Carboniferous and Permian Igneous Rocks of Great Britain

North of the Variscan Front

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Access to the countryside

This volume is not intended for use as a field guide. The description or mention of any site should not be taken as an indication that access to a site is open. Most sites described are in private ownership, and their inclusion herein is solely for the purpose of justifying their conservation. Their description or appearance on a map in this work should not be construed as an invitation to visit. Prior consent for visits should always be obtained from the landowner and/or occupier.

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Ffordd Penrhos,
Bangor,
Gwynedd LL57 2LQ.

English Nature,
Northminster House,
Peterborough PE1 1UA.

Scottish Natural Heritage,
12 Hope Terrace,
Edinburgh EH9 2AS.

Preface

There is such a diversity of rocks, minerals, fossils and landforms packed into the piece of the Earth's crust we call 'Britain' that it is difficult not to be impressed by the long, complex history of geological change to which they are testimony. But if we are to improve our understanding of the nature of the geological forces that have shaped our islands, further unravel their history in 'deep time' and learn more of the history of life on Earth, we must ensure that the most scientifically important of Britain's geological localities are conserved for future generations to study, research and enjoy. Moreover, as an educational field resource and as training grounds for new generations of geologists on which to hone their skills, it is essential that such sites continue to remain available for study. The first step in achieving this goal is to identify the key sites, both at national and local levels.

The GCR, launched in 1977, is a world-first in the systematic selection and documentation of a country's best Earth science sites. No other country has attempted such a comprehensive and systematic review of its Earth science sites on anything near the same scale. After over two decades of site evaluation and documentation, we now have an inventory of over 3000 GCR sites, selected for 100 categories covering the entire range of the geological and geomorphological features of Britain.

This volume, describing the Carboniferous and Permian igneous rocks of Great Britain, is the 27th to be published in the intended 42-volume GCR series. Not only does it contain the descriptions of key localities that will be conserved for their contribution to our understanding of the igneous of rocks of this age, but also provides an excellent summary of the petrological features and palaeogeographical significance to be found in them, and it outlines the research that has been undertaken on them. The book will be invaluable as an essential reference book to those engaged in the study of these rocks and will provide a stimulus for further investigation. It will also be helpful to teachers and lecturers and for those people who, in one way or another, have a vested interest in the GCR sites: owners, occupiers, planners, those concerned with the practicalities of site conservation and indeed the local people for whom such sites are an environmental asset. The conservation value of the sites is mostly based on a specialist understanding of the stratigraphical, palaeontological and sedimentological features present and is therefore, of a technical nature. The account of each site in this book ends, however, with a brief summary of the geological interest, framed in less technical language, in order to help the non-specialist. The first chapter of the volume, used in conjunction with the glossary, is also aimed at a less specialized audience. This volume is not intended to be a field guide to the sites, nor does it cover the practical problems of their ongoing conservation. Its remit is to put on record the scientific justification for conserving the sites.

This volume deals with the state of knowledge of the sites available at the time of writing, in 1998–2001, and must be seen in this context. Geology, like any other science, is an ever-developing pursuit with new discoveries being made, and existing models are subject to continual testing and modification as new data come to light. Increased or hitherto unrecognized significance may be seen in new sites, and it is possible that further sites worthy of conservation will be identified in future years.

There is still much more to learn and the sites described in this volume are as important today as they have ever been in increasing our knowledge and understanding of the geological history of Britain. This account clearly demonstrates the value of these sites for research, and their important place in Britain's scientific and natural heritage. This, after all, is the *raison d'être* of the GCR Series of publications.

N.V. Ellis
GCR Publications Manager
May 2002

Chapter 1

Carboniferous and Permian igneous rocks of Great Britain north of the Variscan Front: an introduction

INTRODUCTION

D. Stephenson

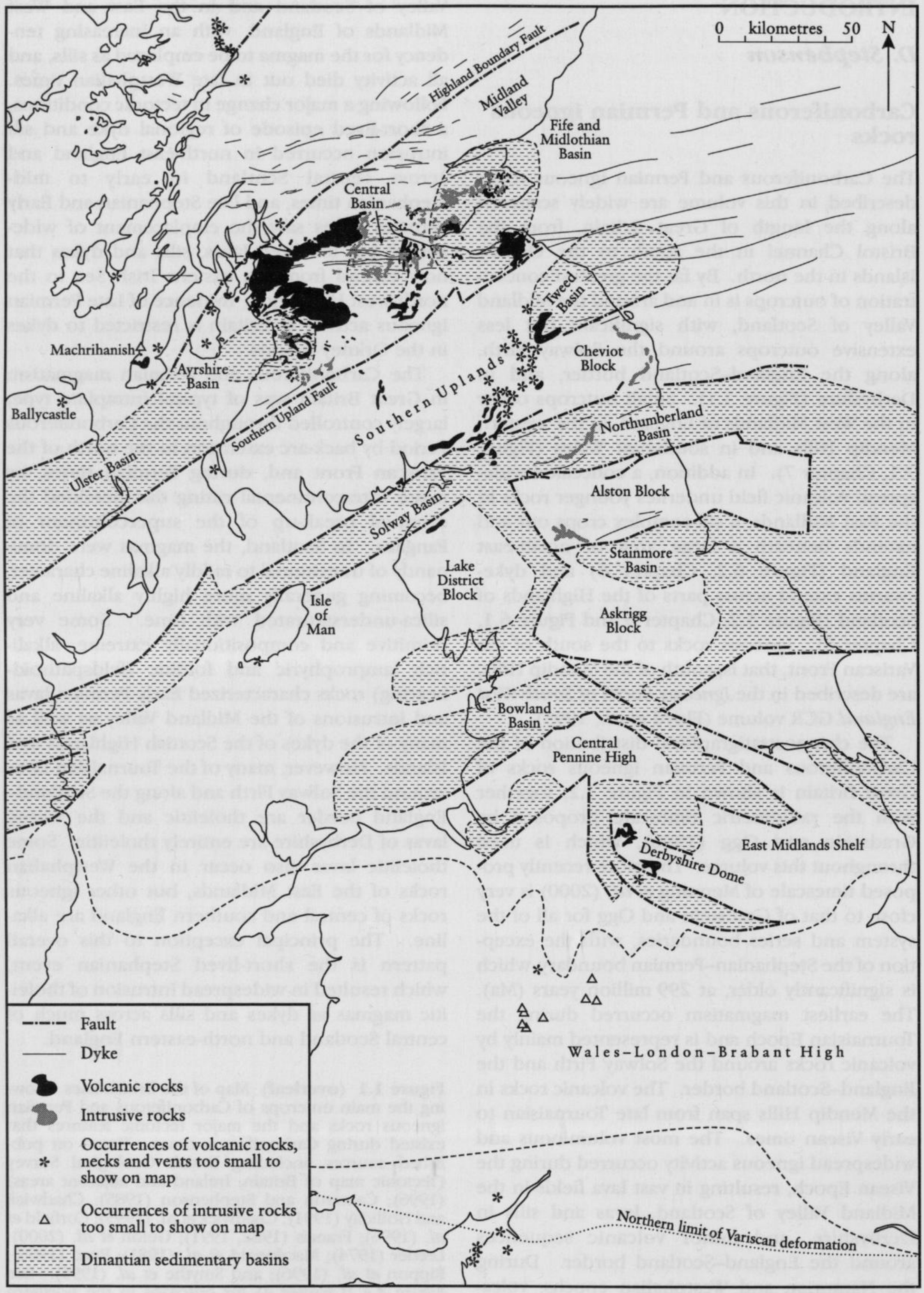
Carboniferous and Permian igneous rocks

The Carboniferous and Permian igneous rocks described in this volume are widely scattered along the length of Great Britain, from the Bristol Channel in the south to the Orkney Islands in the north. By far the greatest concentration of outcrops is in and around the Midland Valley of Scotland, with significant but less extensive outcrops around the Solway Firth, along the England–Scotland border, and in Derbyshire (Figure 1.1). Small outcrops occur in the West Midlands of England, in the western Mendip Hills and in south-east Wales (Figure 7.1, Chapter 7). In addition, a concealed widespread volcanic field underlies younger rocks in the East Midlands, a sill-complex crops out and extends beneath a large area of north-east England (Figure 6.2, Chapter 6) and dyke-swarms extend across parts of the Highlands of Scotland (Figure 5.2, Chapter 5 and Figure 6.1, Chapter 6). Igneous rocks to the south of the Variscan Front, that is, south of the Mendip Hills, are described in the *Igneous Rocks of South-West England* GCR volume (Floyd *et al.*, 1993).

The chronostratigraphical distribution of the Carboniferous and Permian igneous rocks of Great Britain is shown in Figure 1.2, together with the radiometric timescale proposed by Gradstein and Ogg (1996), which is used throughout this volume. The more recently proposed timescale of Menning *et al.* (2000) is very close to that of Gradstein and Ogg for all of the system and series boundaries, with the exception of the Stephanian–Permian boundary, which is significantly older, at 299 million years (Ma). The earliest magmatism occurred during the Tournaisian Epoch and is represented mainly by volcanic rocks around the Solway Firth and the England–Scotland border. The volcanic rocks in the Mendip Hills span from late Tournaisian to early Visean times. The most voluminous and widespread igneous activity occurred during the Visean Epoch, resulting in vast lava fields in the Midland Valley of Scotland, lavas and sills in Derbyshire, and minor volcanic sequences around the England–Scotland border. During the Namurian and Westphalian epochs, volcanism became more localized in the Midland Valley of Scotland and in the East and West Midlands of England, with an increasing tendency for the magma to be emplaced as sills, and all activity died out in late Westphalian times. Following a major change in tectonic conditions, a short-lived episode of regional dyke and sill intrusion occurred in north-east England and across central Scotland in early to mid-Stephanian times, and late Stephanian and Early Permian times saw the emplacement of widespread but localized lavas, sills and dykes that now extend from the eastern Irish Sea to the north-west Highlands. Evidence of Late Permian igneous activity in Britain is restricted to dykes in the Orkney Islands.

The Carboniferous and Permian magmatism in Great Britain was of typical intraplate type, largely controlled throughout the Carboniferous Period by back-arc extension to the north of the Variscan Front and, during Permian times, by major intracontinental rifting that heralded the eventual break-up of the supercontinent of Pangaea. In Scotland, the magmas were dominantly of transitional to mildly alkaline character, becoming generally more highly alkaline and silica-undersaturated with time. Some very primitive and compositionally extreme, alkali-rich lamprophyric and foiditic (feldspathoid-bearing) rocks characterized Early Permian lavas and intrusions of the Midland Valley as well as many of the dykes of the Scottish Highlands and Islands. However, many of the Tournaisian lavas around the Solway Firth and along the Scotland–England border are tholeiitic and the Visean lavas of Derbyshire are entirely tholeiitic. Some tholeiitic lavas also occur in the Westphalian rocks of the East Midlands, but other igneous rocks of central and southern England are alkaline. The principal exception to this overall pattern is the short-lived Stephanian event, which resulted in widespread intrusion of tholeiitic magmas as dykes and sills across much of central Scotland and north-eastern England.

Figure 1.1 (overleaf) Map of the British Isles, showing the main outcrops of Carboniferous and Permian igneous rocks and the major tectonic features that existed during Carboniferous times. Based on published sources, including British Geological Survey (Tectonic map of Britain, Ireland and adjacent areas) (1996); Cameron and Stephenson (1985); Chadwick and Holliday (1991); Chadwick *et al.* (1995); Corfield *et al.* (1996); Francis (1982, 1991); Guion *et al.* (2000); Leeder (1974); Macdonald *et al.* (1981); Read (1988); Rippon *et al.* (1996); and Smythe *et al.* (1995). See Figure 4.4 (Chapter 4) for outcrops in the northern Highlands.


0 kilometres 50
N
Highland Boundary Fault
Midland Valley
Fife and Midlothian Basin
Central Basin
Tweed Basin
Machrihanish
Ayrshire Basin
Cheviot Block
Ballycastle
Southern Upland Fault
Southern Uplands
Northumberland Basin
Ulster Basin
Alston Block
Solway Basin
Stainmore Basin
Lake District Block
Isle of Man
Askrigg Block
Bowland Basin
Central Pennine High
East Midlands Shelf
Derbyshire Dome
Fault
Dyke
Volcanic rocks
Intrusive rocks
Occurrences of volcanic rocks, necks and vents too small to show on map
Occurrences of intrusive rocks too small to show on map
Dinantian sedimentary basins
Wales–London–Brabant High
Northern limit of Variscan deformation

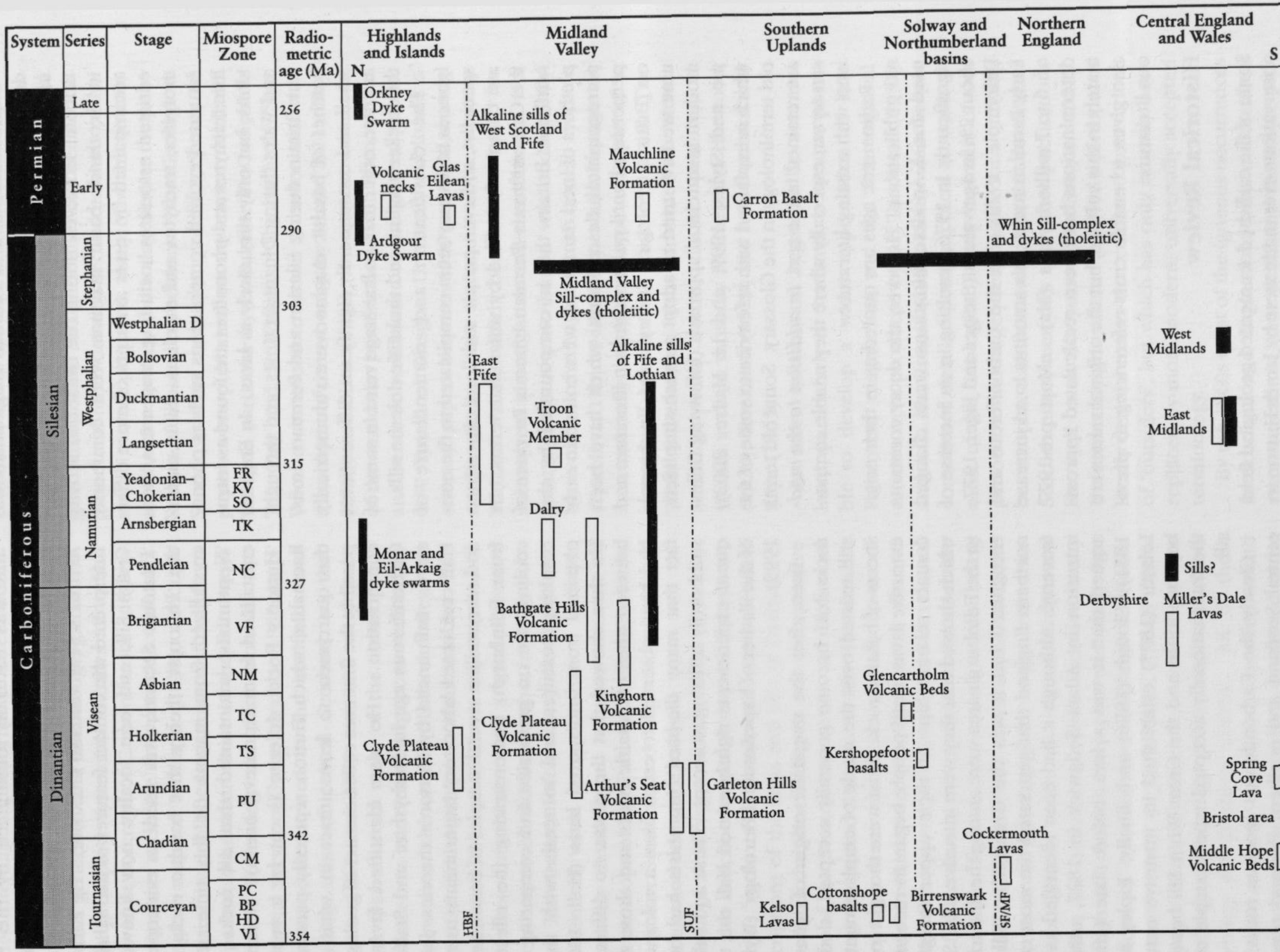


Figure 1.2 Stratigraphical distribution of British Carboniferous and Permian extrusive rocks (open bars) and intrusive rocks (solid bars). Timescale after Gradstein and Ogg (1996). See individual chapters for more detailed stratigraphical charts. (HBF = Highland Boundary Fault; SUF = Southern Upland Fault; SF = Stublick Fault; MF = Maryport Fault.)

