurred too soon.

A number of augite crystals in almost every section do not show the inner zone, but are of a uniform darker tinge, and contain inclusions fairly evenly distributed throughout. In several cases it was possible to cut serial sections through other portions of crystals which presented this appearance (method described in appendix 2). It was found that in sections through the central parts of these crystals both zones were present. When the paler inner zone was missing, the cut had been made through the outer part of the crystal (Pl. xviii, Figs. 2, 3 and 4).

The olivine phenocrysts are less numerous than the augites and have sometimes been completely altered to serpentinous pseudomorphs. Many are euhedral, but some have/

have corroded outlines. The optical properties of the unaltered olivines, and hence their composition, are identical or nearly so with those of the olivine phenocrysts in Dunsapie basalt, but they are less frequently altered than are those in the Dunsapie rock. Many are euhedral, but some show corroded margins, and others irregular edges. Some of the irregular edges may result from fracturing of the crystal prior to consolidation of the basalt, followed by relative displacement of the two or more portions of the original crystal. In one section of rock from the Whinny Hill Intrusion, an olivine crystal may be seen to have broken into two parts, which had time to separate only a short distance before solidification of the basalt prevented further movement (Pl. XIX, Fig. 4). This process is the same as that which has affected phenocrysts of the Lion's Haunch basalt (p. 67).

Large feldspar crystals which range from bytownite to labradorite in composition occur sparsely in all Craiglockhart basalts. These are invariably corroded, usually to a considerable extent. The more strongly corroded crystals show embayments and rounded corners (Pl. XVII, Figs. 3 and 4). A zone of late growth which varies in width is always present, and usually contains inclusions. The large plagioclase crystals frequently form portions of gabbroic/

gabbroic "xenoliths", and, like the augites, have come into contact with liquid with which they were not in equilibrium. Unlike the augites, they do not usually present a honeycombed appearance.

In one section from the Whinny Hill Intrusion, a large plagioclase crystal over 5 mm in length has a strikingly corroded outline (Pl. XIX, Fig. 1). It encloses other smaller plagioclase crystals as well as crystals of unaltered olivine and augite up to 1 mm in length, so that the aggregate of crystals forms a gabbroic "xenolith". Corrosion has occurred between the margins of the crystals forming the "xenolith"; this is best seen around the boundaries of the large plagioclase. A group of the crystals included by the big feldspar have had their edges corroded so far that they are almost completely separated from the oikocryst. Had complete separation been effected, a prominent embayment in the side of the plagioclase would have resulted. It is possible that some embayments in the sides of other plagioclase crystals may have originated in this manner.

When large corroded crystals are zoned, embayments are easily explained, for magma entering the more calcic interior through a crack may readily corrode a hollow therein. However, many embayed crystals, particularly/

ularly in Dunsapie and Markle basalts, are of fairly homogeneous composition, and sometimes they possess reasonably sharp corners. It is difficult to explain by magmatic corrosion alone why embayments should occur in comparatively straight sides when corners are not particularly rounded, and the embayments do not extend into more calcic material. However, if such crystals once formed portions of glomeroporphyritic aggregates which had broken up, retention of sharp corners is readily explained.

The groundmass of Craiglockhart basalts resembles closely that of rocks of Dunsapie type. The essential minerals are labradorite and augite; olivine and iron ore, mostly magnetite, occur in less amount. Also present are apatite, chlorite, sometimes analcite, and occasionally zeolites.

A. Extrusive basalts of Craiglockhart Type.

(i) Lava II of the Whinny Hill Series.

The augite phenocrysts of Lava II usually show well-defined interior portions, with a wide honeycombed outer zone. Both the phenocrysts and the augite

of/

of the groundmass are sometimes chloritised. No unaltered olivine has been observed in this flow; the olivine pseudomorphs, frequently euhedral, are usually composed of bowlingite, chrysotile, and other serpentinous minerals. In one section some of the pseudomorphs are composed of a green pleochroic mineral with pronounced amphibole cleavage. Near the chapel the serpentinous minerals are themselves partially replaced by calcite and a little silica.

The augite of the groundmass occurs as small stumpy prisms, sometimes enclosed within the feldspar crystals. Chlorite and some cloudy analcite occur interstitially, and in druses.

(ii) Lava IIA of the Whinny Hill Series.

Lava IIA, which outcrops only to the north of Pulpit Rock, is very similar to Lava II, but has certain distinctive petrographic features. The olivine phenocrysts of this flow are frequently almost entirely unaltered, in contrast with those of the lower effusion. $2V$ is $90^\circ \pm 2^\circ$ hence the composition of this mineral is approximately $F086$.

Large plagioclase crystals occur sporadically but with greater frequency than in any other Craiglockhart basalt/

basalt and are present both in the outcrop beneath St. Anthony's Chapel, and in the cliff above the ruins. The cores of these crystals average An₇₀₋₈₀ in composition, the outer zone being about An₆₀, the same composition as the groundmass crystals.

Analcite is more plentiful than in Lava II, and occurs usually in amygdales. Almost opaque carbonate material and chlorite also occur as cavity fillings, and zeolites, including thomsonite, are also present.

In one section from this flow (below St. Anthony's Chapel) a small anhedral crystal of plum-coloured pleochroic titan-augite is present. This occurs in association with crystals of magnetite, carbonate and chlorite, forming a composite inclusion within the serpentinous alteration material of a partially serpentinised olivine phenocryst. No other titan-augite approaching the depth of colour or the degree of pleochroism of this crystal has been observed elsewhere in the Arthur's Seat rocks. This particular crystal probably formed as a result of alteration of the olivine.

B. Intrusive basalts of Craiglockhart type.

(i) Dyke in Lion's Head vent.

The rock of this dyke was previously mapped/

mapped as Dunsapie type. Most of the abundant augite and olivine phenocrysts have been altered to carbonate, with a certain amount of quartz. These alteration minerals give the pseudomorphs a leucocratic appearance, and hence the rock in hand specimen resembles Dunsapie basalt.

(ii) Pulpit Rock.

The phenocrysts of this basalt are smaller and more sporadic than those of Lava IIA; in other respects the two rocks resemble each other closely. Many of the olivines are practically unaltered, and are slightly more ferriferous (Fo75) than are those of Lava IIA (Fo86). Thomsonite is present in small amount in several sections. The petrographic similarity of Pulpit Rock to Lava IIA supports the hypothesis (mentioned earlier, p. 28) that the intrusion and the flow were once connected.

(iii) The Whinny Hill Intrusion.

The Whinny Hill Intrusion may be distinguished from other Craiglockhart basalts by the greater numbers of its phenocrysts, and by the fact that they are homogeneously distributed throughout the rock except near its margins. The large augite crystals usually display a wide zone of evenly distributed inclusions, which are larger than those in the augites of other Craiglockhart basalts. Most of the groundmass augite is in the form of small/

small subhedral and euhedral crystals, but some is slightly sub-ophitic in its relation to the feldspar laths.

Many of the large olivine phenocrysts are almost entirely unaltered. Pseudomorphs, mainly of serpentinous minerals, are more common in the vicinity of the margins of the intrusion. Small olivines occur in the groundmass, and, like the phenocrysts, are frequently unaltered. Occasionally picotite is present in some of the larger pseudomorphs.

Plagioclase is slightly more plentiful than in other Craiglockhart basalts. Large crystals of macroporphyritic dimensions occur very sporadically, but many of the "groundmass" laths approach the dimensions of microphenocrysts. Zoning is inconspicuous, and the average composition is slightly more calcic than that of Lavas II, IIA and Pulpit Rock, being approximately An₆₅. Analcite is not conspicuous, but in some slides cloudy analcite is present in amygdales. A zeolite occurs in one section filling a cavity within an augite phenocryst.

Xenoliths of what is probably highly altered sandstone are encountered occasionally. These are reminiscent of the altered quartz grains of the Long Row (p. 64), but are much larger and less regular, and none contain any quartz relics. They are composed mainly of pyroxene, which often forms in section long slender branches, disposed/

disposed in a rather irregular arcuate pattern, against a background of plagioclase, chlorite and cloudy analcite.

Basalts of Markle Type.

Extrusions.

Lavas VII, VIII, IX and XIII of the Whinny Hill Series.

Intrusions.

Dyke in Haunch vent.
Dasses "sills".

The Markle basalts of Arthur's Seat occur mainly as lavas; the Dasses "sills" and a small dyke in the Lion's Haunch vent are the only intrusives of this type of basalt. The rocks are characterised by abundant large phenocrysts of plagioclase, and less numerous olivines. The rocks have all been more or less intensely altered, and the albitised plagioclase phenocrysts appear conspicuously white against the grey or brown background of the groundmass. This appearance accounts for the name "porphyrite" given them by early writers.

The plagioclase phenocrysts of all Markle basalts are large, some exceeding 10 mm by 5 mm, the average length being about 3 mm. They are generally subhedral, and some are euhedral. Evidence of corrosion is lacking, except for the occurrence of occasional embayments in the sides of crystals. However, these embayed crystals have sharp corners, and the embayments may result from the breaking up during eruption of glomeroporphyritic aggregates.

of/

of crystals which have developed subhedral form as a result of their proximity (see p. 84). Aggregates of porphyritic crystals of plagioclase with olivine, and occasionally with augite, occur sporadically throughout the Markle basalts.

Twinning is less complex than in the plagioclase phenocrysts of Dunsapie basalt. Some phenocrysts are completely untwinned, and many others are twinned on the Carlsbad law. When albite twinning is present, the lamellae are rarely numerous.

Almost all the plagioclase phenocrysts have been albitised to a greater or less degree. The alteration of these crystals has been described in detail by Bailey and Grabham (1909). Generally the altered sodic plagioclase has a cloudy appearance, in contrast with the clear unaltered areas of the phenocrysts.

Several Carlsbad-Albite twins with only minor areas of albitisation have allowed determination of the composition of the original plagioclase to be made with a reasonable degree of accuracy. The unaltered parts of these crystals have a composition near An_{65} , and are not zoned. A more extensively albitised phenocryst was found to be slightly more calcic, An_{68} . This was the most calcic crystal determined with any degree of precision; however, /

however, the unaltered portions of an extensively albitised crystal in a section from Lava VII were found to be optically negative, with $2V$ of about 86° . The original composition of this crystal was probably of the order of An_{75} . The same slice also contains only slightly albitised phenocrysts with a composition about An_{65} , and the groundmass feldspar, still less calcic, was scarcely albitised at all. This supports the view of Bailey and Grabham (1909, p. 251), that susceptibility of plagioclase to albitisation in general increases with increase of the anorthite percentage. This factor seems from the present study to apply particularly where the total amount of albitisation was slight. However in most sections, alteration has been considerable, and ratio of surface area to total volume of crystal has also been an effective factor. In such cases, all the groundmass feldspar has been albitised, and the only remaining labradorite is to be found well within the larger phenocrysts. The albitised feldspar usually has the composition of albite-oligoclase.

The cloudy appearance of the albitised plagioclase is caused by the presence of numerous tiny inclusions. Bailey and Grabham (1909, p. 254) noted the presence of minute flakes of sericite scattered through the altered crystals/

crystals. A dusting of iron ore particles may also be discerned. Carbonate, chlorite and analcite are other alteration products present in the albitised feldspars.

The soda responsible for the alteration was considered by Bailey and Grabham to be juvenile. These writers likened conditions during albitisation to the lava "stewing in a concentrated solution of sodium carbonate".

No unaltered olivine has been found in any of the Markle basalts of Arthur's Seat, but many pseudomorphs of macroporphyrific dimensions occur. These are usually subhedral, sometimes corroded. Alteration products are iron ore (mainly haematite), chlorite, analcite, carbonate and occasionally iddingsite. Iron ores are more abundant in olivine pseudomorphs from more highly altered rocks. Augite phenocrysts occur sporadically in some of the lavas. These are often entirely unaltered, but sometimes have been partially replaced by calcite, and occasionally have been completely altered to chlorite, iron ore and carbonate.

The groundmass consists of small crystals of plagioclase, usually albitised and often showing good flow structure, accompanied by alteration products of original augite/

TABLE VI.

Mode of Markle Basalt.

The modal analysis is made from a section cut from a specimen from the Whinny Hill Markle lavas* (Chemical analysis included in Table VII). As a result of the deuteric alteration which has affected this rock, it has not been possible to differentiate between the ferromagnesian pseudomorphs of the groundmass.

Plagioclase phenocrysts	24.6
Augite phenocrysts	0.5
Large ferromagnesian pseudomorphs. (mostly after olivine)	2.4
Plagioclase in groundmass.	37.5
Other minerals in groundmass	32.5

* The precise locality of the analysed specimen (collected by the late Mr. A. G. Stenhouse) is not known. It is labelled "Markle Basalt, Whinny Hill", and its petrographic characters show that it belongs to Lava VII, VIII or IX.

augite, small olivine pseudomorphs and iron ore, mostly haematite. The augite has usually been replaced by nearly opaque carbonate, although sometimes unaltered grains may be observed. Apatite is present in slightly greater amount than in Dunsapie and Craiglockhart basalts, and occasional crystals of epidote occur. Probably the epidote and some of the apatite were formed during the deuteric alteration of the rock, as a result of release of lime from the albitised plagioclase.

A. Extrusive Basalts of Markle Type.

(i) Lavas VII, VIII and IX of the Whinny Hill Series.

Although all the Markle lavas of the Whinny Hill are very similar petrographically, the individual flows are not homogeneous. The degree of alteration has varied within each lava, and the distribution of feldspar phenocrysts is sometimes irregular. Exposures of all flows except those of Lava VII are insufficient for any regular variation to be traced, and even those of Lava VII are barely satisfactory.

There appear to be in general rather fewer feldspar phenocrysts near the base of Lava VII - probably because these light crystals have tended to rise in the flow. Patches of relatively unaltered rock have been found in outcrops/

outcrops not far from the vent margin; generally more olivine pseudomorphs occur in these localities, and even phenocrysts of augite may appear. In one of the most southerly outcrops of Lava VII phenocrysts of augite are fairly common, and the olivine pseudomorphs are more numerous than usual. The feldspar of this outcrop is only slightly albitised, and the rock locally resembles a Dunsapie type. However, this is exceptional, and the paucity of augite phenocrysts present in the lavas over most of their outcrops make it clear that the group of flows as a whole consists of Markle basalt.

(ii) The Markle Flows of the Duddingston Series.

At least two lavas outcrop in the ash above Duddingston Loch. The lower flow is highly altered; the large plagioclase phenocrysts have been completely albitised, and the groundmass plagioclase shows the ragged outlines typical of the Arthur's Seat mugearites (believed by the writer to be intensely albitised rocks cf. p.103). More epidote is present in this rock than in the other Markle basalts. Were the phenocrysts not so numerous, this flow would be better classed as mugearite.

The higher lava is not nearly as intensely altered as its predecessor, and resembles closely parts of Lava VII of the Whinny Hill. The large plagioclase crystals still retain much unaltered labradorite and unaltered augite/

augite phenocrysts also occur sporadically.

(iii) Lava XIII of the Whinny Hill Series.

This flow, the highest effusion from the crater of the Arthur's Seat volcano, is characterised by a very fine-grained groundmass, much finer than that of any other Markle lava. Albitisation has been very intense, and the plagioclase phenocrysts have no unaltered patches of labradorite like those retained by the feldspars of Lavas VII, VIII and IX. Small crystals of water clear albite occur in vesicles in this rock; these were noted by Bailey and Grabham (1909, p. 253) and show that a surplus of material, from which albite could crystallise, remained after albitisation of the original plagioclase had proceeded to completion. Similar small clear albite crystals occur in association with chlorite and carbonate in olivine pseudomorphs.

The groundmass of Lava XIII is so intensely altered that many of the small plagioclase crystals like those of the Lower Duddingston lava, have the ragged outlines characteristic of the mugearites of Arthur's Seat. Many large amygdales of carbonate and chlorite are prominent, and are often connected by veins of the same minerals.

B. Intrusive/

B. Intrusive basalts of Markle type.

(i) Dyke in the Lion's Haunch vent.

The small dyke of Markle basalt which cuts the agglomerate high in the western portion of the Haunch vent has relatively non-porphyrific margins and a highly porphyritic centre. The abundant large plagioclase phenocrysts of the central portion have been partially albitised, and resemble those of Lava VII. The olivines have been completely pseudomorphed. Occasional unaltered or partly altered phenocrysts of augite are present. The groundmass is extremely fine-grained, and contains numerous partly albitised plagioclase crystals approaching microporphyrific size, as well as very tiny feldspar laths and chloritic alteration products of earlier ferromagnesian minerals. Iron ore is plentiful.

The marginal rock of the dyke is slightly finer-grained, and contains considerably fewer phenocrysts. Presumably the large crystals lagged behind the front of intruding liquid, as has been postulated for other macroporphyrific rocks of Arthur's Seat (see p. 34).

(ii) The Dasse's Sills.

The rock of the Dasse's sills has been described in detail by Rutledge (1952, p.380). It contains numerous/

tains numerous phenocrysts of plagioclase, although these are generally rather fewer and smaller than in the rest of the Markle basalts. An additional point of difference is that albitisation has generally been only slight in the Dasses basalt, alteration to analcite and carbonate being more usual. However, although there are differences between this rock and that of the Whinny Hill Markle basalts, the large numbers of plagioclase phenocrysts justify Rutledge's classification of it as a basalt allied to the Markle group.

Basalts of Dalmeny Type.

Extrusions.

Lava III

Intrusions.

Lion's Head.

The Arthur's Seat Dalmeny basalts contain microphenocrysts of olivine set in a groundmass consisting mainly of plagioclase, augite, small olivines and iron ore. The microphenocrysts average about 1 mm in length, and are usually subhedral. The olivine is sometimes unaltered, but has usually been replaced by bowlingite, antigorite, iron ore and other alteration products. 2V of the unaltered olivine is (+) 88° , indicating a composition of Fo81.

The groundmass plagioclase crystals are very numerous/

numerous and closely packed, and show strongly developed flow structure. They are not noticeably zoned, and have compositions ranging from An₅₀ to An₆₀.

Augite varies both in its textural relations with plagioclase and in its composition. Sometimes it occurs as ophitic plates, and sometimes as small euhedral crystals. These textural differences are highly significant, and have been discussed fully in a separate section (see pp. 108-122).

The iron ore is mostly magnetite, probably titaniferous, which occurs as small subhedral grains. Needles of apatite are numerous. Analcite, usually cloudy, occurs interstitially and has often been replaced by chlorite, sometimes accompanied by calcite. Analcite, chlorite and calcite are also present as amygdales and crevice fillings.

Extrusive and Intrusive Dalmeny basalts.

Lava III and the Lion's Head Intrusion are the only Dalmeny basalts of Arthur's Seat. The petrography of these features has been described in the section already referred to (pp. III - III6).

Basalts of Jedburgh Type.

Extrusions.

Lavas IV, V and VI of the
Whinny Hill Series.
Lava in south side of Haunch
vent (exposed in Queen's Drive).

Intrusions.

Raven's Rock Dykes.

The Jedburgh basalts of Arthur's Seat resemble those of Dalmeny type, but are of coarser grain. Chemically there is little difference between the two types (see analyses, p. 120), although the Jedburgh rocks are on an average very slightly richer in the components of feldspar. However, the numerous plagioclase crystals of microporphyrific dimensions which occur in the rocks here referred to the Jedburgh type leave the correctness of their classification in no doubt. Jedburgh basalts from localities other than Arthur's Seat are usually more feldspathic, and are generally regarded as being the microporphyrific equivalents of Markle basalts (MacGregor, 1928, p. 356, and Tomkeieff, 1937, p. 66).

Basalts of Jedburgh type from Arthur's Seat were described and one was figured by Flett (1910, p. 321, and Plate XI), but these rocks were not recorded on the 6 inch Geological Survey Map of the Hill. One of the localities described by Flett is undoubtedly an exposure of one of the Whinny Hill flows, Lavas IV, V or VI. The section figured in Plate XI of the Edinburgh Memoir is probably from the ophitic portion of Lava VI, near the north end of the Whinny Hill.

Flett also recorded Jedburgh basalt from the central part of the Long Row, and from the quarry at Scone Gardens/

Gardens, Parson's Green. The present writer has examined many sections from the Long Row without discovering any basalt other than the sparsely porphyritic Dunsapie type already described (p. 61). However, so sparse are the large phenocrysts of Lava I that some sections examined by Flett may have contained none whatsoever, and the groundmass alone is indistinguishable from the Jedburgh type. The Scone Gardens occurrence is more puzzling. This area is now built upon, and the quarry no longer exists. The locality is one of mugearite, Lava XI of the Whinny Hill Series (Lava XVII on the 1910 map). The present writer believes that the Arthur's Seat mugearites are intensely altered Jedburgh or Dalmeny basalt, and the section studied by Flett may have been collected from a less altered portion of the mugearite flow.

The plagioclase of the Jedburgh rocks is slightly more noticeably zoned than that of Dalmeny basalt, but the average composition of An₅₀₋₆₀ is about the same. The microphenocrysts have substantially the same composition as the smaller crystals. Olivine occurs as fairly small phenocrysts, and as small crystals in the groundmass. Usually the larger olivines are almost completely unaltered, with 2V about 90°. Augite occurs in ophitic plates, and also as small subhedral and euhedral prisms; as with the Dalmeny/

Dalmeny basalts, the significance of the textural differences is discussed elsewhere (p.117). Iron ore, apatite, analcite, chlorite and calcite are present as accessories.

A. Extrusive basalts of Jedburgh type.

(i) Lavas IV, V and VI of the Whinny Hill Series.

The petrographic characters of these flows are described in a separate section (p.116), but one detail of considerable significance remains to be discussed here. Over the majority of outcrops, the rocks show very little evidence of deuteric alteration, and olivine is the only mineral to have been affected. However, in specimens from several localities at high levels within the flows, albitisation of the plagioclase has occurred, and much of the original labradorite has been altered to oligoclase. The augite has usually not been affected, but in some sections from near the top of Lava VI all ferromagnesian minerals have been altered, and the rock in these localities has the petrographic characters of a mugearite.

(ii) Lava in the south side of the Lion's Haunch vent (Queen's Drive).

This flow, which was extruded within the crater of the Haunch vent, outcrops above and below the Queen's Drive, and is the first lava exposed in the section along the Drive east of the Samson's Ribs lavas. It is a partially/

partially altered Jedburgh basalt; much of the plagioclase has been albitised, but the augite, which occurs as large ophitic crystals is unaltered. The rock is petrographically very similar to that of some sections from the upper parts of Lava IV; differences are that the vent lava contains a higher proportion of small olivine pseudomorphs, and occasional very large plagioclase crystals with extremely corroded outlines.

B. Intrusive basalts of Jedburgh Type.

(i) The Raven's Rock Dykes.

The groundmass of the rock of these dykes is finer-grained than that of the other Jedburgh basalts. The microporphyritic crystals of plagioclase have sometimes been albitised, but are frequently unaltered. The original augite and olivine of the rock have been replaced by carbonate and chlorite. Amygdales of chlorite and carbonate are numerous; and sometimes near the margins of the intrusion the rock is brecciated, as has been described on p. 51. During the shattering, fragments of the basalt have been moved only slightly, and when seen in thin section have the appearance of pieces of an assembled jig-saw puzzle (PlateXX, Fig. 3).

Mugearite/

MugeariteExtrusions.

Lavas X, XI and XII of the
Whinny Hill Series.
Lava east of Dunsapie Hill.
Lava exposed in south side of
Haunch vent (Queen's Drive).

Intrusions.

Marginal facies of St.
Leonard's Craigs.

It must be emphasised that none of the rocks of Arthur's Seat which are classed here as mugearites are unaltered rocks. Had it not been for the profound effects of deuteritic constituents during the late cooling histories of the rocks, they would probably have cooled as Dalmeny or Jedburgh basalts.

Flett and Dinham (1927, p. 473) commented on some rocks near Stirling described by Tyrrell and Martin (1908) as mugearites, and pointed out that these rocks were albitised, and some were "perhaps to be regarded as albitised rocks of Jedburgh type". MacGregor (1928, p. 348) also stated that "rocks similar to mugearites in many respects are produced by the more or less complete albitisation of some fine-textured basalts".

The albitisation of feldspar in the Arthur's Seat mugearites was noted by Flett (1921, p. 26) who nevertheless continued to refer to them as mugearite. As the rocks have the petrographic characters of mugearite, it seems preferable to name them as such rather than to use/

use some genetical term such as "albitised Jedburgh basalt".

Petrographically the Arthur's Seat mugearites consist of abundant small cloudy crystals of oligoclase, up to about 0.5 mm in length, usually showing good flow structure which consists of a planar arrangement of the platy feldspars. This fabric frequently produces a platy jointing in the rock, present also in some outcrops of Jedburgh basalt. The oligoclase is accompanied by iron ore, chlorite and carbonate, some of these having been produced by alteration of original ferromagnesian minerals. Small olivine pseudomorphs sometimes contain iddingsite. Flett (1921, p. 26) has also recorded augite, hornblende and biotite from the Arthur's Seat mugearites, but none of these minerals has been found in the course of the present study. The ferromagnesian minerals have been so highly altered that little of their original characters can now be distinguished.

Phenocrysts of plagioclase up to 2 mm in length are present in a number of the rocks, and are particularly numerous in the lava east of Dunsapie Hill. These are oligoclase or albite-oligoclase in composition and, like many of the groundmass crystals, have a cloudy appearance caused by numerous inclusions, mainly of sericite and iron ore. Thus the plagioclase is identical with that of highly/

highly albitised Markle basalt, and the mugearites have apparently been subjected to the same type of deuteric alteration, only to a more intense degree than is usual in the Markle rocks. The outlines of the small plagioclase crystals in the mugearites commonly have a ragged appearance, a characteristic also of the groundmass feldspars of the highly altered lower Markle lava of the Duddingston Series. This appearance may be due to growth of sodic plagioclase on the original crystals after their alteration had been completed in the deuteric stage.

