Revised manuscript 8/5/12
Click here to view linked References

1 The Dalradian rocks of Scotland: an introduction

D. Stephenson, J. R. Mendum, D.J. Fettes and A.G. Leslie

* *David Stephenson* British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA.
dst@bgs.ac.uk
0131 650 0323
John R. Mendum British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA.
Douglas J. Fettes British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA.
A. Graham Leslie British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA.

* Corresponding author

Keywords:
Geological Conservation Review
Grampian Highlands
Dalradian Supergroup
History of Research
Metamorphism
Tectonic evolution

ABSTRACT

The Dalradian Supergroup and its basement rocks, together with younger plutons, underpin most of the Grampian Highlands and the islands of the Inner Hebrides between the Highland Boundary and Great Glen faults. The Dalradian is a mid-Neoproterozoic to early-Ordovician sequence of largely clastic metasedimentary rocks, with some volcanic units, which were deformed and metamorphosed to varying degrees during the Early Palaeozoic Caledonian Orogeny.

Sedimentation of the lower parts of the Dalradian Supergroup, possibly commencing about 730 million years ago, took place initially in fault-bounded rift basins, within the supercontinent of Rodinia and adjacent to sectors of continental crust that were later to become the foundations of North America, Greenland and Scandinavia. Later sedimentation reflected increased instability, culminating between 600 and 570 million years ago in continental rupture, volcanicity and the development of the Iapetus Ocean. This left the crustal foundations of Scotland, together with those of North America and Greenland, on a laterally extensive passive margin to the new continent of Laurentia, where turbiditic sedimentation continued for about 85 million years. Later plate movements led to closure of the Iapetus Ocean and the multi-event Caledonian Orogeny. Most of the deformation and metamorphism of the Dalradian strata peaked at about 470 million years ago, during the mid-Ordovician Grampian Event, which has been attributed to the

collision of an oceanic arc with Laurentia. The later, mid-Silurian Scandian Event, attributed to the collision of the continent of Baltica with Laurentia and the final closure of the Iapetus Ocean, apparently had little effect on the Dalradian rocks but marked the start of late-orogenic uplift and extensive magmatism in the Grampian Highlands that continued until Early Devonian times.

The Dalradian rocks thus record a wide range of sedimentary environments (alluvial, tidal, deltaic, shallow marine, turbiditic, debris flow) and a complex structural and metamorphic history. In areas of low strain, original sedimentary and volcanic structures are well preserved, even at relatively high metamorphic grades. There is convincing evidence for glacial episodes of worldwide importance and economic deposits of stratiform barium minerals are unique. The Grampian Highlands include two of the World's type-areas for metamorphic zonation, Barrovian and Buchan, with spectacular examples of the key metamorphic minerals, and various stages of migmatite development. Polyphase folding is widespread on all scales and gives rise to a range of associated cleavages and lineations. Regional dislocations, both ductile and brittle, are associated with a range of shear fabrics, breccias, clay gouges and veining.

1.1 INTRODUCTION

D. Stephenson

1.1.1 The Dalradian Supergroup

The Dalradian Supergroup is a mid-Neoproterozoic to Early Palaeozoic sequence of largely clastic sedimentary rocks, with some notable carbonate and volcanic units that were all deformed and metamorphosed to varying degrees during the mid-Ordovician Grampian Event of the Caledonian Orogeny. The Dalradian rocks, together with Caledonian intrusive igneous rocks, form the bedrock to most of the Grampian Highlands of Scotland and the islands of the Inner Hebrides between the Highland Boundary and Great Glen faults. Pre-Dalradian basement crops out in parts of the Northern Grampian Highlands and on the Isle of Islay (Figure 1.1). The Dalradian sequence, its basement and the Caledonian intrusions comprise the Grampian Terrane, one of several major crustal blocks that were juxtaposed during the Caledonian Orogeny to form the northern part of the British Isles (Figure 1.2). Dalradian rocks also occur in the Shetland Islands, east of the Walls Boundary Fault, conventionally as part of the Grampian Terrane but possibly part of a separate terrane. Siluro—Devonian and Mesozoic cover rocks crop out mainly around the margins of the Grampian Highlands.

The Grampian Terrane extends south-westwards into the northern and north-western parts of Ireland, where Dalradian rocks crop out over wide areas (Figure 1.2). There, the south-eastern terrane boundary is largely buried beneath younger rocks and is difficult to define. An extension or major splay of the Highland Boundary Fault probably does extend from Cushendun in the east to Clew Bay in the west but, unlike in Scotland, it is not defined by any strong geophysical feature. A Dalradian sequence with remarkable similarities to that of the Grampian Highlands also crops out in Connemara, well to the south of Clew Bay, and hence it seems likely that the boundary of the Grampian Terrane does not coincide with an extension of the Highland Boundary Fault in the west of Ireland and possibly extends south-eastwards as far as a line between south Antrim and Galway (Ryan *et al*., 1995).

