Caledonian Igneous Rocks of Great Britain

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Acknowledgements

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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 or that a right of way exists. 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 in no way be construed as an invitation to visit. Prior consent for visits should always be obtained from the landowner and/or occupier.

Information on conservation matters, including site ownership, relating to Sites of Special Scientific Interest (SSSIs) or National Nature Reserves (NNRs) in particular counties or districts may be obtained from the relevant country conservation agency headquarters listed below:

Countryside Council for Wales,
Plas Penrhos,
Ffordd Penrhos,
Bangor,
Gwynedd LL57 2LQ.

English Nature,
Northminster House,
Peterborough PE1 1UA.

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

Foreword

Britain is exceptional in the continuity of geological history and variety of geological phenomena that are preserved within a comparatively small area. Since the early days of the geological sciences, the area has continued to provide outstanding contributions, theoretical and practical, to the understanding of Earth processes. No section of this long and distinguished history of scientific investigation is more noteworthy than that arising from the outstanding variety and preservation of the Caledonian igneous rocks. This volume describes localities that are regarded as representative of the long and complex evolution of the Caledonian igneous activity. Many of the sites listed have played a key role in interpretations marking major advances in geological thinking. One needs only to recall Hutton's deductions on the origin of granite from observations made in Glen Tilt over two hundred years ago, or the modern realization of the tectonic significance of Caledonian ophiolites. There are many problems remaining and new interpretations to be made, and the descriptions of key localities in this volume will, as well as the basic objective of conservation, provide both a tool and a stimulus for further research.

With regard to further research, one of the features that emerges from a review of the Caledonian igneous rocks and which is brought out in the introduction to the volume, is the breadth of interest these rocks have for different branches of the Earth sciences, including the petrologist looking for plate-tectonic models in explanation of the variety and spatial distribution of the igneous rocks, the structural geologist looking to the igneous rocks for support of his thoughts on ancient plate movements and the isotope geochemist endeavouring to provide a time framework for both. To all those interested in the comprehensive review presented, this GCR volume is potentially of great value in providing, as it does, summary access to both the detail and the broader picture of Caledonian igneous activity.

Accurate description and recording of field data is a fundamental aim of the Geological Conservation Review. Interpretations of the observations may vary over time but the role of the field geologist in providing the key data is paramount. In this review of the Caledonian igneous rocks the importance of detailed field observations is particularly well illustrated by the elegant modern interpretations of volcanological phenomena described at GCR sites in the Lake District and Glen Coe. These are outstanding examples of major advances resulting essentially from 'map and observation geology' (hammers nowadays tend to be rather frowned on, particularly at conservation sites). Detailed laboratory examination without adequate field support is always likely to lose much of its value, or at the worst the interpretations will be incorrect. The GCR review of the Caledonian igneous rocks is a welcome re-affirmation of the fundamental importance of field work.

The rocks described occur in Scotland, England and Wales and the variety and importance of the sites covered inevitably have made this a lengthy compilation. Individual site descriptions from thirty one contributors are organized into nine chapters under seven compilers. In most cases the sites have been described by acknowledged 'experts', many of whom have known and worked on the sites for many years. Some have been described by persons with no previous knowledge of the site, but with a background in related igneous rocks, and almost all have been visited by their author. The few exceptions that have not been visited had recent authorative descriptions that could be summarized. Dr D. Stephenson and his team of co-authors are to be congratulated on the clarity achieved and also in preserving the individuality of presentation of the site descriptions whilst ensuring conformity with the overall aims and standard format of the Geological Conservation Review. The resulting volume will be valuable to both the amateur and professional for many years to come.

P. E. Brown FRSE
Professor Emeritus
University of St Andrews

Chapter 1

Caledonian igneous rocks of Great Britain: an introduction

INTRODUCTION

D. Stephenson

Caledonian igneous rocks

This volume describes the igneous rocks of Scotland, England and Wales that were erupted, intruded or emplaced tectonically as a direct result of the Caledonian Orogeny (Figure 1.1). There is at present no agreed definition of the term 'Caledonian'. It has, for example, been used universally to describe the whole of the Caledonian mountain belt of Upper Proterozoic to middle Palaeozoic rocks (the Caledonides) which, prior to the more recent opening of the Atlantic Ocean, stretched continuously from the Appalachians, through Newfoundland and the British Isles to East Greenland and NW Scandinavia. In this volume the Caledonian Orogeny is taken to include all of the convergent tectonic and magmatic events arising from the closure of the 'proto-Atlantic', Iapetus Ocean in which many of the rocks of Late Proterozoic and Early Palaeozoic age had been deposited. It therefore includes subduction beneath the continental margins; the accretion or obduction of oceanic crust and island-arc material onto these margins; and ultimate collision of the continents, uplift and development of extensional molasse basins. Within this broad orogenic framework many separate 'events' are identified, several of which have commonly used specific names, most notably the mid-Ordovician peak of deformation and metamorphism in the Scottish Highlands, termed the Grampian Event by many authors, and the dominant Early Devonian deformation in northern England and Wales, which is now generally referred to as the Acadian. Many authors refer to these events as separate 'orogenies'. By this definition, most Caledonian igneous rocks of Britain range in age from about 500 Ma (earliest Ordovician) to around 390 Ma (end Early Devonian), with related activity continuing to around 360 Ma (end Late Devonian) in Orkney and Shetland (Figure 1.2). (The time-scale used throughout this volume is that of Harland *et al.* (1990), unless stated otherwise.)

The volume also includes volcanic rocks of Silurian age in southern Britain, which may be the result of the opening of a separate, younger ocean, but which have petrological features suggesting a mantle source modified by earlier Caledonian subduction.

Excluded from this volume are the volcanic rocks contemporaneous with Late Proterozoic sequences and intrusions that were emplaced during earlier (i.e. pre-Ordovician) phases of basin extension or compressive deformation. These rocks, regarded as 'Caledonian' by some authors (e.g. Read, 1961; Stephenson and Gould, 1995), will be discussed in the companion GCR volumes on *Lewisian, Torridonian and Moine rocks of Scotland, Dalradian rocks of Scotland* and *Precambrian rocks of England and Wales*. Devonian volcanic rocks in SW England were emplaced in extensional marine basins outside the area of Caledonian deformation. They were affected by the early deformation phases of the Variscan Orogeny and are described with other Variscan igneous rocks in the *Igneous Rocks of South-West England* GCR volume (Floyd *et al.*, 1993).

As a result of the various contrasting tectonic environments generated during the course of the orogeny, the Caledonian igneous rocks represent a wide range of compositions and modes of emplacement. Intense crustal shortening during the orogeny, followed by uplift and deep dissection since, has resulted in the exposure of numerous suites of oceanic crustal rocks, subaerial and submarine volcanic rocks, deep-seated plutons and minor intrusions, all now juxtaposed at the same erosion level. As in any orogenic province, geochemical affinities are dominantly calc-alkaline, although notable tholeiitic suites are present, particularly in rocks formed during local extensional events in the earlier stages of the orogeny, and there is one major suite of alkaline intrusions. Volcanic rocks with alkaline affinities are a minor component, occurring mostly as relics of Iapetus oceanic crust or as the products of localized crustal extension towards the end of the orogeny. Within each suite, compositions commonly range from basic to acid, and several intrusive suites include ultramafic lithologies. The alkaline intrusive suite of NW Scotland includes some highly evolved silica-undersaturated felsic rocks.

The contribution of Caledonian igneous rocks of Great Britain to igneous petrology and the understanding of igneous processes

All of the sites described in this volume are, by definition, of national importance and all have

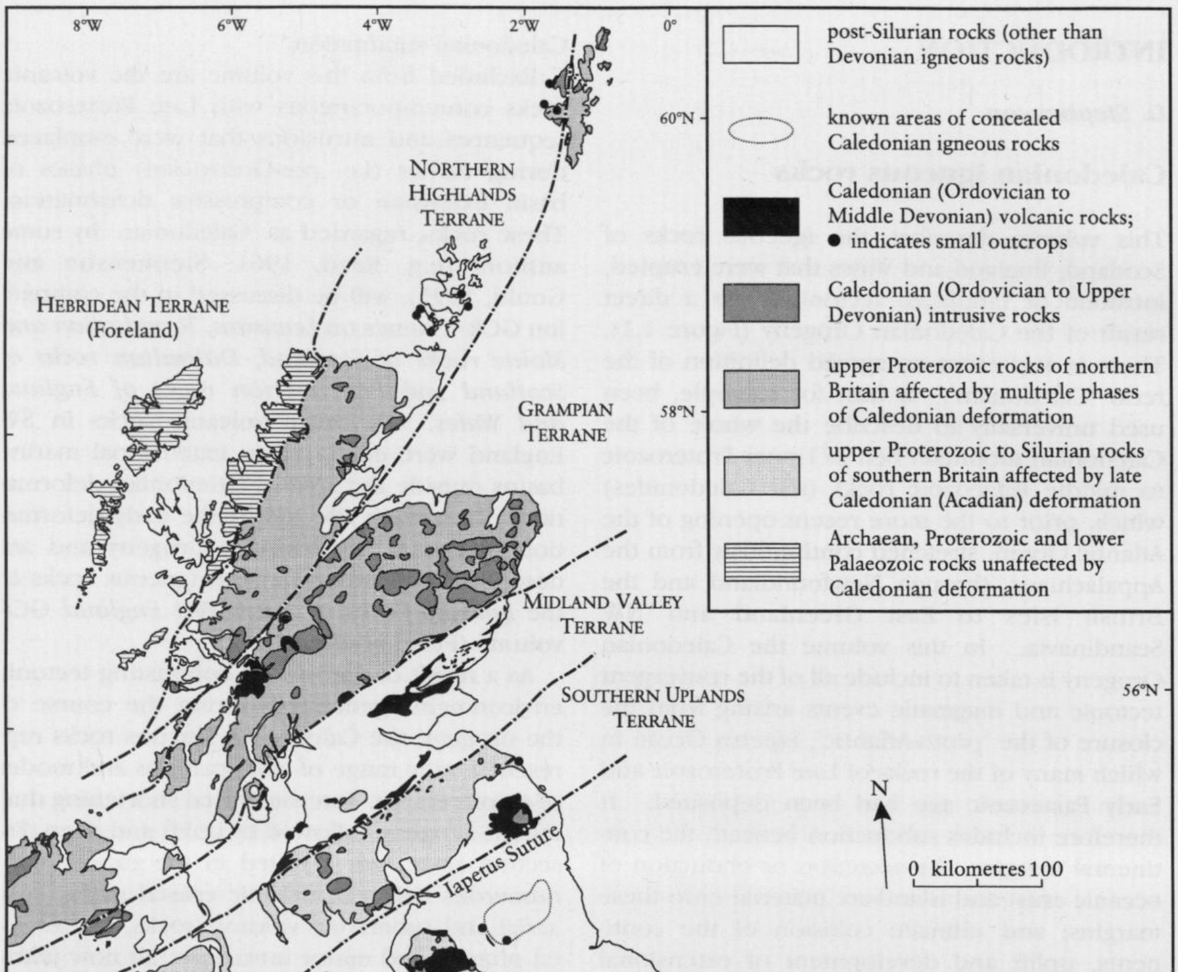

Figure 1.1 Location of Caledonian intrusive and extrusive igneous rocks of Great Britain relative to areas affected by Caledonian deformation and major terrane boundaries. Based on Brown *et al.* (1985). Nomenclature of terranes simplified after Gibbons and Gayer (1985), Bluck *et al.* (1992) and British Geological Survey (1996).

provided evidence crucial to the mapping out and understanding of the British Caledonides. Additionally, because of their variety and their accessibility from major centres of early geological research, the Caledonian igneous rocks of Great Britain have played a major role in the initiation, testing and evolution of many theories of igneous processes. They have been, and no doubt will continue to be, the subjects of many truly seminal studies of major international significance.