A notable feature of the mugearites is the relatively large amount of apatite present. The crystals of this mineral are often larger in the mugearites than in other Arthur's Seat rocks. Probably much of its growth took place during the deuteric stage, assisted by lime released from the plagioclase. Relative abundance of apatite has been noted by Tyrrell in mugearites from the Kilpatrick Hills (1913, p. 239) and Little Cumbrae (1917, p. 264).

A. Extrusive mugearites.

(i) Lavas X, XI and XII of the Whinny Hill Series.

These lavas possess extremely well developed flow structure/

structure, and even in hand specimen show the platy jointing referred to above (p. 104). The upper part of Lava X differs in texture from the rest of the flow, which is comparable in granularity with a Jedburgh basalt. The upper part has small phenocrysts of plagioclase, up to about 0.5 mm in length, small olivine pseudomorphs and numerous amygdaloids of iron ore, chlorite and carbonate, all set in a minutely fine-grained groundmass. This texture suggests that the upper part of this lava had cooled with great rapidity.

Several sections from the outcrop of Lava XI behind the engine shed at St. Margaret's locomotive depot have alternating fine and coarse grained layers. The granularities of the bands are comparable with those of Dalmeny and Jedburgh basalts respectively.

(ii) Lava east of Dunsapie Hill.

This rock is perhaps to be regarded as transitional between the Whinny Hill mugearites and Markle basalt, as it contains a number of albitised plagioclase phenocrysts, some over 3 mm in length. These are not nearly as numerous as in Markle basalt, and the mugearite is much more highly altered than any Markle rock, except perhaps the lower Duddingston lava.

(iii) Lava in south side of Lion's Haunch vent (Queen's Drive).

The/

The rock of this lava differs from the other mugearite extrusions of Arthur's Seat in that it does not show good flow structure. It contains a number of plagioclase phenocrysts, all completely albitised, and ranging up to 1.5 mm in length, and several large ferromagnesian pseudomorphs have also been observed. Probably this rock, like the Dunsapie Hill mugearite, should be regarded as transitional between mugearite and Markle basalt.

B. Intrusive mugearites.

(i) St. Leonard's Craigs (marginal facies).

The rock of the marginal facies of St. Leonard's Sill, described by MacGregor (1936, p. 324) is essentially a mugearite. It is a sparsely porphyritic rock, with occasional phenocrysts and abundant small crystals of altered plagioclase, containing numerous very minute inclusions which give the feldspar a yellowish colour. All original ferromagnesian minerals have been altered to chlorite and carbonate.

The Significance of Flow Structure in the Microporphyrific Ophitic Basalts of Arthur's Seat

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(With Plate II)

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ABSTRACT

Arthur's Seat is the well-dissected remains of a volcano which erupted a series of basalts representative of the Scottish Carboniferous province to which it belongs. Some of the microporphyrific basalts of Arthur's Seat are characterised by ophitic augite which crystallised after flow had ceased. Others have non-ophitic pyroxene, much of which crystallised comparatively early in the course of solidification of the rock. The stage of crystallisation of pyroxene in the cooling history is related to the composition of the basalt: where the proportion of pyroxene to feldspar is low, the crystallisation of augite is late. Chemical analyses of the various rocks have been considered in relation to the quaternary system albite-anorthite-diopside-hypersthene (Barth). All the microporphyrific rocks of Arthur's Seat lie well within the plagioclase field, but those with ophitic augite lie farthest from the boundary between the plagioclase and pyroxene fields.

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I. INTRODUCTION

THE deeply eroded volcanic pile of Arthur's Seat, situated within the boundaries of the City of Edinburgh, affords many excellent exposures of lavas, ashes and intrusions. Most of the familiar Lower Carboniferous basaltic types of the South of Scotland are well represented. The volcano consists mainly of two contiguous

vents—the older Lion's Head and the younger Lion's Haunch—flanked on the south by ashes and a few lava flows, and on the north by a pile of lavas and ashes which form the Whinny Hill (Fig. 1). The volcanics north of the vents will be referred to as the Whinny Hill series, the successive lava flows being distinguished by numbers reckoned from the base upwards. This paper is concerned particularly with Lavas III, IV, V and VI, together with certain associated rocks, including the Lion's Head intrusion, all of which show interesting and significant variations in the textural relationships of their pyroxenes.

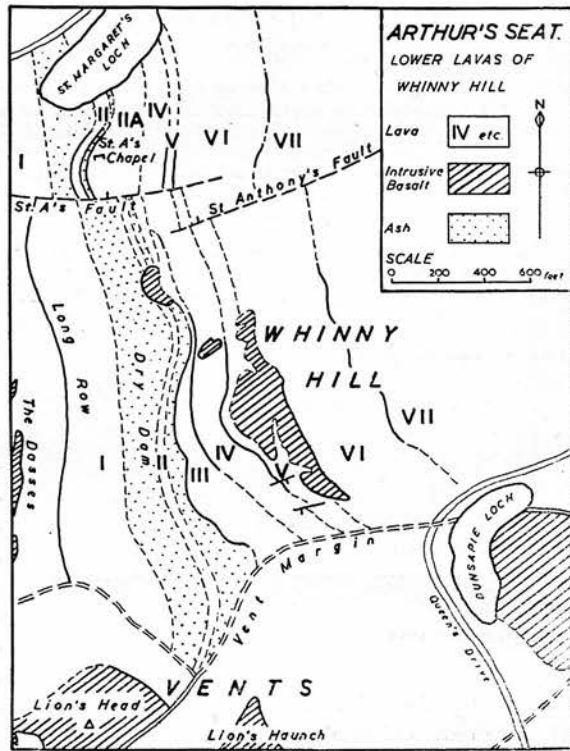


FIG. 1. Geological map of part of Arthur's Seat, Edinburgh.

Much has been written on the geology of Arthur's Seat, especially during the nineteenth century, including Maclaren's first systematic description (1839). The most recent complete account is that given by Peach in the Edinburgh Memoir (second edition, 1910, pp. 57-72). Most of this section of the Memoir was reprinted separately in 1911 (with a second edition in 1921)

as a guide to the geology of Arthur's Seat. The later edition contains a short petrological appendix by Flett, who had already contributed detailed petrographic descriptions of most of the Arthur's Seat rocks to the original Memoir (pp. 316-323).

The late Mr. T. Cuthert Day, one of Edinburgh's many amateur geologists, stimulated a wider interest in the Hill by the publication in 1933 of his book entitled "Arthur's Seat, A Ruined Volcano". Mr. Day analysed a number of rocks collected from Arthur's Seat by the late Mr. A. G. Stenhouse, another prominent local amateur. Dr. Robert Campbell was the friend and colleague of these well-known workers, and Day's analyses were eventually left in his care for publication at some appropriate time. By the generosity of Dr. Campbell these analyses have been made available to the writer; three of them are now recorded on p. 80 of this paper and the others will appear in a contribution now in preparation.

II. TERMINOLOGY

Krokström (1933, pp. 198-199) has discussed the confusion that has existed with respect to the meaning of the terms "ophitic" and "sub-ophitic". He proposed the following definitions:

In both ophitic and sub-ophitic texture, "the pyroxene shows over large areas a uniform orientation.

"Ophitic texture: The plagioclase laths are entirely enclosed within the large pyroxene areas.

"Sub-ophitic texture: The pyroxene is subordinate in amount and forms a filling in the small interstices between the feldspars."

The present writer cannot accept Krokström's definition of sub-ophitic texture, for, as will be shown later (p. 77), sub-ophitic rocks in which enclosure of feldspar by pyroxene is not complete actually contain pyroxene in greater quantity than rocks in which the texture is fully ophitic. Hence it has been found desirable to re-define the terms in the sense in which they are used in this paper:

Ophitic texture: Pyroxene appears in thin section as optically continuous areas which *completely* enclose a number of plagioclase laths. The average length of the plagioclase throughout the rock is not greater than the average length of the pyroxene areas.

Sub-ophitic texture: Pyroxene appears in thin section as optically continuous areas which only *partly* enclose a number of plagioclase laths. The average length of the plagioclase is greater than the average length of the pyroxene areas.

It should be emphasized that the terms "areas" and "laths" are used only to describe the usual appearance in thin section of

the individual crystals of augite and plagioclase respectively. The term "plate" is occasionally used hereafter for broad sections through ophitic areas of augite or tabular crystals of plagioclase.

Krokström also defined doleritic and sub-doleritic textures as those in which the pyroxene occurs as subhedral and anhedral crystals respectively. These terms are not used in this paper, for dolerite, as defined by the Committee on Petrological Nomenclature (1922, p. 139), is essentially a relatively coarse-grained rock of basaltic composition. Thus it is undesirable to use doleritic as a textural term to imply anything other than coarseness of grain (MacGregor, 1928, p. 330).

The basalts referred to in the following pages are Dalmeny, Jedburgh and Craiglockhart Types. The classification of the Scottish Carboniferous olivine-basalts was revised by MacGregor in a paper (1928) to which the reader may refer for full descriptions of the types (see also Tomkeieff, 1937, p. 66). Each of the types mentioned above is characterised by a groundmass of labradorite, augite, olivine, iron ore (more or less titaniferous) and accessory minerals, the distinctive features being:

Dalmeny Type: numerous microporphyritic crystals of olivine.

Jedburgh Type: numerous microporphyritic crystals of plagioclase accompanied by a few of olivine.

Craiglockhart Type: numerous macroporphyritic crystals of augite and olivine.

III. BASALTS OF DALMENY TYPE

Dalmeny basalts are represented by Flow III of the Whinny Hill Series and by the Lion's Head intrusion.

Lava III is about 50 feet in thickness and forms a prominent outcrop along the crest of the east wall of the Dry Dam, extending from the vents northwards to St. Anthony's Fault. On the 6-inch Geological Survey Map, this flow is incorrectly correlated with the lava at St. Anthony's Chapel and marked as being of Craiglockhart type.

The rock is a fine-grained microporphyritic basalt. Small phenocrysts of olivine, usually pseudomorphed by bowlingite, antigorite, iron ore and other alteration products are fairly numerous. Sometimes, however, the olivine is unaltered and 2V has been determined with the Universal Stage to be $(+) 88^{\circ} \pm 2^{\circ}$, indicating that the composition is that of a magnesian chrysolite (Fo_{81}). The groundmass consists of abundant plagioclase, less abundant augite, some small olivine crystals, opaque iron ore, analcite, apatite, chlorite and calcite.

The plagioclase crystals are fairly closely packed, and their lath-shaped sections show a strongly developed preferred orientation. The laths vary in length up to a maximum of about

0.5 mm but most are less than 0.2 mm. Zoning of the feldspars is not particularly marked, the composition ranging between An_{50} and An_{60} .

The iron ore is mostly magnetite, probably titaniferous, which occurs as small subhedral grains. Apatite is conspicuous in the form of fine elongated needles. Analcite, usually cloudy, occurs as interstitial material, and in many sections it has been replaced by chlorite, sometimes accompanied by calcite. Analcite, chlorite and calcite are also present in amygdales and as crevice-fillings.



FIG. 2. Olivine-basalt of Dalmeny Type (Lava III, Arthur's Seat) with granular augite. Small euhedral and subhedral augite crystals are partly and wholly enclosed within a crystal of feldspar. Ordinary light $\times 180$.

Pyroxene, mainly common augite, is comparatively plentiful and its mode of occurrence varies both laterally and vertically within the flow. Near the vents, augite occurs in small granules, some of which have slight sub-ophitic relationship to the feldspar. This enwrapping tendency is not marked, however, and many of the grains are euhedral. Some appear to have interfered with the growth of adjacent plagioclase crystals which frequently partly or wholly enclose the augite prisms (Fig. 2). The pyroxene occurs in this manner throughout the length of the upper part of the exposure of the flow. However, a progressive change is noticeable in the lower part as the flow is traced northwards from the vents. The average size of the augites becomes greater and concomitantly abundance of subhedral and euhedral crystals decreases. The texture becomes

increasingly sub-ophitic until, about 300 feet north of the vent-margin, some plates of augite can be seen to enclose the smaller plagioclase laths completely. Still farther north, the augite plates become fewer and larger; the texture is now definitely ophitic. 800 feet north of the vents the pyroxene plates attain a maximum length of 2 mm. In addition to plagioclase, small olivine pseudomorphs, iron ore and apatite needles are also enclosed in the ophitic plates.

It has already been remarked that the plagioclase laths in this flow show strong preferred orientation. Fabric analysis by the method described by Clark and McIntyre (1951) has proved that this is the trace of a planar fabric. The tabular crystals of plagioclase are arranged in flow-planes with (010) roughly parallel to the base of the flow. Most of the plagioclase laths within the optically continuous augite areas maintain parallelism with those not enclosed; in other words, the flow planes pass undeviatingly through the augite crystals (Pl. II, Fig. 1). This shows that most of the pyroxene crystallised after flow had ceased.

Continuation of flow-structure through the augite of ophitic patches has already been noted by Krokström (1933, p. 202) in basalts from Greenland. He concludes, "it can hardly be doubted that by far the greater part of the feldspar crystallised distinctly in advance of the pyroxene".

Additional evidence in support of the late crystallisation of the ophitic augite in Lava III is afforded by the disposition of the plagioclase laths around olivine phenocrysts. The feldspars in their flow-planes swirl around each obstructing olivine, so that in thin section the laths appear tangential to the phenocryst. Here again many of the swirling plagioclase laths are enclosed in augite plates, which make no difference to their arrangement relative to olivine (Pl. II, Fig. 2).

Throughout the ophitic portion of Lava III, the plagioclase laths enclosed within augite are of all sizes, and some of those that are fully enclosed are as large as any occurring in areas completely free from pyroxene. Where crystals are only partly enclosed, the protruding portion is generally no wider than the part inside the augite.

A slight colour-difference exists between the granular augite in the non-ophitic portion and the optically continuous areas of augite in the ophitic part of the lava. Both are pleochroic; in the granules X and Y are brown, and Z yellowish brown. The ophitic areas are distinctly purplish in the X and Y directions, although Z is still yellowish brown. Probably the ophitic augite is more titaniferous than the granular and euhedral crystals. $2V$ of the ophitic augite is $58^\circ \pm 3^\circ$, and $Z \wedge c$ is 40° .

The basalt of the Lion's Head intrusion is also of Dalmeny type. Petrographically it is almost identical with the parts of



FIG. 1.

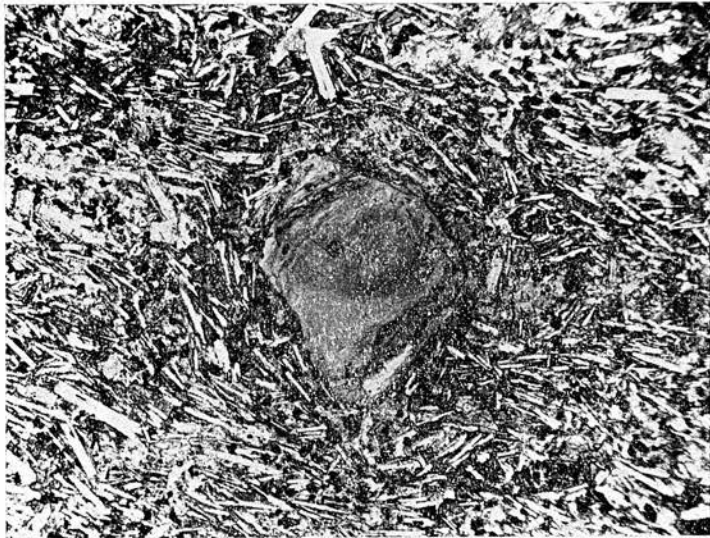


FIG. 2.

Flow structure in olivine-basalt, Arthur's Seat.

Lava III which contain granular pyroxene, although sub-ophitic texture is perhaps a little more developed in the intrusion than in this part of the flow. It is probable that Lava III was the final flow emitted from this vent. This inference is supported not only by petrographic similarity, but also by the structural relationships of the flow to the vent.

A distinct correlation exists between the quantitative ratio of pyroxene to feldspar and the textural relationships of these minerals. The more strongly ophitic parts of the basalt contain less augite than those in which the pyroxene is mainly euhedral. This can be demonstrated by determining the "pyroxene ratios" of rocks of different textures. The pyroxene ratio—100 pyroxene/(pyroxene + plagioclase)—is computed for three basalts of Dalmeny type of which the modes (percentages by volume) have been measured with a Hurlbut counter (Table 1).

TABLE 1

MODES OF BASALTS OF DALMENY TYPE

	A	B	C
Plagioclase	52.1	49.0	46.7
Augite	13.0	17.9	23.4
Olivine	5.3	11.1	6.5
Iron ore	10.5	8.3	9.9
Chlorite, analcite, calcite, apatite, etc.	19.1	13.7	13.5
<i>Pyroxene ratio</i>	20.0	26.7	33.4

- A Lava III, 700 feet north of vent-margin, near base of flow. Augite in ophitic relationship.
 B Lion's Head intrusion. Augite mainly granular.
 C Lava III, 200 feet north of vent-margin. Augite mainly euhedral and subhedral.

The relationship between the pyroxene ratio and the morphological character of the pyroxene was noticed by Tomkeieff (1945, p. 74), who made numerous modal analyses of basalts and dolerites from the Tweed Basin. He also observed that the value of the ratio varies with the composition of the plagioclase, the pyroxene ratio being higher in rocks with more sodic plagioclase and vice-versa. His average ratios are:

Pyroxene ophitic	26.45
Pyroxene sub-ophitic to euhedral	29.25
Pyroxene euhedral	42.50

The ratios obtained from the Arthur's Seat basalts are lower than these and the plagioclase (An_{50-60}) more calcic than that of Tomkeieff's rocks, which averages An_{37-45} (*loc. cit.*, p. 71).

It has already been noted that the portions of Lava III in which the texture is ophitic are relatively distant from the vents, and low within the flow. These parts have crystallised from lava

extruded earlier than the higher and nearer non-ophitic portions. This distribution suggests that a composition gradient was established within the magma column prior to extrusion, thus accounting for the progressive change in the pyroxene-feldspar proportions noted as the vent is approached.

IV. BASALTS OF JEDBURGH TYPE

The Jedburgh basalts are represented by Lavas IV, V and VI of the Whinny Hill Series, and by a flow which occurs within the Lion's Haunch vent and is exposed in the Queen's Drive. The three Whinny Hill flows are about 40, 20 and 80 feet in thickness respectively. In most respects they resemble each other fairly closely, but they differ in the textural relationships of their pyroxenes.

The rocks are of rather coarser grain than the Dalmeny basalts, and in general they are more feldspathic. Fairly numerous micropheocrysts of plagioclase and occasional olivines occur in a groundmass of smaller plagioclase laths, augite, olivine, iron ore, apatite, analcite and chlorite. The plagioclase has about the same average composition as that of Lava III (An_{50-60}), although zoning is perhaps slightly more apparent. The olivine is sometimes serpentinised, but many of the crystals are unaltered, 2V being about 90° . Interstitial material, mainly analcite and chlorite, is less abundant than in the Dalmeny rock. The textural relationships of the augite are found to vary in much the same way as in Lava III, when the three Jedburgh flows are studied as a whole.

Lava IV is characterised by ophitic to sub-ophitic augite, 2V being $55^\circ-60^\circ$, and $Z \wedge c$ about $40^\circ-43^\circ$. Slight pleochroism is noticeable, with X and Y purplish and Z yellowish brown. This pyroxene is therefore practically identical with that found in the ophitic parts of Lava III. The preferred orientation shown by the feldspar laths—again the trace of a planar fabric—continues through the plates of augite, which must have crystallised after flow had ceased.

The augite of Lava V has only a faintly purplish tinge compared with that of Lava IV; it is euhedral to very slightly sub-ophitic. In Lava VI, near the vents, pale euhedral augite is particularly apparent, and many small crystals are wholly or partly enclosed within plagioclase crystals. Further north, and at lower levels within this flow, some slightly sub-ophitic augite becomes noticeable, though many euhedral crystals are also present. At one locality, 700 yards north of the vent-margin, a patch with strongly ophitic texture occurs within Lava VI.

Modal analyses of these Jedburgh basalts reveal variations similar to those characterising the Dalmeny type. Where the pyroxene ratio is low, the texture is ophitic. The ratio is higher in those with sub-ophitic augite, and rises steadily as the abun-

dance of euhedral augite increases (D-G, Table 2). The ophitic pyroxene obviously crystallised after almost all the plagioclase, but in the rocks with euhedral and more abundant augite, enclosure of pyroxene by plagioclase shows that the augite commenced crystallisation earlier, probably at some intermediate stage in the course of the plagioclase crystallisation.

A composition gradient similar to that observed in Lava III is also present in the Jedburgh lavas. The occurrence of a lava of Jedburgh Type within the Lion's Haunch vent and the abundance of blocks of this type of basalt within the agglomerate

TABLE 2
MODES OF BASALTS OF JEDBURGH AND CRAIGLOCKHART TYPES

	D	E	F	G	H	I
Plagioclase	57.4	55.9	53.8	45.4	49.6	40.3
Augite	15.4	16.0	19.3	24.6	13.9	16.7
Olivine	9.8	4.3	8.9	6.5	9.3	7.2
Iron ore	10.2	10.8	8.1	7.9	7.5	6.6
Analcite, chlorite, apatite, etc.	7.2	13.0	9.9	15.6	8.6	3.4
Augite macrophenocrysts	—	—	—	—	8.9	16.0
Olivine macrophenocrysts	—	—	—	—	2.2	9.8
<i>Pyroxene ratio</i>	21.1	22.3	26.4	35.2	21.9*	29.3*

* groundmass only.

- D Lava IV, 1,000 feet north of vent-margin. Augite ophitic.
 E Lava IV, 400 feet north of vent-margin. Augite sub-ophitic to ophitic.
 F Lava V, 500 feet north of vent-margin. Augite euhedral to very slightly sub-ophitic.
 G Lava VI, 450 feet north of vent-margin. Augite mainly euhedral or subhedral.
 H Zone of mixing, margin of Whinny Hill intrusion in Lava V, 500 feet north of vent-margin. Augite ophitic.
 I Whinny Hill intrusion, 1000 feet north of vent-margin. Augite subhedral to slightly sub-ophitic.

of this vent, suggest that Lavas IV, V and VI may have been emitted from this source. Lava IV is more markedly ophitic at the north end of Whinny Hill, furthest from the vents, than at its southern extremity. The two later flows exhibit progressively more euhedral pyroxene, with the exception of the ophitic patch in the northern part of Lava VI. These facts are consistent with the establishment of a composition gradient within the magma column prior to extrusion.

V. WHINNY HILL INTRUSION (CRAIGLOCKHART TYPE)

The Whinny Hill intrusion is the name given here to a coarsely porphyritic mass of basalt of Craiglockhart Type which occurs in the southern part of the Whinny Hill between Lavas V and VI. Petrographically identical material also outcrops as a

roughly triangular patch in Lava IV, about 1000 feet north of the vent-margin.

Peach mapped the main mass as an intrusion, but regarded the triangular occurrence associated with Lava IV as part of a composite flow. The present writer agrees with Peach that the larger mass is intrusive, but considers it probable that the smaller one is also an intrusion, and that it was originally continuous with the main mass. The Craiglockhart basalt was intruded amongst the Jedburgh flows before any of them were fully consolidated.

The porphyritic basalt contains numerous large crystals of augite and olivine, a few of plagioclase, large and corroded, and occasional xenoliths which resemble olivine-gabbro. The "phenocrysts" have had a complex history, and appear to have been rafted along by the intruding liquid. They lagged behind the front of the advancing magma, for they are usually less numerous and sometimes absent near the margins of the intrusion. The groundmass consists of a plexus of plagioclase laths, augite, olivine, iron ore and apatite, with small amounts of analcite and chlorite. The plagioclase is more calcic than that of the Dalmeny and Jedburgh basalts, averaging An_{60-70} . Augite is abundant, and consists of small, rather pale crystals, many of which are euhedral, whilst some have a slight tendency towards sub-ophitic development.

Contacts of the porphyritic rock with the Jedburgh basalt of Lava IV are well exposed. Although the margin of the Craiglockhart basalt is not chilled, there are few signs of mixing, and layering is absent. The contact with the two higher lavas is mostly obscured, but at one locality, about 450 feet north of the vent-margin, good exposures of the junction of Lava V with the porphyritic rock can be seen. Here layering has taken place to a limited degree. Lava V appears to have been partially consolidated when the Craiglockhart liquid was emplaced.

A certain degree of mixing occurred in this locality, and has produced one particularly striking feature. It will be recalled that both in Lava V and in the groundmass of the porphyritic basalt the pyroxene is usually granular to only slightly sub-ophitic. In the zone of mixing, however, the augite occurs as large ophitic plates which may exceed 2 mm in length. These ophitic augites in the marginal zone of the Craiglockhart basalt have the same purplish tint and optical properties as those in the ophitic Dalmeny basalt and in Lava IV. The pyroxene ratio in the zone of mixing (H, Table 2) is appreciably lower than in either Lava V (F) or the groundmass of the Craiglockhart basalt (I), but corresponds closely with that of the ophitic Lava IV (D).