Carboniferous and Permian magmatism was dominantly basic, resulting in basaltic to hawaiitic lavas and doleritic intrusions throughout Britain. However, during the Dinantian activity in Scotland, basic magmas were commonly accompanied by lesser amounts of more differentiated associates including mugearites, benmoreites, trachytes and rhyolites. Silica-undersaturated evolved compositions such as phonolitic trachytes and phonolites are found as intrusions, but only very rarely as lavas. In England and Wales during Dinantian times, and throughout Britain during Silesian and Permian times, batches of basaltic magma were volumetrically small and consequently significant differentiates are rare, other than as late-stage veins in some of the thicker alkaline and tholeiitic dolerite sills.

The classification and nomenclature of igneous rocks may seem complicated to the non-specialist, and even people with long experience are commonly baffled by unfamiliar terms. In the Carboniferous–Permian Igneous Province of northern Britain this is compounded by the plethora of local names that were coined in early petrographical descriptions, which have been perpetuated until quite recently in literature and on [British] Geological Survey maps. In this volume we have tried to adopt a much-simplified, modern hierarchical approach (following Gillespie and Styles, 1999; and Le Maitre, 2002), which is explained with reference to some of the old terminology in the Glossary. Some old terms are retained in the text, ***in addition to the modern terms***, especially where they enable comparison with existing literature.

Radiometric ages are quoted as in their original publications. However, the decay constants used for K-Ar determinations were changed significantly in 1976, resulting in an increase of about 2% in age values (Steiger and Jäger, 1977; Dalrymple, 1979). In the Carboniferous and Early Permian rocks, this amounts to an increase of 6 to 7 million years (Ma). Most pre-1977 determinations have been recalculated approximately in this volume, but the original values are also given to enable cross-referencing to previous literature.

Historical Review

Some of the earliest documented geological field observations ever made were by James Hutton in the course of formulating his *Theory of the Earth* (Hutton, 1788). Hutton lived in Edinburgh and was naturally influenced by the Early Carboniferous igneous rocks of Holyrood Park, Calton Hill and the Castle Rock (i.e. the **Arthur's Seat Volcano** GCR site). He correctly interpreted the contact features of the Salisbury Craigs Sill, and one locality, now known as 'Hutton's Section', was used as evidence for the 'Plutonist' theory that basaltic rocks had crystallized from magma (at this time, many 'Neptunists' maintained that all rocks had crystallized from a primeval ocean). Nearby at 'Hutton's Rock', dolerite is cut by a vein of haematite, which Hutton reputedly persuaded the quarrymen to leave intact in what was possibly the first ever conscious act of geological conservation. He also identified lavas of Carboniferous age in Derbyshire and Staffordshire. Influenced by Hutton's theories, James Hall conducted laboratory experiments to melt and recrystallize several samples of basaltic rock from Edinburgh, demonstrating the effect of cooling rate on grain size and comparing the resulting textures and minerals with those obtained from undisputed lavas (Hall, 1805). He thus showed that there was no difference between ancient basaltic rocks and those that had been observed to erupt from a volcano, a fact that many die-hard Neptunists had been stubbornly refusing to accept. These and subsequent experiments rightly earned Hall the title of the 'Father of Experimental Petrology' (Wyllie, 1999).

Even after the magmatic origin of igneous rocks had become generally accepted, doubts still existed over the mode of emplacement of sheets of basaltic rock. Most were thought to be extrusive lavas, until people began to recognize contact relationships at their upper margins, which showed that they were intrusive sills. Sills in the Edinburgh area were among the first to be recognized but it was the Great Whin Sill in northern England that generated the most controversy. Although it had been identified as an intrusion by Adam Sedgwick in 1827, others argued that it was a lava, before Tate (1867, 1871), Clough (1876) and, finally, Topley and Lebour (1877) established its intrusive nature beyond doubt and the Great Whin Sill became the internationally accepted type example of a sill.

Clearly the Carboniferous igneous rocks of central Scotland and northern England played a major role in the early development of geological principles and hence they rapidly attained international importance. Over a dozen accounts of aspects of the Arthur's Seat Volcano were published in the 19th century and the attention generated and knowledge gained no doubt prompted systematic studies of other areas. Most outcrops of Carboniferous and Permian igneous rocks are shown on MacCulloch's geological map of Scotland (1840), although there are few published accounts that date from this period, other than those of the Edinburgh district. Following the formation of the Geological Survey of Great Britain in 1835, mapping was concentrated in the coalfields and adjoining areas of central Scotland, so that between 1861 and 1879 memoirs were published that covered most of the outcrops of Carboniferous and Permian igneous rock in the Glasgow area, the central Midland Valley, the Lothians and Ayrshire. Memoirs for Fife followed in 1901 and 1902. A major author of all of these memoirs, and of several derivative papers, was Archibald Geikie who, in 1897, published *The Ancient Volcanoes of Great Britain*. This seminal work, in two volumes, includes remarkably detailed and accurate accounts of most outcrops of Late Palaeozoic extrusive rocks throughout Scotland and England, which still have use and relevance today.

Geological Survey memoirs of the 19th century also described most of the Late Palaeozoic igneous rocks of England, and more detailed descriptions of the lavas and sills of Derbyshire, the sills of the West Midlands and the extrusive rocks of the Weston-super-Mare area followed during the period 1894 to 1917. The notable exceptions were the Cockermouth Lavas of Cumbria, which were not described at all until 1928. Descriptive petrography had developed to a fine art during this period and the scientific deductions from such studies were being applied, along with field observations, to create a better understanding of the origin and evolution of igneous rocks. S. Allport's influential treatise on dolerites in 1874 included many Scottish and English examples and many first editions of standard petrographical textbooks appeared, such as J.J.H. Teall's *British Petrography* (1888), F.H. Hatch's *An Introduction to the Study of Petrology* (1891) and A. Harker's *Petrology for Students* (1895). All of these included examples of British Carboniferous and Permian igneous rocks, which continued to be used in subsequent editions to instruct generations of students.

The first half of the 20th century saw an explosion in detailed studies of individual lava fields and intrusions. In Scotland, the primary geological survey of the Midland Valley had been completed and more detailed second editions of the memoirs were prepared, many of which remain as definitive sources to this day, despite the publication of subsequent editions. Non-Geological Survey workers were also prolific. Scores of papers were published on the eastern Midland Valley, in particular by D. Balsillie, R. Campbell, T.C. Day and F. Walker. The Arthur's Seat Volcano continued to attract attention and was the subject of three books, by Peach (1911), Day (1933) and Black (1966); few ancient volcanoes of the world can possibly be so well documented and hence so well known to the general public. G.W. Tyrrell of Glasgow University published a series of papers between 1909 and 1952, mostly on the alkaline basic intrusions of the western Midland Valley, which became the basis for subsequent identification and classification. His most significant contribution was undoubtedly his work on the Lugar Sill of central Ayrshire (Tyrrell, 1917b, 1948, 1952), which became an internationally recognized type example of a layered and differentiated alkaline basic sill. The Whin Sill-complex also continued to attract attention with some classic petrological studies such as those by Holmes and Harwood (1928), Tomkeieff (1929) and A.C. Dunham and Kaye (1965).

As more information began to be accumulated, particularly in Scotland, it became possible to develop a wider appreciation of Late Palaeozoic magmatism and the first regional reviews were produced by S.I. Tomkeieff (1937) and A.G. MacGregor (1937, 1948). MacGregor contributed detailed petrographical accounts to most of the Geological Survey memoirs of this period and was largely responsible for a unifying but complex classification scheme that dominated Scottish maps, memoirs and other publications for well over 50 years (MacGregor, 1928). Unfortunately this scheme involved a plethora of locally derived names that confused generations of 'outsiders', but which has only recently been replaced by more modern, universally accepted terminology.

By the 1960s most of the igneous occurrences in Scotland and England had been described systematically in some detail and the whole province was already one of the best documented in the world. Between then and the present day, most of the key geological maps have been revised and the accompanying memoirs have described the magmatism in an updated stratigraphical and structural setting. During the same period, academic workers have turned to more specific problems, many of which have had international implications.

One of the first themes to be explored was the relationship between volcanism and sedimentation, and foremost in this was E.H. Francis, who drew upon wide experience of mapping and borehole logging for the Geological Survey in the eastern Midland Valley of Scotland. In addition to Geological Survey memoir contributions, Francis produced a dozen papers between 1957 and 1970 on this general theme and more specifically on the development of explosive volcanic vents within piles of wet sediments. Similar phenomena have been described more recently from the English West Midlands by Glover *et al.* (1993) and relationships between volcanism and carbonate sedimentation have been described from the Midland Valley, Derbyshire and south-west England (Walkden, 1977; Jameson, 1987; Faulkner, 1989b). On a broader scale, the presence of igneous rocks has had a major influence upon theories of Late Palaeozoic basin development, a theme that is explored more fully below (see 'Tectonic setting and evolution', this chapter).

Studies of the intrusive rocks have either concentrated upon detailed geochemical and mineralogical investigations (see below), or on mechanisms of intrusion. The most influential paper on the latter theme has been that of Francis (1982), in which he explained the emplacement of the large tholeiitic sill-complexes of northern Britain in terms of the impregnation of sedimentary basins by magma supplied from marginal dykes. Further work on alkaline basic sills of Fife led to the contrasting suggestion that many of these sills were intruded at higher levels into unconsolidated water-saturated sediments and may have been fed by magma emanating outwards from volcanic pipes after the route to the surface had become blocked (Francis and Walker, 1987). Work currently in progress is applying magnetic measurements to determine magmatic flow directions in the Whin Sill-complex, and related dykes, and this could have far-reaching applications (Liss *et al.*, 2001).

Prior to 1975, geochemical analyses were mostly confined to [British] Geological Survey publications, apart from specialist studies on various sills and the review of the 'petrochemistry' of Scottish Carboniferous and Permian igneous rocks by Tomkeieff (1937). Since then, the whole-rock geochemistry of the province has been well documented, initially as a result of R. Macdonald of Lancaster University and co-workers, who have published a series of papers covering most of the major suites in Britain, including Scotland (Macdonald, 1975, 1980; Macdonald *et al.*, 1977, 1981); the Whin Sill-complex (Thorpe and Macdonald, 1985); the Cockermouth Lavas (Macdonald and Walker, 1985); and Derbyshire (Macdonald *et al.*, 1984). A Lancaster University thesis and subsequent paper by Kirton (1981, 1984) investigated the geochemistry of lavas from the English Midlands and some geochemical details of lavas in south-west England were given in a University of Bristol thesis by Faulkner (1989a). The alkaline dyke-swarms of the Scottish Highlands were the subject of a comprehensive geochemical study by Baxter (1987) and the Lugar Sill was re-appraised by Henderson and Gibb (1987). A series of studies at the University of Edinburgh, led by B.G.J. Upton and J.G. Fitton, have produced a number of theses that are vital sources of data and have provided interpretations of magma genesis and evolution based upon trace-element, rare-earth-element and isotope data. These include Smedley (1986a, with subsequent papers 1986b, 1988a,b) on the Dinantian igneous rocks of Scotland, Wallis (1989) on the Silesian and Permian igneous rocks of Scotland, and Howard (1999) on the tholeiitic intrusions of Scotland and northern England.

Carboniferous and Permian igneous rocks have been recognized as key targets for radiometric dating since the very early days of the science, when Arthur Holmes was pioneering the 'Helium Method' (Lewis, 2001). He selected the Great Whin Sill for its proximity to the Carboniferous–Permian boundary during his early attempts to construct a geological timescale (Dubey and Holmes, 1929), and a dyke from Colonsay and one of the Clee Hills sills were selected as intrusions of problematic age for a later study (Urry and Holmes, 1941). Subsequently, K-Ar whole-rock determinations on a wide range of mainly intrusive rocks were determined by F.J. Fitch and co-workers (Fitch and Miller, 1964, 1967; Fitch *et al.*, 1969, 1970). Extrusive rocks were generally considered to be too prone to alteration and consequent argon loss for K-Ar determinations, but De Souza (1974, 1979, 1982) selected the freshest samples from Scottish lavas and intrusions and also performed determinations on separated minerals, which did produce seemingly more precise results. Other workers have also produced many K-Ar dates based on whole-rock and mineral analyses from various localities throughout Scotland, and Wallis (1989) has attempted to select and rationalize the most reliable Silesian and Permian data. However, few of the K-Ar results are satisfactory by modern standards. Clearly there is now much scope for more precise dating of crucial intrusions and, where possible, of lavas at key points in the stratigraphical succession using modern Ar-Ar and U-Pb methods. So far only one reliable U-Pb date, from a zircon megacryst within a volcanic neck (Macintyre *et al.*, 1981), and two Ar-Ar dates, have been published (Henderson *et al.*, 1987; Upton *et al.*, 1998). However, work is currently in progress to improve the situation (M.A. Hamilton, A.A. Monaghan and M. Timmerman, pers. comm., 2001).

One of the most productive lines of study has been the investigation of exotic fragments of crustal and upper-mantle material (xenoliths and megacrysts) that are commonly encountered in volcanic necks and minor intrusions, particularly in Scotland. Over two dozen publications have ensued so far, mainly since 1975. Of these, the vast majority have been by B.G.J. Upton of the University of Edinburgh and his co-workers such as P. Aspen, N.A. Chapman, A.N. Halliday and R.H. Hunter, and there have been several general reviews (Upton *et al.*, 1983, 1984; Hunter and Upton, 1987). This work has greatly increased knowledge of the origin of the Late Palaeozoic magmas and the structure and composition of the lithosphere beneath northern Britain, but it has also had widespread international impact upon crustal and upper-mantle models.

Carboniferous and Permian igneous rocks are responsible for many features that have been identified on regional gravity and aeromagnetic maps and on seismic profiles and hence have prompted many geophysical studies, particularly in the Midland Valley of Scotland. The gravity surveys of the western Midland Valley (McLean, 1966; McLean and Qureshi, 1966) and the seismic surveys of the Clyde Plateau lava field and the Central Coalfield Basin (Hall, 1971, 1974; Davidson *et al.*, 1984; Dentith and Hall, 1989), all by researchers at the University of Glasgow, are particularly noteworthy. One feature that has attracted much interest and speculation over many years is the large magnetic anomaly in the Bathgate area, the most recent interpretation of which is given by K.E. Rollin (in Cameron *et al.*, 1998). The tholeiitic rocks of the Midland Valley Sill-complex, the Whin Sill-complex and their associated dykes are highly magnetic and this has not only proved to be a valuable aid to field mapping (e.g. Armstrong *et al.*, 1985), but it has also resulted in a number of magnetic surveys to elucidate their detailed form and structure (Cornwell and Evans, 1986; El-Harathi and Tarling, 1988; Goulty *et al.*, 2000). The tholeiitic intrusions have also been the main targets of palaeomagnetic studies, which have been a valuable back-up to radiometric age determinations (Creer *et al.*, 1959; Storetvedt and Gidskehaung, 1969; Giddings *et al.*, 1971; Torsvik *et al.*, 1989; Thomas *et al.*, 1995).

Field relationships have always been central to any study of these igneous rocks and for the past 200 years they have been the subjects of organized field excursions for educational and academic purposes or for general scientific interest. The role of geological societies in promoting this interest has been crucial, and the Edinburgh Geological Society, the Geological Society of Glasgow, the Yorkshire Geological Society and the Geologists' Association in particular have opened up many of the sites described in this volume to a wide audience through the publication of numerous excursion guides (Upton, 1969; Bluck, 1973; MacGregor, 1973, 1996; Johnson, 1973, 1997; McAdam and Clarkson, 1986; Lawson and Weedon, 1992; Scrutton, 1995).

As the overall knowledge of Carboniferous and Early Permian magmatism has increased there have been many reviews in a wide range of publications, both British and international. Most of these have been by E.H. Francis (1965, 1967, 1970a, 1978a,b, 1983, 1988, 1991, 1992), apart from chapters in D.S. Sutherland's *Igneous Rocks of the British Isles* (Upton, 1982; A.C. Dunham and Strasser King, 1982) and chapters in the *British Regional Geology* series of the British Geological Survey (e.g. Cameron and Stephenson, 1985). Such reviews have done much to raise international awareness of the province and have provided invaluable background for the preparation of this volume.

GCR SITE SELECTION

D. Stephenson

Although igneous rocks and their contact relationships are on the whole less prone to damage than sedimentary rocks and fossil or mineral localities, they are nonetheless vulnerable to certain potentially damaging activities, some of which may not even be directly related to the igneous rocks themselves. In 1988 a farmer submitted a formal objection to the notification as a Site of Special Scientific Importance (SSSI) of one of the sites described in this volume, questioning the need for any protective measures on the grounds that the land was safe in the custody of his family ownership. He agreed with the need for conservation in general but wrote, 'I cannot imagine anything detrimental happening to this large rock mass, which has not altered one iota during my lifetime'. By 1997 his land was being encroached upon by one of the largest opencast coal sites in Scotland. Fortunately the operators had consulted with Scottish Natural Heritage under the terms of the SSSI notification, access to the igneous rocks was preserved and some exposures were actually enhanced in conservation value.