Some of the first geological field investigations were conducted by James Hutton in the late eighteenth century in order to seek support for his 'Theory of the Earth', read in 1785 (Hutton, 1788). Among these were his excursions to Glen Tilt in the Grampian Highlands and the Fleet pluton in SW Scotland, where he deduced, from the presence of veins and other contact relationships, that granite had been intruded in a hot, fluid state (i.e. as a magma), surely one of the most fundamental geological concepts. By the early nineteenth century geologists were beginning to undertake detailed regional studies, such as those which led to the first accounts of Caledonian igneous rocks in Cumbria (1836) and North Wales (1843) by Adam Sedgwick and the description of the southern Grampians by James Nichol (1863). The Geological Survey was founded in 1835 and by the end of the century, many of the first editions of survey maps and memoirs of 'Caledonian' areas had been published. Based on work of this era, Archibald Geikie's *The Ancient Volcanoes of Great Britain*, published in two volumes in 1897, contains remarkably perceptive detailed accounts of most extrusive Caledonian rocks. The late nineteenth century also saw major developments in the science (and art) of descriptive petrography, exemplified by the work of J. Clifton Ward in the Lake District and Alfred Harker in both the Lake District and North Wales. This led to standard texts, drawing heavily on examples from the Caledonian province, such as Teall's *British Petrography* (1888), Hatch's *An Introduction to the Study of Petrology* (1891) and Harker's *Petrology for Students* (1895a). Subsequent editions of the last two were used to train generations of students into the late twentieth century.

The beginning of the twentieth century saw rapid developments in the understanding of igneous processes, building upon the systematic mapping and petrographic work of the previous half century and ongoing surveys. Between 1909 and 1916, C.T. Clough, H.B. Maufe and E.B. Bailey described their theory of cauldron subsidence, based upon Geological Survey mapping of the Caledonian volcanic rocks and intrusions at Glen Coe and Ben Nevis. This theory, linking surface volcanicity, subvolcanic processes and underlying plutons, was subsequently applied worldwide to both ancient and modern volcanoes and has been fundamental to the interpretation of ring intrusions and caldera structures. More recently, pioneering research on caldera development has once again focused on the British Caledonides, concentrating on the exhumed roots of such structures which are generally inaccessible in modern volcanoes. The work of M.F. Howells and co-workers in Snowdonia and of M.J. Branney and B.P. Kokelaar in the Lake District has been notable and most recently, attention has turned once again to a re-interpretation of the Glencoe volcano (Moore and Kokelaar, 1997, 1998).

The Caledonian volcanic rocks have provided numerous excellent examples of volcanological features and processes, many of which were the first to be recognized in ancient sequences; for example, the recognition of deposits from Peléan-type eruptions (i.e. incandescent ash flows or nuées ardentes) in Snowdonia by Greenly (in Dakyns and Greenly, 1905), which was later confirmed by Williams (1927) in a wider appraisal of the Ordovician volcanicity of Snowdonia. Welded ignimbrites (ash-flow tuffs) were subsequently recognized in the Lake District and Wales by Oliver (1954) and Rast *et al.* (1958) and at the time were the oldest known examples of such rocks. The later recognition, again in Snowdonia, that welding could take place in a submarine environment as well as subaerially (Francis and Howells, 1973; Howells *et al.*, 1973) led to a major re-appraisal of palaeogeographical reconstructions, not just in North Wales but in other volcanic sequences worldwide. In a further development, Kokelaar *et al.* (1985) recognized a silicic ash-flow tuff and related pyroclastic fall-out tuff on Ramsay Island in South Wales, which had been erupted, emplaced and welded, all in a submarine environment; this was the first record in the world of such ash-fall tuffs. It has become accepted that volcanic sequences commonly include shallow sills, many of which were emplaced within wet unconsolidated sediments. Rapid conversion of the water to steam fluidizes the sediment, which becomes intermixed with globules of magma; many examples have been documented in the Caledonian province and throughout the geological column. This is largely a result of a comprehensive account by Kokelaar (1982) which used case studies from the Siluro-Devonian of Ayrshire and the Ordovician of Snowdonia and Pembrokeshire.

Once established, Hutton's theory of the magmatic origin of granite remained virtually unchallenged in Great Britain for over a hundred years, until a growing body of opinion began to consider the possibility that at least some granites could have been generated *in situ* due to the 'transformation' of country rocks by fluid or gaseous 'fronts'. Support for this theory of 'granitization' reached a peak with studies of Caledonian and other granites in Ireland in the 1940s and 1950s. Although British Caledonian granites were not in the forefront of these investigations, several authors attributed the origin of the Loch Doon pluton to such a process (McIntyre, 1950; Rutledge, 1952; Higazy, 1954) and King's (1942) study of the progressive metasomatism of metasedimentary xenoliths in one of the Loch Loyal intrusions was widely quoted. In contrast, the Scottish plutons have prompted many studies of how large volumes of magma move through and become emplaced in the country rock. Read (1961) recognized that this 'space problem' could be overcome in a variety of ways, and made a widely adopted general classification of Caledonian plutons as 'forceful' or 'permitted'. More recent studies have produced more refined models of diapiric ('forceful') emplacement of plutons, such as that of Criffel in SW Scotland (Phillips *et al.*, 1981; Courrioux, 1987), but have also recognized the effects of intrusion during lateral shearing, as seen for example in the Strontian and Ratagain plutons of the NW Highlands (Hutton, 1987, 1988a, 1988b; Hutton and McErlean, 1991), in the Ballachulish, Ben Nevis, Etive, Glencoe, Rannoch Moor and Strath Ossian plutons of the SW Grampian Highlands (Jacques and Reavy, 1994) and the Fleet pluton of SW Scotland (Barnes *et al.*, 1995).

Several early attempts to integrate petrography and field observations with physical principals in order to understand the origin and evolution of igneous rocks were applied to Caledonian igneous rocks. These include the seminal studies by Alfred Harker on the Carrock Fell Complex (1894, 1895b), where in-situ differentiation processes were invoked to explain the lithological variation. Similar processes were also invoked by Teall (in Peach and Horne, 1899) to explain variations in the Loch Doon pluton, and the importance of the dominantly basic intrusions of the NE Grampians as an extreme fractionation series from peridotite to quartz-syenite was recognized by Read (1919). However, probably the most influential contribution was that of Nockolds (1941) on the Garabal Hill–Glen Fyne complex in the SW Grampian Highlands. This was one of the first geochemical studies of a plutonic complex and led to the concept of differentiation of a magma by the progressive removal of crystallized minerals from the remaining liquid (fractional crystallization), which dominated models of magmatic evolution for several decades. Ironically, more recent studies have shown that the evolution of this particular complex cannot be explained entirely by such a process (Mahmood, 1986), but the overall concept is still valid today, even though its application is more restricted. Other plutons of the Caledonian province have subsequently contributed further evidence to differentiation models, especially those in the Southern Uplands that exhibit strong concentric compositional zoning, such as Loch Doon (Gardiner and Reynolds, 1932; Ruddock, 1969; Brown *et al.*, 1979; Halliday *et al.*, 1980; Tindle and Pearce, 1981), Cairnsmore of Cairsphairn (Tindle *et al.*, 1988) and Criffel (Phillips, 1956; Halliday *et al.*, 1980; Stephens and Halliday, 1980; Stephens *et al.*, 1985; Holden *et al.*, 1987; Stephens, 1992). The Shap granite of Cumbria, in addition to being one of Britain's best known decorative stones, has been crucial in studies of metasomatism and crystal growth in igneous rocks (e.g. Vistelius, 1969) and continues to generate interest (e.g. Lee and Parsons, 1997). More-basic intrusions have contributed to other models to explain petrological diversity, such as magma mixing, hybridization and contamination. Studies by H.H. Read of the basic intrusions in the NE Grampians were among the first to recognize and document these processes (Read, 1919, 1923, 1935), and more recently the Appinite Suite of the Scottish Highlands has generated much discussion and speculation (e.g. Fowler, 1988a, 1988b; Platten, 1991; Fowler and Henney, 1996).

The alkaline igneous rocks of the NW Highlands of Scotland were among the first in the world to be recognized. Their distinctive chemistry and mineralogy was first noted by Heddle (1883a), with subsequent detailed descriptions by Teall (Horne and Teall, 1892; Teall, 1900), and they soon became a focus of international attention through the works of S.J. Shand and R.A. Daly who first introduced the crucial concept of silica saturation. For a period of over thirty years, from 1906–1939, the 'Daly–Shand hypothesis' of the origin of alkali rocks by 'desilication' of a granite magma by assimilation of limestone, was based on the common field association of the Assynt alkaline rocks with Cambro-Ordovician limestones and on similar associations worldwide. This hypothesis has now been rejected, but the NW Highland suite has continued to generate interest, not least because of its unusual tectonic setting. Most alkali provinces occur in an extensional, continental setting but the NW Highland rocks occur on the margin of a major orogenic belt. Recent, largely geochemical, studies have sought to relate them to subduction and to integrate theories of their origin with the origin of other, calc-alkaline, plutons of the Highlands (e.g. Thompson and Fowler, 1986; Halliday *et al.*, 1985, 1987; Thirlwall and Burnard, 1990; Fowler, 1992). The Siluro-Devonian volcanic rocks of northern Britain have also been attributed to subduction beneath the orogenic belt by Thirlwall (1981a, 1982) and hence, the whole magmatic province of the Highlands is a valuable complement to other continental margin provinces of the world, in which dominantly high-K calc-alkaline suites also include rare, highly alkaline derivatives.

On a broad tectonic scale, ophiolite complexes in Britain and throughout the orogenic belt are the main evidence for the former existence of the Iapetus Ocean and have enabled the position of the tectonic suture to be traced for thousands of kilometres. The study of these ophiolites has therefore made a major contribution to understanding the composition, structure and ultimate destruction of oceanic lithosphere, which has had implications far beyond the Caledonides since the initial, seminal review of Dewey (1974). In the northern part of the British Caledonides, much recent trace element and isotope work has been directed towards identifying the sources of magmas on the continental margin and, as a result, valuable information has been obtained on regional variations in the continental crust and subcontinental lithospheric mantle (e.g. Halliday, 1984; Stephens and Halliday, 1984; Thirlwall, 1989; Canning *et al.*, 1996). These variations have contributed to a division of the orogenic belt into distinct areas or 'terranes' and clearly have important regional implications in any reconstructions of the tectonic history of the Caledonides (see Tectonic setting and evolution section). Such studies, combined with similar work from the Appalachians, Newfoundland, Greenland and Scandinavia, make the Caledonides one of the most extensively studied and best understood orogenic belts in the world, acting as a stimulus and model for similar work elsewhere.

SITE SELECTION

D. Stephenson

The need for a strategy for the conservation of important geological sites is well illustrated by the words of James MacCulloch, writing in 1816 on his visit to the site in Glen Tilt where James Hutton had first demonstrated the magmatic origin of granite.

> 'Having blown up a considerable portion of the rock, I am enabled to say that it is of a laminated texture throughout, being a bed of which the alternate layers are limestone and that siliceous red rock which I consider as a modification of granite.'

Thankfully, despite the efforts of MacCulloch, the modern description of the Forest Lodge site in this volume can still be matched with the early accounts.

Igneous rocks and their contact relationships are on the whole less prone to damage than sedimentary rocks and fossil or mineral localities, but fine detail can be lost easily through injudicious hammering; minerals and delicate cavity features are subject to the attentions of collectors; and whole outcrops can be obscured by man-made 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 the granite blocks that make up most of the old city of Aberdeen and many of the lighthouses and coastal defences of Britain, to the crushed dolerites that make excellent roadstone, 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. A prime example is the relatively small outcrop of the Shap granite in Cumbria, which was once prized as a decorative stone and worked on a moderate scale, but which is now worked extensively to be crushed and reconstituted to make concrete pipes.