The ophitic texture in the zone of mixing is apparently a result of the addition of material to the margin of the basic intrusive

liquid from the partially crystallised Jedburgh lava. As much of the pyroxene in the Jedburgh basalt crystallised at a comparatively early stage, and the olivine earlier still, it may be conjectured that the residual liquid of the lava was relatively rich in the components of feldspar. The diffusion of this residual liquid into the Craiglockhart magma would, in effect, lower the pyroxene ratio of the latter near its margins and so provide conditions favouring the late crystallisation of the augite.

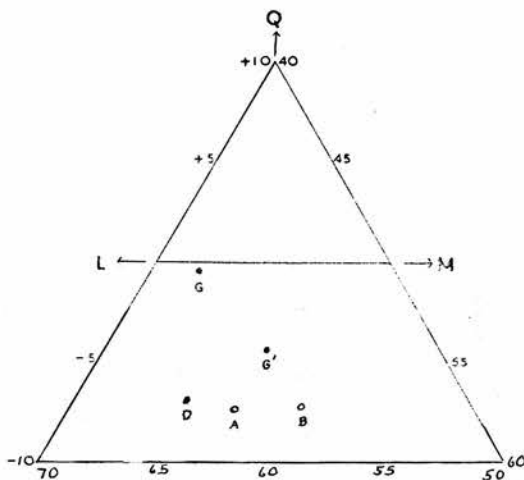


FIG. 3. von Wolff diagram. Open circles: Basalt of Dalmeny Type; Black circles: Basalt of Jedburgh Type. The letters correspond to those of the analyses listed in Table 3.

The feldspar in the zone of mixing is not more strongly zoned than is usual in either rock, but its composition is almost the same as that of the plagioclase in the lava. Hence the addition of Jedburgh material to the Craiglockhart magma probably occurred before crystallisation of its feldspar had proceeded very far.

VI. PETROCHEMISTRY

Chemical analyses of the rocks discussed above are listed in Table 3 and provide additional information which is consistent with the relationships inferred from the modes.

The analyses of the Lion's Head intrusion (B) and the ophitic portion of Lava III (A) are at first sight very similar. The high content of analcite and chlorite in the Dalmeny rocks renders direct comparison rather speculative, but the relative abundance of alumina in the ophitic rock indicates the more

salic character of the latter (despite its lower SiO_2) and this is confirmed by the salic:femic ratios, obtained from the norms.

Analyses of the Jedburgh basalts (D and G)—rocks which contain smaller amounts of analcite and secondary minerals—reveal that the basalt with idiomorphic pyroxene is richer in magnesia and lime but poorer in soda and potash than the ophitic Lava IV (D). Again, the value of the salic:femic ratio is higher for the ophitic rock.

TABLE 3

CHEMICAL ANALYSES AND PARAMETERS

	A	B	D	G	I
SiO_2	44.82	46.39	45.90	45.64	45.36
Al_2O_3	17.02	15.40	16.23	16.76	12.71
Fe_2O_3	3.39	3.09	3.23	5.76	2.49
FeO	8.51	8.46	8.87	4.58	8.60
MgO	7.56	7.08	6.49	7.32	11.53
CaO	8.32	9.07	7.42	9.64	10.85
Na_2O	2.35	2.79	3.21	2.49	1.94
K_2O	1.63	1.71	1.71	0.78	1.12
$\text{H}_2\text{O}-$	0.77	0.31	0.37	1.17	0.42
$\text{H}_2\text{O}+$	3.02	2.29	2.38	2.96	1.92
CO_2	nil	0.20	0.21	nil	0.16
TiO_2	1.96	2.42	3.06	2.23	2.56
P_2O_5	0.37	0.28	0.45	0.43	0.28
MnO	0.26	0.20	0.21	0.35	0.21
FeS_2	—	—	0.24	—	0.24
	99.98	99.69	99.98	100.11	100.39
<u>Salic</u>					
<u>Femic</u>	1.69	1.49	1.75	1.53	
Von Wolff values					
L	60.1	57.4	62.1	58.4	
M	47.0	49.7	44.8	42.0	
Q	-7.1	-7.1	-6.9	-0.4	
f values (Barth)	68.3	83.8	75.6	95.1	

- A Lava III, Dalmeny Type with ophitic augite (location given in Table 1, A). *Analyst:* W. H. Herdsman.
 B Lion's Head intrusion, Dalmeny Type with mainly euhedral and subhedral augite. *Analyst:* T. C. Day.
 D Lava IV, Jedburgh Type with ophitic augite (location given in Table 2, D). *Analyst:* T. C. Day.
 G Lava VI, Jedburgh Type with mainly euhedral and subhedral augite (location given in Table 2, G). *Analyst:* W. H. Herdsman.
 I Whinny Hill intrusion, Craiglockhart Type (location given in Table 2, I) Analysis included for comparison. *Analyst:* T. C. Day.

When the von Wolff parameters calculated from these four analyses are plotted on a triangular diagram (Fig. 3), the points representing the ophitic basalts A and D lie further from the Augite point (M) than those representing the rocks B and G with non-ophitic pyroxene. Although the analysed specimen

of Lava VI (G) is fresh in the sense that it is unweathered, some oxidation, probably during deuteric alteration of olivine, has rendered the $\text{Fe}_2\text{O}_3:\text{FeO}$ ratio abnormally high. This tends to distort the von Wolff plot slightly, as the Mt value is too great. To compensate for this, the proportions of Fe_2O_3 and FeO in this rock have been adjusted to correspond with the $\text{Fe}_2\text{O}_3:\text{FeO}$ ratio of Lava IV (D) and the parameters recalculated. This has the effect of changing the position of G to G' in Fig. 3.

The degree of silica undersaturation as a factor in determining the stage at which pyroxene crystallises, suggested by Krokström (1933, pp. 209-210), does not appear to be important in these rocks. Olivine is present in all the basalts discussed in this paper. The observed abundance of this mineral does not vary very greatly, nor can the variation—such as it is—be correlated with the textural relationships of the pyroxene.

In the appropriate part of the ternary system diopside-albite-anorthite (Bowen, 1915), delay of pyroxene crystallisation is brought about by considerable zoning of the plagioclase. This keeps the composition of the liquid within the plagioclase field for a longer period. However, plagioclase zoning in the ophitic rocks of Arthur's Seat is no more conspicuous than in the non-ophitic rocks.

The quaternary system albite-anorthite-diopside-hypersthene has been discussed by Barth (1936), who found that the boundary surface between the plagioclase and pyroxene fields is a plane, and that the position of an analysed basalt with respect to this plane can be found by calculating its "f(norm)" value from the norm, where $f = ab' + 2di' + 2.3hy'$. He showed that basalts in which pyroxene and plagioclase crystallised simultaneously from the beginning of crystallisation have $f = 123$. If f is greater than 123, the rock falls in the pyroxene field; if less, it falls in the plagioclase field.

All the values of f for the Dalmeny and Jedburgh basalts of Arthur's Seat are considerably less than 123, *i.e.* all these basalts lie well within the plagioclase field. This fact is not surprising, for in none of these rocks has pyroxene commenced its crystallisation before plagioclase. Of considerable significance is the fact that the f value decreases as ophitic texture becomes more marked. It appears that the maximum value of f for fully ophitic pyroxene in these rocks is about 76. With values greater than 84, the pyroxene is predominantly euhedral, while rocks characterised by sub-ophitic texture have intermediate values.

The very considerable departure of the ophitic basalts from Barth's boundary surface constitutes what may be a highly significant exception to an inference drawn from chemical considerations by Bowen (1928, p. 67) to the effect that basaltic

magmas are ordinarily not far from a composition saturated in both plagioclase and pyroxene.

VII. CONCLUSION

The foregoing observations show that in the rocks discussed augite has in some cases crystallised simultaneously with the later part of the plagioclase, and in others has been delayed until after crystallisation of the plagioclase was practically complete. In the former case the pyroxene has formed many small and often euhedral crystals, while in the latter, it has developed as large ophitic crystals. Between these two extremes, all gradations may be observed. The time of crystallisation of pyroxene relative to that of plagioclase, and hence the morphological character of the pyroxene is dependent on the ratio of pyroxene to plagioclase in the rock, which in turn is controlled by the petrochemistry. None of the rocks discussed is saturated in the pyroxene-components; ophitic texture is the result of delayed crystallisation of augite from magma characterised petrochemically by marked undersaturation in the pyroxene-components.

VIII. ACKNOWLEDGEMENTS

The writer wishes to express his grateful thanks to Dr. Robert Campbell for the help and encouragement he has received during his investigations of Arthur's Seat, and to Professor Holmes for valuable advice in the preparation of this paper. He is also indebted to his colleagues in the Grant Institute of Geology, Edinburgh University, for helpful discussion and criticism. Finally, acknowledgment is due to the Royal Society of London, for a grant to defray the cost of two of the chemical analyses.

IX. EXPLANATION OF PLATE II

- FIG. 1. Olivine-basalt of Dalmeny Type (Lava III, Arthur's Seat) with ophitic augite. Flow structure, shown by parallel arrangement of plagioclase laths, passing through ophitic augite. Ordinary light $\times 43$.
- FIG. 2. Olivine-basalt of Dalmeny Type (Lava III, Arthur's Seat) with ophitic augite. Plagioclase crystals, some enclosed by ophitic augite, swirling round an obstructing olivine pseudomorph. Ordinary light $\times 33$.

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TABLE VII.

Chemical Analyses; von Wolff values, and f (norm)
values.

Table VIIa.....Basalts of Normal Dunsapie Type.

Table VIIb.....Basalts of Feldspathic Dunsapie Type.

Table VIIc.....Basalts of Craiglockhart Type.

Table VIId.....Basalts of Markle Type, and Mugearite.

Table VIIe.....Basalts of Dalmeny and Jedburgh Types.

TABLE VIIa.

Chemical Analyses of Basalts of Normal Dunsapie Type.

	A	B	C
SiO ₂	45.10	46.56	46.80
Al ₂ O ₃	14.59	15.68	15.06
Fe ₂ O ₃	4.59	1.90	3.36
FeO	7.93	8.06	7.96
MgO	5.69	8.04	7.99
CaO	8.10	9.71	9.08
Na ₂ O	3.05	2.51	3.11
K ₂ O	1.53	1.36	0.99
H ₂ O ⁺	3.13	2.28	1.99
H ₂ O ⁻	1.17	0.41	0.47
CO ₂	1.22	0.75	0.14
TiO ₂	3.38	2.21	2.36
P ₂ O ₅	0.48	0.28	0.45
Cr ₂ O ₃	nil	0.08	0.04
MnO	0.20	0.20	0.20
BaO	trace	- -	- -
SrO	nil	- -	0.05
FeS ₂	0.15	0.31	0.23
	100.31	100.34	100.28

Von Wolff values.

L	57.92	55.16	55.00
M	44.66	51.46	51.22
Q	-2.64	-6.6	-6.27
f (norm)	107.50	90.40	91.74
values (Barth)			

A. Lava I, from Haggis Knowe.

Analyst : T. C. Day.

B. Lion's Haunch basalt, from northern part of outcrop.

Analyst : T. C. Day.

C. Dunsapie Basalt (Type Rock) from Dunsapie Hill, near middle of eastern shore of Dunsapie Loch.

Analyst : T. C. Day.

TABLE VIIb.

Chemical Analyses of Basalts of Feldspathic Dunsapie Type.

	D	E	F	G
SiO ₂	48.43	46.02	47.01	45.36
Al ₂ O ₃	15.84	16.84	16.96	15.52
Fe ₂ O ₃	3.65	3.17	4.23	12.88
FeO	6.89	6.50	6.01	1.83
MgO	5.09	6.31	4.74	4.14
CaO	7.21	8.39	8.78	8.34
Na ₂ O	4.65	3.61	3.82	3.33
K ₂ O	2.02	1.39	1.69	1.75
H ₂ O+	2.39	4.56	2.61	2.66
H ₂ O-	0.37	0.53	0.78	1.20
CO ₂	0.16	0.40	0.15	nil
TiO ₂	2.56	2.15	2.54	2.56
P ₂ O ₅	0.52	0.40	0.33	0.57
MnO	0.21	0.22	0.40	0.08
BaO	0.08	-	-	-
FeS ₂	0.25	0.09	0.21	-
	100.32	100.58	100.26	100.22
Von Wolff values.				
L	68.08	65.384	67.68	65.44
M	40.26	42.504	38.00	33.23
Q	-8.41	-7.842	-5.69	-1.42
f (norm)				
values (Barth)	92.80	73.05*	82.84	93.80

D. St. Leonard's Sill (central facies), from Kaim Head, 200ft. east of Jeannie Dean's Cottage. Analyst: T. C. Day.

E. Dasses "dykes", southern outcrop. Analyst: T.C.Day.
(Analysis published by Rutledge, 1952)

F. Samson's Ribs. Horizontal columns. Analyst: T.C.Day.

G. Lava in northern side of Lion's Haunch vent. ("Lion's Haunch lava"). Analyst: W. H. Herdsman.

* It is noteworthy that the f (norm) value of the Dasses "dykes" (73) is very low, being less than the maximum value (76) for ophitic augite crystallising very late (see p. 121). From this low f(norm) value it may be predicted that the groundmass augite of this rock is mainly ophitic; this is indeed the case (see p. 77). The presence of augite phenocrysts in this rock is highly significant, and supports the view expressed on p. 134 that the magma composition prior to eruption was heterogeneous on a small scale.

TABLE VIIc.

Analyses of Basalts of Craiglockhart Type.

	H	I
SiO ₂	46.48	45.36
Al ₂ O ₃	13.17	12.71
Fe ₂ O ₃	3.12	2.49
FeO	8.01	8.60
MgO	10.71	11.53
CaO	9.82	10.85
Na ₂ O	2.65	1.94
K ₂ O	1.11	1.12
H ₂ O ⁺	2.49	1.92
H ₂ O ⁻	0.18	0.42
CO ₂	0.08	0.16
TiO ₂	2.01	2.56
P ₂ O ₅	0.28	0.28
Cr ₂ O ₃	- -	nil
MnO	0.20	0.21
BaO	- -	nil
SrO	- -	nil
FeS ₂	0.01	0.24
	100.32	100.39
Von Wolff values		
L	47.12	42.64
M	61.86	66.26
Q	-8.98	-8.90
f(norm) values (Barth)	99.65	100.61

H. Lava IIA, near St. Anthony's Chapel.

Analyst : T. C. Day.

I. Whinny Hill intrusion, smaller outcrop in Lava IV.

Analyst : T. C. Day.

TABLE VIId.

Analyses of Markle Basalt and Mugearite.

	J	K
SiO ₂	48.69	54.39
Al ₂ O ₃	17.98	15.95
Fe ₂ O ₃	8.85	11.41
FeO	1.36	0.64
MgO	5.52	0.60
CaO	4.03	2.85
Na ₂ O	4.18	7.63
K ₂ O	2.41	1.75
H ₂ O ⁺	2.77	0.52
H ₂ O ⁻	1.35	0.44
CO ₂	0.13	0.07
TiO ₂	2.18	2.58
P ₂ O ₅	0.42	0.86
Cr ₂ O ₃	- -	nil
MnO	0.17	0.09
BaO	0.22	nil
SrO	- -	trace
FeS ₂	0.19	0.18
	100.45	99.96

Von Wolff values

L	75.08	85.80
M	25.34	13.29
Q	-0.33	+0.88
f(norm) values		
(Barth)	98.1	99.1

J. Basalt of Markle Type, Whinny Hill.

Analyst : T. C. Day.

K. Mugearite, east of Dunsapie Hill.

Analyst : T. C. Day.

TABLE VIIe.

Analyses of Basalts of Dalmeny and Jedburgh Types (also given on p. 120).

	<u>Dalmeny Type.</u>		<u>Jedburgh Type.</u>	
	<u>L</u>	<u>M</u>	<u>N</u>	<u>O</u>
SiO ₂	44.82	46.39	45.90	45.64
Al ₂ O ₃	17.02	15.40	16.23	16.76
Fe ₂ O ₃	3.39	3.09	3.23	5.76
FeO	8.51	8.46	8.87	4.58
MgO	7.56	7.08	6.49	7.32
CaO	8.32	9.07	7.42	9.64
Na ₂ O	2.35	2.79	3.21	2.49
K ₂ O	1.63	1.71	1.71	0.78
H ₂ O ⁺	3.02	2.29	2.38	2.96
H ₂ O ⁻	0.77	0.31	0.37	1.17
CO ₂	nil	0.20	0.21	nil
TiO ₂	1.96	2.42	3.06	2.23
P ₂ O ₅	0.37	0.28	0.45	0.43
MnO	0.26	0.20	0.21	0.35
FeS ₂	- -	0 -	0.24	- -
	99.98	99.69	99.98	100.11
Von Wolff values				
L	60.1	57.4	62.1	58.4
M	47.0	49.7	44.8	42.0
Q	-7.1	-7.1	-6.9	-0.4
f(norm) values (Barth)	68.3	83.8	75.6	95.1

- L. Lava III, 700feet north of vent-margin, near base of flow. Dalmeny type with ophitic augite.
Analyst: W. H. Herdsman.
- M. Lion's Head intrusion, Dalmeny type with euhedral and subhedral augite.
Analyst: T. C. Day.
- N. Lava IV, 1000 feet north of vent-margin. Jedburgh type with ophitic augite.
Analyst: T. C. Day.
- O. Lava VI, 450 feet north of vent-margin. Augite euhedral. Jedburgh type.
Analyst: W. H. Herdsman.

VI. PETROCHEMISTRY.

So many of the well-known Lower Carboniferous basaltic rock types of the South of Scotland are present in Arthur's Seat that the petrogenesis of the different rocks of the volcano may be of more than local interest. Tomkeieff (1937, p. 76) considered that magma of olivine-basalt composition was the primary source of the mildly alkaline early Carboniferous rocks which range from olivine-basalt to rhyolite. MacGregor (1948, p. 146) in his application of the "two-magma" hypothesis of Kennedy and Anderson (1938) to Scottish Carboniferous-Permian volcanicity, postulated that primary alkaline olivine-basalt magma gave rise to the volcanic rocks of Early Carboniferous Sandstone times.

All the volcanic rocks of Arthur's Seat except the mugearites are olivine-basalts; the chemical analyses (Table VII) show that variations in composition, though significant, are fairly small in those rocks which have not been extensively modified by deuteric alteration. The analyses of the Markle basalt and the mugearite must be considered with caution, particularly that of the mugearite, in which the magnesia content is extremely low. It is highly probable that during or after alteration there/

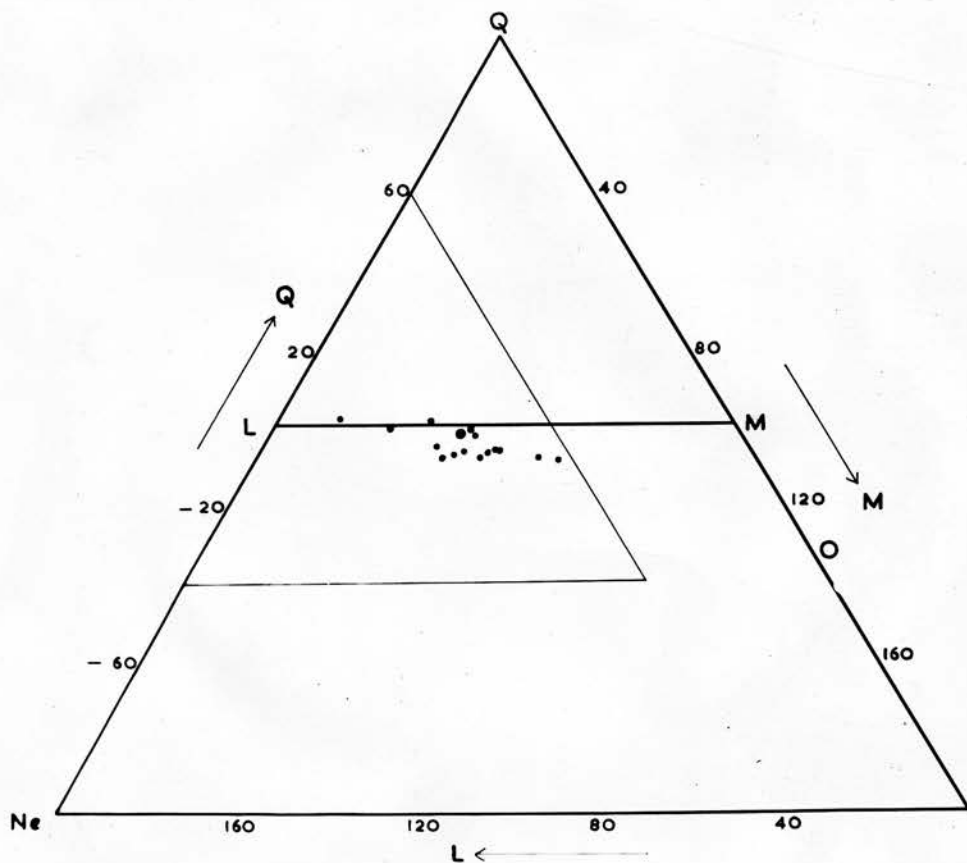


Fig. 4

von Wolff diagram. Small circles : Basalts of Arthur's Seat. Large circle : Average lava of the Midland Valley of Scotland (calculation of Tomkiewf, 1937, p. 71). The area within small triangle has been enlarged in Fig. 5.

The four plots nearest to the L - M line all have a high Fe_2O_3 : FeO ratio, as a result of deuteric oxidation of iron. This has resulted in a high Mt value at the expense of augite. Consequently the Q value is slightly higher than it would have been had the deuteric oxidation not occurred. (see p. 81)

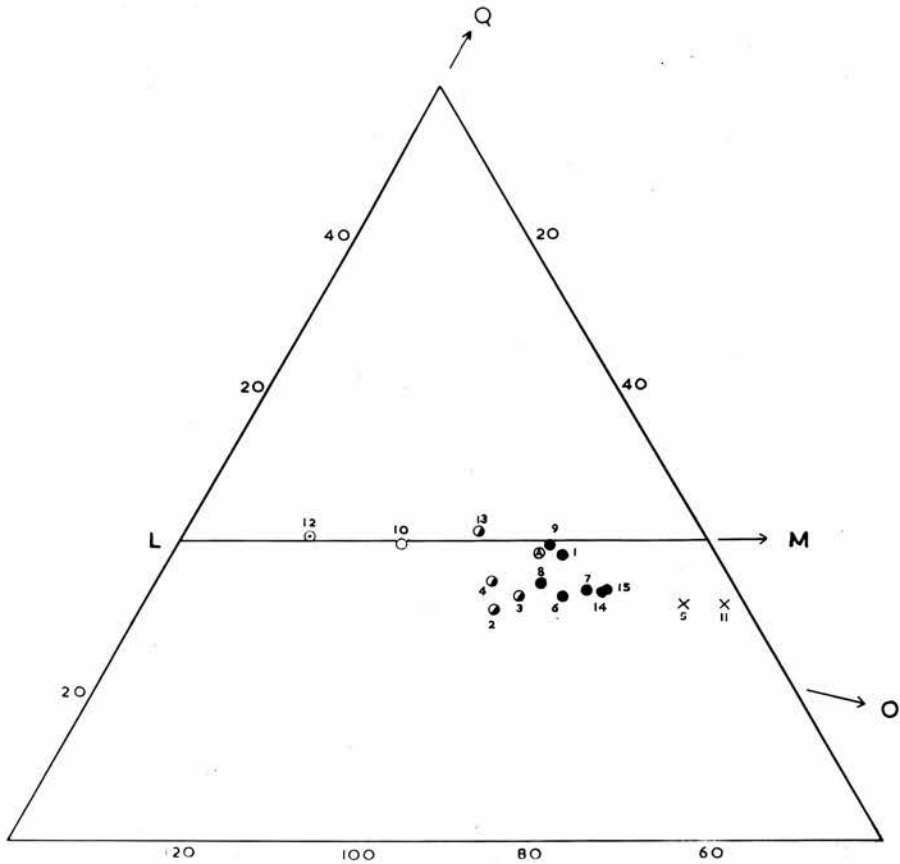


Fig. 5

Enlarged part of Fig. 4.

- Basalts of Normal Dunsapie, Dalmeny and Jedburgh Types.
- ◉ Basalts of Feldspathic Dunsapie Type.
- × Basalts of Craiglockhart Type. ○ Basalts of Markle Type.
- ◉ Mugarite.
- ⊙ Average lava of Tomkeieff (1937, p. 71).

The numbers correspond with the probable chronological sequence of eruption of the various rocks (see pp 147-166)

1. Lava I (Dunsapie)	9. Lava VI. (Jedburgh)
2&3. St. Leonard's Sill and the Dasses.	10. Markle lava of Whinny Hill.
4. Samson's Ribs.	11. Whinny Hill intrusion (chronological position doubtful)
5. Lava IIA.	12. Mugarite.
6. Lava III (Dalmeny).	14.&15. Lion's Haunch basalt and Dunsapie Hill.
7. Lion's Head intrusion (Dalmeny).	
8. Lava IV (Jedburgh).	
13. Lion's Haunch lava.	

there has been loss of magnesia from the rock.

The chemical relationships of the rocks are most clearly seen when the von Wolff parameters calculated from the analyses are plotted on a triangular diagram (Figs. 4+5). Although none of the plots lie very far apart, they are all disposed near the straight line joining the Craiglockhart basalt of the Whinny Hill intrusion to the Markle basalt of a Whinny Hill lava. Dunsapie, Dalmeny and Jedburgh basalts lie near the mid-point of this line, and the Feldspathic Dunsapie rocks nearer the Markle end. The line, if continued beyond the Craiglockhart extremity, reaches the side of the triangle at a point intermediate between the augite and olivine points, and if extended past the Markle end, cuts the Q-F side just above the feldspar point.