The greatest threat to igneous rocks is the possibility of them being obscured by artificial constructions or removed by excavations. Indeed their generally hard and resistant properties make igneous rocks an important source of construction materials and hence particularly vulnerable to large-scale commercial extraction. Whole igneous bodies can be lost in this way. Uses are many and varied; from large blocks formerly used for buildings, walls and coastal defences, to the crushed dolerites that make excellent roadstone and railway ballast, and the multipurpose aggregates that can be derived from less resistant igneous rocks. As demand changes with time, new uses are constantly emerging, so that no igneous body can be considered safe from future exploitation. However, with careful management, both disused and active quarries can provide highly instructive exposures, especially in areas of poor natural exposure, and there are many examples among the sites described in this volume. On a smaller scale, minerals and delicate cavity features are subject to the attentions of collectors and fine detail can be lost easily through injudicious hammering. Such damage is not necessarily malicious and there have been instances of delicate structures being removed for bona fide research purposes. Much of the value of the sites is derived from their research potential, but sampling does need to be controlled carefully and there is a clear need for better dissemination of information about protected sites.

The Geological Conservation Review (GCR) aims to identify the most important sites in order that the scientific case for their protection and conservation is fully documented as a public record, with the ultimate aim of formal notification as Sites of Special Scientific Interest (SSSIs). The notification of SSSIs under the National Parks and Access to the Countryside Act 1949 and subsequently under the Wildlife and Countryside Act 1981, is the main mechanism of legal protection in Great Britain. The origins, aims and operation of the review, together with comments on the law and practical considerations of Earth-science conservation, are explained fully in Volume 1 of the GCR series, *An Introduction to the Geological Conservation Review* (Ellis *et al.*, 1996). The GCR has identified three fundamental site-selection criteria; *international importance*, *presence of exceptional features* and *representativeness*. Each site must satisfy at least one of these criteria, many of them satisfy two and some fall into all three categories (Table 1.1).

The *international importance* of the British Carboniferous and Permian igneous rocks has already been discussed, highlighting significant contributions to the understanding of the origin and evolution of magmas, their mechanisms of ascent, intrusion and extrusion and the resulting diversity of igneous rock-types.

Exceptional features are commonly the reason for international importance, such as the well-preserved tuff-rings of the **North Berwick Coast** GCR site, the volcanic necks that represent the roots of small volcanoes on the **East Fife Coast** GCR site, the range of differentiated alkaline rocks in the layered sill at the **Lugar** GCR site, and the ropy flow structures within flattened amygdales at the **Holy Island** GCR site and Harkess Rocks (**Budle Point to Harkess Rocks** GCR site). In addition, many of the sites provide excellent examples of features and phenomena that, although seen better elsewhere, are invaluable for research and/or teaching purposes. Good examples of the latter include features formed by lava flowing underwater at the **Burntisland to Kinghorn Coast**,

Table 1.1 Carboniferous–Permian Igneous Rocks Block: GCR networks and site selection criteria.

Site name	GCR selection criteria
Dinantian volcanic rocks of the Midland Valley of Scotland and adjacent areas Network, Chapter 2	
North Berwick Coast	Representative of the lower, basic members of the Garleton Hills Volcanic Formation. Exceptional examples of tuff-rings and small-scale volcanic vents. Internationally important for crustal and mantle xenoliths.
Garleton Hills	Representative of the trachytic upper member of the Garleton Hills Volcanic Formation and of Dinantian trachytic volcanism in general.
Traprain Law	Representative of the silica-undersaturated, highly evolved intrusions of East Lothian. Exceptional example of a laccolith.
Arthur's Seat Volcano	Representative of the Arthur's Seat Volcanic Formation. Exceptional examples of classic volcanic features that dominate the city landscape, influencing development and culture. Internationally important for the historical development of geology and understanding of igneous processes.
Burntisland to Kinghorn Coast	Representative of the Kinghorn Volcanic Formation. Examples of fragmented lava (hyaloclastite) with associated pillow lavas, formed in a marine lava delta.
Touch, Fintry and Gargunnock Hills	Representative of the north-eastern part of the Clyde Plateau Volcanic Formation. Exceptional example of a volcanic escarpment with 'trap' features.
Campsie Fells	Representative of the northern part of the Clyde Plateau Volcanic Formation and of the North Campsie Linear Vent System. Exceptional examples of volcanic vents, remnants of ash cones and plugs.
Dumbarton Rock	Exceptional example of a visually striking volcanic plug associated with the Clyde Plateau Volcanic Formation.
Dunrod Hill	Exceptional examples of composite hawaiitic lava flows with potential international importance. Representative of the dominant member in the western part of the Clyde Plateau Volcanic Formation.
Machrihanish Coast and South Kintyre	Representative of Dinantian volcanism north-west of the Highland Boundary Fault. Exceptional example of a trachyte lava dome.
Heads of Ayr	Exceptional example of a Dinantian volcanic neck, comprising the roots of a tuff-ring, with superb three-dimensional coastal exposures. Contains crustal and upper mantle xenoliths.
Dinantian rocks of the Northumberland, Solway and Tweed basins Network, Chapter 3	
Gill Beck	Representative of the Tournaisian Cockermouth Lavas.
Bothel Craggs Quarry	Representative of a tholeiitic andesite lava, rare in the British Carboniferous lava successions and providing evidence for fractionation of the tholeiitic magmas.
Little Mell Fell Quarry	Representative of dykes and pyroclastic rocks of a neck, both associated with the Cockermouth Lavas but well to the east of the main outcrop.
Langholm–Newcastleton Hills	Representative of the Tournaisian Birrenswark Volcanic Formation.
Lintmill Railway Cutting	Representative of the Tournaisian Kelso Lavas.
Hareheugh Craigs	Representative of the plugs associated with the Kelso Lavas. A rare composite example.
Cottonshope Head Quarry	Representative of the Tournaisian Cottonshope basalts.
Kershope Bridge	Representative of the Visean Kershopefoot basalts.
River Esk, Glencartholm	Representative of the Visean Glencartholm Volcanic Beds.
Silesian and Early Permian volcanic rocks of Scotland Network, Chapter 4	
Ardrossan to Saltcoats Coast (Chapter 5)	Representative of the Namurian Troon Volcanic Member and the Ayrshire Bauxitic Clay Member.
East Fife Coast	Representative of Late Carboniferous to Early Permian necks. Internationally renowned for cross-sections through the roots of phreatomagmatic tuff-rings at various structural levels. Exceptional examples of crustal and upper-mantle xenoliths.

Table 1.1 – *contd.*

Howford Bridge	Representative of the Early Permian Mauchline Volcanic Formation.
Carron Water	Representative of the Early Permian Carron Basalt Formation. Exceptional examples of volcanic rocks interdigitating with contemporaneous fluvial and aeolian sedimentary rocks.
Alkaline basic sills and dykes of Scotland Network, Chapter 5	
Arthur's Seat Volcano (Chapter 1)	Representative of alkali dolerite sills of various ages in the eastern Midland Valley. Exceptional examples of both upper and lower contacts that have great historical significance and hence international importance. Spectacular part of the city landscape.
South Queensferry to Hound Point	Representative of alkali dolerite sills in the eastern Midland Valley. Internal mineralogical and textural variations are well displayed. Exceptional examples of hydrothermal alteration to 'white trap'.
Ardrossan to Saltcoats Coast	Representative of the composite alkali dolerite sills of the western Midland Valley. Exceptional examples of internal and external contacts and of metamorphic effects on the sedimentary country rocks.
Lugar	Internationally important example of a composite, alkaline basic sill, both historically and in recent times. Representative of the early Permian alkaline basic sills of the western Midland Valley, exhibiting a wide variety of rock-types from peridotite to spectacular late fractionates termed 'lugarite'.
Benbeoch	Representative of olivine-rich alkaline basic sills of the western Midland Valley. Exceptional examples of fresh, olivine-rich, nepheline-dolerite.
Craighead Quarry	Representative of the rare Late Carboniferous to Early Permian intrusions within the Southern Uplands. An exceptionally fresh and visually striking porphyritic nepheline-gabbro, formerly termed an 'essexite'.
Dubh Loch	Visually striking representative of the Late Carboniferous to Permian lamprophyric dykes of the western Highlands. Contains exceptional examples of mantle xenoliths and xenocrysts.
Tholeiitic sills and dykes of Scotland and northern England Network, Chapter 6	
South Queensferry to Hound Point (Chapter 5)	Representative of the Midland Valley Sill-complex. Exceptional example of a basal contact, exhibiting multiple intrusive sheets and apophyses, chilled margins, thermally altered sedimentary rocks.
North Queensferry Road Cuttings	Representative of the Midland Valley Sill-complex exhibiting a complete section. Exceptional examples of many of the features that characterize large sills, including baked sediments on top of the sill that prove that it is an intrusion.
Wallstale	Representative of the Midland Valley Sill-complex. Exceptional example of a vertical transgression along a fault plane.
Lomond Hills	Representative of the Midland Valley Sill-complex forming a prominent scarp feature. Exceptional example of large-scale transgressive contacts and thermal effects above the sill. Equivocal relationships between the sill and alkaline basic plugs have generated much debate.
Gloom Hill, Dollar	Representative of the Ochil Fault-intrusion.
Mollinsburn Cuttings	Representative of quartz-dolerite dykes of the tholeiitic dyke-swarm of central Scotland. Exceptional examples of horizontal columnar joints.
Corsiehill Quarry	Representative of basalt dykes of the tholeiitic dyke-swarm of central Scotland. Exceptionally well-exposed vertical contacts and horizontal columnar joints.
Whin Sill Exposures in Upper Teesdale	Representative of the thickest part of the Great Whin Sill at its lowest stratigraphical level. Nationally important landscape features exhibit exceptional examples of many of the features that characterize large sills, including baked sedimentary rocks on top of the sill, which prove that it is an intrusion, transgressive upper and lower contacts, columnar jointing and a pegmatitic central facies.

Table 1.1 – *contd.*

Steel Rigg to Sewingshields Crags	Representative of the Great Whin Sill forming a major landscape feature of international historical importance. Exceptional features include offsets in the scarp attributed to transgression between stratigraphical levels and baked sedimentary rocks above the sill, which prove that it is an intrusion.
Longhoughton Quarry	Representative of the Great Whin Sill. Exceptional features include baked sedimentary rocks above the sill, and rafts of sedimentary rock in the upper part, which prove that it is an intrusion. The relationship of the sill to movement on the Longhoughton Fault is also clearly displayed.
Cullernose Point to Castle Point	Representative of the Great Whin Sill. Exceptional features include well-developed columnar jointing, rafts of baked sedimentary rock and late-stage veins.
Budle Point to Harkess Rocks	Representative of the Great Whin Sill. Exceptional for the large number of rafts of sedimentary rocks with varying orientations. Internationally important for the presence of miniature ropy flow texture on the insides of large vesicles.
Greenfoot Quarry	Representative of the Little Whin Sill.
Holy Island	Representative of the Holy Island dyke subswarm, which is related to the Whin Sill-complex. Exceptional example of an intrusion showing 'step-and-stair' transgression and numerous contact features. Internationally important for the presence of miniature ropy flow texture on the insides of large vesicles.
Wydon	Representative of the St Oswald's Chapel dyke subswarm, which is related to the Whin Sill-complex. A rare natural inland exposure of a simple dyke.
Carboniferous and Permian igneous rocks of central England and the Welsh Borderland Network, Chapter 7	
Litton Mill Railway Cutting	Representative of the upper part of the Visean Upper Miller's Dale Lava of Derbyshire. Exceptional example of the brecciation of a lava flow that terminated in an aqueous environment.
Water Swallows Quarry	The Water Swallows Sill, representative of the alkali dolerite sills of Derbyshire, is intruded into the Visean Lower Miller's Dale Lava. Exceptional examples of columnar jointing and of mineral layering in the sill.
Tideswell Dale	The Tideswell Dale Sill, representative of the alkali dolerite sills of Derbyshire, is intruded into the Visean Lower Miller's Dale Lava. The sill shows chilled margins and thermal alteration of country rocks.
Calton Hill	The Calton Hill Volcanic Complex comprises the remains of a phreatic tuff-ring associated with the Upper Miller's Dale Lava, intruded by basanite sills. Internationally important as the only locality in England at which mantle xenoliths can be found.
Clee Hill Quarries	The Clee Hills Sill is representative of the West Midlands suite of Late Carboniferous alkali dolerite sills.
Barrow Hill	The Barrow Hill Complex is an exceptional example of a Westphalian volcanic vent with associated volcanic deposits. Internationally important for the presence of the oldest anatomically preserved conifers found to date.
Middle Hope	Representative of Tournaisian Middle Hope Volcanic Beds of south-west England. Exceptional examples of lapilli-tuffs and pillow lava. Nationally important for the association of igneous, sedimentological and palaeontological features that allow reconstruction of the growth and subsequent subsidence of a volcanic cone on a marine carbonate shelf.
Spring Cove	Representative of Visean volcanic rocks of south-west England. Exceptional example of a pillow lava erupted under water in a marine carbonate environment.
Golden Hill Quarry	Exceptional example of a monchiquite intrusion associated with a Visean volcanic pipe. Internationally important as the only locality in Wales at which mantle xenoliths are found.

Litton Mill Railway Cutting, **Spring Cove** and **Middle Hope** GCR sites; the viscous trachyte lava dome at the **Machrihanish and South Kintyre** GCR site; and the external contacts, columnar jointing and numerous internal features seen in so many of the GCR sites representing alkaline and tholeiitic sills.

The criterion of *representativeness* aims to ensure that all major modes of origin and chronological and petrological groupings of Carboniferous and Permian igneous rocks are represented in the ultimate GCR site lists. It is difficult to do this whilst keeping the number of sites within reason. Hence there are some *regionally* important groups of rocks that are not represented, such as the Silesian volcanic rocks of the Midland Valley and the volcanic necks of the north-west Highlands. In some cases this is because there are no localities that show any exceptional features or there are none that exhibit the typical features of the suite any better than numerous other localities. However, it may be appropriate to designate 'Regionally Important Geological/Geomorphological Sites' (RIGS) to represent them so that, even though such status carries no formal legal protection, their importance is recognized and recorded, facilitating conservation at a local level. An attempt has been made in this volume to include, in each appropriate chapter introduction, a broad description of any group of rocks that is not represented by a GCR site, together with references to key publications. Hence, despite perceived gaps in the representativeness of the GCR site coverage, the volume does constitute a complete review of all Carboniferous and Permian igneous rocks of Great Britain.

Some sites are important in more than just an igneous context. For example, the **Howford Bridge** GCR site exhibits spectacular dune bedding in Lower Permian desert sandstones, and the oldest anatomically preserved conifers in the world occur in the volcanic vent at the **Barrow Hill** GCR site. The **River Esk, Glencartholm** GCR site is one of the most important Palaeozoic fish sites in the world and hence is also described in the *Fossil Fishes of Great Britain* GCR volume (Dineley and Metcalf, 1999). The River Esk GCR site also contains exceptionally well-preserved plant remains, and is described, along with two separate localities within the **North Berwick Coast** GCR site, also noted for their plant remains, in the *Palaeozoic Palaeobotany of Great Britain* GCR volume (Cleal and Thomas, 1995). The Tournaisian limestones and interbedded volcanic rocks at the **Middle Hope** GCR site together allow a reconstruction of volcanism on a subsiding marine carbonate shelf and hence this site is also included in the *British Lower Carboniferous Stratigraphy* GCR volume (Cossey *et al.*, in prep).

Volcanic rocks within the stratigraphical column provide time markers and hence have potential international significance in the construction of geological timescales. They have been, and will continue to be, important targets for radiometric dating, in particular the Lower Permian volcanic successions (**Howford Bridge** and **Carron Water** GCR sites) that on palaeobotanical evidence are known to be very close to the Carboniferous–Permian boundary. Other volcanic successions provide key markers within the Carboniferous Series but the only available dates at the time of writing (2001) are K-Ar determinations of low precision and debatable accuracy. More reliable K-Ar dates have been obtained from numerous intrusions and some, notably the Stephanian Whin Sill-complex (numerous GCR sites) and the Early Permian intrusions (e.g. the **Lugar** and **Dubh Loch** GCR sites), have yielded precise Ar-Ar whole-rock and/or U-Pb zircon dates. Unfortunately intrusions are less precise stratigraphical markers than lavas; work is in progress to obtain more dates from volcanic successions using modern radiometric techniques (A.A. Monaghan and M.S. Pringle, pers. comm., 2002).