On a broader scale, the terranes of the northern British Isles are inherently linked geologically to eastern North America and Greenland, which were in close proximity prior to the opening of the North Atlantic Ocean in Palaeogene times (*c.* 55 Ma ago) (Figure 1.3). The Dalradian Supergroup is similar in age to the Fleur de Lys Supergroup in Newfoundland (Kennedy, 1975) and its lower parts are equivalent to the Eleonore Bay Supergroup in East Greenland (Soper, 1994b; Leslie *et al*., 2008); the three sequences might have been deposited in adjacent basins. The Geological Conservation Review, and hence this volume, considers only the Dalradian rocks of Scotland and Shetland; for reviews of the Irish Dalradian see Alsop and Hutton (1990), Leake and Tanner (1994), Harris *et al.* (1994), Cooper and Johnston (in Mitchell, 2004) and chapters by J.S. Daly and D.M. Chew in Holland and Sanders (2009).

The current best estimate for the age of deposition of the oldest Dalradian rocks, adopted in this volume, is about 730 Ma. The youngest strata that can be assigned to the Dalradian has been a matter of recent debate, but it is now generally accepted that there is stratigraphical and structural continuity through from undisputed Dalradian strata into fossiliferous strata of Early Cambrian age (*c.* 515 Ma) and possibly continuing up into mid-Arenig age strata (Tanner and Pringle, 1999; Tanner and Sutherland, 2007). Those Early Palaeozoic strata were formerly thought to have been juxtaposed tectonically against the Dalradian sequence and consequently they have been described separately in the *British Cambrian to Ordovician Stratigraphy* GCR volume (Rushton *et al.*, 1999). They were assigned originally to the Highland Border Complex, which also includes elements of an ophiolite obducted during the Caledonian Orogeny, but Tanner and Sutherland (2007) have suggested that they should be designated as a separate 'Trossachs Group' and included in the Dalradian Supergroup (see *Introduction* to Chapter 4).

The name 'Dalradian' is derived from that of the ancient Scots' kingdom of Dalriada, which united the coastal areas of Argyll, Arran and Antrim between the 5th and 9th centuries AD. It was first applied to all of the metamorphic rocks that crop out between the Moine Thrust and Highland Boundary Fault by Sir Archibald Geikie in 1891. However, in his explanatory notes to the 1892 edition of Bartholomew's 10-miles-to-one-inch Geological Map of Scotland, he did make it clear that the 'Moine Schists' of the Northern Highlands are different in character to the 'Dalradian' rocks south-east of the Great Glen. As survey work progressed, quartzofeldspathic rocks of apparent 'Moine Schist' facies were also identified in the northern part of the Grampian Highlands and the term 'Dalradian' *sensu stricto* became restricted to the lithologically more-diverse strata now assigned to the Appin, Argyll and Southern Highland groups of the Dalradian Supergroup.

The so-called 'Moine' rocks of the Grampian Highlands have been the subject of much debate and revision of assignment and terminology over the past 100 years. Originally they were referred to variously, from north-east to south-west, as 'Granulitic Schists of the Central Highlands' (Hinxman and Anderson, 1915), 'Struan Flags' (Barrow, 1904) and 'Eilde Flags' (Bailey, 1910). Subsequently, J.G.C. Anderson (1948) reviewed the local successions and proposed that all rocks stratigraphically below a lowermost limestone should be included in a 'Moinian Metamorphic Assemblage', and Johnstone (1975) introduced the term 'Younger Moines' to distinguish them from the Moine rocks north-west of the Great Glen Fault. Detailed mapping in the later part of the 20th century resulted in a subdivision into an older, largely migmatitic 'basement' referred to as the 'Central Highland Division' and an overlying sequence dominated by non-migmatitic quartzofeldspathic rocks termed the 'Grampian Division' (Piasecki and Van Breemen, 1979a,b; Piasecki, 1980). The non-migmatitic 'cover' rocks are now assigned formally to the Grampian Group, the lowest group in the Dalradian Supergroup, on the basis of stratigraphical and structural continuity with the overlying sequences (Harris *et al.*, 1978). The 'basement' rocks, referred to for a while as the

'Central Highland Migmatite Complex' (Harris *et al.*, 1994; Stephenson and Gould, 1995), and referred to in more-recent literature as the Dava and Glen Banchor successions, have been formalised as the Badenoch Group. They might yet prove to be equivalent to the Moine Supergroup of the Northern Highlands, at least in terms of their age (see *Introduction* to Chapter 5).