The Geological Conservation Review (GCR) aims to identify the most important sites in order that the scientific case for the protection and conservation of each site is fully documented as a public record, with the ultimate aim of formal notification as a Site of Special Scientific Interest (SSSI). 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; these are *international importance, presence of exceptional features* and *representativeness.* Each site must satisfy at least one of these criteria (Table 1.1). Many satisfy two and some fall into all three categories, such as the Ray Crag and Crinkle Crags site in the Lake District. The *international importance* of the British Caledonian igneous rocks has already been discussed, highlighting significant contributions to the understanding of igneous processes, many of which were identified, described or conceived for the first time from this province. Many of the sites that show *exceptional features* are also of international importance, and there are many others which 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 the Side Pike site in the Lake District where the three main types of pyroclastic deposit can be demonstrated in close proximity; the many examples of ignimbrite in Wales, the Lake District, the Grampian Highlands and Shetland; and the layered basic intrusions of the NE Grampian Highlands, Carrock Fell in the Lake District and the Llŷn Peninsula and St David's in Wales.

The criterion of *representativeness* aims to ensure that all major stratigraphical, tectonic and petrological groupings of Caledonian igneous rocks are represented. With such a large outcrop area and wide geological and geographical range of Caledonian igneous rocks in Great Britain, it is difficult to do this while keeping the number of sites within reason. Hence there are some regionally important groups of rocks that are not represented, such as the voluminous Cairngorm Suite of granitic plutons or most of the numerous suites of minor intrusions throughout Great Britain. In many cases this is because there are no localities that show any exceptional features and there are none that exhibit the typical features of the suite any better than numerous other localities. Hence, for these suites, conservation is not a problem. However, it may be appropriate to designate 'Regionally Important Geological/Geomorphological Sites' (RIGS) to represent them so that, even though such status carries no legal protection, their importance is recognized and recorded. An attempt has been made in this volume to include, in an 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 apparent gaps in the representativeness of the GCR site selection, the volume constitutes a complete review of all the Caledonian igneous rocks of Great Britain.

Some sites are important for more than just their igneous context. For example, the alkaline intrusions of the Assynt area (Chapter 7) provide vital structural and geochronological evidence for the complex timing of tectonic events in the NW Highlands, in particular the order and scale of movements on the various components of the Moine Thrust Zone. These aspects have been taken into account in the site selection and are relevant to discussions in the *Lewisian, Torridonian and Moine rocks of Scotland* GCR volume. Volcanic rocks within the stratigraphical column are important for radiometric dating and several of the sites in this volume have provided time-markers for regional sequences. Some of these have potential international significance in the construction of geological timescales, in particular the 'Old Red Sandstone' volcanic rocks (Chapter 9), many of which lie close to the Silurian–Devonian boundary on biostratigraphical evidence. Some 'igneous' sites in the Ballantrae ophiolite complex are important for their graptolite biostratigraphy and hence are also included in the *British Cambrian to Ordovician Stratigraphy* GCR volume (Rushton *et al.*, 1999). The Comrie pluton of the southern Grampian Highlands (Chapter 8) has been known for its metamorphic aureole since the days of Nichol (1863). It was the subject of a pioneering study by Tilley (1924) and continues to attract attention as a type example of low-pressure contact metamorphism (Pattison and Harte, 1985; Pattison and Tracy, 1991). At many sites, the igneous rocks have resulted in spectacular features of mountain or coastal geomorphology. In fact most of the more rugged mountains of mainland Britain owe their existence to Caledonian igneous rocks (e.g. those of Ben Nevis, Glen Coe, Glen Etive and most of the mountains of the Lake District and North Wales), while equally impressive coastal features occur within the GCR sites at Eshaness in Shetland, St Abb's Head in SE Scotland and the northern coast of Pembrokeshire in South Wales.

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'. Three blocks comprise this volume, *Ordovician igneous rocks, Silurian and Devonian plutonic rocks,* and *Silurian and Devonian volcanic rocks*. Within each block, sites fall into natural groupings, termed 'networks', which are based upon petrological or tectonic affinites, age and geographical distribution. The ten networks in this volume contain 133 sites, which are listed in Tables 1.1a–c (pp. 19–26 herein), together with their principal reasons for selection. Some sites have features that fall within more than one network or block, for example the Ben Nevis and Allt a'Mhuilinn site, which encompasses an 'Old Red Sandstone' volcanic succession and a Late Caledonian pluton.

Site selection is inevitably subjective and some readers may feel that vital features or occurrences have been omitted or that others are over-represented. But 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 to maintain.

In this volume, most chapters represent a single GCR network as set out in Tables 1.1a–c, pp. 19–26. Continuity and descriptive convenience require two exceptions. Chapter 4 describes all the Caledonian igneous rocks of northern England, including those late Caledonian plutons which lie south of the Iapetus Suture, and Chapter 6 includes early Silurian volcanic rocks of South Wales and adjacent areas. Wherever possible, summaries of regional geology applicable to the whole network are given in the chapter introduction to avoid repetition (chapters 2, 3, 4, 5 and 7), but some networks span such a wide geographical area and range of geological settings that more specific accounts are necessary in the individual site descriptions (chapters 6, 8 and 9). In some cases, sections of general discussion apply to two or more sites (e.g. in the same pluton or group of intrusions) and in Chapter 7 this has necessitated a slight change of format to accommodate the many small sites that represent suites of minor intrusions. Space does not allow for more detailed accounts of country rock successions or structures and the reader is referred to *Geology of Scotland* (Craig, 1991), *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

D. Stephenson

The Iapetus Ocean was created in Late Proterozoic time by the rifting and pulling apart of a large supercontinent known as Rodinia. The opening started sometime around 650 million years (Ma) ago and by the beginning of Ordovician time, at 510 Ma, the ocean was at its widest development of possibly up to 5000 km. On one side of the ocean lay the supercontinent of Laurentia, which is represented today largely by the Precambrian basement rocks of North America, Greenland, the north of Ireland and the Scottish Highlands. On the opposite side lay the supercontinent of Gondwana, consisting of the basements of South America, Africa, India, Australia, East Antarctica and Western Europe (including south Ireland, England and Wales). A separate continent, Baltica (the basement of

Scandinavia and Russia), was separated from Gondwana by an arm of the Iapetus Ocean, known as the Tornquist Sea (Figure 1.3). The wide separation is supported by palaeontological data, which show distinctly different faunal assemblages in the Lower Palaeozoic rocks of each former continent (Cocks and Fortey, 1982; McKerrow and Soper, 1989; McKerrow *et al.*, 1991) and by palaeomagnetic interpretations (Torsvik *et al.*, 1996). Upper Proterozoic and Cambrian sediments were deposited in extensional basins close to and on the passive margins of the flanking continents, and as turbidites that swept down the continental slopes onto the ocean floor. By analogy with modern oceans it can be assumed that new oceanic crust was generated at a mid-ocean ridge, with ocean-island type volcanicity along transform faults and above mantle plumes or 'hot-spots'.

The continental plates of Laurentia, Gondwana and Baltica started to converge during the early Ordovician, initiating new tectonic and magmatic processes that marked the start of the Caledonian Orogeny. The Iapetus oceanic crust was consumed in subduction zones beneath oceanic island arcs and beneath the continental margins and hence little is now preserved, except where slices have been sheared off and thrust over the continental rocks in the process known as obduction. Sedimentation continued in offshore, back-arc basins and in ocean trenches that developed above the subduction zones. These sediments were eventually scraped off and accreted against the Laurentian continental margin, where pre-existing rocks were undergoing deformation and metamorphism, resulting in considerable crustal shortening and thickening. On the margin of Gondwana, great thicknesses of sediment accumulated in marginal basins. Throughout all these events, new magma was being created by the melting of mantle and oceanic crustal material within and above the subduction zones and by melting within the thickened continental crust.

There have been many models to explain the relative movements of tectonic plates during the Caledonian Orogeny and, although at any one time there may be a broad consensus centred around one particular view, each has its drawbacks, and refinements are continually emerging with new evidence or new trains of thought. Early models postulating a straightforward convergence of two plates, Laurentia and Gondwana (Wilson, 1966; Dewey, 1969), were soon refined to encompass oblique closure (Phillips *et al.*, 1976; Watson, 1984). The recognition that sections of the Laurentian margin consist of distinct 'terranes' separated by strike-slip faults of great magnitude (e.g. Dewey, 1982; Gibbons and Gayer, 1985; Hutton, 1987; Kokelaar, 1988; Thirlwall, 1989; Bluck *et al.*, 1997), led to the realization that these terranes were probably not directly opposite each other as the Iapetus Ocean closed. It seems likely that Scotland lay on the margin of Laurentia, initially opposite Baltica, while England and Wales lay on the margin of Gondwana, opposite the Newfoundland sector of Laurentia. The terranes were only juxtaposed into their present relative positions (see Figure 1.3) by large sinistral (left-lateral) movements on the bounding faults during the later stages of the orogeny. The most recent models, which form the basis of the following synthesis, involve three converging continental plates, Laurentia, Baltica and Eastern Avalonia, the latter a microcontinent, including the Precambrian basement of England and Wales, which broke away from the margin of Gondwana in the early Ordovician and drifted towards Laurentia (e.g. Soper and Hutton, 1984; Pickering *et al.*, 1988; Soper *et al.*, 1992; Pickering and Smith, 1995; Torsvik *et al.*, 1996).

The exact sequence and timing of events as the three plates converged is the subject of much debate, in which the distribution, nature and timing of the igneous activity are crucial evidence. Figure 1.3 shows a simplified sequence that reflects a general consensus in which the key elements are as follows.

- Closure of the Tornquist Sea between Eastern Avalonia and Baltica, followed by strike-slip movement along the Tornquist Suture. Palaeontological evidence indicates that the two continents were close enough to share a common faunal assemblage by the late Ordovician, but final closure and suturing may have been later.
- Anticlockwise rotation of Baltica, followed by convergence with Laurentia, with subduction beneath the 'Scottish' sector of the Laurentian margin and closure during the early to mid-Silurian.
- Oblique convergence of Eastern Avalonia with Laurentia, with subduction beneath the Laurentian margin, resulting in closure by the early Silurian in the 'Irish' sector and

later, mid-Silurian closure in the 'Scottish' sector. The junction between the two fused plates passes through the Solway Firth in Britain and is known as the Iapetus Suture.

- Protracted continent–continent collision between Laurentia and Eastern Avalonia plus Baltica, with underthrusting beneath part of the Laurentian margin (?mid-Silurian to Mid-Devonian).
- Separation of a further microcontinent, Armorica, from the margin of Gondwana, which then collided with Eastern Avalonia during the Early Devonian (the Acadian Event).
- Sinistral re-alignment of terrane boundaries (?mid-Silurian to Mid-Devonian).

The main difference of opinion at the time of writing concerns the timing of the Baltica–Laurentia collision, which pre-dates or post-dates the Eastern Avalonia–Laurentia collision according to the model used. The timing and nature of the Eastern Avalonia–Baltica collision is also poorly constrained at present.