Thus the chemical analyses express diagrammatically a relationship which may also be perceived by direct petrographic study of the rocks. All the basalts are similar with respect to the groundmass, which resembles Dalmeny and Jedburgh rocks. Addition of augite and olivine phenocrysts to a melt of Dalmeny or Jedburgh composition would result in the von Wolff plot of the magma being displaced along the line towards the augite and olivine/

TABLE VIII.Comparisons of average analyses.

In order to avoid confusion, only the more significant oxides are given. As deuteric oxidation of iron has occurred in certain of the rocks, Fe_2O_3 and FeO have been added together before averaging, in order to facilitate comparison.

	Av.Cr.	Ma.	Av.G&Ma	Av.N.D.	Av.Dal.	Av.Jed.
SiO_2	45.92	48.69	47.30	46.15	45.60	45.77
Al_2O_3	12.94	17.98	15.46	15.11	16.21	16.49
Na_2O	2.29	4.18	3.23*	2.89	2.57	2.85
K_2O	1.11	2.41	1.76	1.29	1.67	1.24
CaO	10.33	4.03	7.16	8.96	8.69	8.53
Fe_2O_3 + FeO	11.10	10.21	10.65	11.26	11.72	11.21
MgO	11.12	5.52	8.32	7.24	7.32	6.90
TiO_2	2.28	2.18	2.23	2.65	2.19	2.64

* The slightly high soda of the av. Cr. and Ma. is a reflection of the albitisation which has affected the Markle basalt (M).

Av. Cr. = average of two Craiglockhart analyses (H & I, Table VIIc)

Ma = Markle basalt (J, Table VIIId).

Av. Cr & Ma = Average of Av. Cr. and Ma.

Av. N.D. = Average of three Normal Dunsapie analyses (A, B & C, Table VIIa).

Av. Dal. = Average of two Dalmeny analyses (L & M, Table VIIe).

Av. Jed. = Average of two Jedburgh analyses (N & O, Table VIIe).

olivine side of the diagram, while addition of feldspar phenocrysts would displace the plot in the reverse direction, towards the feldspar point. If phenocrysts of all three minerals were to be added in about the same proportions as they occur in the groundmass, no noticeable displacement of the plot would occur.

The evidence provided by chemical analyses and by petrographic examination suggests that the Markle and Craiglockhart basalts are complementary differentiates of magma with an original composition very similar to that of Dunsapie basalt (equivalent chemically to Dalmeny or Jedburgh). This may also be demonstrated by examining average compositions of the three types (Table VIII). It is clear that the average Craiglockhart basalt is low in soda, potash and alumina, but high in magnesia and lime, as compared with Dunsapie basalt. On the other hand, Markle basalt is high in the former oxides, but low in the latter. When the mean of the averages of Craiglockhart and the Markle is calculated (without regard for relative volumes, estimation of which is not practicable) a composition very similar to that of the average Normal Dunsapie basalt of Arthur's Seat is obtained.

Hence it is probable that the parental magma of the/

the Arthur's Seat volcano had a composition very similar to that of Normal Dunsapie basalt. When this magma crystallised under conditions which did not favour the growth of phenocrysts, Dalmeny or Jedburgh basalt was formed. It is of considerable interest to note that Campbell, Day and Stenhouse (1934, p. 169) suggested that the parental magma of the Braefoot Sill had the composition of Dunsapie basalt. In addition, when the parameters of the average lava of the Midland Valley of Scotland (Tomkeieff, 1937, p. 71) are calculated and plotted on the triangular diagram of Fig. 5, the plot (⊙) is seen to lie close to that of the Dunsapie basalt of Lava I.

The production of the different rock types of Arthur's Seat from parental magma may now be considered in detail. It is assumed that there existed throughout the eruptive history of the volcano a magma reservoir in which a certain degree of movement of crystals relative to liquid was possible. Such a reservoir has been assumed by MacDonald (1949, p. 91) to underly the Hawaiian volcanoes. It must be emphasised that only those portions of the contents of the reservoir which were erupted and are now exposed are available for study. Hence speculation regarding processes which were operative within the reservoir are/

are of necessity based on the rather scanty evidence afforded by the present-day exposures of some of the magmatic products.

A. Microporphyritic Basalts and Mugearite.

These rocks, in which the only large phenocrysts are occasional olivines, were probably erupted before crystallisation of any mineral except olivine had occurred.

Dalmeny Type.

Chemically Dalmeny basalt is practically indistinguishable from Dunsapie type, and hence may be considered to represent a near approach to the parent magma. The course of crystallisation of the Dalmeny basalt of Lava III and the Lion's Head intrusion has already been discussed in detail in a separate section (pp. 108 - 122). Olivine was the first mineral to crystallise, and was followed by plagioclase. Augite did not commence crystallisation until plagioclase had been separating for an appreciable period (see pp. 113 - 114). The beginning of pyroxene crystallisation depended upon the composition of the magma, but was frequently very late; in no case is there any evidence that augite formed before plagioclase.

Modes of specimens from Lava III and the Lion's Head basalt (p. 115) and the corresponding norms (p. 120) show that the later erupted Dalmeny basalt is somewhat richer/

richer in pyroxene and poorer in feldspar than that erupted slightly earlier, from which it may be inferred that a composition gradient was established in the magma column prior to eruption. This may have been partly caused by crystallisation of olivine at high levels in the magma column, and sinking and partial refusion of the crystals lower down. However, although large olivine crystals are slightly more numerous in later erupted portions of the Dalmeny basalt than in earlier, the difference in numbers is slight compared with the amount of olivine occurring throughout the flow, and it is therefore unlikely that crystal sinking was the only process operative. The displacement of plots of "early" and "late" Dalmeny basalt on a von Wolff diagram (p. 119) do not show a movement away from the olivine point, but instead a shift is noticeable from near the augite point towards the Ne corner.

Transfer of feldspar components from lower to higher levels in the magma column through the medium of ascending volatiles may have had some effect. It is noticeable that more analcite is present in earlier erupted rocks than in later.

A process which may have been operative, and which would perhaps satisfactorily account for the slight variation of the Dalmeny rocks is the establishment of a composition gradient in the magma column as a result of gravity. This/

This differentiation process was mentioned by Bowen (1928, p. 6), who considered that any such effect must be of very small magnitude. Actually only a very gentle gradient would be required to account for the very slight composition change in the Arthur's Seat Dalmeny basalts.

Jedburgh Type.

The Jedburgh basalts of Arthur's Seat are in general only a little more feldspathic than the Dalmeny rocks, and they are very similar chemically. The slight displacement on the von Wolff diagram between the Dalmeny and Jedburgh plots is along the F - (M.O.) line, and the Jedburgh magma may have been derived from Dalmeny by the sinking of a small amount of olivine. The slight variation of composition within the Jedburgh lavas is similar to that observed in the Dalmeny rocks, and is conjectured to be due to the same cause.

The reason why the Jedburgh rocks are coarser in grain than those of Dalmeny type is difficult to discover. Granularity in these basalts does not appear to depend entirely upon the physical size of the body of rock, for Lavas IV, and V (Jedburgh type) are relatively thin flows compared with Lava III (Dalmeny). However, if (as the writer considers very likely) these two thin flows were erupted quickly, one upon the other, and, while still hot, were/

were covered with the much thicker Lava VI, also of Jedburgh type, the combined bulk of the three extrusions would have tended to produce relatively slow cooling. Against this is the fact that massive intrusions such as Samson's Ribs, the Lion's Haunch and the Dalmeny basalt of the Castle Rock have extremely fine groundmass texture. On the other hand Dunsapie Hill and parts of the Dasses and St. Leonard's Craigs, though not more massive, are much coarser in grain. These coarser rocks are usually more altered by deuteritic processes than those of fine granularity, and this may be the key to the problem of the greater granularity of Jedburgh basalt when compared with Dalmeny. Portions of the Jedburgh rocks are more or less completely albitised, but this is not the case with those of Dalmeny type. This suggests that certain volatiles were more abundant in the coarser rocks and tended to produce coarser texture. The mugearites, intensely altered, are more akin to Jedburgh basalts in granularity than to Dalmeny. It could be argued that the groundmass of Markle lava, much more altered than the Jedburgh, is not coarser in grain size. However, the Markle lavas are intensely shattered and brecciated probably by explosive escape of gas, which would have facilitated cooling, so this objection is perhaps not valid.

Mugearite/

Mugearite.

The most probable explanation for the origin of the magma of the Arthur's Seat volcano which crystallised finally as mugearite is that a high concentration of soda-rich volatiles accumulated in otherwise normal parental magma, such as would have crystallised to produce Dalmeny or Jedburgh or under different conditions Dunsapie basalt. The composition of the analysed mugearite suggests that in addition to soda, silica was added at the deuteric stage. The relatively low magnesia recorded in the analysis suggests that this base was lost from the rock during the alteration. Campbell (1933, p. 342) noted the low magnesia content of an altered basaltic rock of the Braefoot Sill, and discovered a dolomitised limestone which he considered was probably the receptacle of migrated magnesia from the basalt.

The formation of the Arthur's Seat mugearites may be conjectured to have occurred in a number of stages:-

1. Crystallisation of Jedburgh basalt, rich in volatiles.
2. Albitisation of plagioclase, with consequent loss of lime.
3. Replacement of most of the magnesia of augite and olivine by the released lime. Oxidation of ferrous iron.
4. Loss of magnesia in soluble form.

B. Macroporphyrific/

B. Macroporphyrific Basalts.

The macroporphyrific basalts, comprising Dunsapie, Craiglockhart and Markle types, all have practically identical groundmasses, if effects of deuteric alteration are neglected. It has already been suggested (p.125) that Craiglockhart and Markle rocks are respectively the basic and acidic complementary differentiates of parental "Dunsapie" magma. The three types of rocks differ mainly in the numbers and composition of their phenocrysts, and in considering the petrochemistry of the macroporphyrific basalts, it is necessary to account for the diversities of their porphyritic constituents.

Reference has previously been made to the "f(norm)" values of Barth ($f_{-ab'} + 2di' + 2.3hy'$). Basalts with an f value greater than 123 lie in the pyroxene field of the quaternary system albite-anorthite-diopside-hypersthene, and pyroxene should crystallise before feldspar from such a magma. Conversely, those with an f value less than 123 lie in the feldspar field, and plagioclase should crystallise first, if only plagioclase and augite are considered.

It is extremely significant that all the analysed Arthur's Seat basalts, including even those of Craiglockhart type, lie in the plagioclase field, and this result from a petrochemical calculation is supported by the textural/

textural relationships of groundmass plagioclase and augite. These have been described in detail in the Dalmeny and Jedburgh basalts (pp. 111-117), and these basalts are equivalent to groundmass of macroporphyrific types. In no rock is there any evidence of crystallisation of groundmass augite before any plagioclase. In most of the rocks plagioclase appears to have commenced crystallisation earlier than augite, and has usually continued to crystallise along with the augite.

In spite of the fact that the phenocrysts in Craiglockhart basalt are augite and olivine, and not feldspar, its composition lies within the feldspar field instead of in the augite field. This significant fact affords a key to the mechanism responsible for the formation of the two complementary differentiates. The evidence of the f (norm) values (see Table VII) suggests that crystallisation of augite must have been preceded by crystallisation of plagioclase, and either the feldspar was subsequently removed by flotation or else the augite sank away from the lighter mineral. Gravitational differentiation was probably the controlling process in the production of Craiglockhart and Markle basalts.

The concentrations of augite phenocrysts in Craiglockhart basalt, and plagioclase in Markle, together with the fact that flows and intrusions are composed predominantly/

predominantly of one type of basalt, shows that crystallisation of the porphyritic constituents commenced prior to eruption.

Commencement of Crystallisation.

Crystallisation commenced within the reservoir with early separation of feldspar and olivine. In one section of the Lion's Haunch basalt (Dunsapie type) a large olivine crystal partially encloses a number of plagioclase plates (Pl. XIV, Fig. 3), which increase in width towards the margins of the olivine. This indicates that over the interval represented ^{the} two minerals were crystallising simultaneously.

Under conditions of slow cooling within the reservoir, large crystals formed. Around each plagioclase crystal a composition gradient was established, and while in the bulk of the magma the composition still lay in the feldspar field (of Barth), within the vicinity of each plagioclase crystal the boundary between the feldspar and pyroxene fields was reached, thus permitting augite to crystallise. In many such cases the augite and plagioclase continued to grow together, sometimes becoming interlocked by their growth, and even joining other groups and occasionally olivine crystals, to form glomeroporphyritic aggregates indistinguishable/

indistinguishable from fragments of gabbroic rocks. However, when an augite crystal moved from the vicinity of a plagioclase, it became no longer in chemical equilibrium with the surrounding magma, and hence was corroded.

Dunsapie Type.

Eruption of a magma containing crystals formed under the conditions conjectured above could result in a basalt of Dunsapie type. All augites would receive an addition of late growth simultaneously when crystallisation of groundmass plagioclase brought the whole magmatic composition to that of a liquid on the pyroxene-plagioclase boundary, and some, but not all of the phenocrysts would show slight evidence of corrosion prior to the zone of late growth. This is in fact the case with the augite phenocrysts of Normal Dunsapie basalts.

Feldspathic Dunsapie Type.

The Feldspathic Dunsapie rocks of Arthur's Seat approach the Markle basalts in composition. They differ in that the plagioclase has not been albitised to any degree and they do not possess as many feldspar phenocrysts. The concentration of plagioclase phenocrysts probably results from flotation of the relatively light feldspars. The uncorroded nature of the comparatively few augites may be simply explained, for the considerable numbers of the growing/

growing plagioclase crystals would provide larger portions of magma having its composition on the plagioclase-pyroxene boundary.

Craiglockhart Type.

If after growth of large crystals in a magma of Dunsapie composition, eruption did not immediately occur, time would have been available for a certain amount of settling of the crystals under gravity. Before sinking could occur, it would be necessary for the crystals to attain such a size that their specific gravity, greater than that of the liquid, became effective in overcoming viscosity; it is perhaps significant that small phenocrysts of augite are rare in the Craiglockhart ^{rocks} of Arthur's Seat. Both olivine and augite phenocrysts are more abundant in the Craiglockhart type than in any of the other types, and, although the groundmass resembles closely that of Normal and Feldspathic Dunsapie types, the high proportion of the ferromagnesian phenocrysts is sufficient to place the rock in the melabasalt class of Johansen (1928, Vol. 1, p. 157). During and after their sinking the augite phenocrysts suffered severe corrosion, which is made obvious by their skeletal pale-coloured central portions.

The problem of the later growth on these corroded cores calls for consideration, for groundmass plagioclase commenced/

commenced crystallisation before groundmass augite. There could not have been sufficient time for the darker rim, sometimes of considerable size, which characterises almost all the larger augite crystals of the Craiglockhart basalt, to have grown only during the period of crystallisation of groundmass augite. The conclusion that growth did occur prior to eruption seems inescapable, in view of the large amount of dark augite which forms part of the great majority of augite crystals.

The events which led to the growth of the darker zone may be conjectured to have occurred in the following manner. The sinking augite crystals were corroded throughout their descent, and, provided they did not lose too much of their bulk, eventually reached the lower limits of the reservoir. Here further corrosion occurred, probably completely destroying the earlier-arrived crystals, with consequent enrichment of the surrounding magma in the constituents of augite. Subsequent crystals were also corroded until a stage was reached when the magma in the depths of the reservoir was saturated in the components of pyroxene. At this stage corrosion ceased in this region and a "sanctuary" was thus provided within which later sinking augites were protected from further resorption. Any tendency towards the re-establishment of homogeneity of composition/

composition by diffusion between the deep pyroxenic layer and the more feldspathic liquid immediately above it may have been counteracted by the natural tendency towards the development and maintenance of a composition gradient in the liquid within the reservoir as a result of gravity (see p.128). In other words, in so far as gravity opposed diffusion it would tend to maintain the status quo.

The effects of loss of heat upon the magma at this stage must now be considered. Cooling may have been partly due to conduction, but convection is likely to have played some part. Slowly descending currents of relatively cool magma would also have been effective in assisting sinking ferromagnesian crystals to reach lower levels. Ascending magma currents, if slow, would have retarded but not necessarily prevented the sinking of heavy crystals. The basal pyroxenic layer need not have been seriously affected by such currents (if indeed they were present) by virtue of its relatively high specific gravity.

Cooling of the liquid surrounding the augite crystals, by then saturated in components of this mineral, resulted in crystallisation of augite, usually on the skeletal remains of the sunken crystals. The composition of the magma would at this stage have been on the augite-plagioclase cotectic boundary, and as cooling proceeded, would have moved/

moved along the line. Plagioclase would also have crystallised, and would have been more calcic than that which formed at higher levels, as the basal liquid is presumed to have been saturated in the corrosion products of fairly calcic augite. Most of the plagioclase would have risen from the relatively dense liquid of the pyroxenic layer to high levels in the reservoir, but some crystals remained, probably because they became intergrown with ferromagnesian crystals, so that the specific gravity of the aggregates was too great for them to rise.

The rather dense colour of the late augite as compared with the earlier, probably indicates a slightly higher iron and perhaps titanium content in the later material. The difference in composition must be very slight, for the other optical properties are almost identical. It is unlikely that the conjectured slight increase in iron and titanium resulted from the addition of material to the pyroxenic layer through any agency other than the corrosion of augite and possibly olivine. Iron ores in the rocks of Arthur's Seat seem generally to have crystallised rather late, probably after eruption. Certain rocks, such as that of the lava in the northern part of the Lion's Haunch vent, show significant enrichment in iron, but this is deuteric. Generally, magnetite crystals in the microporphyritic/

microporphyrific rocks are as large as those in macro-porphyrific types, and there is no more iron ore in Craiglockhart basalt than in Dunsapie type. Augite which is conspicuously reddish purple, and hence presumably appreciably titaniferous, is restricted to that which has crystallised very late in the post-eruptive period of consolidation. These observations indicate that much of the iron and titanium were retained in the magma until a late stage, as was the case with the magma of the Braefoot Sill (see Campbell, Day and Stenhouse, 1934, p. 171).

Very slight differences in composition between the earlier pale and the later dark augite could be correlated with their different times of origin. It is conjectured that both varieties crystallised from magma which was originally in the plagioclase field, but later reached the boundary between the plagioclase and pyroxene fields. However, the suggested means by which the originally feldspathic magma reached the cotectic are very different in the two cases. The relatively pale augite is thought to have crystallised from magma from which plagioclase components - Na, Ca, K, Al - had been subtracted, and the darker augite from magma to which pyroxene components - Mg, Ca, Fe, Ti - had been added. This may have favoured a slight increase in the iron and titanium content of the later/

later augite. However, it must be emphasised that differences in the oxides of iron and titanium in Craiglockhart and Dunsapie basalts shown in the chemical analyses are negligible, and no definite conclusion can be reached.

Crystallisation in the lower part of the reservoir continued until the eruption of the whole of the lower portion of the magma concerned took place. The movements during effusion or emplacement of the basalt might well have resulted in mixing of the regrown augite crystals and their surrounding pyroxenic liquid with the more feldspathic material immediately above them. Once more the crystals would have been surrounded by a liquid with which they were not in equilibrium, though in most cases the time available during eruption would not have been sufficiently long to permit much more corrosion before crystallisation of groundmass plagioclase permitted groundmass augite to form, and a final layer of growth was added to the complex phenocrysts. Occasionally corrosion of the darker part of the augites is apparent; this is particularly marked in Pulpit Rock (believed to be the filling of a pipe). Crystallisation of the massive Pulpit Rock intrusion was probably fairly slow, permitting considerable corrosion of regrown augite.

The large corroded crystals of highly calcic plagioclase which occur sporadically in Craiglockhart rocks were/

were probably corroded when they came into contact with liquid less calcic than the pyroxenic material in which they are presumed to have grown. Much of the corrosion probably occurred during eruption.

In one section of Craiglockhart basalt of the Whinny Hill intrusion (Pl. X, Fig. 2) one augite phenocryst has been observed to contain several patches of olivine, in optical continuity. The appearance is suggestive of intergrowth of the two minerals, but may have resulted from reaction. No positive evidence suggesting reaction of olivine to form augite has been found in the Arthur's Seat rocks, although some of the corrosion commonly indicated by the shape of olivine phenocrysts may have resulted from this cause.

Craiglockhart basalts from the type locality, (Craiglockhart Hill, Edinburgh) and from Corrie, Arran, have been studied by the writer. These rocks contain augite phenocrysts of complex appearance which resemble those of the Arthur's Seat Craiglockhart rocks, and may have had a similar origin. From descriptions in the East Lothian (1910, p. 118) and North Ayrshire (1930, p. 98) Memoirs, it appears that augites in Craiglockhart basalts from these districts also conform in appearance to those of Arthur's Seat. Although more work remains to be done before/

before any general conclusion can be reached, it appears possible that the pyroxene phenocrysts in all Scottish Craiglockhart basalts may have originally grown in association with feldspar and have sunk away from the lighter crystals.

Markle Type.

If no augite phenocrysts were present in the Markle type of basalt, the magmatic composition could be surmised to have been so feldspathic that abundant crystals of plagioclase were enabled to form and eruption to occur before the boundary between plagioclase and pyroxene fields was reached. In such circumstances augite could only crystallise in the groundmass. This sequence of events has probably occurred to produce Markle basalts elsewhere in the Scottish Lower Carboniferous rocks, but at Arthur's Seat, most sections of the Markle basalts do in fact contain a few porphyritic augites, often altered and recognisable only by their shapes. Sometimes, however, this mineral is present as phenocrysts in a completely unaltered condition, and is then recognisable as the same pale fawn pyroxene as that of the Dunsapie basalts, and of the pale central portions of Craiglockhart augites. Euhedral outlines are sometimes seen, but occasionally the crystals are rounded. As in the Dunsapie rocks, later growth is limited/

limited to a narrow border, presumably formed during crystallisation of groundmass augite.

The crystallisation history of Markle basalt appears to have been very similar to that of Dunsapie basalt, but to have taken place at higher levels in the magma reservoir. Early separation of olivine and plagioclase was followed by localised crystallisation of augite in the vicinities of the plagioclases. Gravitational differentiation consisted of the sinking of some of the larger augites and olivines, (the sunken augites of Craiglockhart basalt are fairly large, but those of Markle basalt tend to be fairly small) and the rising of feldspars. These came from lower levels to increase the numbers of the plagioclase crystals towards the top.

Support to the view that Markle basalt is a product of the upper portion of the magma chamber is provided by the fact that the rock has undergone considerable deuteric alteration. Plagioclase has been albitised, olivine completely serpentised, and most of the groundmass pyroxene altered to carbonate and iron ore (mainly haematite). Volatiles have been abundant, and have introduced soda into the rock. Such volatiles would naturally have been concentrated at high levels in the magma reservoir.

Conclusions/

Conclusions.

A mechanism has been postulated to account for the origin of the three types of macroporphyrific basalt - Dunsapie, Craiglockhart and Markle. Dunsapie is believed to result from partial crystallisation of parental magma prior to eruption, permitting the growth of large crystals, consolidated after eruption in a matrix of crystals of later generation. When the crystallising parent magma within the reservoir was not erupted for some time, fractionation by crystal settling and flotation produced Craiglockhart and Markle basalts respectively as complementary differentiates.

When the temperature of the parental magma within the reservoir did not permit crystallisation of plagioclase and augite to commence prior to eruption, a slight composition gradient within the liquid was produced, and lower and higher levels became slightly enriched in mafic and felsic constituents respectively. This accounts for the higher percentage of pyroxene in later erupted lava than in earlier, which is noticeable even within the same flow.

Some rocks have been modified by deuteric action. These include the Markle basalts and the mugearites, together forming the highest lavas in the succession. Volatile accumulation at high levels within the reservoir has resulted in effects due to the late-stage enrichment in soda/

soda being superimposed upon the other processes responsible for the formation of these rocks.

VII. ERUPTIVE HISTORY.

It is possible to deduce much of the eruptive history of the Arthur's Seat volcano by consideration of the field relations and petrological characters of the various rocks. The chronological sequence of some of the events can be established with reasonable certainty, but for others the evidence available is not always sufficient and in these cases a certain amount of conjecture is still unavoidable.

Peach (1910) expressed his opinions of the time relationships of some of the eruptive rocks rather cautiously. He did not attempt to formulate a definite chronological order but made known his views in the course of his description. Oertel (1952) assembled Peach's opinions as a chronological sequence of events and then gave his own views on the chronology. These differed from Peach's in some details. Two of the differences concerned the relative times of emplacement of (i) the composite intrusion now represented by the Dasses, St. Leonard's Craigs and Giral Craig, and (2) the Samson's Ribs intrusion. Petrological evidence obtained in the course of the present study in the main favours Peach's views rather than Oertel's.

So/

So numerous are the intrusions and flows of Arthur's Seat and so diverse the basaltic types that the detailed eruptive history of the volcano is very complicated. To prevent the evidence from becoming too unwieldy it has been found convenient to divide the whole eruptive period arbitrarily into early, middle and late stages. These divisions have been made mainly on petrographic grounds. During the early stage most of the rocks erupted were Normal Dunsapie, Felspathic Dunsapie, Craiglockhart, Dalmeny and Jedburgh types of basalt. In the middle stage the deuterically altered Markle basalts and mugearites were produced. The products of the last stage were Normal Dunsapie basalts.

(1) Early Stage.

It is generally considered that the volcanic activity of Arthur's Seat began with a local interruption of Cementstone deposition in lagoonal conditions. A band of ash which occurs interbedded with the cementstones below the Long Row * indicates that the activity commenced with explosive phenomena.