Two other units within the Grampian Terrane, whose stratigraphical affinities are uncertain but are most probably Dalradian, are represented by GCR sites in this volume. These are the Bowmore Sandstone Group of Islay and the Colonsay Group of Islay, Oronsay and Colonsay.

Much of the terminology used in this volume is necessarily complex. It is evolving continuously, hopefully towards simpler, more-logical versions that are likely to gain widespread acceptance. Hence it will differ in parts from what has been used historically and even from current usage by some authors. In addition to a glossary of terms used, the '*Glossary and terminology*' section at the end of the volume includes brief details and explanations of radiometric dating methods and timescale adopted, lithological nomenclature (rock names), the method of numbering of structures associated with phases of deformation, the terminology of fold geometry, and the use of the stereographic projection. In each case emphasis is placed upon terms as used in this volume.

1.1.2 History of Research

In 1774, the prominent 'Dalradian' mountain of Schiehallion was the location for a ground-breaking experiment by the Astronomer Royal, Nevil Maskelyne, who set out to measure the gravitational attraction towards the quartzite mountain of a weight suspended on a plumb-line (Smallwood, 2007). The density of the Earth was estimated to be 4.5, possibly the earliest ever geophysical calculation. However, the earliest published description of Dalradian rocks was probably in James Hutton's *Theory of the Earth* (1788), in which the country rocks intruded by granite veins at the critical historical site in Glen Tilt were referred to as 'Alpine schistus' (see the *Forest Lodge* GCR site report; in the *Caledonian Igneous Rocks of Great Britain* GCR volume; Stephenson *et al.*, 1999).

The first geological map of Scotland (one of the first geological maps in the world), by Louis Albert Necker de Saussure in 1808, did not differentiate the Dalradian rocks from the Moine of the Northern Highlands or the Lewisian of the Hebridean Terrane, all of which were described as 'primitive rocks stratified as gneiss, mica slate and clay slate'. Subsequently, John MacCulloch's 1836 map of Scotland showed several distinct metamorphic lithologies within the three, still undivided, terranes. MacCulloch had surveyed almost the whole of Scotland and Shetland himself (Bowden, 2007) and was one of the first to describe and comment upon the origin of the Highland rocks (e.g. MacCulloch, 1814, 1819). In his geological essay on Scotland, Ami Boué (1820) attempted to correlate the metamorphic rocks of Shetland with those of Scotland and was the first to suggest that those of the eastern Mainland of Shetland are equivalent to those of the Grampian Highlands. A truly remarkable geological map from this early period is that of Shetland by Samuel Hibbert (1822), which even shows foliations and lineations in the Dalradian rocks. This was the world's first purely structural geological map and was published in conjunction with an account of tectonite rock fabric (another world first).

By the middle of the 19th century, the metamorphosed nature of the rocks was beginning to be understood but the degree of metamorphism was thought by many to be proportional to the age of the rocks, and many geologists still adhered to the Wernerian doctrine, in which crystalline rocks were thought to have been precipitated in a regular sequence from a primeval ocean (Oldroyd and Hamilton, 2002). For many years these misconceptions greatly hindered attempts to fit the main sequences of the Highlands into an overall timescale. Murchison (1851, 1859) tried to show that the rocks of the Grampian Highlands are more highly metamorphosed equivalents of those in the Southern Uplands and Geikie (1865), although recognizing them as older than those of the Southern Uplands, still assigned them to a 'Lower Silurian' unit. The influence of Murchison and Geikie ensured that their ideas persisted into the next century, although as late as the 1890s George Barrow was arguing that all of the Highland 'schists' were of the same age as the Lewisian gneisses, and merely displayed different degrees of metamorphism.

Eventually, people such as James Nicol (1844, 1852, 1863), professor at Cork and then Aberdeen University, and Robert Harkness (1861) of Cork, whilst recognizing the existence and significance of large-scale folding, started to identify local successions and trace them along strike to establish a regional lithostratigraphy. Then Archibald Geikie, who had been introduced to the Grampian Highlands by Murchison in 1860, began to rationalize the overall Scottish succession and to postulate large-scale overfolds as a means of repeating the stratigraphy (Murchison and Geikie, 1861; Geikie, 1865). Of particular note in this context is the slightly later work of Peter Macnair (1896, 1906, 1908), Curator of Natural History at the Glasgow Museums, who recognized the value of the Loch Tay Limestone as a datum line in reconstructing the broad-scale structural framework of the south-east Grampian Highlands. Remarkably, the correlation of 'boulder beds' on the Garvellach Isles, on Islay and at Schiehallion had been recognized early in the 19th century by MacCulloch (1819), and those on Islay were first interpreted as having a glacial origin as early as 1877 by J. Thomson. By the end of the 19th century, knowledge of large-scale nappe structures in the Alps was being applied to Scotland by the Geological Survey, initially in the North-west Highlands and subsequently to the Grampian Highlands. Systematic field surveys were underway and petrographical techniques and methods of chemical analysis were developing fast.