The tectonic history of the Caledonian Orogeny in Britain is summarized below, linking together coeval magmatic events in the various terranes across the whole orogenic belt (Figure 1.2). At times the magmatism was associated with distinct structural and metamorphic events, discussed in detail in the *Lewisian, Torridonian and Moine rocks of Scotland* and *Dalradian rocks of Scotland* GCR volumes. The most recent general references used in this compilation have been given above and more specific details will be found in the relevant chapter introductions. Although the histories of most individual terranes are now fairly well documented, a coherent overall model is difficult to achieve, particularly for the earlier parts of the orogeny when terranes were separated, possibly by hundreds of kilometres, prior to late-orogenic strike-slip re-alignment. Hence the timing of certain events may vary between terranes so that, for example, one sector of a continental margin may have been experiencing active subduction while another was still a passive margin.

Early Ordovician – Tremadoc and Arenig

In the early Ordovician much of the Iapetus Ocean was still in existence (Figure 1.3a). New oceanic crust was probably still being generated locally at ocean-ridge spreading centres and in oceanic island volcanoes, while elsewhere oceanic crust was being destroyed in intra-ocean subduction zones, generating widespread island-arc volcanism. The Highland Border Complex may have originated in a back-arc basin behind a volcanic arc on the Laurentian continental margin. Most of the Iapetus oceanic crust was destroyed during subsequent ocean closure, but vestiges remain in the form of ophiolite complexes of oceanic crust and upper mantle material that were accreted (welded) or obducted (thrust) onto the Laurentian margin during the earlier stages of closure (Chapter 2). Products of oceanic volcanism preserved in the ophiolites have been dated palaeontologically and/or radiometrically at mid-Tremadoc to Arenig and, in the case of the Highland Border Complex, Llanvirn. The date of accretion or obduction is more difficult to establish and was probably quite variable, since such processes must have continued throughout the early closure of the ocean. Estimates range from Early Cambrian (540 Ma) for the Highland Border Complex on the Isle of Bute to late Llanvirn or early Llandeilo for the complex elsewhere. The Shetland Ophiolite was probably obducted in the late Tremadoc, between 498 and 492 Ma, and the Ballantrae ophiolitic rocks were obducted before the deposition of Llanvirn shallow marine strata, probably in the late Arenig (*c.* 480–475 Ma).

On the opposite side of the Iapetus Ocean, ophiolites are preserved only in Norway, where they were obducted onto the margin of Baltica during the early Ordovician. On the margin of Gondwana, deep-marine turbidites (Skiddaw Group) were deposited on a passive margin in the Lakesman Terrane (cf. Lake District and Isle of Man) from Late Cambrian to early Llanvirn time. However, in the Wales sector, a passive margin gave way to active subduction of Iapetus oceanic crust during Tremadoc time. Subduction was associated with extension in the overlying continental crust and the development of the Welsh Basin, a marine marginal basin flanked by the Midlands Microcraton of the main continental mass and the periodically emergent Monian Terrane (cf. Irish Sea and Anglesey) adjacent to Iapetus. This basin dominated sedimentation and volcanism throughout the Caledonian Orogeny. Remnants of early localized calc-alkaline volcanism within the basin are preserved only at Rhobell Fawr in southern Snowdonia and

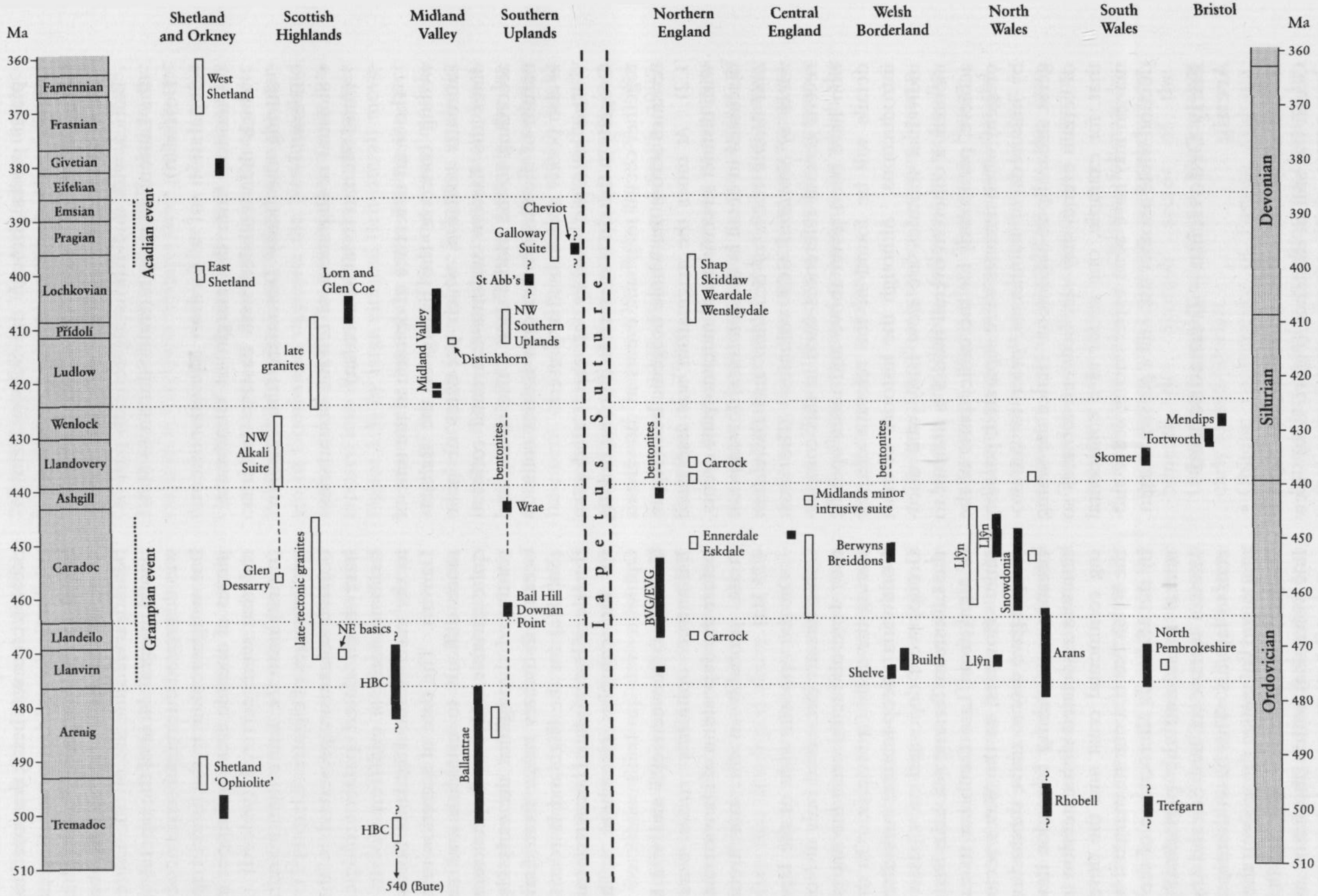

Figure 1.2 Stratigraphical distribution of Caledonian extrusive rocks (solid bars) and intrusions (open bars) in the various terranes of the British Caledonides. The time-scale is after Harland *et al.* (1990); horizontal lines indicate descriptive time units as used in the main text. Wherever possible the extrusive rocks are plotted according to their biostratigraphical range, as are the intrusions of Wales. Other intrusions have little or no biostratigraphical control and hence are plotted according to their currently accepted radiometric ages. This leads to some unavoidable discrepancies, in particular in the upper Silurian to Lower Devonian suites of Scotland, where intrusions and volcanic rocks in the same area are probably much closer in age than the diagram shows (see Chapter 9, Introduction). See individual chapter introductions for more detailed stratigraphical distribution charts.

at Treffgarne in north Pembrokeshire (Chapter 6). Both sequences are of late Tremadoc age and were followed by major uplift and local emergence; there is no evidence of further volcanic activity in the Welsh Basin until the late Arenig.

Mid-Ordovician – Llanvirn and Llandeilo

The mid-Ordovician saw the climax of the Caledonian Orogeny in the Scottish Highlands. This 'Grampian' Event is particularly well defined in the NE of the Grampian Terrane, where the main deformation episodes and the peak of regional metamorphism are dated by major tholeiitic basic intrusions that were emplaced at *c.* 470 Ma (late Llanvirn), towards the end of the event (Chapter 3). In the central Grampian Highlands and the Northern Highlands Terrane, the comparable event may have been a little later (*c.* 455 Ma). The tectonic cause of the Grampian Event is not clear, but current opinion favours collision of an intra-ocean island arc complex with the Laurentian margin, the remains of which may be present in the Highland Border and Ballantrae complexes. Crustal melting, which commenced during the peak of the Grampian Event, resulted in a suite of granite plutons which were intruded throughout late Llanvirn, Llandeilo and Caradoc time.

Volcanism continued in the Iapetus Ocean throughout Arenig to Caradoc time. The products of this activity, sparsely distributed within turbidite-facies sedimentary rocks, were accreted onto the Laurentian margin from Llandeilo time onwards in an imbricate thrust belt that now comprise the Southern Uplands Terrane (Chapter 2).

On the opposite side of Iapetus, the microcontinent of Eastern Avalonia began to drift away from Gondwana at about this time, creating the Rheic Ocean (Figure 1.3b). Areas of continental crust now occupied by the Lake District, central England and Wales were part of Eastern Avalonia, which now began to converge on Laurentia, consuming the Iapetus Ocean. The passive continental margin of the Lakesman Terrane first became unstable during the late Arenig and turbidites deposited during the Llanvirn contain volcanic debris. Widespread volcanism developed for the first time across the Welsh Basin with a mixture of extensional ridge-type magmas and subduction related products (Chapter 6). In north Pembrokeshire a wide range of effusive and pyroclastic rocks were all erupted in a submarine environment during latest Arenig to Llanvirn time. Basic lavas and a basic layered intrusion have tholeiitic affinities, although they do have some subduction-related calc-alkaline characteristics, which are more apparent in the related silicic rocks. In southern Snowdonia, the voluminous Aran Volcanic Group (late Arenig to earliest Caradoc) has transitional tholeiitic to calc-alkaline affinities, while both tholeiitic and calc-alkaline lavas are present in the Llanvirn sequence of the Builth Inlier.

Late Ordovician – Caradoc and Ashgill

The peak of deformation and metamorphism in the Northern Highlands Terrane and the central Grampian Highlands probably occurred during Caradoc time. Crustal melting continued to generate granite plutons and minor intrusions in both terranes (Figure 1.2). It is assumed that subduction continued throughout this period beneath the Laurentian margin, although subduction-related igneous rocks are conspicuously absent, apart from the small alkaline pluton of Glen Dessarry. The geochemistry of this pluton suggests a mantle source, similar to that of the later, more voluminous alkaline magmatism in the Northern Highlands Terrane.

Volcanic rocks, mainly with oceanic island characteristics, occur sporadically within the accreted turbidite sequences of the Southern Uplands Terrane, indicating the continued presence of Iapetus oceanic crust (Figure 1.3c), and calc-alkaline volcanic detritus suggests the presence of island arcs.

