Carboniferous and Permian igneous activity, Midland Valley of Scotland

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Carboniferous and Permian igneous activity

Volcanic rocks of Carboniferous and Permian age in Midland Valley. P915542.

Diagrammatic representation of geographical and stratigraphical distribution of Carboniferous and Permian igneous rocks of the Midland Valley.
Following a long period of magmatic quiescence during the Middle and Upper Devonian, igneous activity became widespread in the Midland Valley during the early to middle Viséan when thick plateaux of alkali olivine-basalt and related lavas were formed. Thereafter, smaller, localised centres of more explosive pyroclastic activity and/or alkali basalt lava flows erupted somewhere in the Midland Valley throughout almost the entire succession, up to and including the Lower Permian. The later volcanic episodes were accompanied by the intrusion of thick, widespread sills-complexes of various alkali dolerite types, notably during the late Namurian and early Westphalian in the east, and during the Stephanian and Lower Permian in the west. The alkali basalt activity was interrupted during the late Westphalian or early Stephanian by a widespread suite of tholeiitic sills and dykes with no known extrusive equivalents.

The alkali olivine-basalts, dolerites and related differentiates constitute a major continental, alkaline province which has been studied extensively since the early days of igneous geology.

**Volcanic activity**

**Distribution in space and time**

Outcrops of Carboniferous and Permian volcanic rocks are shown on [P915542](#). Many of the volcanic formations are interbedded with well established, often fossiliferous, stratigraphical successions and it is relatively easy to trace their development. This is particularly true of the late Viséan and Silesian volcanic sequences and some of the early Viséan outcrops of the eastern Midland Valley. Correlation is less easy in the Viséan of the western Midland Valley where sedimentary intercalations are rare within the thick lava sequences, which replace much of the poorly fossiliferous parts of the Calciferous Sandstone Measures. The principal volcanic developments of the Midland Valley are shown in relation to the established Carboniferous stratigraphy in [P915543](#).

**Petrography of the lavas**

The majority of lavas are basaltic and range from ankaramite to basalt to hawaiite in bulk chemical composition. Lavas of intermediate composition are mainly mugearites, although trachybasalts and trachyandesites are recorded and trachytes, quartz-trachytes and rhyolites are present in some centres. Nepheline-bearing differentiates such as phonolitic trachyte and phonolite are restricted to subvolcanic intrusions.

The basaltic rocks are almost always porphyritic, enabling a classification based upon the size and occurrence of the plagioclase, clinopyroxene and olivine phenocrysts which is easily applied to field mapping (MacGregor, 1928). Names are based upon type localities in central and southern Scotland and the classification is still in active use. Although some of MacGregor’s petrographic categories include a range of petrochemical compositions, a general correlation is possible with currently accepted terminology (See table; Macdonald, 1975). Notable departures from a true ‘basalt’ composition are the very mafic flows (Craiglockhart type) which are ankaramitic, the feldsparphyric flows (Jedburgh and Markle types) which are often hawaiites and some Hillhouse types which are basanites.
### Basalt type of MacGregor (1928)

<table>
<thead>
<tr>
<th>Phenocrysts - sometimes present in lesser amounts</th>
<th>Chemical classification of Macdonald (1975)</th>
<th>Type locality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenocrysts abundant</td>
<td>± ol, Fe-oxide</td>
<td>Markle Quarry, East Lothian (flow)</td>
</tr>
<tr>
<td>Phenocrysts - sometimes present in lesser amounts</td>
<td>ol-cpx-plag-Fe-oxides-phyric basaltic hawaiites, or ol-cpx-plag-phyric basalts</td>
<td>Dunsapie Hill, Edinburgh (vent intrusion)</td>
</tr>
<tr>
<td>glaciers</td>
<td>Antarctic</td>
<td></td>
</tr>
</tbody>
</table>

**Macrophyrophytic**
- Marke: plag
- Dunsapie: plag + ol + cpx, Fe-oxide
- Craiglockhart: ol + cpx

**Microphyrophytic**
- Jedburgh: plag, ol, Fe-oxide
- Dalmeny: ol, cpx, plag
- Hillhouse: ol + cpx

The mugearites are typically fine-grained and aphyric with a platy parting parallel to a planar flow-alignment of plagioclase crystals. Titanomagnetite and apatite are more abundant in rocks of intermediate composition and hornblende phenocrysts are sometimes present in the trachybasalts and trachyandesites. Trachytes and rhyolites may contain phenocrysts of sanidine, quartz and rarely biotite, hornblende or augite.