Although the Geological Survey had started work in Scotland in 1854, mapping to the north of the Highland Boundary Fault did not start until 1875. For the first few years this was concentrated on the sedimentary rocks around the fringes of the Grampian Highlands, but by the early 1880s, with Archibald Geikie as Director General, J. Horne, J.S. Grant Wilson, L.W. Hinxman and J. Linn were mapping large areas of the North-east Grampian Highlands and W. Gunn, C.T. Clough, J.B. Hill and H.M. Cadell were active on the Cowal peninsula. The work in Cowal led to the recognition of polyphase deformation, and the first use of minor structures to interpret the overall pattern of major folds (Clough, in Gunn *et al.*, 1897). In 1895, work started in the Glen Coe–Appin area, with a highly experienced team that included B.N. Peach and C.T. Clough, after completion of their ground-breaking survey of the North-west Highlands, and J.S. Grant Wilson. They were joined, among others, by H.B. Maufe and E.B. Bailey who were soon to make their mark with their exposition of cauldron subsidence in the volcanic rocks of the area, as well as unravelling the complex structure and proposing a succession for the Dalradian strata. Thereafter, until well into the 20th century, survey work was concentrated in the South-west Highlands, where large areas were surveyed by J.B. Hill, H. Kynaston, R.G. Symes, S.B. Wilkinson and others. The notable exception at that time was the work of G. Barrow and E.H. Cunningham Craig in north-east Perthshire and Angus, which led to Barrow's (1893) seminal work on metamorphic zones. Although Barrow initially attributed the zonation to contact metamorphism above concealed igneous masses, ironically the 'Barrovian zones' became the world standard for the progressive regional metamorphism of aluminous sedimentary rocks at medium pressure. As this concept was extended throughout the Highlands it played a major part in deciphering the geological history of the whole region.

There then followed a period dominated by the work of Edward Battersby Bailey, who was undoubtedly the most dynamic, prolific and controversial figure ever to set foot upon Dalradian rocks. Bailey was decorated for bravery in the First World War and legends abound concerning his resilience and eccentricity in the field (Figure 1.4). After distinguishing himself with the Geological Survey, and then becoming disillusioned by official restrictions upon his personal scientific investigations, he left in 1930 to take a chair at the University of Glasgow. However, he subsequently returned to the survey as Director in 1937, was knighted in 1945 and continued to publish on Highland geology well into retirement.

Bailey started work in the Highlands in 1902, and in a series of papers between 1910 and 1940 he elucidated the structure and stratigraphy of Dalradian rocks over a wide swathe of ground from Islay to Loch Awe, Loch Leven, Glen Roy, Glen Orchy, Glen Lyon, Schiehallion, Loch Tummel, Blair Atholl, Glen Shee, Glen Clunie and Braemar. Most of this was based upon his own mapping, much of it in his own time, but he also re-interpreted ground that had already been covered by others, most notably Barrow, with whom he had fundamental disagreements. This was all in addition to his ground-breaking work on the igneous rocks of Glen Coe and Mull. He could never be described as a precise detailed mapper, and was certainly not out of the same mould as the likes of Clough, Peach and Horne, but he moved over the ground at incredible speed and was a master at tracing out large-scale structures. In fact most of the major folds recognized today in the above areas are the ones that were first identified by Bailey.