The first lava to be erupted, Lava I, may have issued from the Western vent (see p.25). The basalt is of/

* Personal communication from Dr. Robert Campbell.

of Normal Dunsapie type, having a chemical composition very close to that of the conjectured parental magma. The sporadic phenocrysts present in this flow show that between the establishment of a magma chamber and effusion of the first lava from it sufficient time had elapsed for crystallisation to commence in the chamber.

The asymmetry of the volcanic rocks above Lava I with respect to the Lion's Head and Lion's Haunch necks suggests that a cinder cone may have existed on the present site of these vents after the first effusion. The Head vent was the first of these two to erupt (Peach, 1910, p. 66), and it is likely that this older vent became active and erupted the ashes which, with calcareous lagoon sediments, cover the top of Lava I. Sediments in contact with the basalt were baked by the residual heat of the flow. Most of the higher lavas erupted by the volcano appear only to the north of the vents, and are not found in the Duddingston Series to the south. However, the Duddingston Series contains a much greater amount of ash in a stratigraphical position equivalent to that of the missing flows. This suggests that during the period of eruption of the volcano the prevailing wind was northerly, tending to build up the cinder cone on the southern side of the crater with the bulk of the ashes emitted, and at the/

the same time permitting escape of lava to the north. Asymmetry of Recent volcanic cones resulting from prevailing winds has been described by Daly (1925, p. 10) at Ascension Island, which lies in the trade-wind belt.

After effusion of Lava I crystallisation within the magma reservoir continued during the building of the cinder cone. Gravitational differentiation resulted in the formation of two complementary fractions; potential Feldspathic Dunsapie and Markle high in the chamber, and Craiglockhart in the depths. The magma chamber was tapped at different levels, and the next lava to flow on the slopes of the cone consisted of Craiglockhart material from the lower levels. This flow, Lava II, may have been emitted from the Western vent, for the presence of Craiglockhart fragments in the agglomerate of this vent proves that it was still active at this stage. Alternatively, the lava may have flowed down the northern flanks of the cone from the Lion's Head orifice. This is the more likely source, for Lava II outcrops very close to the northern side of the Head vent, but is not present to the south. In addition it is significant that a dyke of Craiglockhart basalt, with strong petrographic resemblance to Lava II, cuts the agglomerate in the northern part of the Head vent.

Evidence/

Evidence which will now be discussed renders it very probable that the relatively feldspathic and volatile-rich material postulated as existing at this stage in the higher levels of the magma reservoir was erupted at about this time to produce:-

(i) The composite intrusion now forming the Dasses, St. Leonard's Craigs and Giral Craig (Combinations of Markle, Feldspathic Dunsapie and Mugearitic rocks).

(ii) The Duddingston basalt (Feldspathic Dunsapie basalt).

(iii) The Samson's Ribs lavas (Feldspathic Dunsapie basalt).

(iv) The Samson's Ribs intrusion (Feldspathic Dunsapie basalt).

MacGregor (1936, p. 327) suggested that the composite intrusion (i above) was earlier than the vents, and Oertel (1952, p. 363) considered that this intrusion was the first igneous episode of the volcano. A serious objection to the opinions of MacGregor and Oertel is that blocks of Markle and Feldspathic Dunsapie basalt have not been found in the agglomerate of the Lion's Head vent, and there should be abundant fragments of both these types if the vent had blown through the composite intrusion (which consists mainly of these two types). Fragments in the Head vent are of the Dunsapie rock of Lava I, Dalmeny and Craiglockhart basalt. Hence it is likely that the composite intrusion was not injected until explosive activity in/

in the Head vent had practically ceased. It had earlier been considered by Peach (1910, p. 72) that this intrusion was injected at a time subsequent to the establishment of the main orifice. He based his views on the resemblance of the basalt of the Dasses to the rocks of the Lion's Haunch, Dunsapie Hill and Samson's Ribs intrusions. The Feldspathic Dunsapie basalt of the composite intrusion does indeed bear a very close resemblance to the Samson's Ribs rocks but not to those of the Lion's Haunch or Dunsapie Hill intrusions. So striking are the resemblances to the Samson's Ribs lavas that petrographic evidence strongly favours a time of injection not far removed from the eruption of the Samson's Ribs rocks.

Field and petrographic evidence combined support the belief that the Samson's Ribs lavas and intrusion were erupted early in the history of the Lion's Haunch vent. The field relations of the rocks in the south-west corner of the vent (described on pp. 49-52) and the petrographic characteristics of the basalts suggest that the probable sequence of events in the very early stages of the Lion's Haunch vent was as follows:-

(i) Extrusion of Samson's Ribs lavas over the crater floor.

(ii) Eruption of agglomerate.

(iii) Emplacement of Samson's Ribs intrusion.

(iv) Further/

(iv) Further period of agglomerate formation.

(v) Extrusion of Jedburgh lava over the crater floor and emplacement of Jedburgh dykes in agglomerate.

According to this reading, which is consistent with all the evidence now available, the Samson's Ribs basalts preceded eruption of the Jedburgh rocks.

If the eruption of Jedburgh basalt within the vent may be regarded as contemporaneous with the eruption of the Jedburgh lavas of the Whinny Hill - which seems a probability - then establishment of the time of eruption of the Samson's Ribs rocks with reference to the rocks of the Whinny Hill Series (outside the vents) may be attempted. The Jedburgh lavas IV, V and VI of the Whinny Hill probably followed each other in quick succession. The base of Lava IV rests directly upon the crust of Lava III, the Dalmeny flow, and it is likely that no great time interval elapsed between the extrusion of these two flows, which are petrographically closely related. Below Lava III is the upper ash of the Dry Dam, a bed which is of considerable thickness near the vents. This ash may perhaps be correlated in time with at least some of the agglomerate underlying the Jedburgh lava within the Haunch vent. Hence it may be conjectured that the Samson's Ribs eruptions occurred shortly before the effusion of/

of Lava III.

If eruption of the contents of the upper portion of the magma reservoir is now considered in detail, a probable sequence of emplacement of the various rocks produced may be suggested. The rocks showing least evidence of the former presence of volatile constituents are likely to have come from relatively low levels in the reservoir, and when a gradation in degree of alteration can be observed it may be reasoned that the less altered rocks were erupted later than the more altered and formerly volatile-rich rocks which presumably came from higher magmatic levels, whence they would be the first to be expelled. The composite sill includes rocks more highly altered than any of the Samson's Ribs basalts, and hence its magma was probably injected in advance of the series of eruptions which produced the Samson's Ribs rocks.

It is likely that the sparsely porphyritic and highly albitised marginal facies of the St. Leonard's composite sill was the first material to have been injected. This rock contains only sporadic phenocrysts and shows by the considerable alteration it has undergone that it originally contained abundant volatiles. The lack of phenocrysts suggests that the magma may have just started to crystallise, or may have been erupted under conditions which/

which, in some way favoured separation of liquid from phenocrysts. The feldspathic and highly altered Dasses "sills" of Markle basalt were probably coeval with or followed shortly after the marginal St. Leonard's facies. Here, however, phenocrysts of plagioclase with olivines and probably a few augites were rafted along by the advancing magma.

Following injection of the highest part of the magma reservoir, evacuation of magma in the level immediately below commenced. This material, only slightly less feldspathic in its phenocryst content and fairly rich in volatiles, invaded the earliest incompletely consolidated St. Leonard's injection, and also cut through the unconsolidated Dasses "sills" to form the domed Dasses "dykes". The Girnall Craig is less altered by deuteritic processes than either the central porphyritic St. Leonard's rock or that of the Dasses "dykes". It probably represents material from a slightly lower level in the reservoir. It is probable that, in general, the less altered (and hence later) rocks occur closer to the source of intrusion than do the more highly altered types. Hence it is possible that the source was situated not far from the Girnall Craig, which, it may be noted, is in fairly close proximity to the Samson's Ribs rocks.

The/

The petrographic similarities of the Feldspathic Dunsapie rocks of the Dasses, St. Leonard's Craigs and Girnal Craig to the basalt of Duddingston have already been noted. The rock of the Duddingston mass, which is fairly close to the Girnal Craig, is even less altered than the Girnal Craig basalt, and contains rather more augite and olivine phenocrysts. The Duddingston basalt may be part of the filling of a fissure through which some of the magma of the composite intrusion was emplaced, or it may be a transgressive offshoot from the magma reservoir, but in either case its eruption probably occurred at this period.

MacGregor (1936, p. 326) concluded that the source of the intrusion lay to the west or south-west, as he believed that the completely porphyritic rock of the Dasses and Girnal Craig indicated that the later porphyritic magma had flowed beyond the original limits of intrusion of the earlier non-porphyritic magma forming the marginal St. Leonard's facies. He considered that the trend of the parallel corrugations on the upper surface of part of the Dasses "sills" (N 40° W) supported his contention, for he regarded these as drag folds developed at right angles to the direction of magma movement.

However, the evidence put forward by MacGregor may be interpreted differently. If the source lay to the east/

east of the St. Leonard's sill, it is possible that the non-porphyrific magma was injected only to the west and not to the north or east. Subsequent movement of porphyritic magma in all directions could have produced the features seen today. The non-porphyrific St. Leonard's rock is of greater thickness to the east than to the west (MacGregor, 1936, p. 326); this supports an easterly source. If, as the present writer believes, the Lion's Head vent existed at the time of injection of the composite intrusion, the vent would have acted as an obstacle to the injected magma and complicated the flow pattern to the north; so it is doubtful if any consideration should be given to the trend of the Dasses corrugations. It appears that there is insufficient field evidence for any firm conclusion as to the location of the source of the intrusion to be reached, and hence the easterly source suggested by petrographic considerations need not be disregarded.

It is probable that a short pause ensued after the emplacement of the composite intrusion before eruptive activity was renewed. The Samson's Ribs lavas show some signs of deuteric alteration and were probably more highly charged with volatiles than portions of the Giral Craig basalt. A short interval of time would have been sufficient for a small concentration of gaseous materials to/

to accumulate near the top of the magma chamber, and explosive release of the gas may have initiated the Lion's Haunch vent. The lavas were erupted into the crater and their eruption was followed by a short period of agglomerate accumulation. The Samson's Ribs basalt was then emplaced as a marginal intrusion which probably sealed the fissure through which the lavas had been emitted. This ended the episode of eruption of basalt of Feldspathic Dunsapie type.

The rocks of the composite intrusion, together with those of the Samson's Ribs lavas and the Samson's Ribs intrusion, comprise a considerable volume of Markle and Feldspathic Dunsapie basalt. The complementary fraction is Craiglockhart basalt and it has already been suggested that some of this more basic rock had already been erupted as Lava II. However, a much greater quantity of the basic fraction remains to be accounted for if the lava chamber was emptied or nearly emptied at this stage. A large quantity of Craiglockhart basalt was erupted from the northern slopes of the volcano as Lava IIA, and probably issued at this stage from a fissure now filled with the Craiglockhart plug forming Pulpit Rock (see p. 28).

The basalt of Lava IIA bears very strong petrographic resemblances to the rock of the lowest lava of the Calton/

Calton Hill. In addition both lavas are intensely brecciated and show many signs of gas action. It is probable that the Calton flow was extruded at the same time as Lava IIA and may even be its north-western continuation. Lavas II, IIA and the Calton flow together make up a volume of Craiglockhart basalt of the same order as the probable volume of the erupted Feldspathic Dunsapie and Markle rocks.

Most of the contents of the magma chamber had by now been erupted as Normal Dunsapie basalt (Lava I), and the two complementary differentiates, Markle and Feldspathic Dunsapie basalts on the one hand, and Craiglockhart on the other. Some of the Craiglockhart material may have remained in the reservoir, for a notable eruption of this basalt was to recur very soon; this will be discussed later.

The western vent had by now ceased activity. The focus of eruption lay further to the east, where the Lion's Head and Lion's Haunch vents were both still active. The magma chamber underlying these vents became charged with a fresh supply of parental magma. A short pause ensued, sufficient to allow slight differentiation of the magma column immediately underlying the Head vent, but cooling did not reach the stage at which plagioclase or augite could commence crystallisation. Part of the fresh supply/

supply of magma was at this stage erupted as Lava III, of Dalmeny type, probably from the Lion's Head vent. The Lion's Head intrusion, also of Dalmeny type, was then emplaced. Cooling of this mass choked and sealed the Lion's Head vent, putting an end to its period of activity.

The focus of lava emission appears to have shifted a short distance to the south, and three flows of Jedburgh basalt were emitted from the Haunch vent, while one thin lava flow covered the crater floor. Probably the Jedburgh dykes of the Raven's Rock immediately south of the Lion's Head vent were parts of the feeder system during this phase of activity. The Jedburgh basalt has a chemical composition similar to that of Dalmeny basalt and does not contain large phenocrysts of plagioclase or augite. As with the Dalmeny basalt (Lava III), the composition gradient evidenced by the series of Jedburgh flows is not considerable. Apparently conditions were still not suitable for crystallisation of minerals other than olivine to occur in the magma reservoir.

The Craiglockhart basalt of the Whinny Hill intrusion was injected before the Jedburgh lavas were fully consolidated. There are several possible hypotheses to account for the origin of this rock. It may represent the remains of the basic fraction of the magma which had provided/

provided the previous eruptions of macroporphyrific basalt. If this is the case it must have been stored in a sealed-off portion of the magma chamber until the time of its eruption as a flank intrusion, for the Dalmeny and Jedburgh basalts show no traces of any mixing with Craiglockhart material prior to their extrusion. Alternatively, the Craiglockhart rock of the Whinny Hill intrusion may be the complementary differentiate of the later Markle basalt which followed the Jedburgh lavas as a series of flows. However, if this is the case, the Jedburgh lavas must have remained unconsolidated during the period of magmatic differentiation which followed their eruption. Lava has been known to remain at a high temperature for a period of years after its extrusion, and no estimation can be made of the time necessary for differentiation, so this possibility, although most unlikely, cannot be ruled out. A third hypothesis is that early in the eruptions of Dalmeny and Jedburgh liquids a mass of parental magma came to occupy a portion of the chamber clear of the main conduit, which may even have completely bypassed the chamber. Differentiation then proceeded within this chamber until after the cessation of Jedburgh activity, when the complementary products were erupted.

Middle Stage.

The eruption of the Jedburgh lavas of the Whinny Hill Series was followed by the effusion of a number of flows of albitised Markle basalt. Before the Markle flows were erupted, crystallisation had commenced within the magma reservoir and proceeded to a stage sufficient for gravity differentiation to become fairly well advanced; and in addition volatiles had accumulated in considerable quantity in the higher levels of the magma reservoir. The uppermost Jedburgh flow (Lava VI) is overlain by the Markle Lava VII with no separating ash band, and the upper surface of Lava VI shows no sign of weathering. Hence it is likely that no considerable time interval elapsed between the eruptions of Lavas VI and VII, and that Markle basalt was available for eruption very shortly after cessation of Jedburgh activity. This evidence supports the third solution proposed to explain the origin of the Craiglockhart basalt of the Whinny Hill intrusion, namely, that differentiation was taking place in part of the magma chamber while the main conduit carried parental magma (Jedburgh) directly to the surface.

The degree of albitisation shown by the various Markle lavas on north and south sides of the vent affords evidence regarding the probable order of extrusion of these rocks/

rocks. The most highly altered is the lower Markle lava of the Duddingston Series, and this flow was probably the first to have been emitted. It flowed to the south from the Lion's Haunch vent, and was followed by the emission of Lavas VII, VIII and IX of the Whinny Hill Series from the north side of the crater. A good deal of ash containing abundant Markle fragments fell on the southern slopes of the cone, and a second lava flowed southwards. The dyke of Markle basalt which outcrops high in the western part of the Haunch vent was probably emplaced at this stage, for it is very similar petrographically to the higher Markle flow of the Duddingston Series.

The juvenile soda responsible for the albitisation of the Markle basalts so far erupted was probably present in the parental magma prior to its differentiation. The higher degree of alteration undergone by these rocks suggests that the volatile content of the parental magma was higher than was the case in the early stages of the volcano's history. This enrichment of parental magma in volatiles was apparently progressive, for the mugearites, which followed the Markles as a series of lavas, are extremely highly albitised. It may be supposed that, following the Markle eruptions, the reservoir filled with parental magma very rich in deuterio constituents, including abundant/

abundant soda, and that before crystallisation could commence, the liquid with its high volatile content was erupted as a series of lavas. The mugearite lava east of Dunsapie Hill contains a number of phenocrysts of albitised plagioclase, and may have been the first of the flows. The phenocrysts present in this flow may have resulted from mixing of the new magma with the remains of the Markle material. Three mugearite lavas flowed down the northern slopes of the cone, and a layer of extrusive mugearite covered the crater floor to form the highest lava in the south side of the Haunch vent, exposed above the Queen's Drive.

Emission of the final mugearite flow of the Whinny Hill Series (Lava XII) was followed by an interval during which crystallisation commenced in the reservoir. The highest material was then erupted to form Lava XIII, of Markle basalt. However, the intense albitisation which affected this flow shows that the volatile content was still high, and greater than that of almost all the earlier Markle flows.

The time of eruption of the lava erupted in the northern part of the Lion's Haunch vent is a matter of some doubt. It is probable that a general easterly movement of the focus of eruption, noticeable in the early period of/

of activity, continued throughout the eruption of Markle basalt and mugearite. The Lion's Haunch lava occurs at a fairly high level within the vent, and was probably erupted after Lava XIII. The basalt is of Feldspathic Dunsapie type, and although not albitised, shows signs of considerable deuteric enrichment in iron. It probably represents a differentiate from the upper levels of the magma chamber which was not erupted until after the soda-rich volatiles had escaped.

Late Stage.

The final eruptions of the volcano were highly porphyritic Normal Dunsapie rocks, and formed the Lion's Haunch and Dunsapie Hill basalts. Oertel (1952, pp. 373-377) considered that the Lion's Haunch basalt was part of a lava lake, and the Dunsapie Hill a group of lava bulges. He considered (p. 377) the Dunsapie Hill rock to be younger than that of the Lion's Haunch, mainly because the Dunsapie Hill material occupies a higher structural position in the crater than does the Lion's Haunch. If the Lion's Haunch basalt was indeed a lava lake, then Oertel's argument is conclusive. However, fabric analyses of the Haunch rocks made during the course of the present study have yielded results which do not always coincide with Oertel's field measurements. Oertel's opinion that the Lion's/

Lion's Haunch basalt once formed part of a lava lake cannot be regarded as proven, and this feature may be intrusive, in which case the age relationship deduced by Oertel would require revision. Petrographic evidence favours the interpretation that the Lion's Haunch is the younger rock, for although both basalts are very similar both mineralogically and chemically (see modes, p. 61 and analyses, Table VII), the rock of Dunsapie Hill shows considerably more signs of the former presence of volatiles than does that of the Lion's Haunch. Both rocks were probably formed by intrusion of magma in which crystallisation had been proceeding for some time prior to eruption. The erupted material may have been drawn from an intermediate level in the magma chamber, below that which produced Lava XIII and the Lion's Haunch lava.

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APPENDIX A.FABRIC STUDIES OF THE BASALTS OF ARTHUR'S SEAT.I. Introduction.

It was originally intended by the writer to continue the structural mapping of Arthur's Seat commenced by Oertel (1952). A start was made on the Whinny Hill intrusion, using the methods of direct interpretation and measurement in the field evolved by Hans Cloos. However, considerable difficulties were encountered at an early stage, the principal one being that it was usually not possible to determine from field exposures whether the fabric of the rock was linear or planar.

Hence the Cloos method was abandoned, and an alternative means was sought. Conventional petrofabric techniques were found to be too time-consuming in view of the considerable number of measurements required. Finally a new macroscopic method making use of the stereographic projection was developed jointly by Dr. D. B. McIntyre and the writer.

Before a satisfactory description of the method could be written, it was found necessary to attempt to clarify/

clarify the terminology used for describing the space orientation of a lineation or a trace. Hence a discussion of the use of the terms "pitch" and "plunge" was written for publication jointly with Dr. McIntyre. Papers dealing with the nomenclature and method appear in the American Journal of Science for 1951, and are included as sections of this appendix.

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THE USE OF THE TERMS PITCH AND PLUNGE

R. H. CLARK AND D. B. McINTYRE

ABSTRACT. Attention is called to the fact that "pitch" and "plunge" are used in varied senses by different authors. "Pitch" appears to have been used originally as a measure of the obliquity of ore-shoots in the plane of the vein. Since 1908, "plunge" has been used as an angular measure in a vertical plane. Tectonicians are today seeking terms for concepts whose nomenclature was standardised by mining engineers forty years ago. It is highly desirable that the established usage should be continued in this new sphere. Application of the terms to igneous and granitic bodies is briefly dealt with; the nomenclature of folds is discussed in more detail.

GENERAL

WHEREAS the orientation of a coal-seam is given by its dip and strike alone, in metal mining, not only is the position of the vein to be defined, but the obliquity of the ore-shoot on the plane of the vein is also to be determined. The direction of maximum elongation, or "pitch-length," of an ore-shoot may be defined, independently from the vein in which it is contained, by means of two co-ordinates: *viz.* (i) the bearing of the projection of the pitch-length on a horizontal plane, and (ii) the vertical angle between the pitch-length and the horizontal. These co-ordinates, however, are not normally employed by mining engineers. The underground worker naturally refers all data to the plane of the vein in which the ore-shoot lies; *e.g.* in a vein striking north-south, an ore-shoot is said to "pitch" either north or south, whatever either its obliquity to the strike, or the dip of the vein may be. In short, the obliquity of the shoot is measured from the horizontal, *in the plane of the vein.*

As early as 1868, G. H. Cook noted that the term "pitch" had come into use among those engaged in iron mining to denote the obliquity of the long axis of elongated iron-ore bodies with reference to the bedding. Unfortunately his definition is inconsistent and there are certain ambiguities in his diagrams. It is clear, however, that he was endeavouring to describe a linear structure lying on a plane. The strike of the plane (N 45° E) can be estimated from the sketch map, and its dip (55° to the southeast) from the "cross-section" at right angles to the strike. Further, a "section," the inclina-

tion of which was not stated, was included to show the angle of "pitch" (35° to the northeast). As this "section" contains both the lineation and the strike of the plane, it follows that Cook measured "pitch" on an *inclined plane*. Thus, in Cook's example, the co-ordinates (mentioned above) of the linear structure are, (i) N 65° E, and (ii) 28° to the northeast. Elsewhere, however, the same author used "pitch" for a measurement in a vertical plane. The need for separate terms for these two different angles did not merge until forty years later.

In 1908, Professor H. Louis of Armstrong College, Newcastle, called attention (Raymond *et al.*, 1908) to the absence of any recognised English term for the vertical angle between the pitch-length and the horizontal, and proposed that "pitch" should be used for this. R. W. Raymond, of New York, objected to this proposal (1908). According to Raymond, the "practically universal" usage of American mining engineers was to measure "pitch" on the plane of the vein. He had himself used "pitch" in this sense for forty years prior to 1908, and he believed that there was no instance to the contrary in the twenty-seven volumes of the Transactions of the American Institute of Mining Engineers that he had edited. In the discussion which followed, all contributors agreed that Raymond's usage had been standard practice for many years amongst American mining engineers.

It was obvious, however, that it had become necessary to have two terms; one was required for each of the two angles in question. "It is evident," wrote Raymond, "that if Professor Louis's definition of 'pitch' were accepted, what I call 'pitch' would need a new name—and *vice versa*; and it is probable that the question which pitch should hereafter be the standard pitch would be largely affected by the extent of the present intelligent usage." While Louis naturally preferred his own use of the term, he wrote, "I do not think that it matters very greatly which definition of pitch we adopt; the essential thing is that we shall definitely decide upon one, and keep to it."

The man most keenly interested in pitch was the practising engineer engaged in metal mining, and, for him, Raymond's angle, measured in the plane of the vein, was more convenient than Louis', measured in the vertical plane contain-

ing the pitch-length. For this reason, as is now a historical fact, the following usage has become standard (Lindgren, 1933, pp. 155-156; Bateman, 1942, p. 133):

With reference to a linear structure *contained in a plane*,

Pitch is the angle between the lineation and the horizontal, as measured in the plane (angle DAC in text-fig.).

Plunge (the term for Louis' angle suggested by H. L. Smyth in 1908) is the vertical angle between the lineation and the horizontal (angle ACE in text-fig.). In a certain sense it may be said that plunge is thus the special case in which pitch is measured in a vertical plane.

Trend is the strike of the vertical plane containing the lineation (CE in text-fig.).

Structural geology is a young science. Even in 1937, R. Balk, in a specialised memoir, found it necessary to devote several pages to demonstrate that a preferred orientation of crystals, seen on a random surface, might represent the trace of either a planar or a linear arrangement in the rock. In fact, in endeavouring to define the position of either a lineation on an *s*-surface, or a trace on a random plane, we encounter today precisely the same requirements in nomenclature as did our mining colleagues over forty years ago. It seems clear that we should recall Louis' advice and act on it. Having definitely decided upon our nomenclature, it is essential that we should keep to it.