More significant igneous activity occurred at this time on the opposite side of the ocean, where active subduction was by now taking place beneath Eastern Avalonia. In the Lakesman Terrane regional uplift was closely followed by intense igneous activity. This resulted, in late Llandeilo and Caradoc time, in the extensive volcanic sequences of the Eycott and Borrowdale volcanic groups and emplacement of parts of the Lake District granitic batholith, early parts of the Carrock Fell Complex and numerous other intrusions (Chapter 4). The Eycott and early Carrock Fell magmas were continental-margin tholeiites, whereas the Borrowdale Volcanic Group originated from typical continental-margin calc-alkaline volcanoes with extensive

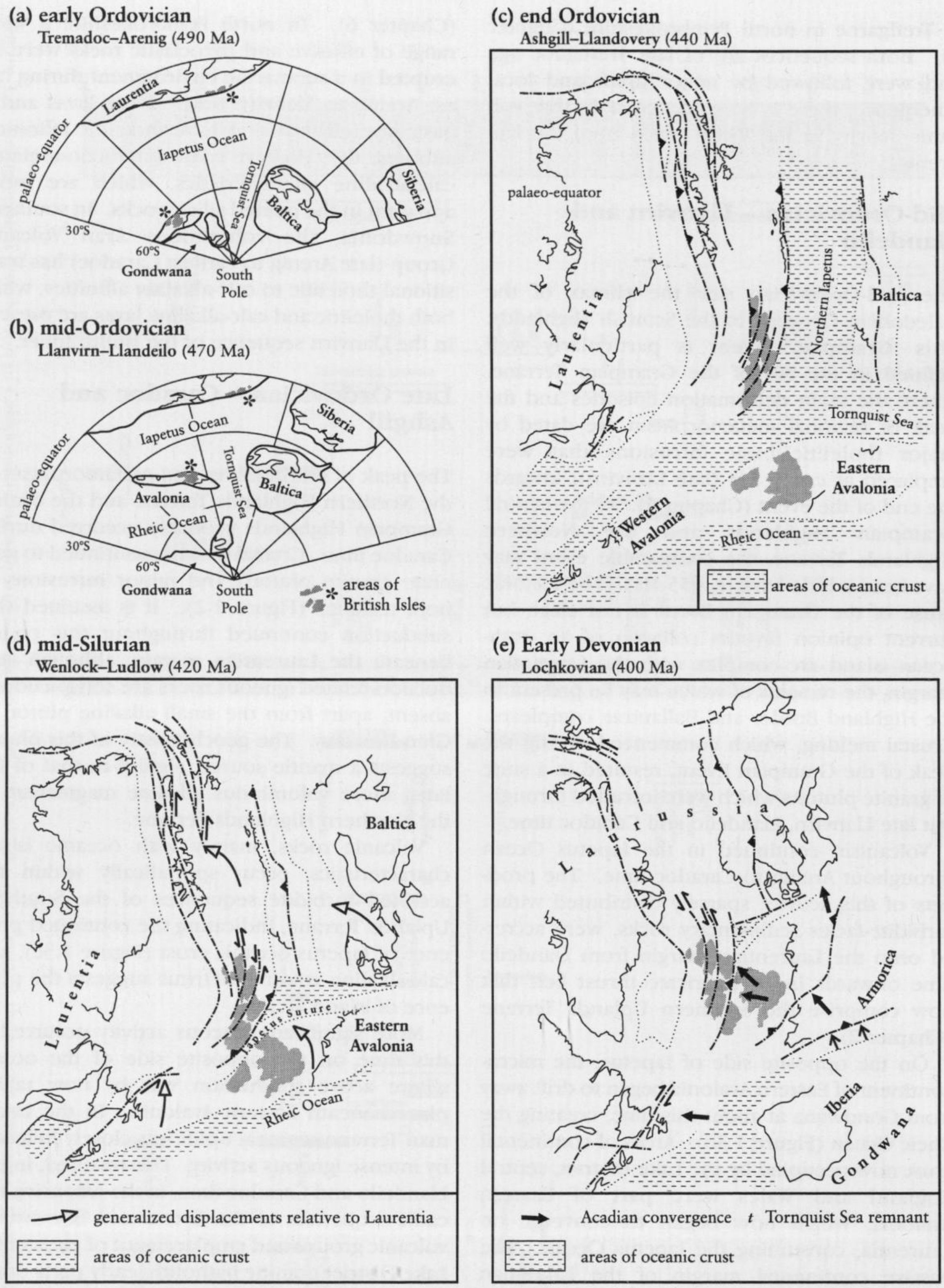

Figure 1.3 Reconstructions of the movements of continents bordering the Iapetus Ocean and Tornquist Sea during the Caledonian Orogeny. (a) and (b) are broad 'views' that are neccessary to encompass the great width of the ocean during the early stages of the orogeny. Note the separation of Avalonia from Gondwana during this time. Adapted from Torsvik *et al.* (1992) by Trench and Torsvik (1992). (c), (d) and (e) show the later stages of the orogeny in more detail, with progresssive narrowing of the oceanic areas, convergence of the continents and ultimate continent–continent collisions and strike-slip re-alignment of terranes. Adapted from Soper *et al.* (1992).

caldera development. The volcanoes were subaerial, of low relief, and were probably located in extensional basins, into which there was only one short-lived marine incursion, though subsidence at the end of the volcanic episodes allowed persistent marine conditions to become established. In Ashgill to early Llandovery time localized silicic volcanism occurred in a shallow marine setting and the later, tholeiitic, phases of the Carrock Fell Complex were emplaced.

In the Welsh Basin, the most intense and extensive episode of Caledonian volcanism occurred during Caradoc time, with major centres developed in Snowdonia, on the Llŷn Peninsula and in the Breiddon and Berwyn hills in the Welsh Borderland (Chapter 6). Both Snowdonia and Llŷn were also the focus for a number of major subvolcanic intrusions. Although extensive, the volcanic activity was relatively short lived in mid-Caradoc time, but the ages of intrusions range into the earliest Silurian. As with the earlier activity, there was a mixture of magma types, ranging from mid-ocean-ridge-type tholeiites, through low-K tholeiites to calc-alkaline, suggesting both extensional basin and subduction-related magmatism. In contrast to the Lake District, the volcanism was mostly submarine with some emergent centres, both within the basin in northern Snowdonia and in a shallow marine environment closer to the basin margins in the Welsh Borderland. Much of the volcanicity was controlled by contemporaneous faults, suggesting an extensional tectonic setting and major calderas were developed. This volcanic climax was the last Caledonian igneous activity to occur in North Wales and shows a geochemical transition towards a 'within-plate' environment. It has been suggested therefore that this marks the end of subduction of Iapetus crust beneath Eastern Avalonia.

In central England, calc-alkaline volcanic and plutonic rocks of Caradoc age occur mainly on the NE margin of the Midlands Microcraton (Chapter 5). These form part of a belt of arc-related rocks that extends eastwards into Belgium. Poor exposure means that their tectonic setting is not well understood, but their position on the eastern margin of Eastern Avalonia suggests that they may have been the product of subduction of oceanic lithosphere beneath the microcraton during closure of the Tornquist Sea (Figure 1.3c). It is, however, difficult to accommodate this subduction direction geometrically with the subduction of the Iapetus Ocean, which was occurring at the same time.

Early and mid-Silurian – Llandovery and Wenlock

It was during this period that the Iapetus Ocean finally closed along most of its length. Most current three-plate models show a triangular remnant of oceanic crust around the Laurentia–Baltica–Eastern Avalonia triple junction in mid-Llandovery time, but most authors agree that the ocean had closed completely by the end of Wenlock time, with the continents welded together along the lines of the Iapetus and Tornquist sutures (Figure 1.3d). Following the closure, a foreland basin developed, which propagated across the suture during Wenlock to Ludlow time and established for the first time continuity of sedimentation between the Southern Uplands and Lakesman terranes. There is little evidence for 'southward' active subduction beneath Eastern Avalonia after the end of the Ordovician and, away from the immediate proximity of the suture (i.e. the Lakesman Terrane), there is no igneous activity at all after Wenlock time. However, major igneous events on the Laurentian margin continued until well into the Early Devonian and all have subduction-related characteristics.

Both the Northern Highlands and the Grampian terranes were undergoing tectonic uplift during the early Silurian, but the only significant magmatic event was on the extreme 'north-western' edge of the Northern Highlands. Here, highly alkaline magmas were emplaced as plutons and minor intrusions, overlapping in time with large-scale thrust movements, which resulted in considerable crustal shortening and transposed the edge of the whole Caledonian 'mobile belt' over the foreland of Archaean and unmetamorphosed Proterozoic and Lower Palaeozoic rocks (Chapter 7). The timing and nature of these movements have much in common with the Scandian Event in the Norwegian sector of Baltica, so it may be that the Northern Highlands Terrane was still adjacent to Baltica at this time. Although alkaline magmatism is normally associated with crustal extension, it is now accepted that it can be generated by small degrees of partial melting in deep levels of a subduction zone or within mantle that contains relics of earlier subduction. Such an origin seems appropriate for the Caledonian alkaline rocks, which were emplaced farther from the continental margin (and hence the surface trace of the subduction zone) than any other igneous suite in the orogenic belt.

Evidence for contemporaneous volcanism is lacking in northern Britain. Calc-alkaline volcanic detritus in the Midland Valley and Southern Uplands terranes may have had a fairly local source. However, scattered metabentonites throughout Llandovery, Wenlock and early Ludlow sequences on the site of the former Iapetus Ocean probably represent ash-fall tuffs from very distant sources and it is impossible to speculate on their origin.

On the 'southern' margin of the Welsh Basin in south Pembrokeshire, localized volcanic activity occurred within a shallow marine sequence of Llandovery age (Chapter 6). This magmatism was more alkaline than that of earlier episodes and geochemical evidence suggests a within-plate oceanic mantle source that had been modified by the earlier subduction events. It is possible that this magmatism was generated during crustal extension on the margin of the Rheic Ocean, which was opening on the opposite side of Eastern Avalonia (Figure 1.3c, d), and hence may not be classed strictly as 'Caledonian'. On the southern edge of the Midlands Microcraton near Bristol, two local volcanic episodes of Llandovery and Wenlock age have a more definite calc-alkaline nature, but these too are very close to the inferred margin of the Rheic Ocean. Their tectonic affinities are uncertain, as are those of metabentonites in Silurian inliers of South Wales and the Welsh Borderland.

Late Silurian and Early Devonian – Ludlow to Emsian

By late Silurian time the continents had welded together along the Iapetus Suture to form the new supercontinent of Laurussia (Figure 1.3e). There is geophysical evidence that continental crust of Eastern Avalonia continued to be underthrust (?subducted) beneath Laurentia after the continent–continent collision, but only as far as the Moniaive shear zone in the centre of the Southern Uplands Terrane. However, calc-alkaline magmatism, with subduction-zone characteristics became widespread and voluminous throughout the former Laurentian terranes in the late Ludlow and continued throughout the Early Devonian. (The paradox of apparent subduction-related magmatism continuing after the cessation of active subduction is discussed in more detail in the next section.)

Large, essentially granitic, plutons were emplaced at all crustal levels in the Scottish Highland terranes and in eastern Shetland during early Ludlow to early Lochkovian time (Chapter 8). Their magmas were derived mainly from lower crustal sources, but with a recognizable mantle component. Granitic plutons with similar lower crustal and mantle characteristics were also emplaced at high crustal levels in late Ludlow to early Lochkovian time in the Midland Valley Terrane and in the NW part of the Southern Uplands Terrane. High-level granitic plutons and dyke-swarms were emplaced slightly later (Lochkovian to Pragian) in a broad zone that spans the projected position of the Iapetus Suture in the SE part of the Southern Uplands Terrane (Chapter 8) and in the Lakesman Terrane (Chapter 4). Of these, the youngest are those immediately NW of the suture, in the zone in which the Southern Uplands thrust belt was underthrust by Avalonian crust. These last plutons all have components with distinctive characteristics that have been attributed to derivation from the mid-crustal melting of sedimentary rocks, either Silurian greywackes similar to the country rocks or Late Cambrian to mid-Ordovician turbidites similar to those in the Lake District. Plutons SE of the suture have many geochemical similarities to those to the NW, but the influence of sedimentary rocks in their origin is more equivocal.