The range of lava types present in any one area varies considerably but Macdonald (1975) defines three main volcanic associations. The first includes a full range of compositions from ankaramite to trachyte such as occurs in East Lothian and most of the southern Clyde Plateau. The second is characterised by feldspar-phyric hawaiites and mugearites with local trachytes as in the north-eastern part of the Clyde Plateau. The third has a restricted range of ankaramites and olivine- or olivine-pyroxene-microporphyrstic basalts such as occurs in most of the Namurian and younger suites.

The basaltic lavas can be remarkably fresh, although olivine is usually replaced by red-brown pseudomorphs. Less fresh material shows varying degrees of albitisation, chloritisation, oxidation, hydration and replacement by carbonate. Albitisation in particular can lead to considerable difficulties in petrographic and petrochemical classification. A high proportion of many flows consists of zones of amygdaloidal material, autobrecciated and/or hydrothermally altered rubble and slaggy, vesicular flow tops. Typical amygdale and vein assemblages involve combinations of chlorite, hematite, calcite, quartz and chalcedony. Zones of intense, possibly penecontemporaneous, hydrothermal alteration commonly contain a range of zeolites and related minerals (e.g. stibite,
heulandite, analcime, prehnite, apophyllite, pectolite) and native copper is known from several localities (e.g. Boylestone Quarry, Barrhead). The more differentiated rocks are usually heavily altered throughout and silicification is common in the rhyolites.

**Inclusions in volcanic and sub-volcanic rocks**

A wide variety of xenolithic igneous inclusions and megacrysts are found in many intrusions, pyroclastic deposits and more rarely lavas, particularly in east Fife, East Lothian and Ayrshire. The nodule suites are regarded as broadly contemporaneous with their host rocks and this has been supported by radiometric age determinations in east Fife. Particularly well-documented suites have been extracted from vents at Partan Craig, East Lothian and Elie Ness, east Fife.

In addition to fragments of metamorphic continental crust and contemporaneous lavas, often of a basanitic or monchiquitic nature, inclusions of ultramafic and ultrabasic material are relatively abundant. Magnesian peridotites, usually showing a metamorphic texture, may represent upper mantle wallrock depleted by partial melting episodes. Undeformed rocks may represent slightly younger intrusions within the mantle and consist of a wide spectrum of clinopyroxene-bearing ultramafites, orthopyroxenites and garnet-spinel-peridotites. In some areas (e.g. East Lothian) the pyroxenites contain potassic hydrous minerals such as amphibole (kaersutite) and biotite, suggestive of potash metasomatism within the mantle. Ultrabasic and basic rocks, often with a cumulus texture, consist of combinations of plagioclase, olivine, augite, kaersutite and biotite. Such minerals also occur as disaggregated megacrysts along with titaniferous garnet (known locally as ‘Elie ruby’), zircon, corundum and apatite in assemblages suggestive of a high pressure origin.

Higher level, crustal or sub-crustal magma chambers are a more likely source for xenoliths of layered gabbro and picrite or more rarely syenite, and for megacrysts of anorthoclase.

**Magma genesis and tectonic setting**

The magmatism which persisted in the Midland Valley for some 70 Ma during the Carboniferous and early Permian is typical of that which occurs in continental rift environments throughout the world. The alkaline basic rocks range from hypersthene-normative, transitional basalts to more strongly-alkaline, nepheline-normative basanitic and nephelinitic varieties. The rocks of the quartz-dolerite suite have been classed as ‘High Fe-Ti tholeiite’ type and are intermediate in alkali content between true tholeiitic and alkali basalt magma types.