The GCR sites vary greatly in size and character, from large upland areas such as the **Campsie Fells** and the **Touch, Fintry and Gargunnock Hills** GCR sites that form part of the vast Clyde Plateau lava field, to small quarries such as the **Craighead Quarry** and **Golden Hill Quarry** GCR sites, exposing single small intrusions. There are also long coastal sections (**North Berwick Coast**, **East Fife Coast** GCR sites), disused railway cuttings (**Litton Mill Railway Cutting** GCR site), river sections (**Lugar**, **River Esk**, **Carron Water**, **Howford Bridge** GCR sites), working quarries (**Benbeoch**, **Wallstale**, **Clee Hill Quarries** GCR sites) and road cuttings (**Mollinsburn Cuttings**, **North Queensferry Road Cuttings** GCR sites). At many sites, the igneous rocks have resulted in spectacular landscape and geomorphological features such as those that dominate the city of Edinburgh (**Arthur's Seat Volcano** GCR site), the Clyde Plateau lava field that surrounds

Glasgow on three sides, the many craggy features formed by the Midland Valley Sill-complex, and the Great Whin Sill that controlled the siting of Hadrian's Wall (**Steel Rigg to Sewingshields Crags** GCR site) and is responsible for many of the scenic attractions in Upper Teesdale and the Northumberland coast (**Cullernose Point to Castle Point**, **Budle Point to Harkess Rocks**, **Holy Island** GCR sites).

Site selection is inevitably subjective and some readers may feel that vital features or occurrences have been omitted or that others are over-represented. However, the declared aim of the GCR is to identify *the minimum number and area of sites needed to demonstrate the current understanding* of the diversity and range of features within each block or network. To identify too many sites would not only make the whole exercise unwieldy and devalue the importance of the exceptional sites, but it would also make justification and defence of the legal protection afforded to these sites more difficult.

Features, events and processes that are fundamental to the understanding of the geological history, composition and structure of Britain are arranged for GCR purposes into subject 'blocks'. Carboniferous and Permian igneous rocks comprise a single GCR Block. Within each block, sites fall into natural groupings, termed 'networks', which in this volume are based upon petrological affinity, age and geographical distribution. The six networks, each represented by a single chapter, contain 52 sites, which are listed in Table 1.1 together with their principal reasons for selection. Some sites have features that fall within more than one network, for example the **South Queensferry to Hound Point** GCR site, which encompasses alkali dolerite sills (Chapter 5) and a tholeiitic sill (Chapter 6), and the **Ardrossan to Saltcoats Coast** GCR site, selected principally for its alkaline sills (Chapter 5) but which also includes Namurian lavas (Chapter 4). These sites are described in the chapters appropriate to their dominant features but are mentioned in the chapter introductions of any other relevant networks and are cross-referenced in Table 1.1.

Aspects of regional geology applicable to each network are given in the chapter introductions. However, space does not allow for more detailed accounts of country-rock successions or structures and the reader is referred to the *Geology of Scotland* (Craig, 1991; Trewin, in press), *Geology of England and Wales* (Duff and Smith, 1992) and volumes in the British Geological Survey's *British Regional Geology* series.

TECTONIC SETTING AND EVOLUTION

K.M. Goodenough, D. Stephenson and S.C. Loughlin

Following the end of the Caledonian Orogeny, in Late Devonian time (*c.* 370 Ma), the area of continental crust that now makes up the British Isles was part of the supercontinent of Laurussia (informally known as the 'Old Red Sandstone Continent'). This had formed during the orogeny by the amalgamation of several pre-existing continents. The crust of Scotland and the far north-east of England had lain on the margin of the continent of Laurentia, which included Greenland and most of North America, whereas England and Wales were part of the microcontinent of Avalonia (Figure 1.3). The junction between these two plates, now concealed beneath younger rocks, is called the 'Iapetus Suture' and trends approximately north-east from the Solway Firth to the coast of Northumberland, around Seahouses (Leeder *et al.*, 1989; Soper *et al.*, 1992).

From Late Devonian times onwards, the southern continent of Gondwana was in collision with the southern margin of Laurussia, leading to the Variscan Orogeny, and creating the supercontinent of Pangaea (Figure 1.4). The main orogenic belt associated with this collision was located far to the south of Great Britain in the Iberia–Armorica–Massif Central region (Leeder, 1982; Fraser and Gawthorpe, 1990). However, the northern limit of strong Variscan deformation, commonly known as the 'Variscan Front', migrated northwards during the orogeny and the final limit extends across southern Britain, between the Thames and Severn estuaries (Figure 1.1). To the north of this orogenic front, back-arc extension controlled structure, sedimentation and igneous activity in the British Isles throughout Late Devonian and Carboniferous times.

Five main depositional 'provinces', separated from each other by important palaeogeographical highs (Figure 1.1), have been recognized by Guion *et al.* (2000). These provinces are as follows:

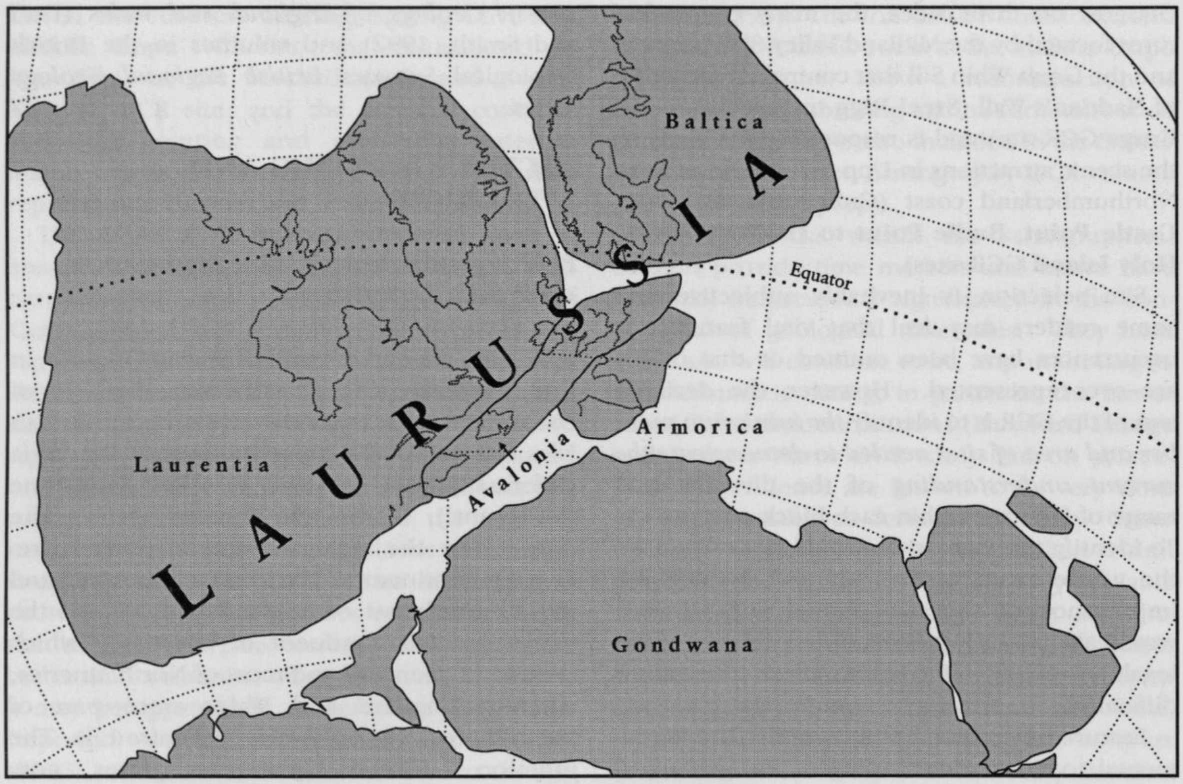


Figure 1.3 Continental dispositions in Late Devonian time (*c*. 380 Ma). Microcontinents including Avalonia and Armorica have collided with the margin of Laurentia, completing the assembly of the crust that now forms the British Isles. Gondwana lies to the south. The absolute positions of the continents on the globe at this time are still not known exactly, so the ocean between Laurentia and Gondwana may have been wider than is shown here. After McKerrow *et al*. (2000).

1. The Scottish Province, consisting essentially of the Midland Valley of Scotland, bounded by the Caledonian Highlands to the north and the Southern Upland High to the south.
2. The Pennine Province of central and northern England, bounded by the Southern Upland High to the north and the Wales–London–Brabant High to the south.
3. The Irish Province in the west.
4. The Southern Province, south of the Wales–London–Brabant High.
5. The Culm Basin of Devon and Cornwall.

The Scottish, Pennine and Southern provinces comprise the tectonic settings for the igneous rocks described in this volume. The Culm Basin, south of the Variscan Front, is the setting for those described in the *Igneous Rocks of South-West England* GCR volume (Floyd et *al*., 1993).

Dinantian tectonics

At the beginning of the Carboniferous Period, Britain lay within low latitudes (*c*. 10° south) on the fringe of the southern arid climatic belt, and most of Britain north of the Variscan Front was made up of the eroded remnants of mountains that had been generated by rapid crustal uplift towards the end of the Caledonian Orogeny. During Late Devonian and much of Dinantian times, north–south lithospheric extension to the north of the Variscan Front brought about active continental rifting, which led to the development of a series of fault-bound basins. The majority of these basins were controlled by the re-activation of Caledonian faults and thrusts (Figure 1.1) (Leeder, 1982; Kimbell *et al*., 1989; Fraser and Gawthorpe, 1990). Stable basement blocks, many of which were cored by Caledonian granitic plutons, separated the basins. The process of rifting and thinning of the lithosphere

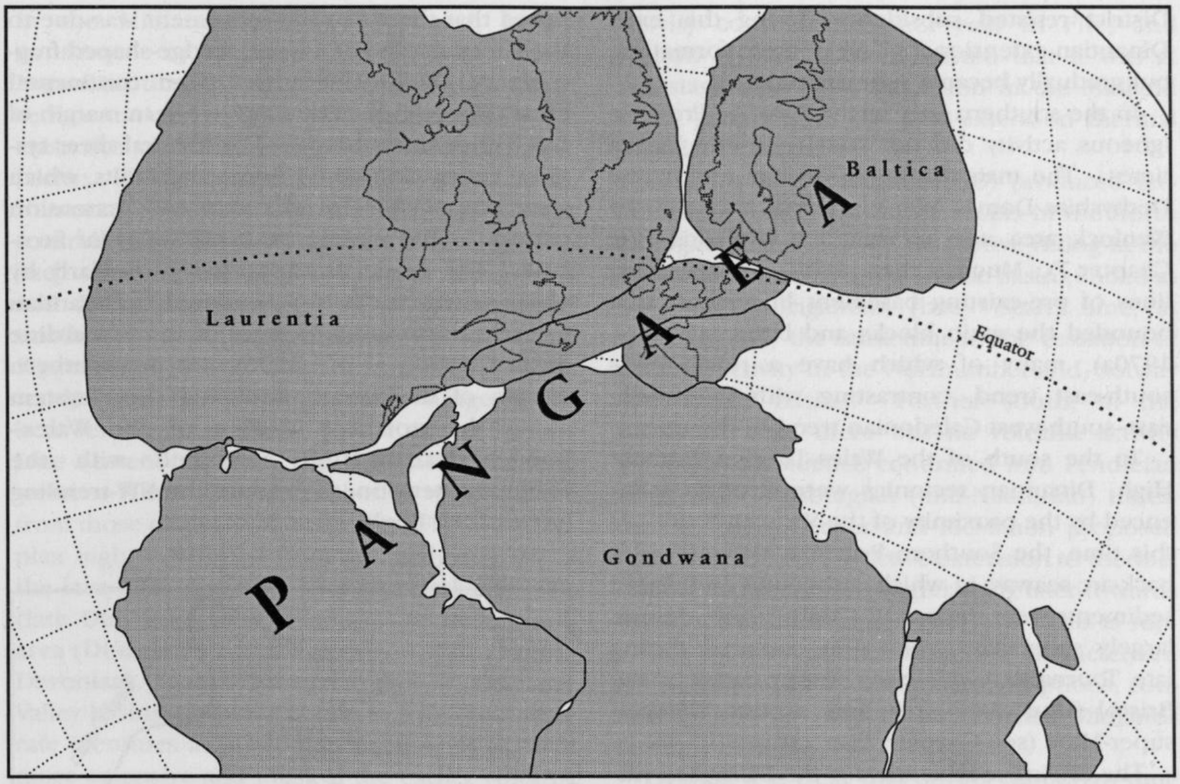


Figure 1.4 Continental dispositions in Late Carboniferous time (*c.* 320 Ma). Gondwana has collided with Laurentia, creating the supercontinent of Pangaea, and the crust of the British Isles lies close to the equator. After McKerrow *et al.* (2000).

led to high heat flow and thus promoted mantle melting (Macdonald *et al.*, 1977; Smedley, 1986b), producing basaltic magmas. The earliest volcanism began during the Tournaisian Epoch and was relatively local in extent, but much more extensive and persistent activity developed from early Visean times onwards.

Large volumes of alkali basaltic lavas were erupted across the Midland Valley of Scotland during the Visean Epoch, forming the Clyde Plateau Volcanic Formation in the west and the Arthur's Seat and Garleton Hills volcanic formations in the east (see Chapter 2). These volcanic piles subsequently formed topographical 'highs', which separated sedimentary basins to the east and west. In the western and central part of the Midland Valley, basin development was controlled by faults with a Caledonian (north-east–south-west) trend, and volcanic eruptions were focused along distinct NE-trending lineaments such as the Dumbarton–Fintry line (Figure 2.3, Chapter 2; Whyte and Macdonald, 1974). However, towards the end of Visean time, basins in the eastern Midland Valley began to develop along north–south axes (Haszeldine, 1988; Read, 1988), and the margins of these basins became the focus of volcanism in the Burntisland area of Fife and around the Bathgate Hills.

In the northern part of the Pennine Province, volcanism occurred intermittently during Tournaisian and Visean times around the margins of the Northumberland, Solway and Tweed basins (see Chapter 3). Here, the basin-bounding growth faults typically follow north-east or ENE Caledonian trends, and volcanism has also been focused along those lines. In fact the Northumberland and Solway basins lie above the inferred line of the Iapetus Suture. Interpretations of deep seismic profiles across southern Scotland and northern England show these basins lying within the hanging-wall block of a set of northerly dipping crustal-scale shears (Chadwick and Holliday, 1991; Smith, 1992; Chadwick *et al.*, 1995). The rigid and buoyant, granite-cored Lower Palaeozoic massifs of the Southern Uplands, Alston Block and the Lake

District resisted subsidence during this early Dinantian extensional phase of basin formation, but gradually became submerged later.

In the southern part of the Pennine Province igneous activity did not start until late Visean times. The main centre of activity was in the Derbyshire Dome, with minor volcanism in the Wenlock area and in the East Midlands (see Chapter 7). Much of the activity occurred along lines of pre-existing basement lineaments that bounded the main blocks and basins (Francis, 1970a), many of which have a north-west–south-east trend, contrasting with the north-east–south-west Caledonian trend to the north.

To the south of the Wales–London–Brabant High, Dinantian tectonics were strongly influenced by the proximity of the Variscan Front. At this time, the Southern Province represented a back-arc seaway, in which carbonates and clastic sediments were deposited (Besly, 1998). Minor, largely submarine, volcanism occurred during late Tournaisian and early Visean times in the Bristol–Gloucester area and around Weston-super-Mare (see Chapter 7).

The driving mechanism for the Dinantian rifting has been a matter of debate for some time. Leeder (1982) proposed that rifting in Scotland and northern England could be explained by north–south to north-west–south-east tension, related to back-arc extension behind the Variscan Front to the south. A contrasting theory was put forward by Haszeldine (1984, 1988), who suggested that the north–south lineaments in the eastern Midland Valley could be attributed to long-lived east–west tension that was initiated in late Silurian times, and continued to influence sedimentation and volcanism through to the opening of the North Atlantic during Cretaceous and Palaeogene times. However, neither of these models could explain the contrasting extension directions in the Scottish and Pennine provinces, and more recent work (e.g. Read, 1988; Coward, 1993) has attributed the development of Dinantian basins to back-arc extension acting in conjunction with strike-slip shearing along major fault zones.

According to these last models, during Dinantian times Scotland lay within a zone of major sinistral strike-slip movement between the North America–Greenland and the European sectors of Laurussia. Most of this movement took place along re-activated NE-trending Caledonian fractures such as the Highland Boundary and Southern Upland faults. Coward (1993) proposed that the strike-slip movement was due to the lateral escape of a large, wedge-shaped fragment of the northern European continental crust (Figure 1.5). The north-western margin of this fragment was bordered by sinistral shear systems, acting along the NE-trending faults, which were responsible for the east–west extension pattern in the eastern Midland Valley of Scotland. The model is supported particularly by observations on the N–S-trending late Dinantian to early Namurian structures of the Kincardine Basin (Rippon *et al.*, 1996). At the southern margin of the wedge, a dextral shear system along the northern margin of the Wales–London–Brabant High combined with the regional extension, to produce the NW-trending faults of the English East Midlands.