With reference to a particular type of lineation, mining

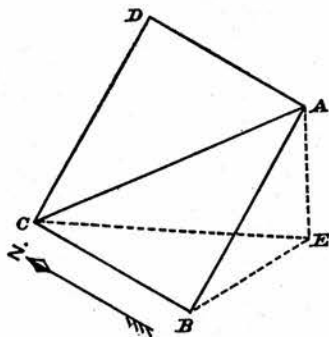


Fig. 1. Isometric projection, showing position of plane of bed or vein, and axis of ore-body therein. ABCD, plane of vein; AC, axis of body; AE, vertical; BC, CE and BE, horizontal. (Figure and explanation after Louis and Raymond, 1908).

engineers, for more than eighty years, have used "pitch" for an angle measured in a plane, vertical only in a particular case. Now that the need to define other types of lineation has arisen, it would be folly to restrict "pitch" to angles measured solely in this special case. It is always somewhat perilous, as Raymond pointed out in 1908, to restrict the meaning of a term previously used in a wider sense. Moreover, if "pitch" were thus restricted, a new term would be required. The term "pitch" cannot, of course, be used in different senses when applied to different types of lineation. There is here no dilemma; the terms established by mining engineers in the course of nearly a century of practice fit our requirements perfectly. Either we take advantage of the experience of our mining colleagues, or we invent a parallel set of completely new terms with the same definitions. Any other course will lead to chaos. To invent new terms for angles already carefully defined will serve no useful purpose, and, indeed, many leading tectonicians in the English-speaking world have already adopted the definitions given above (*e.g.* Billings, Bucher, Nevin, and others).

APPLICATION TO FOLDS

Although folds are three-dimensional structures, they have, in most cases, an important linear aspect. In any highly folded region, and in particular in a segment of a geosynclinal chain, the folds are found to be conspicuously elongate. The direction in space of this elongation is referred to as the *axis* of the fold or system of folds. Its determination is a primary requisite for tectonic analysis.

For the tectonician, the most useful definition of fold-axis is that given by Wegmann (1929), based as it is on the usage of the Alpine structural geologists (especially Lugeon and Argand) since the 1890's. The axis of a fold is defined as the nearest approximation to the line, which, moved parallel to itself in space, generates the fold. The utility of this definition lies in the fact that many complex folds maintain remarkably constant profiles (sections at right angles to the axis) even when the sections are spaced at distances many times greater than the amplitude.

A fold-axis is a linear structure, and, in defining its orientation, our terminology must conform to that used for all other

linear structures. Thus, the pitch of a fold-axis has meaning only when related to the plane on which it has been measured. In practice the plunge of a fold-axis is usually measured directly, but, on occasion, it is more convenient to measure the pitch of the axis on some inclined plane, the dip and strike of which must, of course, be specified. Some authors have used the terms "pitch" and "plunge" synonymously for the vertical angle between the horizontal and the fold-axis; others have used the term "pitch." This differing usage leads to confusion.

Definitions of fold-axis, other than that given above, will be found in most of the current text-books. The majority of these definitions conform, in principle, to one of three different types:—

1. The fold-axis is sometimes defined as "the median line of the fold, along the top of an anticline or the bottom of a syncline." The trend and plunge thus determined are the same as those found when using Wegmann's definition. But, whereas Wegmann's axis is a line with orientation alone, the definition just cited fixes position as well as orientation. This is analogous to requiring that a crystallographic axis must pass through the centre of the crystal; the restriction is unnecessary, and is, indeed, a disadvantage.

2. For some geologists, "an axis of a fold is the line in which any bed intersects the axial plane." The obvious difficulty with regard to this definition is that it is first necessary to define the term "axial plane." Most attempts to do this either have been too vague, or have been so worded that strict application is not possible when the fold-axis (of Wegmann) plunges.

Bonté (1945, p. 35), following Haug and others, defines the *axial surface* as the locus of the hinges of all beds forming the fold. This appears to be the only sound definition possible, and if employed it automatically ceases to be necessary to use axial surface in defining fold-axis. The latter then becomes synonymous with "hinge," *i.e.* with the locus of points of maximum curvature of the cylindroidal surface constituting the fold. Thus, the fold-axis would be fixed in a position which is nearly, but, in the general case, not quite coincident with the median line, *i.e.* with the apex-line or *arête*.

3. The axis of a fold has been defined as "the line of inter-

section of the axial surface with the topographic surface." Even if "horizontal surface" were to be substituted for "topographic surface," this definition would remain unsatisfactory. (i) There would be no way of indicating the plunge of the fold-axis in Wegmann's sense; (ii) except in a special case, a curved axial surface would necessitate a curved "fold-axis," even although the form of the fold were ideally cylindrical, and (iii) as Argand (1911) and Wegmann (1929) have emphasised, general strike and axial trend, in the sense of Wegmann, coincide only in a limiting case.

It seems clear that Wegmann's concept and definition of the axis as the generatrix of the fold is the most logical proposed. It is a linear structure and the terms pitch and plunge with reference to it must be used in the same way as for all other linear structures.

To the proposals made here, it may be objected that the term "plunging" has already been used to denote downward closure at the hinge of a recumbent anticline. Bailey and McCallien (1937, fig. 1), and Bailey (1939, fig. 51) have published a diagram in which this use of the term is implied. Although no definition is given by these authors in their texts, it appears inherent in their diagram that, for them, an anticline is said to be "plunging" where it is a synform. Thus, before the term may be applied to a specific fold, it is necessary to establish that it is in fact an anticline (*sensu stricto* of Bailey and McCallien). The term is apparently limited to terrains where the stratigraphy is unravelled.

For more than half a century, Alpine geologists have recognised examples, not only of recumbent folds, but of folds whose axial surfaces (see definition above) have locally been rotated through more than a right angle from their presumably vertical, original positions. These folds are the "false anticlines" and "false synclines" of Lugeon, Haug, and others. Perhaps the best known illustration is Lugeon's diagrammatic stereogram of the structural units of the Tatra (1903, fig. 1). The use in French of the adjective "plongéant" for such folds, may have influenced the choice of the term "plunge" by British geologists. It should, however, be realised that, in French, the same term may apply, not only to the "plunging anticline" of Bailey and McCallien, but to the dip of a bed,

or to the "plunge" of a fold-axis, in our sense. For examples of the latter usage we may cite Lugeon's classic Memoir on the Origin of the Valleys of the Western Alps (1901).

When we refer to the "plunge of a fold-axis" (in our sense), we imply, and in general specifically state, a quantitative measure. On the other hand, Bailey and McCallien, in describing a "plunging anticline" have indicated no way in which the amount of "plunge" is to be measured. The measure which suggests itself is as follows:—

The amount of "fold-plunge" along any specified line on the axial surface is given by the angle, as measured on the profile plane (*i.e.* the plane at right angles to the fold-axis), between the horizontal and the tangent to the axial surface along the line specified.

According to this measure, a recumbent fold would have zero "fold-plunge". It would be, of course, possible to determine "fold-plunge" only along a specified hinge-line.

All this, however, exposes the weakness of the term "fold-plunge." *Plunge* is an angular measure in a vertical plane. *Pitch* is used when a linear structure is related to the inclined plane on which it is measured. The value of Bailey and McCallien's "plunge" obviously depends on the axial-plunge of the fold, and it is therefore a typical *pitch* measurement and not a *plunge*. For this reason it is suggested that, if it is felt necessary to specify Bailey and McCallien's "fold-plunge," it be measured and given as *fold-pitch* and be stated together with the *axial-plunge*, without which it has no meaning.

Whereas the concept of Bailey and McCallien refers to the form of the fold in profile (*i.e.* in transverse section), axial-plunge denotes the inclination of the longitudinal section. There is, therefore, no reason why the two should not be used side by side, and, indeed, they have thus been used in numerous instances in the literature (see for example Lugeon, 1902).

APPLICATION TO IGNEOUS AND GRANITIC BODIES

In an igneous or granitic body, a preferred orientation of crystals, observed on a random plane, may represent the intersection with that plane of a linear, a planar, or a cylindroidal arrangement of the crystals within the rock mass, or a combination of these arrangements. It is suggested that the term

"trace" is to be preferred to "lineation," "apparent lineation," or "mineral parallelism" when reference is made to observations on a random plane. The method of distinguishing between the traces of linear and planar structures will be discussed in another publication.

It may sometimes be convenient to measure the plunge of a trace directly. But, as a trace has no meaning except when related to the plane on which it has been observed, it is more logical, and usually more convenient, to record the obliquity of the trace on the plane of the exposure as a *pitch*.

CONCLUSIONS

It is necessary to have separate terms to refer to each of the following:—

1. The angle between a line and the horizontal as measured in some specified plane containing the line.
2. The vertical angle between a line and the horizontal.

This case is a limiting example of the first.

Discussion of the different usages of the terms *pitch* and *plunge*, due consideration having been given to the question of precedence, has led to the conclusion that the most logical system of nomenclature at the present day is to adopt the former for the first angle and the latter for the second. The following definitions are therefore offered:—

Pitch is the angle, measured in some specified plane, between a lineation, or a trace, and the horizontal.

Plunge is the vertical angle between a lineation, or a trace, and the horizontal.

Trend is the strike of the vertical plane containing a lineation or a trace.

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A MACROSCOPIC METHOD OF FABRIC ANALYSIS

R. H. CLARK AND D. B. McINTYRE

ABSTRACT. The study of a rock is not complete unless the nature and orientation of its fabric have been determined. The whole fabric of a rock cannot be determined without the use of the universal stage, for the crystal lattices may have a preferred orientation which cannot be detected macroscopically. For this reason many petrologists, lacking the necessary apparatus, make no attempt to analyse the fabrics of the rocks which they are investigating. The object of this paper is to describe a rapid and accurate method of macroscopic fabric analysis that is applicable to a large variety of rocks, and that requires no complex equipment; indeed, it is often possible to use the method directly in the field. If the lattice fabric can be detected only by optical methods, the universal stage must, of course, be used. The danger of reaching erroneous conclusions by using insufficient data is pointed out. In view of the simplicity of the method and its widespread applicability, it is suggested that it should be used to complete routine petrological examination of a rock.

NOMENCLATURE

DISCUSSION of the terminology will be found in Knopf and Ingerson (1938), Fairbairn (1949), and Clark and McIntyre (1951). For the purpose of this paper, the following definitions are adopted:

The *fabric* of an object is described by all the spatial data (fabric elements) which it contains. A rock is said to have a *simple fabric* when it contains a single fabric element (*e.g.* lineation or plane). A rock is said to have a *compound fabric* when it contains more than one fabric element (*e.g.* lineation + plane; 3 planes; etc.).

A *face* is an exposure-plane, either natural or artificial.

A *trace* is the intersection of a fabric element with a given plane.

Pitch is the angle, measured in some specified plane, between a lineation, or a trace, and the horizontal.

Plunge is the vertical angle between a lineation, or a trace, and the horizontal.

Trend is the strike of the vertical plane containing a lineation or a trace.

In this paper the writers are concerned only with the geometric analysis of the fabric; the genesis of the fabrics discussed is not dealt with. For example, the origin of even a "simple" fabric is commonly far from simple.

INTRODUCTION

In the course of a structural investigation of the macro-porphyrific basalts of Arthur's Seat, Edinburgh, one of the writers (Clark) encountered considerable difficulty in determining whether the fabric was linear or planar. The method used was that developed by Hans Cloos (see R. Balk, 1937). The direction of preferred orientation of the macro-phenocrysts is determined in the field on two or more faces of an outcrop, and the nature and orientation of the structure responsible for these traces is estimated by eye. Provided that only a planar structure is present, this method is satisfactory, being both simple and reasonably accurate. However, in localities where lineation may be present, visual determination of the structure is not practicable unless the exposures are unusually perfect.

Balk (1937, pp. 139-155) suggested, although in different terms, that strength of trace might be used as an aid to fabric analysis. Unfortunately, in many outcrops degree and nature of weathering play an important role in determining the apparent strength of a trace. Moreover, in the field, the number of suitable faces is rarely sufficient for the fabric to be determined by eye with complete confidence.

If traces can be measured with reasonable accuracy on a minimum of three suitable, non-parallel faces, although a larger number is to be preferred, the nature and space orientation of the structure responsible can be determined with the aid of a stereographic projection. Should sufficient suitable field exposures be lacking, an oriented hand specimen can be collected, and the required number of faces cut or ground upon it. The fabric can then be determined by analysis of the traces observed on these faces.

THE USE OF THE STEREOGRAPHIC PROJECTION¹

Fabric may be planar, linear, or cylindroidal, but the last is rarely developed on so small a scale that the curvature of the traces is noticeable in a single hand specimen or small outcrop, except in the case of metamorphic rocks. For this

¹ Like all structural geologists who use the stereographic projection, the writers owe a debt to Professor Bruno Sander, the pioneer of modern fabric studies. Readers unfamiliar with the use of the projection should refer to the useful article on the subject by W. H. Bucher (1944).

reason, only linear and planar fabrics are considered here. An interesting example of a cylindroidal fabric, developed on a macroscopic scale in an igneous rock, has been described by Tomkeieff (1946).

1. *Simple Fabrics.*—If the structure is planar, the traces on random faces are the intersections of the planes with these faces. In this case all traces have one common feature: *viz.* they lie parallel to the structure planes. Any two traces define the space orientation of the planar arrangement; the remainder must all lie in this plane. Thus in a stereographic projection, the poles of the traces must lie upon the great circle representing the planar structure.

If the structure is linear, the traces are the projections of the lineation upon the faces studied; *i.e.*, any trace is the intersection of the exposure face with the plane which contains the lineation and which is normal to the exposure face. If the orientations of the faces and traces are known, the great circles representing these normal planes are easily constructed

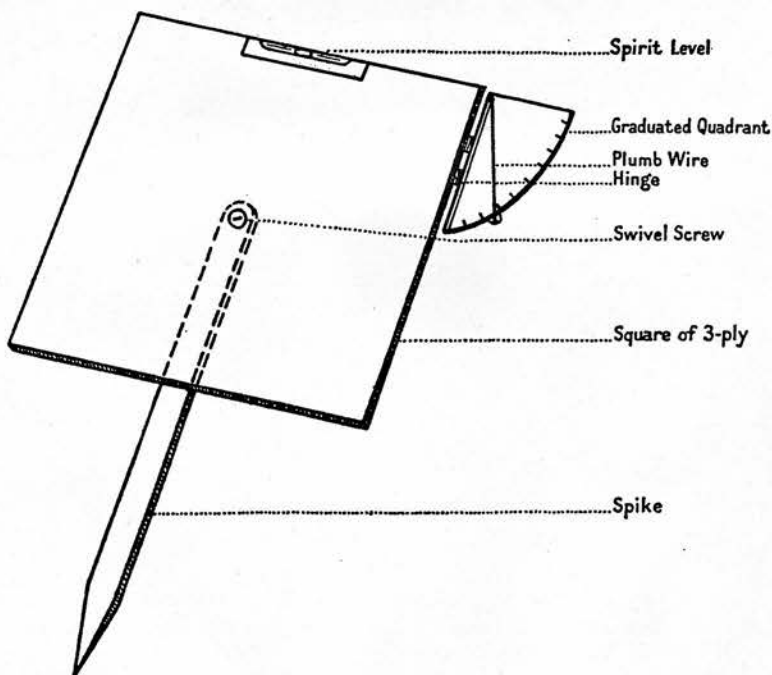
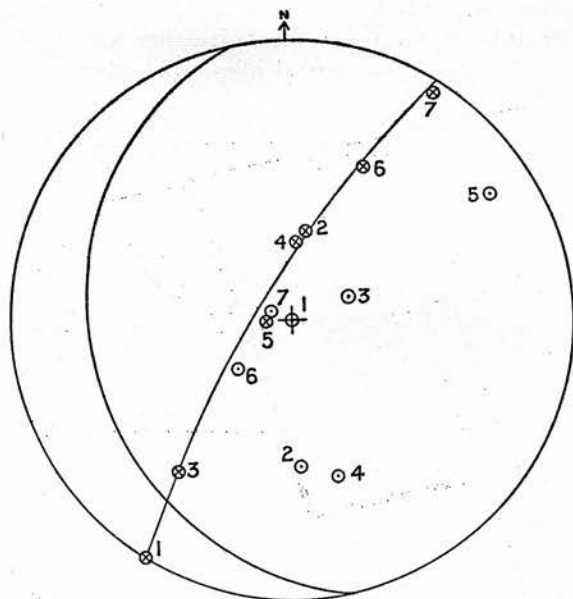


Fig. 1. Apparatus to assist field determination of fabric.

on the projection. The point at which these great circles intersect is the pole of the lineation (Lowe, 1946).

To determine the nature and orientation of the fabric elements in an outcrop or hand specimen, it is necessary to know the strike and dip of each face, and the pitch of the trace upon it. These data are plotted on the projection. If the poles of the traces lie upon, or are close to a great circle, then the fabric is probably planar (fig. 2.). The great circle may be constructed and its strike and dip read directly from the projection.

Should the traces not lie on a great circle, lineation may be suspected, and the normal planes referred to above must be constructed. For each exposure surface, and for each trace, the required normal plane is represented by the great circle containing the pole of the trace and the pole of the face on



Figs. 2—8. Lower hemisphere projections. \odot , Pole of face; \oplus , Trace on that face.

Fig. 2. Single plane. Macro-porphyrific basalt of Dunsapie-type, Lion's Haunch, Arthur's Seat, Edinburgh. For convenience, the traces were plotted with reference to face no. 1. This face strikes $N 62^{\circ} E$ and dips 68° to the south-east. The corrected orientation of the planar structure, relative to the horizontal, is shown by the heavy great circle.

which that trace was observed. If these great circles, representing the normal planes, intersect at or near a point, then the fabric is linear and the trend and plunge of the lineation can be determined (figs. 3 and 4).

Example. An oriented specimen of macro-porphyrific basalt (fig. 3) had six faces cut and ground upon it, and traces were marked upon each face. The following orientations of faces and traces were recorded:

Face	Strike	Dip	Pitch of Trace
1	—	0°	106° E of N (trend)
2	168°	85° E	45° N
3	45°	90°	44° SW
4	157°	80° W	46° N
5	53°	85° SE	50° SW
6	134°	18° SW	36° NW

Plotting procedure: A sheet of tracing paper is laid over a Wulff stereographic net; centre and north points are marked by a cross and an arrow respectively.

Face 1. As this face is horizontal the normal to it is vertical, and its pole lies at the centre of the net. The pole of the trace on this face is at the circumference, 106° east of north.

Face 2. The tracing paper is rotated until the north arrow on it is 168° in an anticlockwise direction from the north point of the net. The north-south meridian on the net then gives the strike of the face, and the pole of the face-normal lies on the east-west diameter, 5° from its eastern end. The projection of the face itself is the great circle 90° distant measured along the east-west diameter. The trace lies on this great circle, 45° from its north-western extremity. The remaining face-normals and traces are plotted in a similar way.

Analysis of the fabric: No great circle can be drawn through the poles of the traces; hence the fabric is not planar. Normal planes must now be constructed. The paper is rotated until face-normal 1 and trace 1 lie on the same great circle on the underlying net. This great circle, which in this case is a straight-line, is the required normal-plane. This procedure is repeated for each pair of faces and traces. The six normal planes thus constructed intersect nearly at a point. Hence the fabric is linear, and the point of intersection represents the pole of the lineation. Its trend is given by the diameter passing through the point. If the paper is rotated until the pole of the lineation lies on the east-west diameter of the net, the amount of plunge is given by the angular distance from the circumference measured along this diameter.

Result: Lineation, trend 106°; plunge 30° down to west.

The traces produced by a linear fabric may chance to lie near a great circle. This is particularly likely to happen if several exposure surfaces are nearly parallel to the lineation. For this reason normal planes should always be constructed, as a "test" for lineation, even when the existence of a planar structure seems obvious. If any ambiguity should remain, it is necessary to cut control faces with selected orientations,

e.g. one in the suspected plane and another normal to the possible lineation.

The stereographic projection should be regarded as a "structural tool" rather than as an infallible geometric construction. On completing the construction, the specimen must be re-examined to ensure the absence of traces on faces parallel to a planar or normal to a linear arrangement. Traces on faces nearly normal to a lineation should show random orientation of platy minerals, and cross sections of prismatic crystals. Surfaces almost parallel to a purely planar structure should contain a large proportion of flat surfaces of platy crystals, with a random orientation of their long axes, and/or the long axes of prismatic crystals with random orientation.

The projection furnishes information as to which faces can be expected to be unreliable. If lineation has been correctly determined, then, unless some of the crystals are unusually transparent, poles of faces on which traces have been measured will not lie near the pole of the lineation; the latter will lie close only to those poles representing faces on which no trace could be found (fig. 4, faces 2 and 5). Conversely, traces

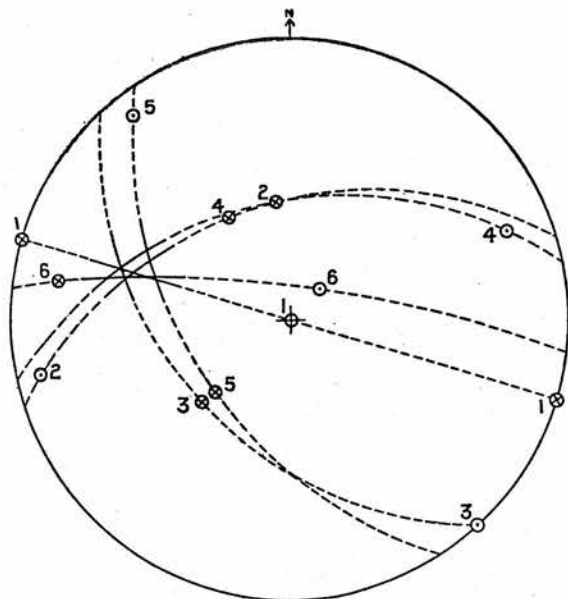


Fig. 3. Lineation. Macro-porphyrritic basalt of Dunsapie-type, Lion's Haunch, Arthur's Seat, Edinburgh.

will be strongly developed on faces whose poles are 90° from the pole of the lineation. With a planar fabric, on the other hand, the nearer the pole of the face lies to the great circle of the fabric plane, the stronger the trace upon that face will be.

It may be remarked here that faces cut upon a hand specimen are analogous to perfect natural exposures. The relative strength of the traces on them depends solely on the nature of the fabric and its orientation with respect to the observation surfaces. The effect of directed weathering has been eliminated.

2. *Compound Fabrics.*—In some specimens of certain rocks, particularly metamorphic rocks, granites, and micro-porphyrific basalts, more than one trace may be clearly recognised on some or all of the faces. In such cases the fabric is compound. Two traces may be produced by two lineations, two planes, or a plane with a lineation either on or off it, and still more complex combinations occur; but fabric analysis is still comparatively simple if a sufficient number of measurements are accurately made and carefully plotted. Two traces

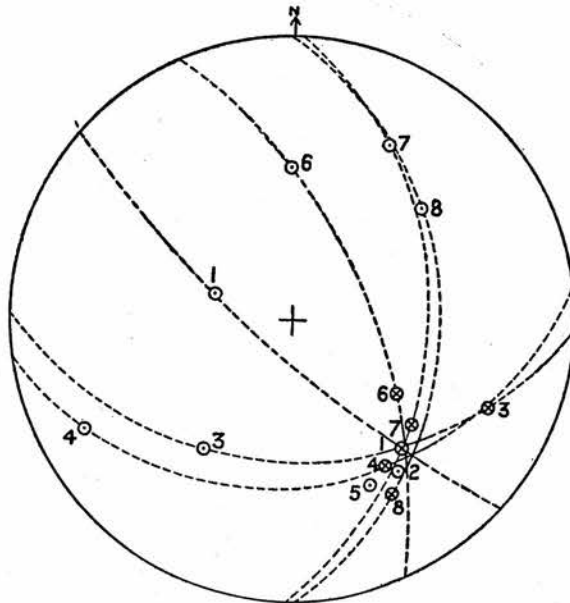


Fig. 4. Lineation. Amphibolite ("Lewisian"), An Sguman, Fannich. The absence of traces on faces 2 and 5 is to be expected, for these are almost normal to the lineation.

on a single face cannot both be produced by the same fabric element, and this most important point must be kept in mind while the determination is being made.

Example 1. Fig. 7.

A specimen has six faces, of which five display two traces and the sixth, one. The poles of the eleven traces fall into two groups. Six, each from different faces, lie upon one great circle, and six upon another great circle. Intersections of normal planes are widely scattered. The fabric therefore consists of two planes. The face yielding only one trace, face 3, contains the line of intersection of the two planes.

Example 2. Fig. 6.

A specimen has six faces, each with two distant traces upon it. When the twelve traces are plotted it is found that the poles of six of the traces, no two of which are from the same face, lie near a great circle. The normal planes containing these six traces intersect at widely scattered points, but the normal

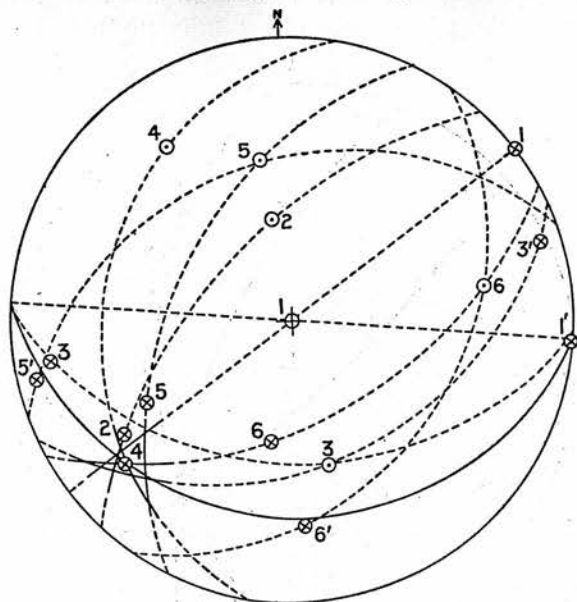


Fig. 5. Planar structure with lineation on the plane. Micro-porphyrific basalt of Jedburgh-type, Whinny Hill, Arthur's Seat, Edinburgh. Normal planes have been constructed through all traces; those through traces produced solely by the planar structure intersect at random. Faces 4 and 2 contain the lineation; hence the traces of plane and lineation coincide.

planes which contain the other six traces (1, 2, 3, 4, 5', 6') intersect near a point. Hence the fabric consists of a plane and a lineation. One of the traces observed on each face was that of the plane; the other, that of the lineation. In this case, the lineation is normal to the plane.