The late granitic plutons were emplaced during and immediately following the rapid crustal uplift which produced the Caledonian mountain chain. High-level crustal extension led to local fault-bound intermontane basins in the Grampian Highland and Southern Uplands terranes and the larger basins of the Midland Valley Terrane. Rapid erosion of the newly formed mountains resulted in the deposition of great thicknesses of continental molasse sediments in these basins during the latest Silurian and Early Devonian (the 'Old Red Sandstone'). The last major volcanic episode of the Caledonian Orogeny was coeval with the later stages of pluton emplacement throughout these terranes and resulted in great thicknesses of volcanic rocks within many of the Old Red Sandstone basins (Chapter 9). It is these high-K calc-alkaline volcanic rocks that provide the most compelling evidence for subduction-related magmatism in the late stages of the orogeny, after the closure of the Iapetus Ocean. In addition to their general arc-like geochemical and petrographical characteristics, these rocks exhibit marked spatial variations comparable with those of more recent continental-margin volcanic provinces. A more detailed discussion of possible explanations for this apparently anomalous style of magmatism is given in the next section.

To the south of the Iapetus Suture a major compressional deformation event produced folds, faults and a regional cleavage, which are seen particularly well in the 'slate belts' of the Lake District and Wales. North of the suture, broad folds were generated in the Lower Old Red Sandstone sequences of the Midland Valley Terrane. This event occurred in the Early Devonian with a probable climax in the Emsian and was coeval with the Acadian Orogeny in the Canadian Appalachians. Hence it is referred to in Great Britain as the Acadian Event (Soper *et al.*, 1987). The latest granite plutons of the Lakesman Terrane and the SE of the Southern Uplands Terrane were intruded during this time and the Shap, Skiddaw and Fleet plutons in particular have provided important evidence that emplacement was synchronous with cleavage development and lateral shearing. It has been suggested that the event was caused by further northward compression of Eastern Avalonia against Laurentia by the impact of Armorica, a microcontinent that had been drifting 'northwards' from the margin of Gondwana throughout the Silurian (e.g. Soper, 1986; Soper *et al.*, 1992) (Figure 1.3e).

Mid- and Late Devonian – Eifelian to Famennian

Plutons and dykes in eastern Shetland are of Early Devonian age and are comparable to the latest plutons elsewhere, but all other 'Caledonian' igneous activity in Orkney and Shetland is notably later than elsewhere in the British terranes. Volcanic activity occurred over a short period in the late Eifelian to early Givetian (Figure 1.2). By this time the orogeny had passed into an extensional phase and the 'Old Red Sandstone' sequences of mainly fluvial and lacustrine sediments were being deposited in fault-bound basins, which formed part of the wider Orcadian Basin. Most of the volcanic rocks have subduction-related characteristics but, in contrast to the late Caledonian volcanic rocks elsewhere in the province, many are transitional between calc-alkaline and tholeiitic in their chemistry. This has led to the suggestion that they acquired their characteristics from a much shallower subduction zone than the earlier rocks and hence at one time the area may have been close to a continental margin or trench. However, their tectonic relationship with the rest of the province is unclear. The lavas of the Isle of Hoy in the Orkneys are alkaline in nature and hence are more in keeping with the continental extensional setting; they may mark the start of the intra-plate alkaline volcanism that became widespread in northern Britain during the Early Carboniferous.

Plutons to the west of the Walls Boundary Fault in Shetland have yielded Frasnian to Famennian radiometric dates (Chapter 9). These probably represent minimum ages, but one pluton postdates early Givetian volcanic rocks. It is closely associated in space and time with a late phase of compressive deformation and metamorphism that post-dates the main extension responsible for the Orcadian Basin and is the last phase of Caledonian folding in Britain.

Given the unusual timing of the magmatic events and the unique structural sequence, it is tempting to suggest that Shetland must have originated in a separate terrane, well separated from the Northern and Grampian Highlands. The plutons are affected by movements on the Walls Boundary Fault (a possible continuation of the Great Glen Fault), but it is difficult to accommodate much lateral movement after the Mid-Devonian, by which time the Orcadian Basin covered Shetland, Orkney and parts of both the Northern Highlands and Grampian terranes, with a coherent pattern of sedimentation and common elements of stratigraphy throughout.

ORIGIN OF THE LATE CALEDONIAN MAGMAS

D. Stephenson and A.J. Highton

The source of the Caledonian magmas during the earlier parts of the orogeny, while the Iapetus Ocean was still in existence, is generally well constrained. Geochemical 'fingerprinting' enables suites of igneous rocks to be assigned to sources in various tectonic settings, although caution must be applied to most early Caledonian volcanic suites, which are commonly affected by varying degrees of of alteration and low-grade metamorphism. Most of the earlier suites have been attributed to mantle melting beneath spreading centres and within-plate oceanic islands, or to melting above island-arc subduction zones. All of these processes could have taken place either within the main ocean or in extensional marginal basins. The effects of subduction of oceanic crust beneath the continental margin of Avalonia can also be identified, by the presence of voluminous calc-alkaline igneous rocks. On the Laurentian margin, however, there is little evidence for subcontinental subduction during the early part of the orogeny, when the igneous activity was dominated by melting of mid- to upper-crustal late Proterozoic metasedimentary rocks.

Magmatism had more or less ceased in Eastern Avalonia at the end of the Ordovician, which implies that subduction had ceased on this margin of the Iapetus Ocean before final closure. However, magmatism on the Laurentian continental margin continued well after ocean closure and continent–continent suturing. Unlike the earlier magmatism, this later activity was markedly calc-alkaline; it has many subduction-related features and even shows spatial variations in geochemical parameters that are usually related to increasing depths of a subduction zone beneath a continental margin. The most compelling evidence for a subduction zone origin for the magmas is found in the geochemistry of the late Caledonian volcanic rocks (Groome and Hall, 1974; Thirlwall, 1981a, 1982; see Chapter 9: Introduction), although certain geochemical features of the plutonic rocks have led to similar conclusions (Stephens and Halliday, 1984; Thompson and Fowler, 1986; see Chapter 8: Introduction). Although the subduction model is attractive, in that it explains and unites many of the observed features of the late Caledonian igneous activity, it is beset by serious problems related to the overall timing of tectonic events and the distribution of some of the magmatism (Soper, 1986).

It is now generally accepted from sedimentological and structural evidence (e.g. Watson, 1984; Stone *et al.*, 1987; Soper *et al.*, 1992), palaeomagnetism (Trench and Torsvik, 1992) and geochemical studies (Stone *et al.*, 1993), that the Iapetus Ocean had closed by the end of Wenlock time, that is before the onset of the late Caledonian volcanicity and indeed prior to the emplacement of most late Caledonian granitic plutons. There is no evidence for subsequent deformation in the Scottish Caledonides until the end of the Early Devonian, even though underthrusting of previously accreted oceanic sediments and Avalonian continental crust beneath the Laurentian margin must have continued for a while after the closure. Geophysical evidence and the sediment-derived isotope signatures of the plutons in the SE part of the Southern Uplands suggest that this underthrust material extends as far NW as the Moniaive shear zone, which overlies a geophysically defined basement discontinuity (Stone *et al.*, 1987, 1997; Kimbell and Stone, 1995).

The continent–continent collision, marginal underthrusting and consequent crustal thickening probably resulted in rapid uplift of the Laurentian margin. The magmatism responsible for both the late Caledonian plutons and the volcanicity occurred during this continental uplift. The geochemistry of most of the plutons suggests that they are derived dominantly from the melting of a lower crustal, igneous source. In particular, their isotope characteristics (Halliday, 1984; Stephens and Halliday, 1984; Thirlwall, 1989) and the presence of inherited zircons from older crustal material, point to significant crustal recycling (O'Nions *et al.*, 1983; Frost and O'Nions, 1985; Harmon *et al.*, 1984). However, most authors are agreed that there is also a significant background input of magma from the subcontinental lithospheric mantle (Harmon *et al.*, 1984; Stephens and Halliday, 1984; Tarney and Jones, 1994). This mantle-derived material is seen as mafic enclaves and appinitic rocks associated with many of the plutons and, possibly in its least modified form, in the calc-alkaline lamprophyres of the dyke swarms and in the near-contemporaneous lavas. These 'shoshonitic' basic to intermediate rocks, rich in potassium and other 'incompatible elements', are consistent with the melting of a hydrated K-rich mantle (Holden *et al.*, 1987; Canning *et al.*, 1996; Fowler and Henney, 1996), modified by mixing, both in the source region and on emplacement, with melts derived from the lower continental crust or subducted oceanic crust (Thirlwall, 1982, 1983b, 1986).

In an attempt to explain the apparently subduction-related geochemical signatures of the late Caledonian magmas, it has been suggested that the primary magmas may have originated by partial melting, during ultrametamorphism of a stationary slab of subducted oceanic crust, beneath the post-collision craton (Thirlwall, 1981a; Fitton *et al.*, 1982). Fitton *et al.* (1982) cited the Cascades of California as a modern example of active volcanism at a continental margin, possibly initiated by continued volatile loss from a now stationary slab. Watson (1984) favoured a two-stage model in which fluids expelled from a descending slab of oceanic crust rose into and metasomatically altered the overlying mantle wedge during active subduction. Partial melting of this modified mantle in response to lateral shearing and high-level movement on block faults after the end of subduction then gave rise to volcanic and plutonic rocks with subduction-related characteristics (Watson, 1984; Hutton and Reavy, 1992). A study of deep-seismic reflection profiles across the Iapetus Suture led Freeman *et al.* (1988) to suggest that the subcontinental mantle beneath the Avalonian crust became detached after continental collision and continued to be subducted, even though subduction of the continental crust had ceased. Zhou (1985) cited modern examples of continent–continent collision zones in Turkey, Iran and Tibet, where post-collision calc-alkaline magmatism is voluminous and Seber *et al.* (1996) presented geophysical evidence for the presence of detached slabs of subcontinental lithosphere, consequent upon collision and thickening of continental crust between Spain and Morocco. It therefore seems possible that the detachment and continued subduction or subsidence of a slab of metasomatized mantle and former oceanic crust may release residual melts or even generate new melts for some time after collision.

However, a further problem with the subduction model is that the volcanic rocks in the south-eastern Midland Valley are relatively close to the projected line of the Iapetus Suture. If the suture approximates to the original position of the trench, the inferred arc-trench gap of *c.* 60 km is substantially smaller than modern gaps (around 140 km minimum). This problem is only partly resolved by invoking significant crustal shortening as a result of deformation and underplating, or strike-slip movement during the later stages of the orogeny, juxtaposing terranes which were originally much more widely separated. The problem is even more acute in the Southern Uplands, where the significantly younger lavas and granite of the Cheviot Hills, for example, lie almost on the projected position of the suture. Analyses of volcanic rocks from the Cheviot Hills and St Abbs sequences do not fit into the spatial patterns seen NW of the Southern Upland Fault. Although these lavas, together with many of the dykes in the area (Rock *et al.*, 1986b), are undoubtedly calc-alkaline, their chemistries suggest derivation from a far deeper subduction-zone source than is possible given their position close to the suture. Therefore, any apparent subduction-related component must either derive from the mantle above a subsiding detached slab of lithosphere beneath the continental suture (cf. Zhou, 1985; Seber *et al.*, 1996), or be related to some other, post-Iapetus subduction zone yet to be identified (Soper, 1986); subduction of the Rheic Ocean beneath the southern margin of Eastern Avalonia is one possibility.

Table 1.1a Ordovician Igneous Rocks Block: networks and GCR site selection criteria

Volcanic Rocks and Ophiolites of Scotland Network, Chapter 2

Site name	GCR selection criteria
The Punds to Wick of Hagdale	Representative of lower part of Shetland Ophiolite, in particular the controversial intrusive relationship of dunite to mantle components. Internationally important in that it offers a rare section across the petrological Moho.
Skeo Taing to Clugan	Representative of lower part of Shetland Ophiolite, providing evidence for intrusive rather than layered cumulate relationships. Internationally important in that it offers a rare section across the geophysical Moho.
Qui Ness to Pund Stacks	Representative of upper part of Shetland Ophiolite, and illustrates relationships between dykes and underlying gabbro. Exceptional exposure of sheeted dyke complex, the clearest and most extensive in Britain.
Ham Ness	Representative of major structural relationships in Shetland Ophiolite with ultramafic rocks, gabbro and sheeted dykes brought into close proximity. Exceptional demonstration of emplacement of ultramafic nappe over sheeted dykes.