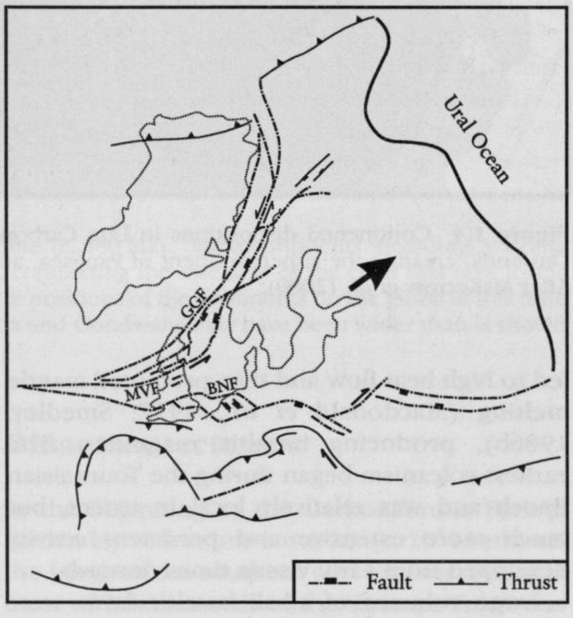


Figure 1.5 Early Carboniferous tectonics of Europe. A fault-bounded wedge of northern Europe was moving eastwards, creating strike-slip movements along pre-existing lineaments. (GGF = Great Glen fault system; MVF = Midland Valley fault system; BNF = Brabant–North Sea fault system.) After Coward (1993).

Namurian tectonics

By late Dinantian time, the part of Laurussia that was to become northern Britain lay in wet equatorial regions. The general land surface remained close to sea level throughout Namurian and early Westphalian times, although in the Midland Valley of Scotland, basins continued to subside rapidly until mid-Namurian times (Read, 1988), with patterns of sedimentation being strongly influenced by the existence of 'highs' formed by earlier volcanic rocks. In the western and central parts, Namurian sedimentation and volcanism were controlled by ENE-trending fault blocks between such structures as the Dusk Water, Inchgotrick and Kerse Loch faults, reflecting continued north-west–south-east tension (Read, 1988; Rippon *et al.*, 1996). Farther east, the volcanism tended to concentrate upon hinge areas between basins and highs, such as the Bo'ness Line (extending from the Bathgate Hills into western Fife). The central basins were divided from those of Midlothian and East Fife by a complex high, developed from an amalgamation of the lava piles that now form the Bathgate Hills (late Dinantian to Namurian), the Burntisland area (Dinantian) and the Pentland Hills (Siluro–Devonian). Later in Namurian time, the Midland Valley basins gradually began to lose their separate identities as marine transgressions became more extensive and most of the earlier volcanic piles were submerged. The Highland and Southern Upland terranes generally acted as highs, though attenuated sedimentary successions began to accumulate in small basins at Thornhill, Sanquhar and Stranraer in late Dinantian times; the latter includes a thin Namurian lava.

McKenzie (1978) proposed a two-stage model for the development of sedimentary basins, in which a primary stage of active rifting, caused by lithospheric thinning and extension, is followed by a period in which the lithosphere cools and thickens through thermal conduction to the surface, causing thermal subsidence. The active rifting tends to be associated with mantle melting and abundant volcanism, whereas volcanic activity is less common during the thermal subsidence episode. This model has been applied to the evolution of Carboniferous basins in northern Britain by Dewey (1982), Leeder (1982) and Leeder and McMahon (1988).

The continuing importance of volcanic activity, combined with rapid basin subsidence, indicates that active rifting and lithospheric stretching were still the dominant controls on evolution of Midland Valley basins during early- to mid-Namurian times. Volcanism on the Bo'ness Line ceased in late Namurian times (end-Arnsbergian onwards), although volcanic activity continued farther east in Fife, and Rippon *et al.* (1996) suggested that it was at this stage that active extension in the Midland Valley gave way to the post-extension thermal subsidence phase.

Leeder and McMahon (1988) produced tectonic subsidence curves for basins in the north of England, and showed that active rifting in the Northumberland and Stainmore basins ended at the end of Brigantian (late Visean) time, at approximately the same time as the cessation of volcanic activity in the Northumberland, Solway and Tweed basins. Farther south, in the Bowland Basin, there was no volcanic activity but rapid subsidence continued into Pendleian or possibly Arnsbergian (mid-Namurian) times. On this basis, Leeder and McMahon proposed that the change from active extension to thermal subsidence occurred progressively later towards the south in the Pennine Province. This is supported by the fact that volcanism, characterized typically by small-scale explosive eruptions, continued intermittently in the English Midlands during Namurian time.

Overall, it is clear that during Namurian time active extension gave way to a thermal subsidence phase across the British Isles. The end of active rifting led to the cessation of the large-scale volcanic outpourings which characterized Dinantian times, so that during later Namurian times volcanic eruptions were relatively rare, sporadic and short-lived. To the south of the Wales–London–Brabant High, there was no volcanism at all during Namurian time. Basin subsidence in this region has been entirely attributed to flexural subsidence of the crust under the weight of Variscan thrust sheets to the south (Kelling, 1988; Maynard *et al.*, 1997; Burgess and Gayer, 2000).

Westphalian tectonics

Thermal subsidence in the north, and flexural basin development in the south, continued from Namurian into early Westphalian times. The Variscan deformation front migrated northwards during this time and compressional tectonics began to dominate, so that the sedimentary rocks within the basins were deformed into large-scale folds. The compression also caused the direction of movement on basin-bounding faults to be reversed. This led to the sedimentary rocks within some basins being uplifted and eroded, whilst rapid subsidence occurred in previously high areas, so that regional unconformities developed within the sedimentary succession. This reversal process is known as 'tectonic inversion'.

In the Scottish Province, there was little volcanism during Westphalian time, and activity was mainly restricted to Fife and the Firth of Forth. One of the greatest areas of subsidence at this time, the Leven Basin of East Fife, was also the site of most known Westphalian volcanism (Read, 1988). The effects of Variscan compression and the consequent tectonic inversion also led to a reversal of lateral shear sense on pre-existing faults in the Midland Valley, so that the NE-trending major strike-slip faults, which had a component of sinistral movement during Dinantian times, now moved with a dextral shear sense. This dextral strike-slip produced a component of east–west compression, developing N–S-trending fold structures such as the Clackmannan Syncline (Read, 1988; Bénard *et al.*, 1990; Rippon *et al.*, 1996).

In the southern part of the Pennine Province, some igneous activity occurred in earlier Westphalian times, with the formation of dolerite sills and localized explosive volcanism in the East and West Midlands. In later Westphalian times, deformation (uplift, folding and faulting) occurred and, as in the Midland Valley, this has been attributed to a period of east–west compression that effectively marked the end of thermal subsidence (Bénard *et al.*, 1990; Waters *et al.*, 1994; Johnson and K.C. Dunham, 2001).

The model of Coward (1993) provided an elegant explanation for the episode of Westphalian tectonic inversion. He suggested that inversion occurred because the fault-bounded wedge of European crust that had 'escaped' from between Laurentia and Gondwana during Dinantian times (Figure 1.5) was being pushed back owing to plate collision in the Urals (Figure 1.6), thus reversing the movement generated in Early Carboniferous times. This re-activated the faults bounding the continental wedge in the opposite directions to those that had acted during Dinantian times, producing dextral movement on faults in the Scottish Province and sinistral movement on faults in southern and central England. Coward noted that at this time there must also have been an effect due to north-west–south-east compression associated with the Variscan Orogeny, and other workers, such as Maynard *et al.* (1997), have

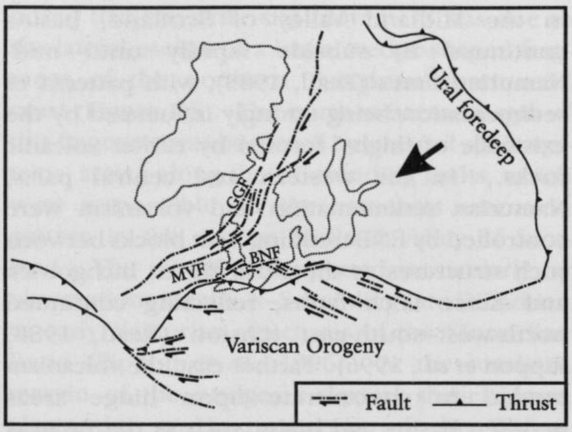


Figure 1.6 Late Carboniferous to Early Permian tectonics of Europe. Closure of the Ural Ocean led to the continental wedge being driven back to the west, reversing the directions of strike-slip movement. (GGF = Great Glen fault system; MVF = Midland Valley fault system; BNF = Brabant–North Sea fault system.) After Coward (1993).

preferentially emphasized the effects of the Variscan collision, rather than invoking collision in the Urals.

In the Southern Province, a rapidly subsiding foreland basin formed during Westphalian time owing to continued flexure of the crust in front of the Variscan Orogeny. The effects of loading of the Variscan thrust sheets spread northwards, and by Westphalian D time, the foreland flexural basin extended north of the Wales–London–Brabant High into the Pennine Province (Burgess and Gayer, 2000). Waters *et al.* (1994) suggested that earlier small-scale phases of localized extension and compression in the southern Pennine Province could also have been due to flexure of the crust under the weight of the Variscan thrust sheets, superimposed onto the thermally subsiding basin. However, since passive extension due to thermal subsidence is unlikely to have generated mantle melting, an alternative explanation is needed for the local Westphalian magmatism. Waters *et al.* suggested that melting during the localized extension was caused by movement on crustal thickness faults, which then acted as conduits for the transport of magma.

Igneous activity to the south of the Variscan Front is described in the *Igneous Rocks of South-West England* GCR volume (Floyd *et al.*, 1993). Possibly associated with this activity are thin felsic ash-fall tuffs (bentonites), which cover very large areas extending into the English Midlands. These are assumed to have been associated with Westphalian volcanic activity at a destructive plate margin to the south of Britain.

End-Carboniferous to Permian tectonics

During early Stephanian times, tholeiitic sills and dykes with a general east–west trend were emplaced into the sedimentary rocks of the Midland Valley and northern England (see Chapter 6). The arcuate dyke-swarm extends from the Atlantic margin as far as the Central Graben of the North Sea, and has been linked to lavas and dykes of similar age and composition in Scandinavia. These intrusions mark an end-Carboniferous period of approximately north–south extension (Read, 1988; Rippon *et al.*, 1996). Subsequently, in late Stephanian to Early and possibly later Permian times, alkaline basic magmas exploited fractures of similar trend over a wide area of western Scotland from Ayrshire to the Orkney Islands (see Chapter 5).

Francis (1978a) suggested that the short-lived tholeiitic event was a result of decompressive mantle melting caused by rotation of a micro-continental plate fragment involved in the Variscan Orogeny to the south. However, Russell and Smythe (1983) modified earlier theories (Russell, 1976; Russell and Smythe, 1978) to suggest that the intrusions formed as a result of extensional stresses associated with propagating rifts in the Rockall Trough (the proto-North Atlantic Ocean) and the eastern Norwegian Sea. They proposed that an area of ancient continental lithosphere between the rifts in the Faeroe region was resistant to extension, causing stresses to be offset to thinner lithosphere around the Oslo Graben and in northern Britain. The short period of extension in northern Britain was halted when the lithosphere in the Faeroes region ruptured, forming the incipient Faeroe–Shetland Trough (Smythe *et al.*, 1995). This model predicts correctly the arcuate orientation of the regional dyke-swarm from northern Britain to the Oslo Graben and also accounts for thickening of the dykes in the western North Sea. However, it does not explain the intrusion of dykes in southern Sweden. More recently, Wilson *et al.* (2000) have suggested that the extension was caused by the impingement of a mantle plume on the base of the lithosphere beneath Scandinavia, and that the tholeiitic magmas may represent laterally transported melts of plume material.

By Early Permian time, the crust that was to become the British Isles had drifted northwards into the northern semi-arid climatic belt, and the distant effects of the Variscan Orogeny had raised the land surface above sea level. The main Variscan fold belt in southern Britain may have created a mountainous barrier to possible 'monsoonal' moisture-bearing winds from the south, accentuating the arid conditions (Parrish, 1993). Regional tension with a general north-west–south-east orientation was giving rise to intracontinental rifting along the line of the Rockall Trough, the Faeroe–Shetland Trough and the Norwegian–Greenland Sea (Smythe *et al.*, 1995). Smaller, mainly half-graben structures developed in Britain, commonly on the site of Late Carboniferous basins. Anderson *et al.* (1995) argued that the geometry of most of these structures in the north-west of the British Isles was strongly influenced, in a variety of ways, by underlying Caledonian basement structures. Thus, in the Grampian Terrane, the largely offshore Rathlin Basin is orientated north-east–south-west, parallel to the general strike of the underlying Dalradian rocks. However, in the Southern Uplands Terrane, small basins such as Thornhill, Dumfries and Stranraer are elongated perpendicular to the structural fabric of the underlying Lower Palaeozoic rocks. Anderson *et al.* (1995) argued that these Southern Upland basins originated by ENE–WSW along-strike crustal stretching and dip-slip re-activation of north–south or north-west–south-east Caledonian fractures that formed conjugate sets with the more obvious north-east–south-west structures. Basins in the onshore and offshore Midland Valley (e.g. Mauchline) have a less regular shape as they are sited on deep Carboniferous basins with little or no inherited Caledonian trend. They commonly have a general north-west to NNW elongation that has been attributed to structural control of subsidence and volcanism, possibly dating back to Early Carboniferous times (MacGregor, 1948; Mykura, 1967; Hall, 1974; McLean, 1978; Russell and Smythe, 1978). Fractures with this trend in the west of the Midland Valley have subsequently controlled the siting of Permo–Triassic major baryte vein mineralization and Palaeogene regional dyke-swarms (Cameron and Stephenson, 1985). However, Rippon *et al.* (1996) cited E–W-orientated dykes with petrological affinity to the Mauchline Volcanic Formation as evidence that the Stephanian north–south extension continued during Early Permian development of the Mauchline Basin.

MAGMA SOURCE AND EVOLUTION

D. Stephenson, S.C. Loughlin, D. Millward and C.N. Waters

Although the geochemistry of all the various suites of Carboniferous and Permian igneous rocks in Great Britain has been studied in some detail, there is a considerable bias towards those of central and southern Scotland. Many theses and publications on the Scottish suites provide a wealth of data and interpretation, much of which has broad implications for magma genesis and the tectonic setting of the whole igneous province. The less voluminous suites of England and Wales have received less attention, usually only a single study on each area. These smaller studies too are of great value to the overall model, but their detailed conclusions are limited by geographical extent and compositional range. This bias is reflected unavoidably in the following discussions.

Dinantian magmas

In central and southern Scotland, Dinantian igneous activity mainly involved transitional to mildly alkalic basaltic and hawaiitic magmas, and the rocks are characterized by relatively small amounts of normative hypersthene or nepheline. Rare low-K tholeiitic basalts occur at Machrihanish and some basalts with normative quartz and therefore of tholeiitic affinity are recognized among the Birrenswark Volcanic Formation and the Kelso Lavas on the north-west margins of the Tweed and Solway basins. However, the Cockermouth Lavas on the southern margin of the Solway Basin and the lavas of Derbyshire are almost entirely tholeiitic. Most of the sills in the English Midlands are alkaline, as are the lavas of the western Mendip Hills.

Midland Valley of Scotland and adjacent areas (Chapter 2)

A major review of Dinantian lavas in Scotland by Macdonald (1975) identified the full range of compositions, classified the rocks in terms of established magma series, and divided the local successions into geochemical 'lineages' and petrographical associations. The petrogenesis of the lavas was discussed and general trends were identified. Variations in major-element chemistry with time were explored in a subsequent paper (Macdonald *et al.*, 1977) and a study of trace-element variations led to conclusions regarding heterogeneity in the mantle source regions (Macdonald, 1980). The evolution of the Campsie Fells lavas was described by MacDonald and Whyte (1981), but otherwise much of the detailed geochemical data for the Midland Valley resides in unpublished theses (Whyte, 1963a; MacDonald, 1965; De Souza, 1979; Craig, 1980). Specific aspects of the magmatic evolution have also been investigated in theses by Boyd (1974) and Russell (1984). It was a PhD thesis by Smedley (1986a) that provided the most detailed review of Dinantian magmatism in northern Britain, and more general aspects of this work, mainly concerned with the mantle source and magma generation, have been published as papers (Smedley, 1986b, 1988a,b). Some aspects of the Dinantian magmas, based upon Smedley's data, were discussed subsequently in comparison with those of Silesian and Permian age from Scotland in a thesis by Wallis (1989).