Recent geochemical studies, mostly by Macdonald and others (1975, 1977, 1980, 1981), suggest that all the magmas have been derived by variable degrees of partial melting of an upper mantle source and that crustal contamination has been negligible. Trace element studies have revealed variations between the basic lavas of different areas and also between individual quartz-dolerite dykes, which have been attributed to long lasting inhomogeneity in the mantle source rocks. Further evidence of the nature of the mantle source has been obtained from mineralogical studies and melting experiments on xenolithic nodules and megacrysts.

Fractionation of alkali basalt magma at crustal levels to give intermediate and salic lavas appears to have been active only during the Dinantian activity. Almost all of the more fractionated lavas are silica-saturated or oversaturated, although undersaturated, feldspathoidal trachytic rocks occur as intrusions. These differentiates have enabled several magmatic lineages to be recognised from major element chemistry. Field evidence of high-level fractionation processes is seen in several varieties of composite lava flow, which are relatively common in the Dinantian sequences. The tholeiitic magmas probably fractionated at depth from an olivine-tholeiite to quartz-tholeiite and limited high-level
fractionation is seen in a few dykes of tholeiitic andesite composition (e.g. the Kinkell dyke, Stirlingshire).

Throughout the period of Carboniferous-Permian magmatism, there is a progressive general tendency for more-alkaline, highly-undersaturated basic rocks to constitute an increasingly higher proportion of the lavas and intrusions. This overall pattern is interrupted by the eruption of transitional or mildly-alkaline basalts, for example in the Passage Group of Ayrshire, and also by the late Carboniferous tholeiitic intrusions. It is therefore probable that several magmatic cycles occurred throughout the period. Macdonald and others (1977) interpret such cycles as separate thermal events during which large volumes of silica-saturated magmas were generated at high mantle levels, under the high geothermal gradients of the initial stages, followed by smaller volumes of more undersaturated magma from deeper levels as gradients were reduced in the waning stages.

Following the closure of the Iapetus Ocean in Lower Devonian time, the Midland Valley graben began to develop as an intra-continental rift. By Lower Carboniferous time, the area had become part of the southern marginal shelf of the N. America–N. Europe craton and the nearest plate boundaries were well to the south and east of the British Isles. In such a mid plate environment, tensional stress conditions prevailed and lithospheric stretching led to rifting and increased thermal gradients with consequent mantle melting.

Fundamental crustal fractures with a Caledonian NE–SW trend, which had probably acted as tectono-magmatic controls during the Lower Devonian, continued to influence upper crustal faulting and the siting of volcanic centres during the Dinantian (e.g. the Dumbarton–Fintry line). Such fractures acted as hinge lines, dividing the rift into basins and swells and thereby influencing both volcanicity and sedimentation.

By late Namurian and Westphalian time, the rift structures had become less active, the structural swells had begun to lose their identity and more widespread sedimentary basins were developed. This coincided with a change towards reduced amounts of generally more-undersaturated and more explosive alkali basaltic volcanicity and the emplacement of alkali dolerite sills within the thickening sedimentary sequences.

During the main phase of the Hercynian Orogeny, plate collision to the south of the British Isles generated dominantly compressive forces in the Midland Valley. Caledonian structures were reactivated and uplift resulted in the absence of Stephanian strata. Subsequent stress release generated new E-W major fractures, extending from Scotland and N England across the North Sea. High geothermal gradients resulted in mantle melting at relatively shallow levels and tholeiitic magmas rose along the E-W fractures.

The igneous activity which followed the tholeiitic episode in the late Stephanian/early Permian was entirely of a more-undersaturated nature than any of the preceding episodes and should possibly be considered as a separate tectono-magmatic event. In the eastern Midland Valley volcanicity was still controlled by NE-SW structures (e.g. the Ardross Fault), but in the west, activity seems to have been controlled by new NW- or NNW-trending structures. It has been suggested that these structures are part of a new rift extending from Arran to the Vale of Eden and contemporaneous with similar rifts in the North Sea and Norway. This Permian rift system may signify the initial crustal thinning and break-up of the N America–N Europe craton prior to the formation of a proto-N Atlantic oceanic rift.

**Bibliography**


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