Tressa Ness to Colbinstoft	Exceptional section in Shetland Ophiolite through base of ophiolitic nappe, illustrating tectonics of emplacement and enigmatic metasomatic relationships.
Virva	Representative of basal structures in Shetland Ophiolite with exceptional evidence pertaining to unusual intrusive relationships. Internationally important in terms of the tectonic emplacement mechanism of ophiolite complexes.
Garron Point to Slug Head	Representative of part of Highland Border Complex, containing a variety of ophiolitic igneous lithologies.
Balmaha and Arrochymore Point	Representative of part of the Highland Border Complex, providing evidence of the relationship of serpentinite to overlying clastic rocks.
North Glen Sannox	Exceptional section through pillow lavas of the Highland Border Complex, containing evidence for the tectonic relationship with adjacent Dalradian rocks.
Byne Hill	Representative of an important component of the Ballantrae Ophiolite. Exceptional illustration of a zoned gabbro–leucotonalite body intruded into ophiolitic serpentinite.
Slockenray Coast	Representative of several components of the Ballantrae Ophiolite. Exceptional features of upper part include ophiolitic mélange, mixing of coeval lava flows of different compositions and a lava-front delta. Lower part is an exceptional gabbro pegmatite contained within serpentinite cut by pyroxenite veins.
Knocklaugh	Representative of basal zone of Ballantrae Ophiolite. Internationally important section allowing interpretation of the metamorphic dynamothermal aureole at the base of an ophiolite in terms of its obduction while still hot.
Millenderdale	Unique representative within the Ballantrae Ophiolite of multiple dyke intrusion into gabbro. Exceptional development of unusual metamorphic and textural relationships.
Knockormal	Exceptional occurrences of blueschist and garnet-clinopyroxenite within the Ballantrae Ophiolite. Internationally important historically as a possible zone of very high pressure metamorphism.
Games Loup	Representative of interveining between ultramafic components of the Ballantrae Ophiolite and juxtaposition of ultramafic rock and spilitic pillow lavas by faulting.
Balcreuchan Port to Port Vad	Representative of Balcreuchan Group, the upper part of the Ballantrae Ophiolite. Exceptional example of structural imbrication of varied lava sequence, and the only unambiguous British example of boninitic lavas.
Bennane Lea	Representative of highest exposed part of Ballantrae Ophiolite, faulted against ultramafic rock. Exceptional illustration of relationships between deep-water chert, volcaniclastic sandstone, mass-flow conglomerate and submarine lava.
Sgavoch Rock	Representative of the earliest accreted component of the Southern Uplands thrust belt. Exceptional display of pillow lavas and associated volcanic features; arguably the finest in Britain.

Intrusions of the NE Grampian Highlands of Scotland Network, Chapter 3

Site name	GCR selection criteria
Hill of Barra	Representative of olivine-rich cumulates from lower part of Lower Zone in Insch intrusion.
Bin Quarry	Representative of troctolitic and gabbroic cumulates from upper part of Lower Zone in Huntly intrusion. Exceptional for small-scale layered structures.
Pitscurry and Legatesden quarries	Representative of cumulates from Middle Zone of Insch intrusion associated granular gabbros and later pegmatite sheets
Hill of Johnston	Representative of late-stage differentiates (ferromonzodiorites and quartz-syenites) of the Insch intrusion. Exceptional mineralogical and geochemical features.

Hill of Craigdearg	Representative example from Boganclogh of the quartz-biotite norites found in many of the 'Younger Basic' intrusions. Exceptionally fresh and Mg-rich ultramafic rocks, unlike the Lower Zone cumulates.
Balmedie Quarry	Exceptional examples in the Belhelvie intrusion of layered gabbros, sheared and crushed by post-magmatic tectonic events.
Towie Wood	Exceptional exposures in the Haddo House–Arnage intrusion of xenolithic complex and associated norites developed near the roof of a 'Younger Basic' intrusion.
Craig Hall	Representative example from Kennethmont granite–diorite complex of variety of rocks found in granitic intrusions broadly coeval with 'Younger basic' intrusions.

Lake District Network, Chapter 4

Site name	GCR selection criteria
Eycott Hill	Representative of Eycott Volcanic Group. Exceptional locality for 'Eycott-type' (orthopyroxene-plagioclase megaphyric) basaltic andesite.
Falcon Crags	Representative of pre-caldera volcanism in Borrowdale Volcanic Group. Internationally important example of dissected plateau-andesite province.
Ray Crag and Crinkle Crags	Internationally important for understanding 'piecemeal' caldera collapse. Representative type areas in Borrowdale Volcanic Group of stratified Scafell Caldera succession. Exceptional example of structures within an exhumed hydrovolcanic caldera and of welded ignimbrites.
Sour Milk Gill	Internationally important exposures of large-magnitude phreatoplinian ash-fall tuff, associated with development of 'piecemeal' caldera collapse.
Rosthwaite Fell	Exceptional illustration of variations in magmatic and hydromagmatic volcanism in internationally significant Scafell Caldera. Exceptional example of post-caldera lava, its vent and feeder.
Langdale Pikes	Exceptional examples of volcanotectonic faults. Internationally important example of caldera-lake sedimentary sequence and of subaqueous lag breccia associated with ignimbrite.
Side Pike	Exceptional exposures illustrating distinction between rocks of pyroclastic fall, flow and surge origin, and for rocks formed through magmatic, phreatomagmatic and phreatic processes. Representative of volcanic megabreccia within the internationally significant Scafell Caldera.
Coniston	Representative of post-Scafell Caldera volcanism and sedimentation in Borrowdale Volcanic Group.
Pets Quarry	Exceptional example of features of magma intrusion into wet sediment.
Stockdale Beck, Longsleddale	Representative of late Ordovician, post-Borrowdale Volcanic Group, volcanism in the north of England.
Bramcrag Quarry	Representative of Threlkeld microgranite.
Bowness Knott	Representative of Ennerdale granite.
Beckfoot Quarry	Representative of Eskdale granite.
Waberthwaite Quarry	Representative of Eskdale granodiorite.
Carrock Fell	Representative of Carrock Fell Complex. Internationally important for historical contributions to understanding of crystallization mechanisms.
Haweswater	Representative of Haweswater basic intrusions.

Central England Network, Chapter 5

Site name	GCR selection criteria
Croft Hill	Representative of South Leicestershire diorites.
Buddon Hill	Representative of Mountsorrel complex.
Griff Hollow	Representative of Midlands Minor Intrusive Suite.

Wales Network, Chapter 6

Site name	GCR selection criteria
Rhobell Fawr	Representative of Rhobell Volcanic Group (Tremadoc), the earliest manifestation of Caledonian igneous activity in Britain south of the Iapetus Suture.
Pen Caer	Representative of Fishguard Volcanic Group (Llanvirn). Exceptional locality for products of major submarine basic–silicic volcanic complex. Internationally important for occurrence of silicic lava tubes.
Aber Mawr to Porth Lleuog	Internationally important for presence of silicic welded submarine ash-flow and ash-fall unit (Llanvirn), the first to be recognized worldwide.
Castell Coch to Trwyncastell	Representative of the youngest (Llanvirn) volcanic episode in north Pembrokeshire.
St David's Head	Exceptional composite intrusion showing evidence of multiple magma injection and in-situ fractional crystallization.
Cadair Idris	Representative of Aran Volcanic Group (Arenig–Caradoc), the most important volcanic episode in southern Snowdonia.
Pared y Cefn Hir	Representative of Aran Volcanic Group, with best exposed sequence of volcanic rocks of Arenig to Llanvirn age in North Wales.
Carneddau and Llanelwedd	Representative of Builth Volcanic Group (Llanvirn), the most important Ordovician volcanic episode in the Welsh Borderland.
Braich tu du	Representative of 1st Eruptive Cycle (Caradoc; Soudleyan) of Snowdon Centre.
Llyn Dulyn	Exceptional exposures of silicic ash-flow tuffs emplaced in subaerial environment, allowing palaeogeographical reconstruction of part of 1st Eruptive Cycle of Snowdon Centre. Complements Capel Curig.
Capel Curig	Exceptional exposures of silicic ash-flow tuffs emplaced in submarine environment, allowing palaeogeographical reconstruction of part of 1st Eruptive Cycle of Snowdon Centre. Complements Llyn Dulyn. Internationally important historically, for first recognition of welding in submarine ash-flow tuffs.
Craig y Garn	Representative site illustrating initiation of 2nd Eruptive Cycle (Caradoc; Soudleyan–Longvillian) of Snowdon Centre. Exceptional preservation of one of the thickest and most complete intra-caldera sequence of ash-flow tuffs in British Caledonides.
Moel Hebog to Moel yr Ogof	Representative of ash-flow tuffs of subaerial outflow facies from caldera at Craig y Garn GCR site, belonging to 2nd Eruptive Cycle of Snowdon Centre. Exceptional preservation of fault and subsidence related brecciation, sliding and widespread disruption of previously deposited ash-flow tuffs.
Yr Arddu	Representative of earliest activity from Snowdon Centre; ash-flow tuffs erupted from submarine fissure.
Snowdon Massif	Representative of main phases of intrusive and extrusive activity linked to evolution of major submarine caldera, of 2nd Eruptive Cycle of Snowdon Centre. Exceptional demonstration of complex inter-relationships, through time, between alternating basic–acid magmatism, changing styles of volcanic activity and effect on sedimentation.
Cwm Idwal	Exceptional illustration of thinned sequence representing outflow facies of major submarine caldera, linked to 2nd Eruptive Cycle of Snowdon Centre. Complements Snowdon Massif.
Curig Hill	Representative of lowest unit of final phase of magmatism related to 2nd Eruptive Cycle of Snowdon Centre.
Sarnau	Representative of middle and upper units of final phase of magmatism related to 2nd Eruptive Cycle of Snowdon Centre.
Ffestiniog Granite Quarry	Representative of sub-volcanic granitic intrusion linked to 2nd Eruptive Cycle of Snowdon Centre.
Pandy	Representative of Ordovician (Caradoc) igneous activity in the northern Welsh Borderland.
Trwyn-y-Gorlech to Yr Eifl	Representative of Garnfor multiple intrusion, a sub-volcanic intrusion related to the Upper Lodge Volcanic Group (Caradoc).
Penrhyn Bodeilas	Representative of Penrhyn Bodeilas Granodiorite, a sub-volcanic intrusion linked to Upper Lodge Volcanic Group (Caradoc).

Moelypenmaen	Representative of the Llanbedrog Volcanic Group (Caradoc).
Llanbedrog	Representative of high-level silicic intrusion associated with Llanbedrog Volcanic Group (Caradoc).
Foel Gron	Representative of most evolved member of suite of peralkaline intrusions associated with Llanbedrog Volcanic Group (Caradoc).
Nanhoron Quarry	Representative of least evolved member of suite of peralkaline intrusions associated with Llanbedrog Volcanic Group (Caradoc), preserving rare contact with lower Ordovician sedimentary rocks.
Mynydd Penarfynydd	Exceptional coastal exposures through layered basic sill, ranging from pictites through gabbros to intermediate compositions.

Table 1.1b Silurian and Devonian Plutonic Rocks Block: networks and GCR site selection criteria.