For a case where lineation lies in the plane, see figure 5.

Example 3. Fig. 8.

A specimen has seven faces. Four of these contain two traces; the remaining three contain one single trace. It is found that no great circle can be drawn through the poles of any seven traces from different faces. The eleven normal planes appear at first to intersect at random on the projection, but, on careful examination, it is found that seven of them intersect near one point, and six near another point. Each of these groups comprises normal planes which contain traces from different faces. Therefore the fabric consists of two lineations.

PRACTICAL DETAILS

Field Exposures.—When it is desirable to work directly from field outcrops, strikes and dips of surfaces must be

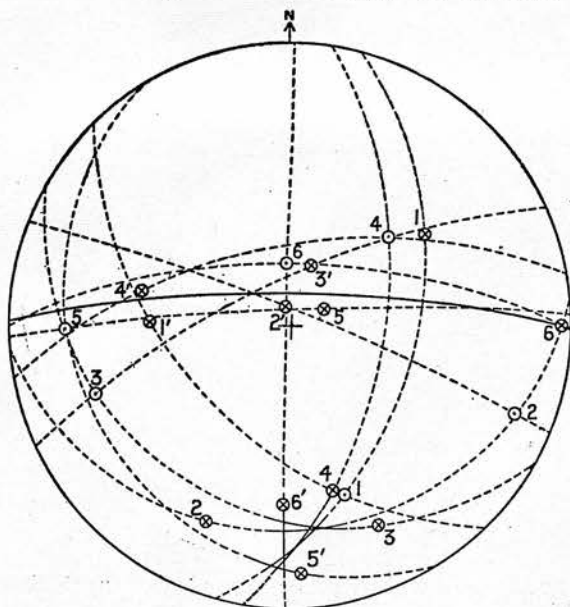


Fig. 6. Planar structure with lineation normal to plane. Hypersthene rock, Loch Riecaur, Loch Doon.

measured with reasonable accuracy. If faces are smooth, this is simple, but, when they are uneven, an instrument such as that shown in figure 1 is useful. The pitch of a trace is best measured with a protractor and a small spirit level.

Collection of Oriented Specimens.—A suitable specimen should be broken from the outcrop and fitted back into place. North is indicated by an arrow marked upon the upper surface. Two horizontal lines, drawn with the aid of a small spirit level upon two steep surfaces at suitable angles to each other, complete the orientation. The marks should be made permanent as soon as possible by cutting them into the specimen with a diamond wheel.

Facing of Specimens.—Much time is saved if, where possible, faces are cut instead of ground. A horizontal face is not necessary; five or six random, non-parallel surfaces are all that are required. Unless the rock is fine-grained the faces need not be polished. Strike and dip, with respect to the face nearest to the horizontal plane, is measured using the instrument shown in figure 1, with its spike removed.

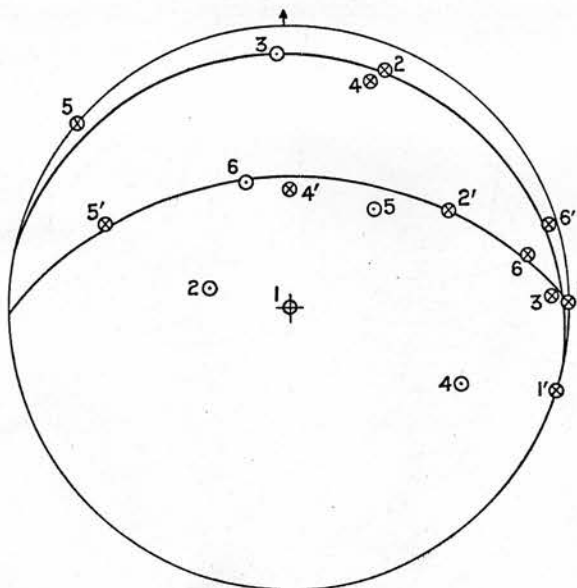


Fig. 7. Two planes. Schist (Moine), Sgurr Mor, Fannich. Specimen not oriented. The single trace on face 3 is the line of intersection of the two planes. The trace of the flatter plane is visible on face 1 because this plane is so strongly developed.

Etching of Faces.—The ease and accuracy with which traces may be determined depend upon the degree of visibility of the oriented minerals. Dark minerals are very easily seen in leucocratic rocks; but in melanocratic rocks, such as basalt, phenocrysts of feldspar and ferromagnesian minerals are barely discernible against the dark groundmass. If such specimens are immersed for some minutes in a moderately dilute solution of hydrofluoric acid, the large crystals become clearly visible. The small crystals of the groundmass are attacked relatively rapidly by the acid, and a gray colour results. Ferromagnesian phenocrysts remain black. The large feldspars become coated with transparent silicic acid; the black rock beneath gives them a dark appearance. Thus, if the rock is washed and kept wet, all phenocrysts appear dark against a light gray background. Traces may be marked with considerable accuracy. If the specimen is allowed to dry, the silicic acid gel on the

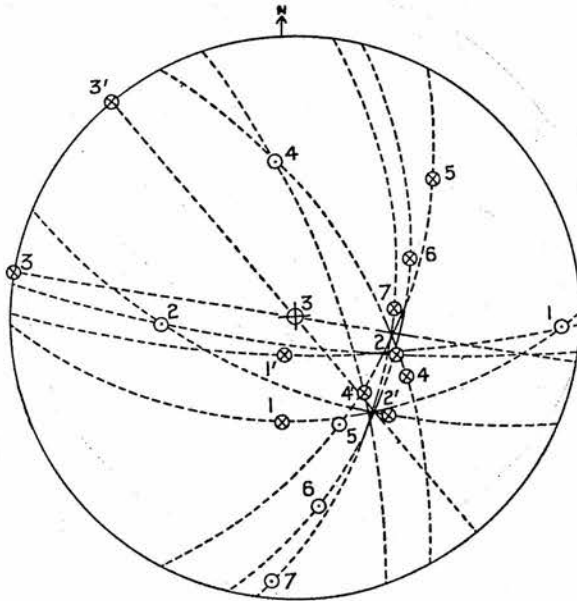


Fig. 8. Two lineations. Porphyritic granodiorite, Glen Fyne. Traces were determined by observing preferred orientations of ferromagnesian crystals. Faces 6 and 7 each display only one trace, for these faces contain the normal to the plane of the two lineations. Face 5 is nearly normal to one of the lineations; the single trace on this face is that of the other lineation.

feldspars forms a white powder (SiO_2), and only the ferromagnesian minerals remain clearly visible. Hence drying should not be permitted until fabric determination is complete, unless, of course, no feldspar phenocrysts are present, *e.g.* in Scottish Carboniferous basalts of Craiglockhart type.

Trace Determination.—In many cases, preferred orientation of crystals on a particular face is obvious at a glance, and the trace or traces may be drawn at once with considerable accuracy. When some of the crystals are transparent, the others are often seen in three dimensions. Sometimes the direction is not so clear, and considerable care must be exercised. The face should be observed from all directions; if doubt remains, no trace should be recorded. Fine-grained rocks, such as micro-porphyrific basalts, should be lightly etched and then examined under strong light with a hand lens

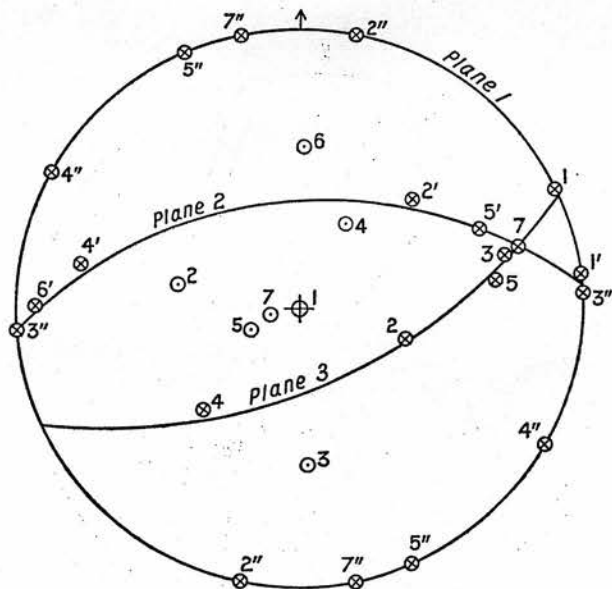


Fig. 9. Three planes. Graphite schist (Dalradian), Glen Livet. Specimen not oriented. The fabric was determined from the traces on faces 1 to 6. Subsequently the space orientation of a face which would contain the line of intersection of the two inclined planes (2 and 3) was predicted from the projection. This face (no. 7) has been ground; one of the traces on it lies on the intersection of planes 2 and 3. It may be noted that planes 2 and 3 are very nearly symmetrically inclined with respect to plane 1.

or binocular microscope of low power. If the rock is very fine-grained, oriented sections may be necessary.

Relating the fabric to the horizontal.—When the orientation of the fabric has been determined with respect to a non-horizontal face, the true strike and dip of this face must be found so that the orientation of the fabric can be related to the horizontal plane. This is most simply accomplished with an instrument similar to that designed by Knopf and Ingerson (1938, plate 20, fig. 2). This may be constructed with two pieces of three-ply and the universal joint of a camera tripod. The specimen is clamped on the upper board with elastic bands, and the board moved until the horizontal marks on the specimen are restored to the horizontal. Strike and dip of the board are measured, and the appropriate correction applied to the projection.

CONCLUSIONS

It is possible to obtain with considerable precision the nature and space orientation of the fabric of any rock which contains a definite and continuous structure. If the fabric is indistinct, so also will be the traces. As the only possible source of significant error need be the determination of the traces, it is obvious that this should be carried out with great care.

ACKNOWLEDGMENTS

Interest in macroscopic methods of fabric analysis was greatly stimulated in Edinburgh by the visit, during 1948-1949 of Dr. Gerhard Oertel of the University of Bonn. It was in the course of structural studies undertaken as a result of this interest, that the method described here was evolved. The writers wish to record their indebtedness to Dr. Oertel for introducing them to this aspect of tectonics. They also wish to thank Mr. J. Dennis and Mr. D. J. Hooten for several valuable suggestions which have been incorporated in the paper.

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IV. Fabrics of certain rocks of Arthur's Seat.

The fabrics of a large number of specimens from various basalts of Arthur's Seat were determined by means of the macroscopic method. It was found that the construction of flow maps of the various intrusions and lavas, as had been intended, was not practicable, because of the complexity of the swirls and currents that characterised the flowing magma immediately before consolidation. Nevertheless, information was obtained which was of critical value in interpreting the field relations of some of the features. In addition, evidence provided by fabric analysis proved valuable, when used in conjunction with petrographic study, in attempting to determine the crystallisation history of the Dalmeny and Jedburgh basalts (see p. 113). The fabrics of some of the lavas and intrusions are discussed in the following pages.

The Microporphyrritic Lavas.

The microporphyrritic extrusive rocks of Arthur's Seat generally have well-developed planar fabric, caused by parallel arrangement of the 010 faces of the platy plagioclase crystals which are so abundant in these rocks. This suggests that laminar flow preceded consolidation, as is usual in lava streams (Nichols, 1939).

Some of the specimens from Lava IV were found to possess/

possess an interesting compound fabric, consisting of a lineation lying in a plane (see Fig. 5, p.194). Microscopic examination revealed that the planar element of the fabrics consisted of the usual parallelism of the tabular feldspars, while the lineation resulted from a preferred orientation of elongated crystals of ophitic augite. This is consistent with the view postulated on pp.116 that the augite in Lava IV crystallised at a later stage in the consolidation of the flow. As described on p.116, the planar fabric passes through the ophitic augite crystals, which must therefore have crystallised after flow had practically ceased. It may be conjectured that the pyroxenic liquid was extended into elongated masses during the final flow movements immediately prior to the crystallisation of augite.

Some of the Jedburgh basalts and most of the mugearites possess a platy jointing, and many of Jedburgh type show a faint banding. These characters appear to be a large scale reflection of the fabric possessed by the rocks, for they are normally parallel to the planar arrangement of the feldspars. The platy jointing has probably been produced by shattering as a result of shrinkage during cooling, although it may sometimes be an effect of post-volcanic fault movement. The planar fabric may be conjectured to have facilitated parting parallel to itself/

itself, for the platy feldspars are all disposed with their 010 cleavages parallel. The banding is probably a result of preferential weathering parallel to the fabric planes.

The Macroporphyrritic Basalts.

The Lion's Haunch Basalt (Dunsapie Type).

About 25 specimens from the Lion's Haunch basalt were examined, and 21 were found to possess a recognisable fabric. Of these, 9 have lineation while the remaining 11 are characterised by planar fabric.

The phenocrysts of the specimens possessing linear fabric are arranged with their long axes roughly parallel. In several specimens the degree of alignment is very strong, and sometimes more than 80% of the total number of phenocrysts are so aligned. The small plagioclase crystals of the groundmass generally do not conform to the fabric imparted to the rock by the phenocrysts, being disposed more or less tangentially to the nearest large crystal.

The Dasses sills (allied to Markle type).

Analyses were made of two specimens from the Dasses sills. Both were found to possess a linear arrangement of the tabular plagioclase phenocrysts.

The/

The Pulpit Rock (Craiglockhart Type).

The fabric of the rocks of both the smaller and larger outcrops of the Whinny Hill intrusion is predominantly linear, though locally planar arrangement is present. The rather stumpy augite and olivine phenocrysts are disposed with their long axes parallel. Rock faces normal to the lineation show basal sections of the prismatic crystals.

In the smaller outcrop, nearly vertical lineation was found near the middle. The larger outcrop is characterised by generally poorly developed lineation which is usually nearly horizontal and lies in a plane delineated by the general strike and dip of the Whinny Hill lavas.

APPENDIX B.METHOD DEvised FOR CUTTING SERIAL SECTIONS THROUGH
AUGITE PHENOCRYSTS.

In the course of petrographic work on the large augite phenocrysts of Craiglockhart basalt, it was found to be necessary to make a three-dimensional study of single crystals, which entailed cutting serial sections through a number of phenocrysts. Attempts to extract large augites from the rock were not particularly successful, as most of the phenocrysts became damaged during extraction. The augites which were finally separated were too small to yield more than one section. Hence it became desirable to devise a means of making serial sections without removing the crystals from the rock. The method finally devised and found to be satisfactory is here briefly described.

First, several specimens from localities of Craiglockhart basalt possessing lineation were examined and fabric analyses made. The specimen which possessed the best developed linear arrangement of phenocrysts was selected.

Three or four large slices were cut at right angles to the lineation. These slides were made as thin and as close together as was possible with the cutting apparatus/

apparatus available, and were marked so that their orientation and position relative to each other remained known. They were then immersed in dilute hydrofluoric acid for a few minutes, washed and dried. The etching so produced caused the augite phenocrysts to appear conspicuously black against a light grey background (see p.197).

It was found possible to trace the longer prismatic crystals from slice to slice, by observing their positions relative to each other. A few of the longest appeared on three consecutive slices. These crystals were marked and numbered.

A sketch was made of the relative positions of the marked crystals in the middle slice, which was then mounted on glass and ground down to a thin section in the usual manner. By means of the sketch the required crystals were located in the sections and ringed.

At this stage, in order to avoid confusion, the other slices were broken up so that each marked augite was contained in as small a fragment as possible. The fragments containing the marked augites were then mounted on glass slides and ground into thin sections. Care was necessary during the mounting to ensure that fragments were not inverted.

Each section of a particular crystal was then examined/

examined in turn under the microscope. Verification that groups of the sections were indeed parts of a single crystal was carried out by noting vibration directions, extinction angles and interference colours.

PLATES.

PLATE I

Fig. 1

The southern aspect of Arthur's
Seat and Salisbury Craigs.

Fig. 2

The Calton Hill. View from the
summit of Whinny Hill, facing north-west.

PLATE I



Fig. 1



Fig. 2

PLATE II

Fig. 1

Contact between Loch Craig (lower) and Lion's Haunch (higher) basalts, at the southern margin of the Lion's Haunch vent. The head of the hammer is resting on the contact (see p. 17).

Fig. 2

Contact between Loch Craig (left) and agglomerate of the Lion's Haunch vent (right). (see p. 17)

PLATE II



Fig. 1



Fig. 2

PLATE III

Fig. 1.

The dip slope of the Haggis Knowe
(Lava I) showing cultivation terracing.
(see p. 1)

Fig. 2

The rocks in the vicinity of St.
Anthony's Chapel (described on pp. 24-27).
Above Lava II may be seen the columnar lower
portion of Lava IIA, on which the Chapel ruins
stand. Behind the ruins is the cliff com-
posed of the upper part of Lava IIA (also fig-
ured in Plate IV).

PLATE III



Fig. 1



Fig. 2

PLATE IV

Fig. 1

The cliff of St. Anthony's Chapel (p. 26). The columnar basalt near the figure grades into less massive rock, which in turn grades into brecciated material.

Fig. 2

The cliff east of St. Anthony's Chapel. Close-up view of some of the highly brecciated basalt of Lava IIA.

PLATE IV



Fig. 1



Fig. 2

PLATE V

Fig 1.

Pulpit Rock, viewed from the south, showing the columns curving radially outwards (described on p. 28).

Fig. 2.

View, facing north, of part of the northern end of the Whinny Hill. The scarp is that formed by Lavas VI and VII, and trends almostⁿ north down the slope (see p. 32).

PLATE V



Fig. 1



Fig. 2

PLATE VI.

Fig. 1

The smaller outcrop of the Whinny Hill intrusion, viewed from the south (described on pp. 34-40).

Fig. 2

Vertical banding in the Jedburgh basalt of Lava IV, near the north-western contact between Lava IV and the smaller outcrop of the Whinny Hill intrusion (p. 36).

PLATE VI

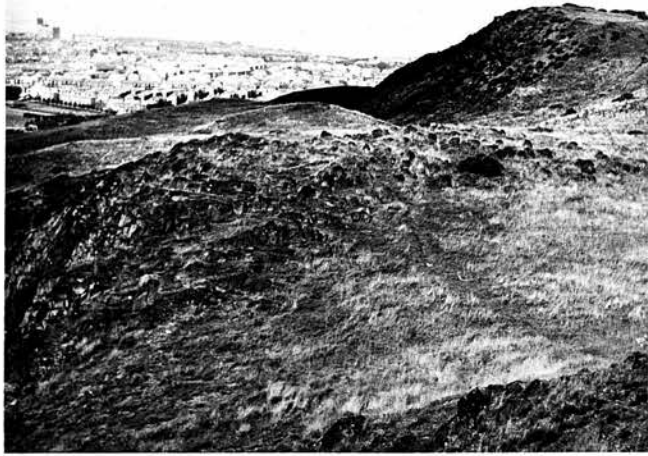


Fig. 1



Fig. 2

PLATE VII

Fig. 1

"Plum pudding" appearance of a weathered surface of Craiglockhart basalt in the Whinny Hill intrusion. The large ferromagnesian phenocrysts stand out conspicuously (p. 34).

Fig. 2

Layered contact between the larger outcrop of the Whinny Hill intrusion and the Jedburgh basalt of Lava V (described on p. 118). The Craiglockhart basalt of the intrusion occupies most of the right and left portions of the photograph; the coin marks the Jedburgh basalt of the flow. The speckled appearance of the Jedburgh basalt results from the presence of ophitic augite, restricted to portions of the lava near the contact with the Craiglockhart rock.

PLATE VII

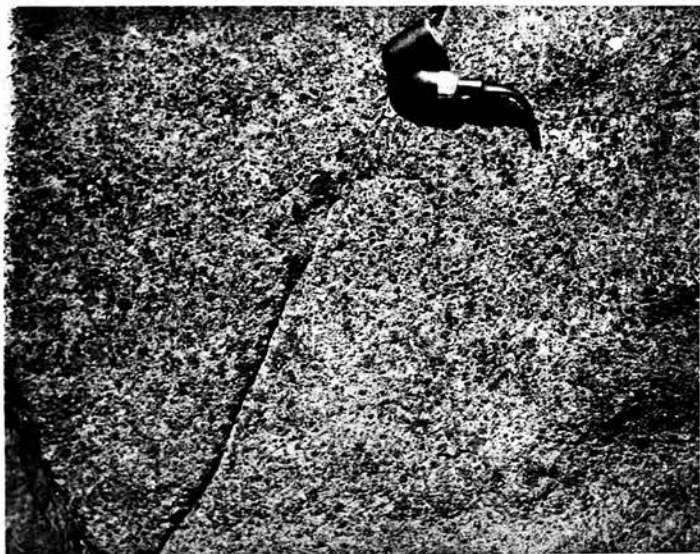


Fig. 1

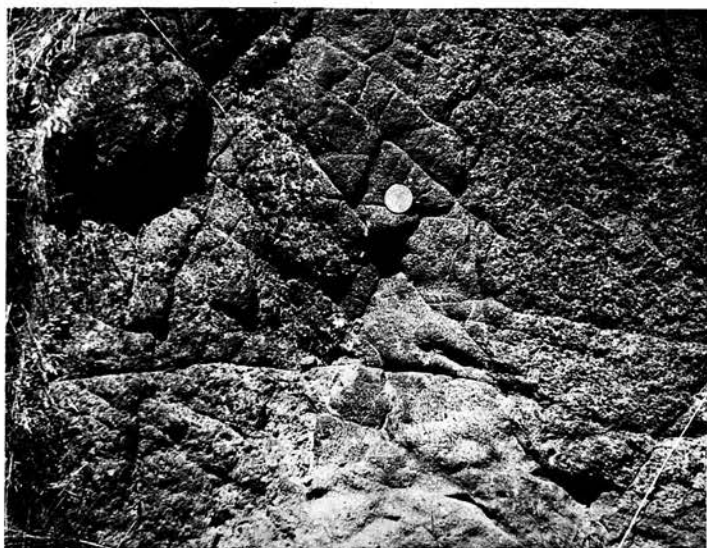


Fig. 2

PLATE VIII

Fig. 1

Slaggy markle basalt of Lava VIII,
Whinny Hill.

Fig. 2

Samson's Grave, Whinny Hill (described
on p. 31).

PLATE VIII



Fig. 1



Fig. 2

PLATE IX

Fig. 1

The uppermost exposure of the Whinny Hill Series (Lava XIII). St. Margaret's Locomotive Depot.

Fig. 2

Sandstone band (marked by hammer) between two of the Samson's Ribs lavas, exposed in the south-west corner of Lion's Haunch vent.

PLATE IX



Fig. 1

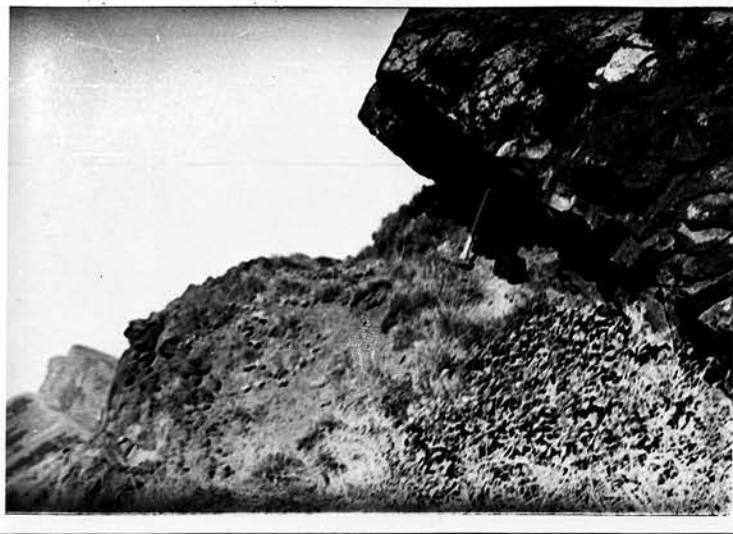


Fig. 2

PLATE X

Fig. 1

Glacial striae on the side of a roche moutonnée, exposed in the Queen's Drive near Samson's Ribs. The rock is part of the Samson's Ribs lavas.

Fig. 2

Finely columnar tongue of basalt from the Samson's Ribs intrusion penetrating agglomerate in the Lion's Haunch vent. The columns are about six inches in diameter.

PLATE X



Fig. 1



Fig. 2

PLATE XI

Fig. 1

Junction of dyke of Jedburgh basalt (below) and agglomerate (above), near Raven's Rock, in the Lion's Haunch vent described on p. 51. The dyke is highly brecciated near its margin.

Fig. 2

Agglomerate of the Lion's Haunch vent, exposed in the Queen's Drive.

PLATE XI



Fig. 1



Fig. 2

PLATE XII

Fig. 1

View from the Queen's Drive, towards Duddingston Loch. The prominent feature is Giral Craig, and above it may be seen the Loch Craig. Immediately above the Loch Craig, the Duddingston basalt is visible.

Fig. 2

The north-eastern aspect of the vents. To the right centre is the Lion's Head; left centre the Lion's Haunch. On the extreme left is a corner of Dunsapie Hill.

PLATE XII



Fig. 1



Fig. 2

PLATE XIII.

Lava I (Basalt of Normal Dunsapie Type, described on pp. 61-66).

Fig. 1

Representative field of analysed specimen from Haggis Knowe.
Ordinary light x 13.