The most basic lavas (those with MgO   4%) show trace-element enrichments and isotope ratios that are typical of within-plate magmatism (Macdonald, 1980; Smedley, 1986a,b, 1988a). Many rapidly accumulated continental flood-basalt sequences are associated with the rise of anomalously hot deep mantle in mantle plumes. However, geochemical and mineralogical evidence does not favour an unusually deep source for the Dinantian magmas, and the absence of any systematic change in the location of magmatism with time makes plume-generated melting unlikely (Smedley, 1986a,b). It seems more likely that all of the Carboniferous and Permian alkali basaltic magmatism in Britain was due to pressure-release melting of the upper mantle during extension related to subduction processes occurring several hundred kilometres farther south (see 'Tectonic setting and evolution', this chapter). The abundance of spinel lherzolite and the absence of garnet lherzolite in inclusion suites (see 'Xenoliths and megacrysts', this chapter) suggests that the magmas rose through an attenuated lithosphere that was too thin for its lower levels to be within the garnet lherzolite stability field (Smedley, 1988a). Hence, it is inferred that the rapid onset of widespread and voluminous igneous activity at a time of general subsidence, sedimentation and extensional faulting in the Midland Valley was a result of passive rifting and diapiric upwelling from the upper mantle during a period of lithospheric stretching (Smedley, 1986b).

It is generally agreed that the alkaline basic magmas of northern Britain were derived by small-fraction partial melting (less than 5%) of upper-mantle material at depths of 80–60 km (B.G.J. Upton, pers. comm., 2001). Light rare-earth-element enrichments in the Dinantian basalts imply that garnet was an important phase in the mantle source, which was therefore most likely to have been garnet lherzolite, present only in the sub-lithospheric mantle (Smedley, 1986a). The incompatible element patterns and isotope ratios do not allow unequivocal distinction between lithospheric and sub-lithospheric mantle sources, but data from the most basic rocks strongly resemble those from ocean island basalts (OIB), suggesting that interaction with continental lithosphere was minimal and that an asthenospheric or sub-asthenospheric origin was more likely (Smedley, 1986a,b, 1988a).

Smedley (1986b) showed that certain trace-element and isotopic values of the most basic Dinantian lavas are similar to those of the preceding, late-Caledonian calc-alkaline lavas that were erupted in the Midland Valley some 60–70 Ma earlier (Thirlwall, 1982). She concluded that similar portions of mantle were melted in each event and hence that the Dinantian magmas could have come from a relatively shallow depth in the upper mantle, equivalent to the supra-subduction zone mantle wedge of the earlier event. In a later paper (Smedley, 1988b), she noted spatial variations in isotope ratios of Dinantian lavas across the Highland Boundary Fault that correlate well with a general increase in enrichment towards the north and north-west observed in earlier calc-alkaline lavas and granitoid intrusions. This is seen particularly in differences in Sr, Nd and Pb isotope ratios between Dinantian lavas of Kintyre and Arran and those of areas south-east of the Highland Boundary Fault. Such long-term spatial isotopic distinctions, implying differing styles of enrichment of the sources prior to partial melting, could suggest that the mantle sources were immobile, non-convecting and therefore lithospheric. However, the overall element and isotope variation within the Dinantian basic lavas falls entirely within the range of OIB and hence Smedley (1988b) concluded that their principal source could have been within heterogeneous convecting asthenosphere as originally proposed (Smedley 1986b, 1988a).

Macdonald (1975) demonstrated that volcanic sequences from geographically separate areas produced distinctive magmatic lineages, each, to a greater or lesser degree, distinguishable in terms of silica-saturation, Fe/Mg and Na_2O/K_2O ratios, TiO_2 and P_2O_5. This geochemical provinciality was subsequently confirmed by the contrasting incompatible trace-element and isotopic characteristics of different areas that in some cases persisted throughout Silesian and into Permian times (Macdonald, 1980; Smedley, 1986a, 1988a). Although all authors have invoked a degree of mantle heterogeneity (see below), some of this variation could be due to varying degrees of partial melting. Wallis (1989) observed that Dinantian magmatism seemed to have been more productive in the west and that this is reflected by greater degrees of silica-saturation, implying a greater degree of partial melting (2–4%), as opposed to less than 2% for the eastern Dinantian and subsequent alkali magmatism. Anomalously low potassium in many of the Midland Valley basic lavas, particularly those with high contents of incompatible elements, suggests that a K-bearing phase such as phlogopite was present as an accessory in the sources of the magmas and that this was consumed only during higher degrees of partial melting (Macdonald, 1980; Smedley, 1986a, 1988a). Hence, the most silica-saturated western lavas of Kintyre and the Clyde Plateau do not show K-depletion, having gained potassium from phlogopite as a result of greater melting.

However, these geochemical variations cannot be accounted for entirely by variable degrees of partial melting or by crystal fractionation of observed phenocryst phases, and they must be due in part to differing mantle compositions. Smedley (1988a) used Ce/Y and Zr/Nb ratios of the most basic rocks to show that the best model involves varying degrees of partial melting, superimposed upon slight heterogeneity of the source region. There is no isotopic evidence in any of the basic rocks for crustal contamination or for input from a relict lithosphere slab, so the heterogeneity is not related to either of these processes. Smedley (1988a) considered that the variation reflects to some extent the relatively high speed of northward migration of the lithospheric plate (15° of latitude in 40 Ma; Irving, 1977), during the course of which magmas could have been extracted from an enormous volume of varied convecting sub-lithospheric mantle over a wide area. However, in her re-assessment of the earlier data, Wallis (1989) suggested that the amount of enrichment observed in some areas could not be derived entirely from heterogeneous asthenosphere and invoked a small input from enriched mantle at the base of the lithosphere.

Subsequent evolution of the magmas was largely by fractional crystallization, as is suggested by a general close agreement between major elements, compatible trace elements and the phenocryst assemblages (Smedley, 1986a, 1988b). For example, the behaviour of Al and Ca in relation to Mg in whole-rock compositions demonstrates that fractionation of clinopyroxene played a major role and Macdonald (1975) suggested early crystallization of clinopyroxene only above 13 kbar or of olivine + clinopyroxene + plagioclase at slightly lower pressure (above 9 kbar). The complex zonation of clinopyroxene phenocrysts from basalts of the Castle Rock and Holyrood Park (**Arthur's Seat Volcano** GCR site) provides a classic illustration of polybaric crystallization commencing at pressures of up to 11.5 kbar, i.e. at sub-crustal depths (Clark, 1956; Russell, 1984; Smedley, 1986a). It appears likely that primitive picritic magmas were arrested at, or close to, the crust–mantle boundary as 'underplated magmas' where they resided until fractionation of olivine, clinopyroxene and subordinate spinel had reduced the melt densities sufficiently for further crustal ascent to take place. This interpretation is supported by the observation that primitive high-Mg melts are not represented among the Dinantian lavas and intrusions. Although some of the olivine-clinopyroxene-phyric rocks have bulk MgO contents of up to 12%, these almost certainly experienced concentration of both augite and olivine prior to eruption, the groundmass compositions (taken as indicative of melt compositions) being no more magnesian than *c.* 10% (Smedley, 1986a). Therefore, it may be inferred that olivine-clinopyroxene cumulates (wehrlites) and subsequent olivine-clinopyroxene-plagioclase cumulates (gabbros) were produced in abundance at depth during the interrupted ascent of the magmas. Fragments of such materials are found more commonly in Silesian and Permian vents and intrusions (see 'Xenoliths and megacrysts', this chapter), but Clark (1956) drew attention to the presence of coarse clusters of crystals in some of the Arthur's Seat lavas that could be autoliths (cognate xenoliths) of gabbroic, anorthositic and pyroxenitic facies acquired at depth.

The strongly porphyritic nature of many of the Dinantian extrusive and intrusive rocks, together with their broad compositional range (Figure 1.7a), suggests that magma residence in sub-crustal and crustal magma chambers was general and widespread. High-pressure clinopyroxene-dominated fractionation was followed by fractionation of olivine + plagioclase ± magnetite at lower pressures (Macdonald, 1975; MacDonald and Whyte, 1981) and hence the bulk of the Dinantian magmas were erupted in a relatively fractionated condition. In some areas, basaltic hawaiites and hawaiites predominate over basalts proper. Further crystal fractionation (mainly of plagioclase) in small, near-surface magma chambers can be deduced from hawaiitic lavas in the Renfrewshire Hills and Campsie Fells that exhibit slight variations in composition during the course of a single eruption (Kennedy, 1931; MacDonald, 1967; Boyd, 1974). Such composite flows are particularly well illustrated in the **Dunrod Hill** GCR site. Macdonald (1975) noted that there is compositional continuity throughout the whole series, and the trachytes, phonolitic trachytes and rhyolites are all regarded as having been derived by further fractional crystallization from the mugearitic stage of magma differentiation. However, it is reasonable to suspect that genesis of some of the more highly siliceous magmas involved varying degrees of crustal contamination. Some evidence of this has been found in Kintyre, from the presence in basalts of quartz xenocrysts with complex reaction rims of clinopyroxene and from the isotopic composition of trachytic rocks (Smedley, 1986a).

Solway, Northumberland and Tweed basins (Chapter 3)

Collectively the Dinantian volcanic rocks of the Solway, Northumberland and Tweed basins are part of the transitional, mildly alkaline to tholeiitic suite that characterizes all of the Dinantian volcanism of northern Britain (Macdonald, 1975). The Tournaisian Cockermouth Lavas, Birrenswark Volcanic Formation and Kelso Lavas have similar compositions and hence the

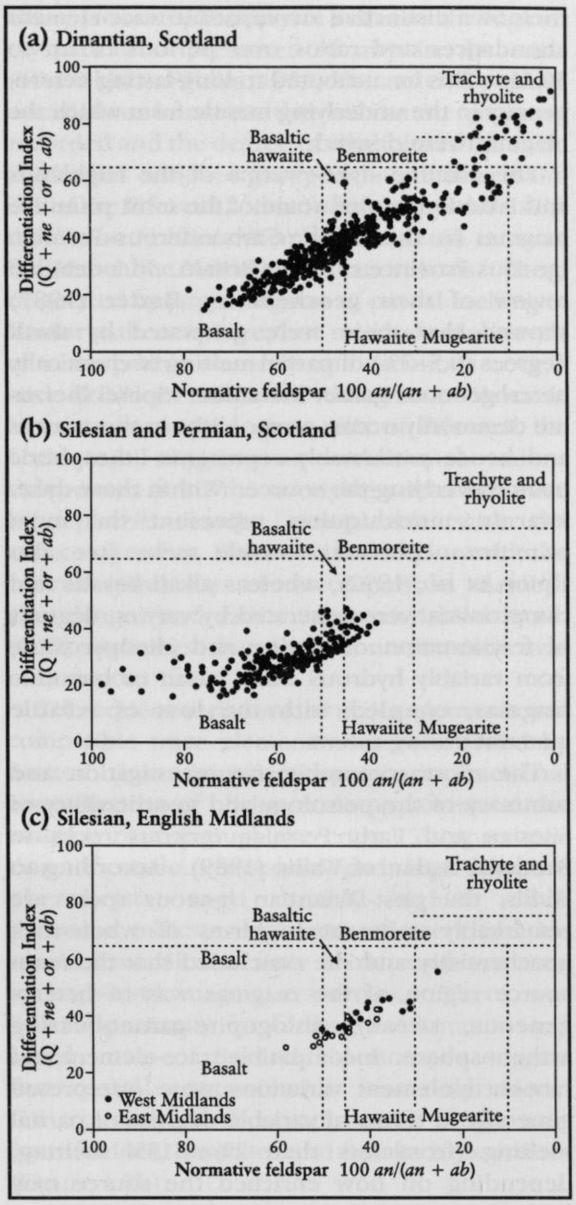


Figure 1.7 Range of compositions of Carboniferous and Permian igneous rocks, illustrated by a plot of Differentiation Index (normative % quartz + nepheline + orthoclase + albite) against normative feldspar composition (% anorthite/(anorthite + albite)), as used in the classification of Coombs and Wilkinson (1969); and Macdonald (1975). (a) Dinantian igneous rocks of Scotland, after Smedley (1986a); (b) Silesian and Permian igneous rocks of Scotland, after Wallis (1989); (c) Silesian igneous rocks of the English Midlands, after Kirton (1984).

juxtaposition of Laurentian and Avalonian lithosphere across the Iapetus Suture appears to have had no detectable influence on the geochemistry of the early Dinantian magmas (Macdonald and Walker, 1985). Most of these rocks contain normative quartz and hypersthene and are thus tholeiitic, though some nepheline-normative lavas (hawaiite and mugearite) are present in the formations from the northern margins of the basins (Macdonald and Walker, 1985; Smedley, 1986a). Smedley (1988a) showed that, in terms of trace-element concentrations, such as Ce, Nb and Ba, these early basalts are some of the least enriched of the Dinantian volcanic rocks of northern Britain. However, despite their close proximity to the Birrenswark Volcanic Formation, the slightly younger Kershopefoot basalts have very distinctly different Ce/Y and Zr/Nb ratios. These and other geochemical characteristics were interpreted by Smedley (1988a) to have arisen from the partial melting of a chemically heterogeneous mantle. In contrast, the Cockermouth Lavas were interpreted by Macdonald and Walker (1985) as having formed by varying degrees of partial melting of homogeneous mantle, followed by fractional crystallization and equilibration at high crustal levels to produce some tholeiitic andesites. There is no evidence of significant crustal contamination.

Central England (Chapter 7)

The geochemistry of Derbyshire Carboniferous igneous rocks has been detailed by Macdonald *et al.* (1984). The bulk of the volcanism was tholeiitic, as is shown by normative hypersthene and typically tholeiitic trace-element abundances in the whole rock and by clinopyroxene compositions. However, some nepheline-normative alkaline compositions occur in sills. Incompatible trace-element data show a wide variation in Zr/Nb, suggesting derivation from a mantle source that was highly heterogeneous and that each lava or sill represents a discrete melting event. Most of the major-element variation can be attributed to varying degrees of partial melting, followed by fractional crystallization and final equilibration within the lower crust, with no low-pressure fractionation in higher level magma chambers. Crustal contamination, if it occurred at all, was only slight. There is no consistent relationship between compositional variations and time or geographical location. Macdonald *et al.* (1984) considered this to be consistent with relatively short-lived, small vents with each event derived from melts that passed through the crust via small unconnected conduits, dykes and sills.

Silesian and Early Permian alkaline magmas

Scotland (Chapters 4 and 5)

Like those of the preceding Dinantian times, the Silesian and Early Permian igneous rocks of Scotland are typical of extension-related intraplate continental volcanism but also have similarities to ocean island basalts (OIB). The lavas and intrusive rocks range generally from hypersthene-normative transitional basalts to nepheline-normative mildly alkaline basalts and basanites, but the latest Early Permian assemblages are characterized by highly silica-undersaturated foidites and monchiquites (Macdonald *et al.*, 1977; Macdonald, 1980; Wallis, 1989). This range lies within a general trend from tholeiitic to transitional basalts in early Dinantian times in the Northumberland, Solway and Tweed basins, to transitional to mildly alkaline types in the Midland Valley in later Dinantian and Silesian times, to the highly silica-undersaturated rocks of the Permian basins and wider dyke-swarms. However, Macdonald *et al.* (1977) pointed out that the overall trend is seriously interrupted by the presence of hypersthene-normative, almost tholeiitic lavas in the Troon Volcanic Member, and proposed that volcanism in the Midland Valley was related to two magmatic or thermal cycles. Each of these began with the eruption of hypersthene-normative magmas, which then gave way through time to increasingly nepheline-normative types. The late Namurian to Early Permian rocks therefore define the second cycle.

This two-cycle model is almost certainly an over-simplification; it fails to take into account the voluminous injection of tholeiitic magma during early Stephanian times (see Chapter 6) and further analyses (Wallis, 1989) 'cloud' the geochemical trends proposed by Macdonald *et al.* (1977, fig. 1). However, there does seem to be a trend towards increasingly silica-undersaturated magmas with time in several individual areas (Upton, 1982) which may reflect progressively lower geothermal gradients and smaller degrees of partial melting at greater mantle depths, producing less magma in the later stages of each local thermal event. Macdonald (1980) showed that separate geographical areas of the Midland Valley retained their own distinctive incompatible trace-element abundances and ratios over periods of up to 50 Ma. This he attributed to long-lasting heterogeneity in the underlying mantle from which the magmas were derived.

The alkaline dyke-swarms of the Highlands and Islands sampled some of the most primitive magmas in the whole Carboniferous–Permian Igneous Province of Great Britain. In a detailed review of their geochemistry, Baxter (1987) showed that these were generated by small degrees (0.5–2%) of partial melting of chemically heterogeneous garnet lherzolite. Spinel lherzolite commonly occurs as xenoliths in these rocks and hence presumably represents lithospheric mantle overlying the source. Within these dyke-swarms, monchiquites represent the most primitive nephelinitic mantle melts (see also Upton *et al.*, 1992), whereas alkali basalts and camptonites were generated by varying degrees of fractionation of olivine and clinopyroxene from variably hydrous alkali basalt or basanitic magmas, coupled with the loss of volatile material during ascent.