Alkaline Intrusions of the NW Highlands of Scotland Network, Chapter 7

Site name	GCR selection criteria
Loch Borralan Intrusion	Representative of the intrusion. Exceptional as only British examples of several rock types, including nepheline-syenite, pseudoleucite-syenite and carbonatite. Radiometric age and structural relationships important for timing of movements in Moine Thrust Zone. Internationally important for some of the most extreme potassium-rich igneous rocks found anywhere on Earth. Historically of great importance in development of hypotheses for evolution of igneous rocks.
Loch Ailsh Intrusion	Representative of the intrusion. Radiometric age and structural relationships important for timing of movements in Moine Thrust Zone. Internationally important as type-locality of alkali-feldspar-syenite 'perthosite', and because of unusually sodium-rich character of syenites.
Loch Loyal Syenite Complex	Representative of the complex and the only extensive British intrusion composed of peralkaline quartz-syenite (nordmarkite).
Glen Oykel south	Representative of 'grorudite' (peralkaline rhyolite) suite of dykes which are emplaced only in Ben More Nappe. Important structural relationship of dyke cutting Loch Ailsh intrusion establishes that the latter was emplaced prior to movements on Ben More Thrust.
Creag na h-Innse Ruaidhe	Representative of 'grorudite' suite of dykes in one of the outliers (klippen) of the Ben More Nappe, an important structural relationship.
Beinn Garbh	Representative and exceptional exposures of sills of 'Canisp Porphyry'(a striking feldspar-phyric quartz-microsyenite), the largest development of Caledonian magmatism in the Foreland.
The Lairds Pool, Lochinver	Representative of 'Canisp Porphyry' as a dyke cutting Lewisian basement, which indicates the western extent of this suite in the Foreland.
Cnoc an Leathaid Bhuidhe	Representative of Canisp Porphyry as a sill, close to, but not above the Sole Thrust, confirming the restriction of the suite to the Foreland.
Cnoc an Droighinn	Representatives of 'Hornblende Porphyrite' suite of sills in a setting of great structural complexity, in which the sills are repeated by imbrication.
Luban Croma	Representative of sills of 'Hornblende Porphyrite' suite, and others, illustrating range and variation of pre-deformational minor intrusive rocks in Assynt.
Allt nan Uamh	Representative of unaltered hornblende-rich lamprophyre (vogesite), an otherwise rare rock type which occurs widely in the Moine Thrust Zone of Assynt and Ullapool.
Glen Oykel north	Exceptional locality at which an enigmatic diatreme of brecciated dolomitic limestone in a fine-carbonate matrix is associated with a vogesite sill. May represent only example of transport by gas in Caledonian alkaline suite.
Allt na Cailliche	Representative of suite of quartz-syenite (nordmarkite) sills which occur only close to the Moine Thrust; the only igneous suite in Assynt whose emplacement was localized by the thrusts themselves.
Camas Eilean Ghlais	Representative of nepheline-syenite ('ledmorite') dykes, emplaced in the Foreland yet clearly trending towards the Loch Borralan Intrusion, with

	implications for timing of thrust movements. Internationally important historically in demonstrating that alkaline magmatism did not involve reactions with limestone.
An Fharaid Mhór	Representative example of nepheline syenite ('ledmorite') dyke in the Foreland, trending towards the Loch Borralan intrusion.

Granitic Intrusions of Scotland Network, Chapter 8

Site name	GCR selection criteria
Loch Airighe Bheg	Representative of pluton within Rogart complex, Argyll and N. Highlands Suite. Exceptional examples of appinitic xenoliths exhibiting hybridization with host quartz-monzodiorite.
Glen More	Representative of Ratagain pluton, transitional alkaline member of Argyll and N. Highlands Suite. Exceptional for wide range of compositions, range of mantle and crustal sources, and extreme enrichment in Sr and Ba.
Loch Sunart	Representative of Strontian pluton, Argyll and N. Highlands Suite. Exceptional evidence for basic magmatism coeval with granodiorite emplacement. Internationally important for relationship to Great Glen Fault and deformation during emplacement and crystallization.
Cnoc Mor to Rubh' Ardalanish	Representative of eastern part of Ross of Mull pluton, Argyll and N. Highlands Suite, which shows reverse concentric zoning. Exceptional features of passive emplacement with stoping and assimilation of country rock.
Knockvologan to Eilean a' Chalmain	Representative of central part of Ross of Mull pluton. Exceptional examples of mafic enclaves, hybrid granitic rocks and internationally important example of 'ghost' stratigraphy in metasedimentary xenoliths.
Ben Nevis and Allt a'Mhuilinn (Chapter 9)	Representative of Ben Nevis pluton, Argyll and N. Highlands Suite. Internationaly important historically, for development of cauldron subsidence theory.
Bonawe to Cadderlie Burn	Representative of Etive pluton, Argyll and N. Highlands Suite and dyke swarm. Internationally important example of upper crustal, multiple pulse intrusion by a combination of block subsidence and diapirism within a shear-zone.
Cruachan Reservoir	Representative of marginal facies and hornfelsed envelope of Etive pluton, dyke swarm and screen of Lorn Plateau volcanic rocks.
Red Craig	Representative of Glen Doll diorite, South of Scotland Suite. Exceptional examples of assimilation of metasedimentary xenoliths with high-grade hornfelsing, local melting and hybridization.
Forest Lodge	Internationally important historically, as the site in Glen Tilt where Hutton first demonstrated the magmatic origin of granite in 1785.
Funtullich	Representative of Comrie pluton, South of Scotland Suite, a good example of a normally zoned, diorite to granite pluton. Exceptional internal contacts.
Craig More	Representative of Comrie pluton and aureole. Exceptional section across aureole, which has historical international importance.
Garabal Hill to Lochan Strath Dubh-uisge	Representative of Garabal Hill–Glen Fyne complex, South of Scotland Suite. Exceptional orderly sequence of intrusion from basic to acid. Internationally important historically, for studies of fractional crystallization.
Loch Dee	Representative of Loch Doon pluton, South of Scotland Suite, a fine example of a normally zoned pluton. Internationally important for studies of origin of compositional variation.
Clatteringshaws Dam Quarry	Representative of outer part of Fleet pluton, Galloway Suite, derived from melting of underthrust Lower Palaeozoic sedimentary rocks similar to those of Lake District.
Lea Larks	Representative of more evolved inner part of Fleet pluton, one of the most evolved late Caledonian granites. Internationally important for studies of extreme fractionation.
Lotus quarries to Drungans Burn	Representative of complete zonation of Criffel pluton. Internationally important for unusual transition from outer, mantle-derived rocks to inner granites derived from melting of sedimentary rocks.

Millour and Airdrie Hill	Representative of outer, mantle-derived part of Criffel pluton, Galloway Suite. Exceptional for mafic enclaves and foliation associated with emplacement. Internationally important for studies of diapirism.
Ardsheal Hill and peninsula	Representative and type area of Appinite Suite. Exceptional for range of ultramafic to acid compositions and for breccia-pipes. Internationally important for study of open system feeders to surface volcanism.
Kentallen	Representative example of appinitic intrusion. Exceptional Mg- and K-rich lithology, well-exposed contacts and complex age relationships.

Northern England Network, Chapter 4

Site name	GCR selection criteria
Grainsgill	Exceptional relationships of granite intrusion, greisen formation and mineralization in Skiddaw Granite.
Shap Fell Crags	Representative of Shap granite. Exceptional evidence for timing of Acadian deformation. Internationally important for study of K-feldspar megacrysts.

Table 1.1c Silurian and Devonian Volcanic Rocks Block: networks and GCR site selection criteria.

Scotland Network, Chapter 9

Site name	GCR selection criteria
South Kerrera	Representative of Lorn Plateau volcanic succession. Exceptional examples of subaerial lava features and interaction of magma with wet sediment.
Ben Nevis and Allt a'Mhuilinn	Representative of Ben Nevis volcanic succession. Exceptional intrusive tuffs. Internationally important as example of exhumed roots of caldera, and historically for development of cauldron subsidence theory.
Bidean nam Bian	Representative of entire succession of Glencoe volcanic rocks. Exceptional examples of ignimbrites, intra-caldera alluvial sediments and of sill complex intruded into unconsolidated sediments. Internationally important historically for development of cauldron subsidence theory and currently for evidence of graben-controlled volcanism.
Stob Dearg and Cam Ghleann	Representative of succession in eastern part of Glencoe caldera, including basal sedimentary rocks. Exceptional rhyolites, ignimbrites and intra-caldera sediments. Possible international importance for radiometric dating in conjunction with palaeontology close to Silurian/Devonian boundary.
Buachaille Etive Beag	Representative of Glencoe Ignimbrites. Exceptional exposures of pyroclastic flows separated by erosion surfaces and alluvial sediments.
Stob Mhic Mhartuin	Representative of Glencoe ring fracture and ring intrusion. Exceptional exposures of crush-rocks and intrusive tuff.
Loch Achtriochtan	Representative of Dalradian succession below Glencoe volcanic rocks. Exceptional topographic expression of ring fracture and ring intrusion.
Crawton Bay	Representative of Crawton Volcanic Formation.
Scurdie Ness to Usan Harbour	Representative of 'Ferryden lavas' and 'Usan lavas', comprising lower part of Montrose Volcanic Formation.
Black Rock to East Comb	Representative of 'Ethie lavas', comprising upper part of MontroseVolcanic Formation.
Balmerino to Wormit	Representative of eastern succession of Ochil Volcanic Formation. Possible international importance for radiometric dating in conjunction with palaeontology close to Silurian/Devonian boundary.
Sheriffmuir Road to Menstrie Burn	Representative of western succession of Ochil Volcanic Formation. Exceptional topographic expression of Ochil fault-scarp.
Craig Rossie	Representative of rare acid flow in upper part of Ochil Volcanic Formation.
Tillicoultry	Representative of diorite stocks, intruded into Ochil Volcanic Formation, sur-

	rounded by thermal aureole, and cut by radial dyke swarm. Exceptional examples of diffuse contacts, due to metasomatism and contamination, with 'ghost' features inherited from country rock.
Port Schuchan to Dunure Castle	Representative of Carrick Hills volcanic succession. Exceptional features resulting from interaction of magma with wet sediment are of international importance.
Culzean Harbour	Representative of inlier of Carrick Hills volcanic succession. Exceptional features resulting from interaction of magma with wet sediment are of international importance.
Turnberry Lighthouse to Port Murray	Representative of most southerly inlier of Carrick Hills volcanic succession. Exceptional features resulting from interaction of magma with wet sediment are of international importance.
Pettico Wick to St Abb's Harbour	Representative of volcanic rocks in the SE Southern Uplands. Exceptional vent agglomerates, block lavas, flow tops and interflow high-energy volcaniclastic sediments.
Shoulder O'Craig	Representative of vent and minor intrusions in SW Southern Uplands.
Eshaness Coast	Representative of late Eifelian, Eshaness volcanic succession, NW Shetland. Exceptional exposures of ignimbrite, hydromagmatic tuffs, pyroclastic breccias, flow tops and magma–wet sediment interaction, all in spectacular coastal geomorphology.
Ness of Clousta to the Brigs	Representative of Givetian, Clousta volcanic rocks, Walls, Shetland, including phreatomagmatic deposits.
Point of Ayre	Representative of Givetian, Deerness Volcanic Member, mainland Orkney.
Too of the Head	Representative of Givetian, Hoy Volcanic Formation, Isle of Hoy, Orkney, unusual for alkaline character. Potential international importance as radiometric time marker in Mid-Devonian.

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Site name	GCR selection criteria
Skomer Island	Representative of most complete section through Skomer Volcanic Group (Llandovery), the most significant expression of late Caledonian volcanism in southern Britain.
Deer Park	Representative of Skomer Volcanic Group, providing critical biostratigraphical age constraints.