Fig. 2

Long Row, 1400ft. north of vent-margin. Partially digested quartz xenocryst, surrounded by radially arranged augite prisms. (pp.64-65)
Ordinary light x 48.

Fig. 3

Part of the field of Fig. 1, enlarged to show interstitial chlorite, and an olivine pseudomorph. The central part of the pseudomorph consists of quartz, which is surrounded mainly by cloudy carbonate. x 41

Fig. 4

Loch Craig, near Duddingston Loch. Augite phenocryst with corroded central portion occupied mainly by plagioclase crystals. (see p. 63).
Ordinary light x 40

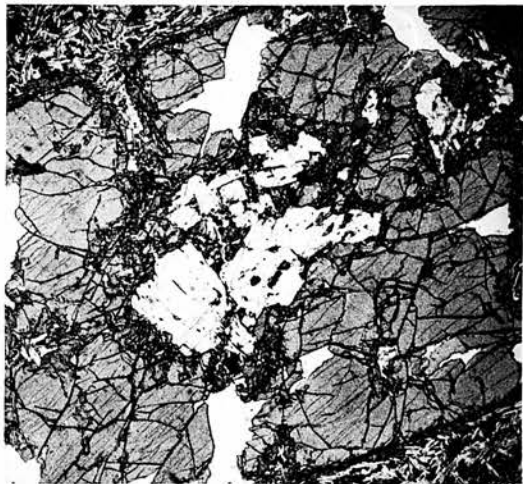
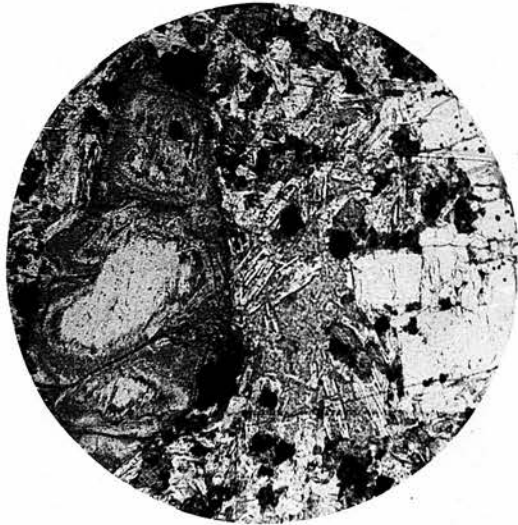
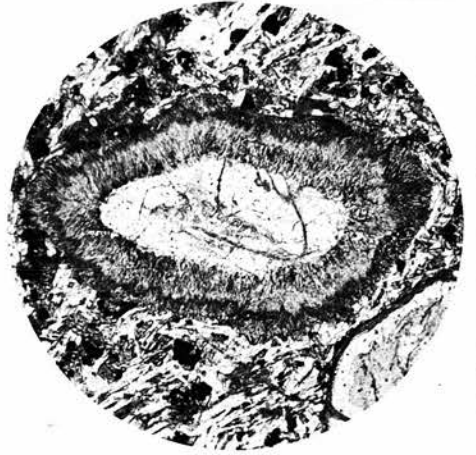
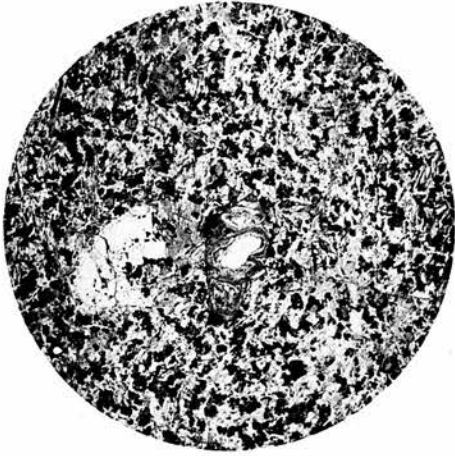


PLATE XIV.

Lion's Haunch basalt (Normal Dunsapie Type, described on pp. 66 - 69).

Fig. 1

Representative field of Lion's Haunch basalt, analysed specimen. Ordinary light, x 13

Fig. 2

Augite phenocryst, with one corner separated from the rest of the crystal (see p.67). The corner is completely separated, for its extinction position is 4° from that of the remainder.
Ordinary light x 14

Fig. 3

Plagioclase crystals partly enclosed within an olivine phenocryst (p, 134)
Ordinary light x 20

Fig. 4

Large plagioclase phenocryst which has been broken into small rectangular fragments.
(p. 67)
Ordinary light x 11

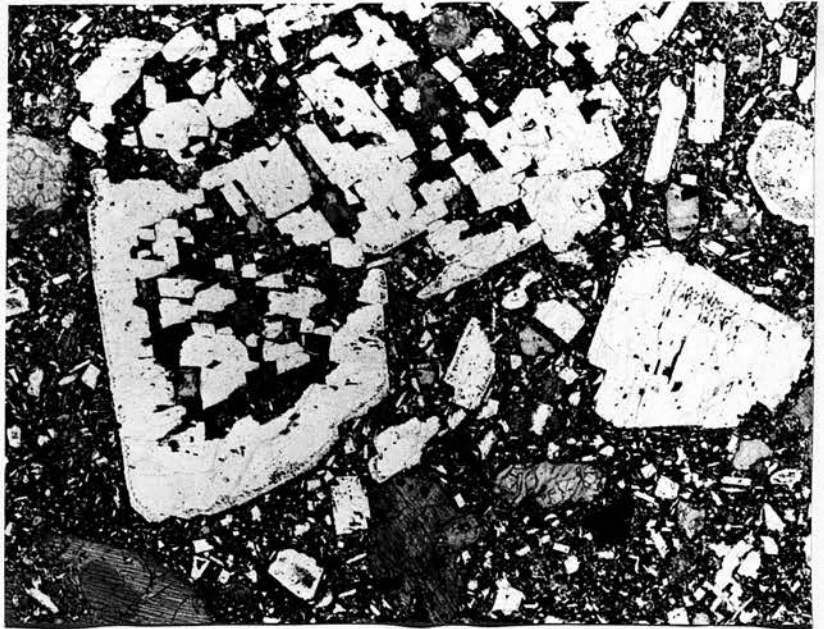
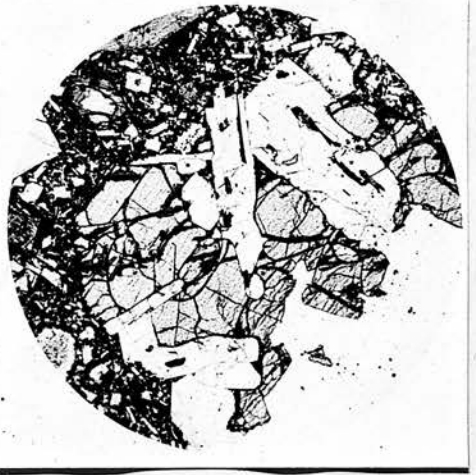
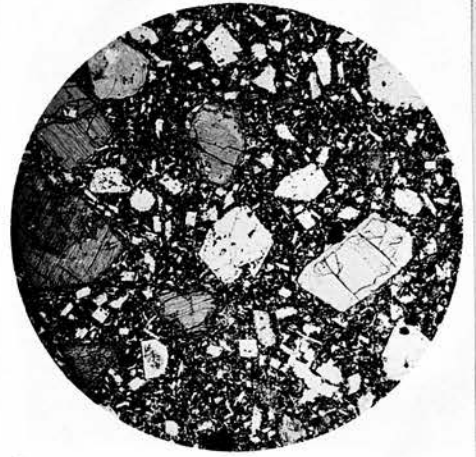
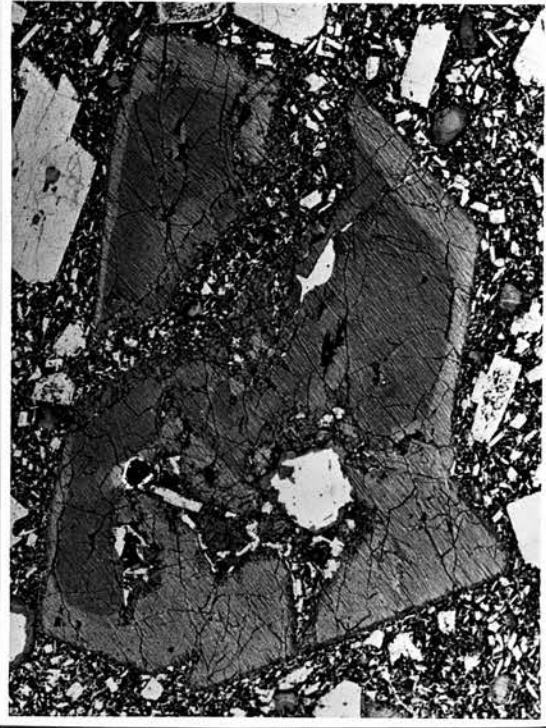


PLATE XV.

Dunsapie Hill (Normal Dunsapie Type, described on pp.
69 - 70).

Fig. 1

Representative field of analysed
specimen.
Ordinary light x 15.

Fig. 2

Euhedral olivine phenocryst.
Ordinary light x 18.

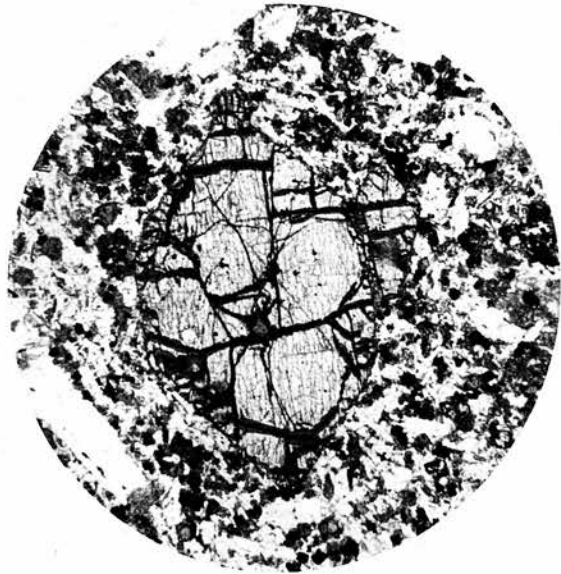
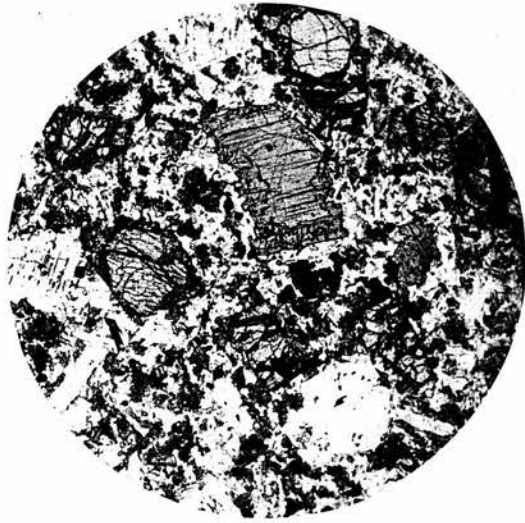


PLATE XVI.

Basalts of Feldspathic Dunsapie Type.

Fig. 1

Porphyritic central facies of St. Leonard's Sill, described on p. 76. Section cut from analysed specimen. The plagioclase phenocrysts contain numerous inclusions.

Ordinary light, x 13.

Fig. 2

Lava in north side of Lion's Haunch vent (p. 73). Representative field of section cut from analysed specimen.

Ordinary light, x 15.

Fig. 3

Section from same specimen as Fig. 2. Olivine pseudomorphs composed of quartz and iron ore. Minute inclusions are arranged in parallel planes, which give the appearance of a cleavage in the quartz (see p. 73).

Ordinary light, x 60.

PLATE XVI.

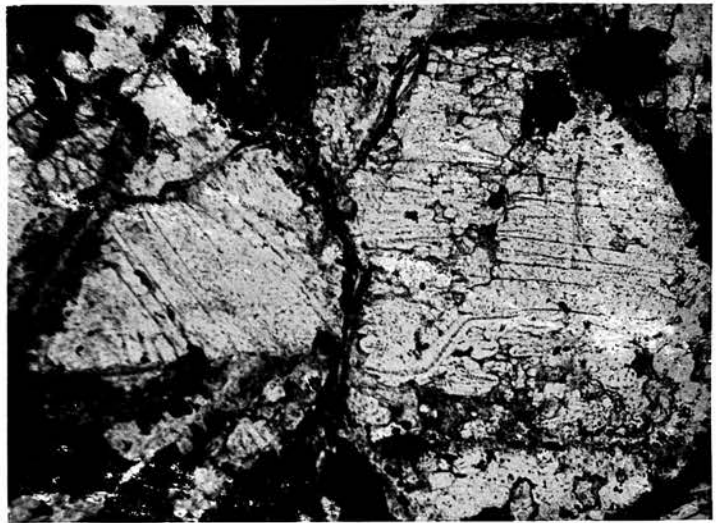
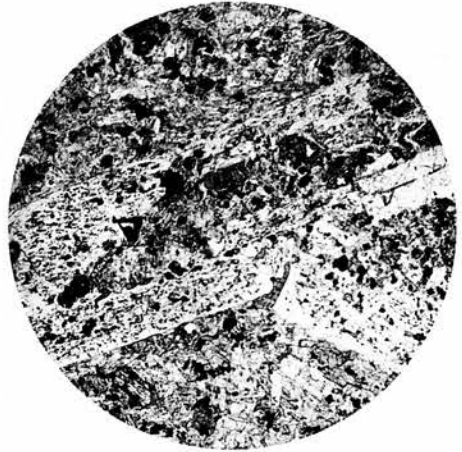


PLATE XVII.

Basalts of Craiglockhart Type (described on pp. 78 - 89).

Fig. 1

Lava IIA. Representative field of section from analysed specimen. The augite phenocryst has a corroded core of early pale augite surrounded by later dark augite (described on p. 78). Ordinary light, x 14.

Fig. 2

The Whinny Hill Intrusion, smaller outcrop. Representative field of section cut from analysed specimen. Ordinary light, x 13.

Fig. 3

Lava IIA. Large corroded crystal of plagioclase. Ordinary light, x 13.

Fig. 4

Lava IIA. Large corroded ^{crystal} of plagioclase. Ordinary light, x 13.

PLATE XVII.

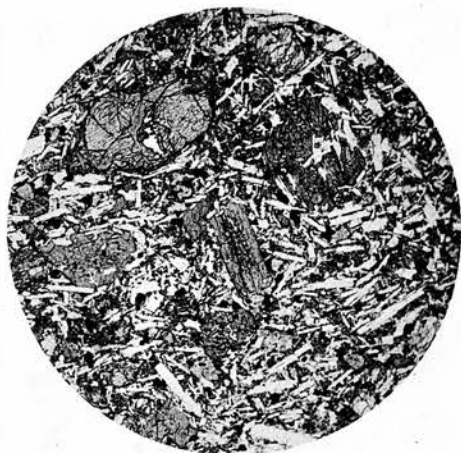
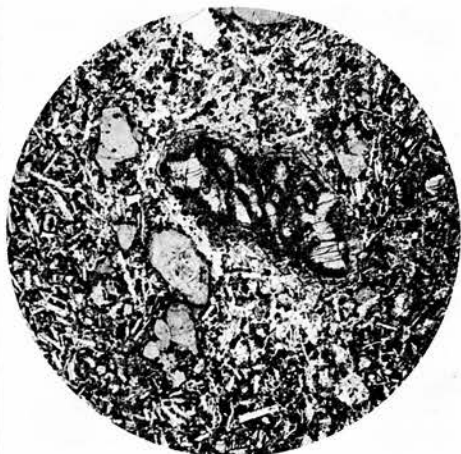


PLATE XVIII.

Augite phenocrysts from the Craiglockhart type basalt of the Whinny Hill Intrusion (described on pp. 78 - 81)

Fig. 1

Deeply embayed crystal with very narrow dark zone of late growth.
Ordinary light, x 11.

Fig. 2

Corroded and regrown crystal with later dark zone of medium size.
Ordinary light, x 37.

Fig. 3

Corroded and regrown crystal with wide later dark zone. In both Figs. 2 and 3 the pale core is free from inclusions.
Ordinary light, x34.

Fig. 4

Augite crystal apparently consisting only of darker augite. The cut of the section has been made through the outer parts of the crystal, and has missed the core.
Ordinary light, x 15.

PLATE XVIII.

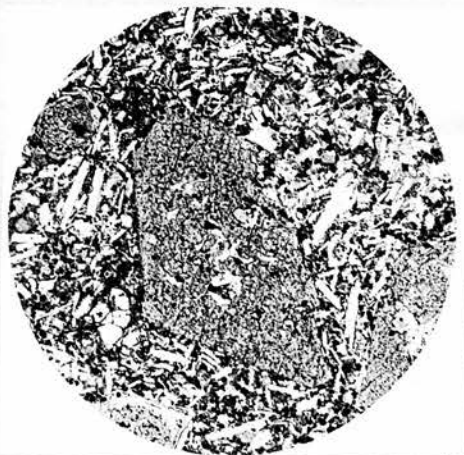
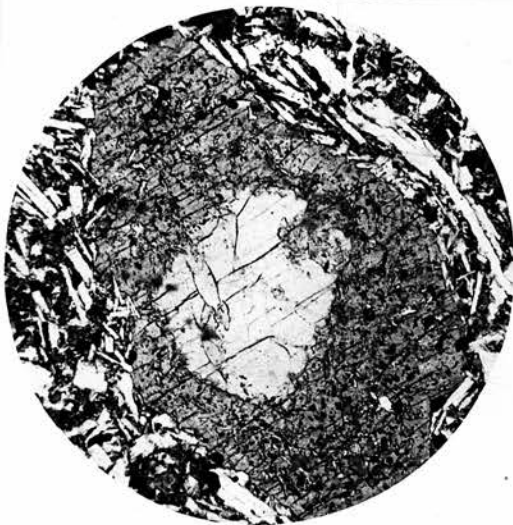
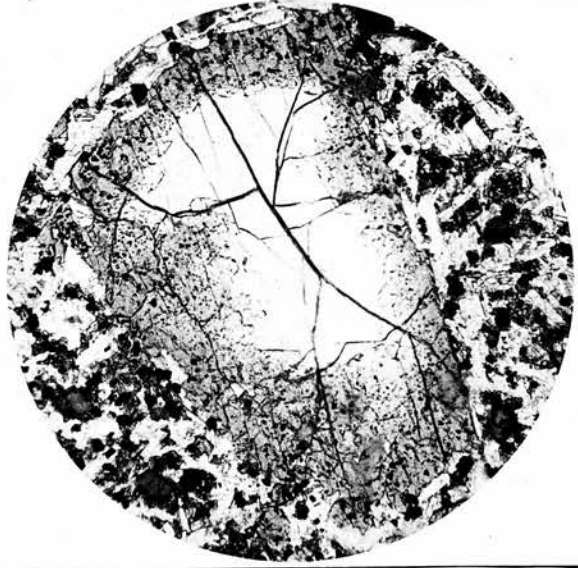
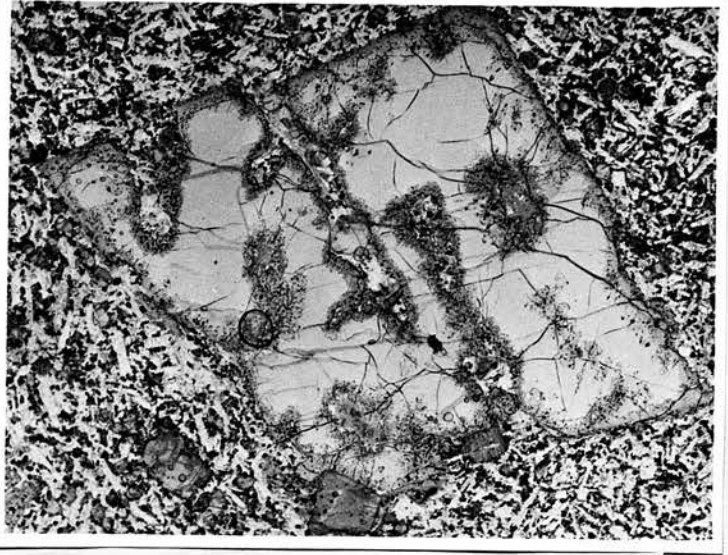


PLATE XIX.

Basalts of Craiglockhart Type, from the Whinny Hill intrusion.

Fig. 1

Large corroded plagioclase crystal partly or wholly enclosing augite, olivine and other plagioclase crystals, forming a gabbroic xenolith. Corrosion has occurred around the margins of some of the partially enclosed crystals, and a group of two augites and an olivine crystal (6 o'clock) have been almost completely separated from the group (see p. 83).
Ordinary light, x 20.

Fig. 2

Intergrowth (?) of augite and olivine (described on p. 142).
Ordinary light, x 35.

Fig. 3

Partial enclosure of small augite crystal by an almost euhedral olivine.
Ordinary light, x 29.

Fig. 4

Broken olivine crystal. The two halves have moved apart, and are not quite in optical continuity with each other.
Ordinary light, x 16.

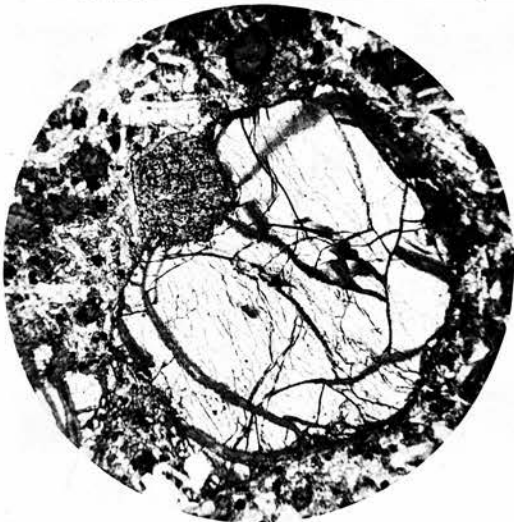
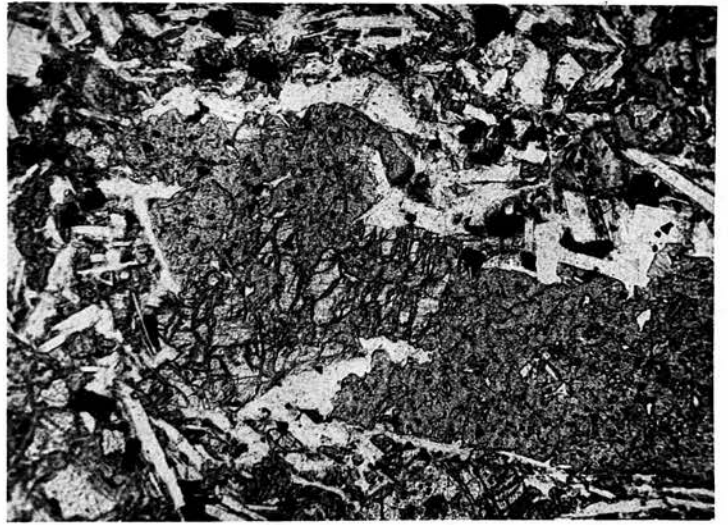


PLATE XX.

Fig. 1

Basalt of Markle type, Whinny Hill
lava (pp. 93 - 94). Representative
field of section cut from analysed
specimen.
Ordinary light x 13.

Fig. 2

Basalt of Dalmeny type (described on
p. 97), Lion's Head intrusion.
Representative field of section from
analysed specimen.
Ordinary light x 13.
(Photomicrographs of the Dalmeny
basalt of Lava III appear on p. 114).

Fig. 3

Basalt of Jedburgh type.
Margin of dyke, Raven's Rock, Lion's
Haunch vent. The margin of the dyke
has been brecciated, and slight move-
ment of the fragments has occurred
(see p. 102).
Ordinary light, x 15.

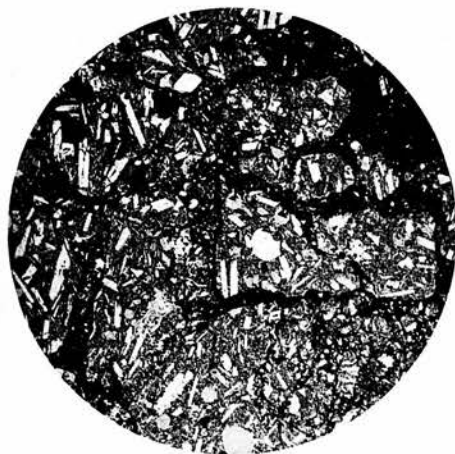


PLATE XXI.

Fig. 1

Mugearite, from lava east of Dunsapie Hill (described on p. 106).
Crossed nicols, x 34.

Fig. 2

Basalt of Jedburgh type with ophitic augite. Lava IV, Whinny Hill, 700ft. north of vent margin (p. 116).
Ordinary light, x 50.

Fig. 3

Basalt of Jedburgh type with euhedral and subhedral augite. Lava VI, Whinny Hill, 450 feet north of vent margin (p. 116).
Ordinary light, x 50.



ARTHUR'S SEAT

- | | | |
|--|-------------------------|---|
| | Lower Carboniferous | } Sediments |
| | Upper Old Red Sandstone | |
| | Tuff | Lst. ... Limestone
Sdst. ... Sandstone |
| | Vent agglomerate | O ... Mugarite
t ... Teschenite |
| | Intrusive basaltic rock | V ... Dalmeny type
W ... Jedburgh type |
| | Lava | X ... Craiglockhart type
Y ... Normal Dunsapie type
Y' ... Feldspathic Dunsapie type
Z ... Markle type |