The most comprehensive investigation and summary of the petrology and geochemistry of Silesian and Early Permian igneous rocks in Scotland is that of Wallis (1989). According to Wallis, the post-Dinantian igneous rocks are remarkably coherent in terms of whole-rock geochemistry and she concluded that the main source region of the magmas was in heterogeneous, streaky, phlogopite-garnet-bearing asthenosphere. Incompatible trace-element and rare-earth-element variations were interpreted generally in terms of variable degrees of partial melting (from less than 2% to 15% melting, depending on how enriched the source may have been), and the lavas and intrusions were divided into two broad geochemical groups based on their content of incompatible trace elements.

The most enriched group included most of the Highland dykes, about half of the Fife and Lothian sills, the smaller basanitic intrusions associated with volcanic necks in the eastern Midland Valley and a few of the lavas of the Mauchline Volcanic Formation. These represent the smallest degrees of partial melting of the asthenosphere and show no evidence of lithospheric contamination. Clinopyroxene fractionation played an important part in their early evolution and the Al^{iv}/Al^{vi} content of clinopyroxene phenocrysts indicates the highest crystallization pressures of any in the suite (10–20 kbar). Wallis (1989) also noted a positive correlation between the maximum pressure recorded and the degree of alkalinity of the rock.

The less enriched group included the remainder of the Fife and Lothian sills, the Ayrshire sills, the Troon Volcanic Member lavas and most of the Mauchline Volcanic Formation lavas. These originated by larger degrees of partial melting of similar asthenosphere, but relatively high levels of incompatible elements and variations in Ce/Y and Zr/Nb in some of the Troon Volcanic Member lavas (and some sills of Fife and the Lothians) suggest an additional minor component from the overlying sub-continental lithospheric mantle, comparable with the source of earlier, Dinantian lavas. However, the overall similarity of incompatible element abundances and ratios to ocean island basalt (OIB) indicates that such contamination was only minor.

Subsequent variations in major elements and compatible trace elements were controlled by limited (less than 36%) polybaric fractional crystallization of olivine ± clinopyroxene as the magmas rose through the crust. The preservation of mafic xenocrysts and high-pressure phenocrysts, most notably high-Al clinopyroxene, indicates high rates of ascent and this would have allowed little or no residence time in high-level magma reservoirs. There was little opportunity for further fractionation and initial ratios of Sr and Nd isotopes suggest that crustal contamination was only minor. Consequently, rock compositions range only from foidites, basanites and basalts to hawaiites (Figure 1.7b).

Central England (Chapter 7)

The whole-rock major- and trace-element geochemistry of the Silesian volcanic rocks and associated sills of the East and West Midlands of England has been described by Kirton (1981, 1984). Both alkaline and tholeiitic magmas were recognized in the East Midlands, where compositions range from basanite and basalt to hawaiite. However, in the slightly younger sills of the West Midlands only alkaline rocks occur and these are a little more differentiated, ranging from basaltic hawaiite to hawaiite, with mugearitic late-stage veins (Figure 1.7c).

Stephanian tholeiitic magmas (Chapter 6)

The extensive tholeiitic sill-complexes and dykes of central Scotland and north-east England were all intruded during a relatively short time interval during the Stephanian Epoch and also show close geochemical similarities. The chemical composition of the basalts and dolerites is similar to those from Hawaii and to Fe-Ti basalts from the Palaeogene North Atlantic Igneous Superprovince and implies large degrees of shallow-level mantle melting. Such melting tends to occur in regions where active lithospheric spreading is taking place and there is excess basaltic discharge due to the influence of a mantle plume (Brooks and Jakobsson, 1974). Investigations by Pederson and van der Beek (1994) found no evidence of a plume associated with the Oslo Graben, but Ernst and Buchan (1997) suggested that a mantle plume in the Skaggerak area could be the centre of a giant radiating dyke-swarm, with the Whin Sill-complex and Midland Valley Sill-complex, the Oslo Rift and the Scania dykes marking the arms of a 'triple junction'. Wilson *et al.* (2000) supported this idea and suggested that magma could have been transported horizontally by dyke injection for great distances from the Skaggerak source region, so that any thermal anomaly need not have been widespread.

Slight geochemical variations across the Whin Sill-complex imply that it was emplaced as a number of pulses of tholeiitic olivine basalt magma (Thorpe and Macdonald, 1985; Howard, 1999). The variations may be due to a heterogeneous mantle source but, based on incompatible element abundances, Howard (1999) suggested that crustal contamination was also an important factor in the evolution of both the Whin Sill-complex and the Midland Valley Sill-complex. Systematic minor variations in both major- and trace-element geochemistry between the two sill-complexes suggest that they were not comagmatic (Howard, 1999). Similarly Macdonald *et al.* (1981) showed that although most dykes from the Scottish swarm fall within a restricted compositional range (which reflects the same compositional variation observed in the Midland Valley Sill-complex), there are also slight, non-systematic trace-element variations between dykes. In fact, some dykes were found to have a unique chemical 'fingerprint', which assists in the tracing of discontinuous dykes across the region. Macdonald *et al.* considered this to be proof that the dyke system was not fed by a single homogenous magma but that fissures were filled by a number of small, partly independent magma chambers reflecting a heterogeneous mantle source. They found no evidence for crustal contamination in the Scottish dykes.

The generation of tholeiitic magmas beneath part of the Midland Valley during Stephanian time may have had an effect upon later magmas by depleting the basal lithosphere in incompatible elements. Wallis (1989) argued that the basanitic intrusions associated with late Stephanian–Early Permian necks in Fife and East Lothian, together with some sills in the area, lack a lithospheric mantle signature because the enriched lithosphere had been 'swept clean' of the more easily melted phases by the tholeiitic melts. However, the Early Permian Mauchline Volcanic Formation lavas originated some 20–30 km to the south of the limit of tholeiitic intrusions, and here interaction of the magmas with the basal lithosphere is reflected by higher Sr and lower Nd initial isotope ratios.

XENOLITHS AND MEGACRYSTS

D. Stephenson

Many of the Carboniferous and Permian igneous rocks of the British Isles contain suites of xenoliths and related individual inherited crystals (megacrysts) that are valuable samples of the otherwise inaccessible underlying continental lithosphere. These bring added conservation value to many of the GCR sites as, apart from geophysical interpretations and indirect observations of geochemical features, they are the only direct source of information on the nature of the upper mantle and deep crust beneath the region. The majority of xenoliths occur either in pyroclastic rocks preserved within volcanic vents and necks or in fine-grained minor intrusions; they are rare within lavas. The minor intrusions include plugs, sills and inclined sheets but xenolith-bearing dykes are particularly common. These dykes are typically narrow (less than 1 m), with xenolith-free marginal zones and axial zones that are crowded with xenoliths; in inclined sheets, the xenoliths are typically concentrated at the base. Host magmas are predominantly the more silica-undersaturated, alkaline basanitic, lamprophyric and foiditic varieties, and consequently xenoliths are most commonly associated with the Silesian and Early Permian magmatism; they are scarce in the transitional to mildly alkaline sequences that characterize the Dinantian rocks of Scotland and northern England.

Over 70 xenolith-bearing localities in the north and west of the British Isles collectively constitute the oldest documented basaltic 'nodule province' in the world, others being of Mesozoic or younger age. A general review of upper-mantle and deep-crustal xenoliths in the British Isles by Upton *et al.* (1983) includes a list of all occurrences known at the time of publication. Most of the localities are in the Midland Valley of Scotland or in the north-west Highlands, Inner Hebrides and Orkney Islands, with a scattering in the Southern Uplands; the Midland Valley and Southern Uplands localities have been reviewed by Upton *et al.* (1984). Notable localities in Scotland that are GCR sites are **North Berwick Coast**, **East Fife Coast**, **Heads of Ayr** and **Dubh Loch**. In England, mantle xenoliths are known only from Derbyshire (see **Calton Hill** GCR site report) and from boreholes in the East Midlands (Kirton, 1984). In Wales, Late Palaeozoic igneous rocks are rare but the occurrences near Usk both contain mantle xenoliths (see **Golden Hill Quarry** GCR site report).

The abundance of xenoliths and megacrysts, and the proportions of different lithologies, vary widely between sites but the reviews by Upton *et al.* (1983, 1984) have identified up to 11 categories. In addition to those of upper-mantle and deep-crustal origin, cognate xenoliths ('autoliths') associated with the evolution of the host magmas themselves and fragments of upper-crustal country rocks are commonly present. For descriptive purposes, the various suites will be described below in relation to their inferred site of origin.

Upper mantle

The nature of the upper mantle beneath the British Isles, as deduced from xenoliths, has been reviewed by Hunter and Upton (1987) and there have been numerous studies of xenolith suites from individual intrusions. A detailed trace-element and isotopic study of mantle material from Scotland by Menzies and Halliday (1988) identified lateral heterogeneity, with discrete domains of variably depleted or enriched mantle resulting from successive tectonomagmatic events. Mantle xenoliths are particularly relevant to discussions of Carboniferous and Permian igneous activity as they are representative samples from the possible source region of the magmas or provide information about the processes of magma generation. They are widespread, occurring in almost all of the known xenolith localities, and they are normally the most abundant 'deep-source' xenoliths at any locality. They are all ultramafic and can be divided into two main groups: (a) olivine-dominated magnesian peridotites, mainly spinel lherzolite but with some spinel harzburgite, and (b) clinopyroxene-dominated rocks, including wehrlites, clinopyroxenites, websterites, hydrous clinopyroxenites and rare garnet pyroxenites.

Xenoliths of spinel lherzolite (ol + opx + cpx + sp) and spinel harzburgite (ol + opx + sp) are generally less than 5 cm in diameter. Although fresh at some localities (Figure 1.8; and Figure 7.11, Chapter 7), they have commonly undergone low-temperature hydrous alteration to serpentine, carbonates and clay minerals. They exhibit a variety of textures that reveal a history of deformation and recrystallization and some have a pronounced foliation.

Clinopyroxene-rich ultramafic rocks commonly accompany peridotites in xenolith suites. They are generally slightly larger (5–10 cm), coarser grained and darker in colour than the peridotites (Figure 1.9) and their minerals are more Fe-rich. Metamorphic textures are absent but relict igneous textures, including cumulates, are commonly preserved and there is some evidence of mineral layering. A protracted cooling history is indicated by re-equilibration, recrystallization and unmixing of the clinopyroxene, with exsolution of orthopyroxene and spinel (Chapman, 1975). The most common varieties are wehrlites and clinopyroxenites, which contain varying proportions of clinopyroxene and olivine; some have spinel. Websterites (opx + cpx + sp) are less common. Mica pyroxenites are widespread and are abundant locally (e.g. **East Fife Coast** and **North Berwick Coast** GCR sites); virtually monomineralic mica rocks, known as 'glimmerites', also occur. Amphibole-rich pyroxenites are less widespread although these too are abundant locally, for example in East Fife (Chapman,

Figure 1.8 Peridotite xenolith with a thin rim of altered chilled basalt in the Weaklaw Vent, **North Berwick Coast** GCR site. The coin is 24 mm in diameter. (Photo: B.G.J. Upton.)

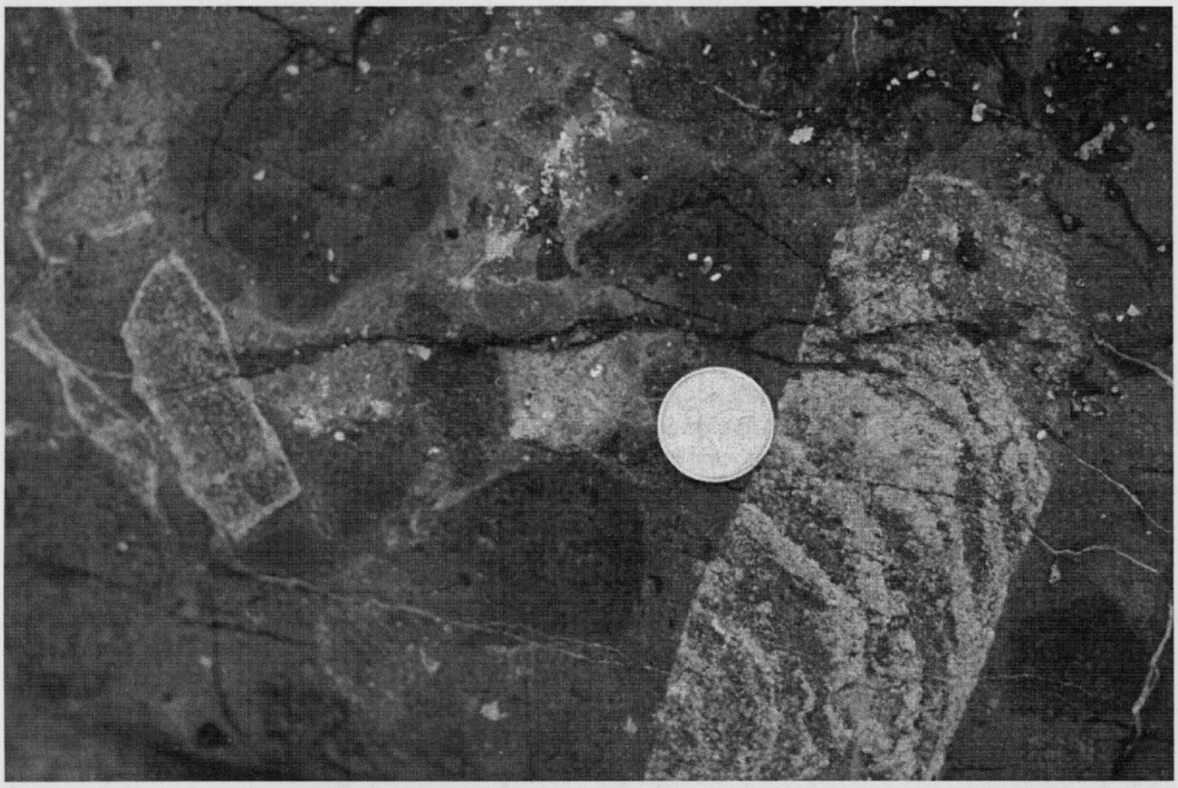


Figure 1.9 Xenoliths in an Early Permian olivine nephelinite dyke at Gribun, Isle of Mull; dark pyroxenites and pale-coloured granulite-facies gneisses. Note the folding in the large block of gneiss. The coin is 24 mm in diameter. (Photo: B.G.J. Upton, from Upton *et al.*, 1998.)

1976), and in Mull (Upton *et al.*, 1998). The hydrous ultramafic rocks tend to be enriched in Fe and Ti relative to the anhydrous equivalents and commonly contain apatite indicating an enrichment in phosphorous. Garnetiferous ultramafic rocks, possibly garnet websterites, are rare; these rocks have granoblastic equilibrium textures but the pyroxene is commonly altered and the garnet appears to have formed by reaction between clinopyroxene and spinel.

It is generally agreed that peridotitic xenoliths originated in the upper mantle and detailed mineralogical studies of lherzolites from Calton Hill (Derbyshire), the western Highlands and the North Berwick Coast (Donaldson, 1978; Praegel, 1981; Hunter *et al.*, 1984) have resulted in estimates of equilibrium conditions in the range 884–1200°C and 8–23 kbar, corresponding to depths of *c.* 30–70 km. The pyroxene-rich ultramafic rocks could be either from the upper mantle or the lower crust, although geophysical properties and phase equilibria studies favour the upper mantle. Elsewhere in the world, where tectonically emplaced upper-mantle is exposed, lherzolites and pyroxenites are intimately associated, and rare composite wehrlite-lherzolite xenoliths from East Fife and North Berwick suggest that this is also the case beneath Scotland. The overall impression gained is of an extremely heterogeneous upper mantle consisting of deformed magnesian peridotites, cut by a stockwork of sheets or by larger bodies of younger pyroxenite (Upton *et al.*, 1983, 1984). The peridotites are probably residual mantle material ('restites') depleted by episodes of partial melting during the Proterozoic and Palaeozoic eras. It is not possible to determine when the deformation and recrystallization occurred but Hunter *et al.* (1984) speculated that it could have been due to solid flow associated with the initial stages of lithospheric rifting in Early Carboniferous times. The pyroxenites represent high-pressure crystallization products from basic magmas retained at depth, and their rare-earth-element patterns in particular suggest that they may have been related to their host basalts (Downes *et al.*, 2001). Many could have been side-wall cumulates in narrow magma conduits. It has also been argued that underplated pyroxene-rich rocks form a substantial layer between peridotitic upper-mantle and feldspathic lower-crust (Menzies and Halliday, 1988; Upton *et al.*, 2001).

The hydrous, mica- and amphibole-bearing pyroxenites (and rare hydrous peridotites) probably indicate local metasomatic enrichment of volatiles, K, Ti and P, probably from a volatile-rich alkali basalt melt rather than a fluid (Upton *et al.*, 1998). The local nature of the metasomatism is well demonstrated in the **North Berwick Coast** GCR site, where the change from dominantly anhydrous to dominantly hydrous xenolith assemblages occurs over a very short distance from west to east. However, Chapman (1976) proposed a cumulitic origin for biotite- and kaersutite-pyroxenites at Elie Ness (**East Fife Coast** GCR site) as a result of high-pressure fractional crystallization of a primitive alkali basalt magma, trapped at uppermost-mantle and lower-crustal levels. In this model, the cumulate pyroxenites and their associated megacryst assemblages (see below) were comagmatic with the host intrusions of basanite and monchiquite, which represent middle to late stages of evolution of the same primitive magmas.

Lower crust

Although the crust–mantle boundary (the Moho) is usually well defined in deep seismic profiles across northern Britain (e.g. Bamford, 1979), it is less distinct petrologically. At most of the xenolith localities, ultramafic clinopyroxenite and wehrlite cumulates, as described in the previous section, are associated with mafic granulite-facies meta-igneous rocks. The densities of the latter lithologies correlate well with seismic velocities observed above the Moho and mineral assemblages are consistent with equilibration at depths of 18–30 km (Hunter *et al.*, 1984). Hence they probably constitute the bulk of the lower crust. However, around the base of the crust the pyroxenites and mafic rocks are probably interleaved in a broad zone. They have similar rare-earth-element abundances and patterns and, together with their general similarity in mineralogy, this suggests that they may be genetically related as parts of cumulate complexes (Upton *et al.*, 1998, 2001; Downes *et al.*, 2001).

Xenoliths of mafic lower-crustal materials are less common than ultramafic rocks from the mantle but they are known from many of the localities in Scotland. Much detailed work has concentrated upon the Partan Craig Vent in the **North Berwick Coast** GCR site, which has yielded by far the most examples (Upton *et al.*, 1976; Graham and Upton, 1978), the Fidra Sill, also near North Berwick (Hunter *et al.*, 1984; Downes *et al.*, 2001), the Gribun Dyke on Mull (Upton *et al.*, 1998) and the Tingwall Dyke, Orkney and Duncansby Ness Neck, Caithness (Upton *et al.*, 2001). A detailed isotopic and geochemical study by Halliday *et al.* (1993) provided a review of all lower- and middle-crustal xenoliths in Scotland, and the influence of the host magma upon the trace-element and isotopic composition of the xenoliths was investigated by Lee *et al.* (1993).

The mafic lower-crustal xenoliths are mostly metagabbroic or metadioritic and are composed essentially of pyroxene (clino- ± ortho-) and plagioclase (labradorite to oligoclase), with common magnetite. Biotite, amphibole and apatite are present in some. The more plagioclase-rich varieties grade into meta-anorthosite, and with the development of quartz, the compositions become meta-quartz-dioritic and metatonalitic. Garnet-pyroxene-plagioclase assemblages, common in many other continental lower-crustal xenolith suites, are rare. Relict igneous textures are preserved but textures are more commonly granoblastic, with some gneissose mineral layering (Figure 1.9), and there are indications of partial melting. These mineralogical and textural features signify granulite-facies metamorphism and the lithologies have been referred to collectively as 'basic granulites' in many publications.

The detailed studies of lower-crustal mafic xenoliths by Hunter *et al.* (1984) and Upton *et al.* (1998) have both suggested that their parental magmas were of alkali basalt composition, and Halliday *et al.* (1993) calculated that the average composition of all of the lower crust beneath Scotland is alkalic. The compositions of the principal minerals and regional whole-rock trace-element variations suggest that the xenoliths represent high-pressure cumulates formed by crystal fractionation (Halliday *et al.*, 1993). These may have originated from the differentiation of basic magmas that were trapped at the crust–mantle boundary as part of a process known as 'underplating'. Here they probably formed layered mafic igneous complexes that were subjected to varying degrees of recrystallization, partial melting and possible local metasomatism as they became incorporated into the lower crust (Hunter *et al.*, 1984). The rarity of garnetiferous lithologies in the xenolith suites implies that these must represent only a minor component of the deep crust and/or upper mantle and hence that the crust was not much more than 30 km thick in Late Palaeozoic times (Halliday *et al.*, 1993).

Although the mafic gneisses resemble and have similar seismic properties to those of the Lewisian Gneiss Complex of the north-west Highlands, there are significant differences in whole-rock geochemistry (Hunter *et al.*, 1984; Halliday *et al.*, 1993) and, from various lines of evidence, it seems unlikely that the Lewisian crust extends for more than 20–30 km east of the Moine Thrust (e.g. Smythe, 1987). In fact, U-Pb dating of zircons in an anorthositic xenolith from the Gribun Dyke, Isle of Mull, has indicated a crystallization age of 1850 ± 50 Ma, which is considerably younger than the Lewisian and more like the Rhinns Complex on the Isle of Islay (Upton *et al.*, 1998). Less precise estimates of radiometric age, described by Halliday *et al.* (1993), indicate that many of the igneous protoliths of the mafic gneiss xenoliths were formed and metamorphosed during magmatic underplating in Late Proterozoic and Palaeozoic times. However, the stable isotope and trace-element data also show that a significant component of the Palaeozoic deep crust beneath Scotland is derived from recycling of Archaean and Palaeoproterozoic lithosphere through sedimentary processes, arc volcanism and subduction, the latter as recent as during the later stages of the Caledonian Orogeny.

Middle crust

Xenoliths of granulite-facies quartzo-feldspathic gneiss have densities compatible with mid-crustal layers that have been identified on seismic profiles across northern Britain (e.g. Bamford, 1979). They are much less common than the lower-crustal mafic rocks, probably because the more felsic compositions are more easily melted and hence less likely to survive in high-temperature basaltic host magmas. They have been described principally from Partan Craig by Graham and Upton (1978) and from eight other Midland Valley occurrences by Halliday *et al.* (1993). Typical mineral assemblages involve quartz, plagioclase, biotite and alkali feldspar, but rutile, sillimanite, kyanite, graphite, magnetite, zircon and monazite also occur. Biotite is the only hydrous phase and that is scarce. Some xenoliths contain large porphyroblasts (up to 8 mm) of garnet (almandine–pyrope) with chloritic rims, and mineral layering of garnet-rich and garnet-poor layers is common on a centimetre to decimetre scale. Textures range from equigranular to gneissose and some are blastomylonitic. Whereas most of the quartzo-feldspathic xenoliths are considered to have had a metasedimentary origin, foliated quartz-plagioclase (trondhjemitic) xenoliths may be from meta-igneous segregations. Although these lithologies probably dominate mid-crustal levels, they may well be interleaved in subordinate proportions in the lower crust (Upton *et al.*, 1984).

The felsic (and mafic) gneisses are presumed to be representative of a high-grade basement, extending beneath the Midland Valley and the north-western part of the Southern Uplands. Whereas the top of this crystalline basement may be at a depth of no more than 7 km beneath the Midland Valley (Bamford, 1979), lithologies of this general type may characterize much of the middle crust down to depths of 18–20 km, where they grade down into rocks for which meta-igneous origins are more probable. Mineral compositions suggest that the pressure and temperature of metamorphism exceeded 11 kbar and 850°C in places (Graham and Upton, 1978). Although they have geochemical similarities to quartzo-feldspathic gneisses of the Archaean Lewisian Gneiss Complex (Graham and Upton, 1978), isotopic studies of xenoliths from Partan Craig have cast doubt upon such an old age (van Breemen and Hawkesworth, 1980; Halliday *et al.*, 1984). Combined U-Pb zircon and Sm-Nd whole-rock data from these studies suggest that the sedimentary protoliths of the granulite-facies gneisses were derived from crust of varying age, some older than 2200 Ma, but some no older than 1000 Ma. Both the sedimentation and the metamorphism of these rocks must therefore have occurred after *c.* 1000 Ma (Late Proterozoic). Similar isotopic characteristics of the gneisses to sedimentary rocks of the Southern Uplands have led Halliday *et al.* (1993) to suggest that they may have originated from Caledonian events, involving high-grade metamorphism of Lower Palaeozoic metasedimentary rocks that were underthrust beneath the Midland Valley.

Upper Crust

Xenoliths of upper-crustal origin are mainly of local derivation, either from earlier eruptive phases or from the immediately adjacent country rocks, and hence are specific to each individual vent or intrusion. Lithologies are many and varied and many examples are described in the GCR site reports. Some xenoliths of undeformed layered gabbroic rocks, diorites and syenites have been recorded and these are most likely to be the result of fractionation of the host magmas in middle- to upper-crustal magma chambers. Some necks also contain xenoliths of unfoliated granitic rocks that have been attributed to plutons of probable Caledonian origin (Upton *et al.*, 1983).

Megacrysts

In addition to xenoliths, many of the Carboniferous and Permian intrusions also contain single crystals or crystal aggregates of a wide range of minerals of igneous origin. Many are clearly out of equilibrium with the host magmas that carried them to current erosion levels and can be termed xenocrysts, but others are remarkably idiomorphic, suggesting that they grew as phenocrysts within the magma. Because of their commonly large size (up to 10 cm) relative to the grain size of the host rock, they have usually been referred to in the literature as 'megacrysts', a purely descriptive term that covers any mode of origin. The crystals include alkali feldspar (oligoclase, anorthoclase, sanidine), clinopyroxene (diopside, augite, ferrosalite), orthopyroxene, amphibole (kaersutite), mica (phlogopite, biotite), garnet (pyrope), magnetite, ilmenite, zircon, apatite and Nb-rich phases.

Some of the mafic megacrysts can be matched in composition with the component minerals of the ultramafic and mafic xenoliths and hence result from simple disaggregation (e.g. Alexander *et al.*, 1986). However, others have to be attributed to earlier (higher pressure) or later (lower pressure) stages of magmatic evolution than those represented by the xenoliths. At the Elie Ness Neck, Chapman (1976) showed from experimental studies that megacrysts of subcalcic augite and pyrope garnet (the 'Elie rubies'; see **East Fife Coast** GCR site report) could have coprecipitated at a depth of over 70 km from primitive alkali basalt magmas, formed by partial melting of garnet lherzolite at still greater depths (over 100 km). Donaldson (1984) accepted the high-pressure origin of these phases, with some qualification, though he cast doubt on their coprecipitation. Chapman (1976) interpreted other megacryst phases as having formed from the same magma or from related more evolved magmas; kaersutite at low crustal levels and anorthoclase from small bodies of evolved alkaline magma trapped in the upper crust. A trace-element and stable isotope study by Long *et al.* (1994) confirmed the association of most megacryst suites with the host alkaline magmas and the Midland Valley volcanicity. Density calculations have shown that the evolved magmas must have been of trachyandesite composition in order for the anorthosite crystals to remain suspended and grow to large sizes, prior to being picked up and transported by later surges of more basic magma that also carried the higher pressure phases (Chapman and Powell, 1976). A geochronological study of megacrysts from East Fife necks by Macintyre *et al.* (1981) supported this model by showing that the cumulus minerals (biotite, amphibole and pyroxene) plus zircon were formed at *c.* 315 Ma, contemporaneous with the local Namurian volcanism, but that the anorthoclase did not complete crystallization until 295 Ma, just before the eruption of the host basanite magmas at 290 Ma during the Stephanian Epoch.

There is increasing evidence that many of the megacrysts could not have been derived from the fractionation of basanitic, foiditic or lamprophyric magmas related to their host rocks. Much of this evidence comes from alkali feldspar megacrysts and feldspathic xenoliths, which are common in several of the East Fife Coast necks, at Fidra off the North Berwick Coast and at several other localities (Aspen *et al.*, 1990). A few composite xenoliths show that the feldspathic rocks may occur as pegmatitic veins traversing hydrous pyroxenites. The mineral phases are out of compositional and isotopic equilibrium with their host rocks, are not associated with any obvious more primitive parental lithologies, and Aspen *et al.* (1990) considered that they had crystallized from geochemically extreme low-temperature trachytic melts present in the upper mantle and/or deep crust at the time of the Carboniferous–Permian magmatism. They suggested that the melts may have originated through very small-scale partial melting of lithospheric mantle under the influence of volatile fluxes.

Of particular interest are anorthoclase-rich syenitic xenoliths (anorthoclasites) that also contain corundum and Nb-, Zr-, U-, Th- and rare-earth-element-rich minerals (Upton *et al.*, 1999). The very high content of incompatible trace elements and the presence of calcite veinlets in these xenoliths suggest the possible involvement of asthenosphere-derived alkali-rich carbonatitic melts that permeated and interacted with the uppermost mantle to produce carbonated trachytic melts (as suggested by Long *et al.* (1994) for megacrysts in a Palaeogene dyke cutting the Lewisian craton). In the most extreme compositions, the presence of corundum reflects a highly aluminous melt that would have been almost impossible to achieve by fractional crystallization and hence some mechanism of alkali loss has to be suspected. Upton *et al.* (1999) proposed that the alkalis could have been removed in a carbonatitic fraction that separated from the trachytic melt to leave an aluminous residuum.

With the exception of the far north-west, which was subjected to magma generation and ascent during Palaeogene time, the nature of the deep lithosphere of Great Britain has probably changed little since it was sampled by the Late Palaeozoic magmas. Hence the information gained from the xenoliths and megacrysts, and summarized in Figure 1.10, is as relevant to the present-day deep structure of Britain as it is to their time of emplacement. The extensive literature summarized above demonstrates the importance that has been attached to this subject already, and the xenolithic vents and intrusions of the GCR sites will no doubt continue to supply material for further studies.

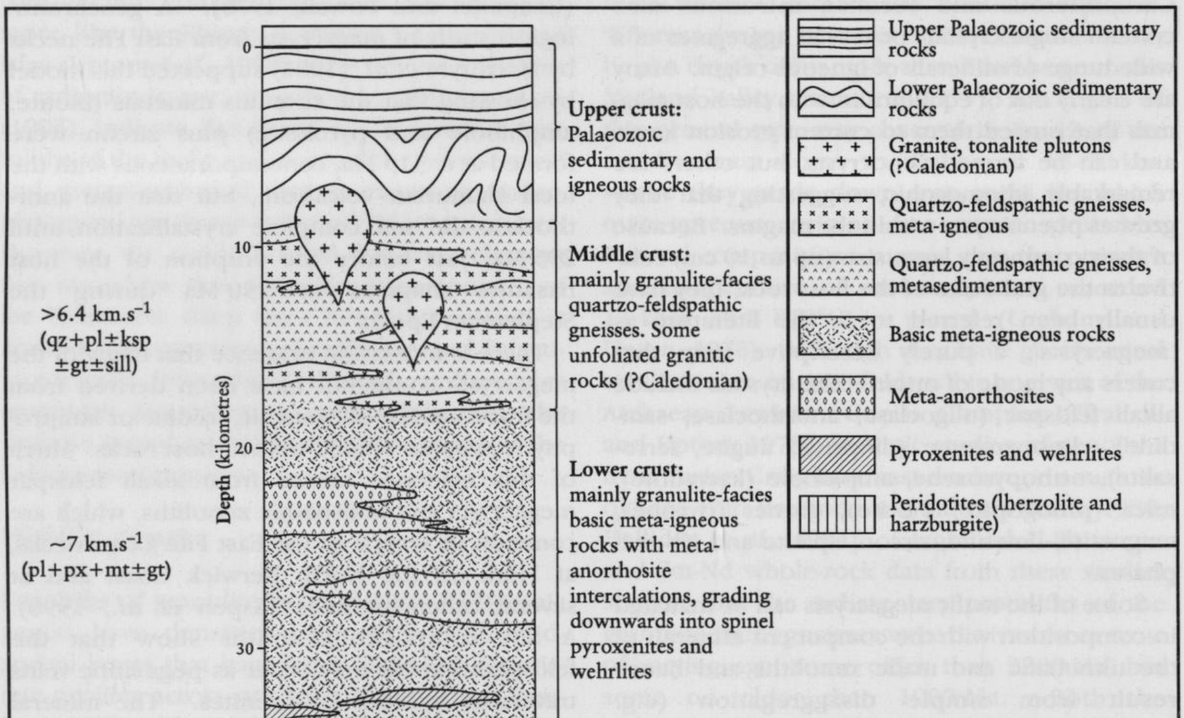


Figure 1.10 Generalized section through the upper continental lithosphere beneath the Midland Valley of Scotland. The left-hand column shows mean seismic velocities after Bamford (1979) and principal mineral assemblages (in brackets). (gt = garnet; ksp = potassium feldspar; mt = magnetite; ol = olivine; pl = plagioclase; px = pyroxene; qz = quartz; sill = sillimanite; sp = spinel.) After Upton *et al.* (1984).