It was Bailey who first made use of the ungainly verb ‘to young’ and coined the terms ‘antiform’ and ‘synform’. He also introduced the concept of ‘slides’ (or ‘fold-faults’) – very low-angle faults associated with recumbent folds, which would be described generically as 'ductile dislocations' in modern parlance. These he divided into extensional ‘lags’, along which fold limbs and significant parts of the succession can be excised, and compressional ‘thrusts’, which generally result in the repetition of parts of the succession. In 1922 he produced a comprehensive synthesis in which major slides were perceived as fundamental tectonic dislocations separating huge, Alpine-scale nappe complexes, each complex having its own stratigraphical succession and structural style. Initially three such nappe complexes were recognized and named, in ascending structural order, the *Ballappel Foundation* (from the type areas of *Ball*achulish, *App*in and Loch *Eil*de), the *Iltay Nappe* (comprising most of the ground between *Isl*ay and Loch *Tay*), and the *Loch Awe Nappe*, but these were subsequently reduced to two when Bailey (*in* Allison, 1941) accepted the stratigraphical correlations of other investigators which removed the need to invoke a separate Loch Awe Nappe. We now know that both the structure and the stratigraphy of the Grampian Highlands are more integrated and continuous than inferred by Bailey, and hence many of the slides have lost much of their original significance as major tectonic and stratigraphical boundaries.

At the beginning of the 20th century, the use of sedimentary structures as way-up criteria was virtually unknown and Bailey, along with everyone else, struggled to establish the correct order of succession. Possibly the first use of graded bedding in the Scottish Highlands to determine the younging direction was by Peach *et al.* (1911) at a location within the *Kilmory Bay* GCR site, and current-bedding was first used by J.F.N. Green on Islay (Green, 1924). But the key event happened in 1924, when two graduate students from the University of Wisconsin, Sherwood Buckstaff and Olaf Rove, accompanied Thorolf Vogt of the University of Trondheim on a visit to Ballachulish and deduced that the succession established by Bailey (1910, 1922) was in fact upside down. This radical new interpretation was communicated to Bailey who was then invited to attend a Princeton University summer school in Canada in 1927, where he became convinced of the need to apply sedimentary structures to interpret folded rocks. As a result of this, in 1929, he acted as guide for a visit by a Princeton group to Scotland, where all agreed that his original (1922) order of succession needed to be reversed. Vogt and Bailey published their findings as linked articles in the *Geological Magazine* (Vogt, 1930; Bailey, 1930), and Bailey went on to re-appraise key sections around Loch Leven and throughout the whole area, confirming the presence of recumbent folds of many kilometres amplitude with extensive inverted limbs. The legacy of this fundamental ‘about face’ lives on to this day in the archives of the British Geological Survey (BGS), where the original 6-inch to 1 mile maps of the Loch Leven area, prepared prior to 1924, still show Bailey’s original succession.

Survey mapping was severely curtailed by the First World War (1914–18) although a detailed revision of part of the North-east Grampian Highlands was carried out by H.H. Read, after he had been discharged from active service on medical grounds. That work formed the basis of a lifetime of investigation into the structure, metamorphism and magmatism of the North-east Grampians, in a career that ranged widely through the Scottish and Irish Caledonides and took him from the Geological Survey to the University of Liverpool and the Royal School of Mines (later Imperial College), London. He was the first to recognise that the Buchan metamorphism originated at lower pressures and higher temperatures than the Barrovian sequence, became even more-widely known for his survey work in the Northern Highlands, and was also part of a large team that carried out the primary survey of the Shetland Islands in the early 1930s. Previous publications on Shetland geology had concentrated mainly upon mineral occurrences (e.g. Heddle, 1878, 1901) and the only published maps were based upon that of Hibbert in 1822. The Dalradian rocks were surveyed by D. Haldane, J. Knox, J. Phemister, H.H. Read, T. Robertson and G.V. Wilson but the only ensuing publications were those of Read, which concentrated upon the metamorphism (Read, 1933, 1934, 1936, 1937) and the Caledonian ophiolite-complex of Unst and Fetlar (see the *Caledonian Igneous rocks of Great Britain* GCR volume; Stephenson *et al*., 1999).

Geological Survey work in Scotland between the wars and during the Second World War (1939–45) was concentrated in the coalfields, the Northern Highlands and the Inner Hebrides. Some sheet memoirs based upon pre-1914 mapping of the Grampian Highlands were published and the first edition of *British Regional Geology: the Grampian Highlands* appeared in 1935. The latter was written by H.H. Read who, by the time of its publication, had taken the chair at Liverpool University, where his influence no doubt laid the first foundations of the Dalradian research that was to flourish there in the second half of the 20th century (see below). Other than those by E.B. Bailey, there were few 'Dalradian' papers by survey geologists. E.M. Anderson did small amounts of official survey mapping in the Grampian Highlands and, inspired by Bailey, he produced a paper based on his own work in the Schiehallion area that significantly advanced understanding of the overall Dalradian succession (Anderson, 1923). He retired due to ill health in 1928, but continued 'indoor work' for many years and is best remembered for '*The Dynamics of Faulting and Dyke Formation*', drawing upon his experience in the Grampians and elsewhere. It was first published in 1942, revised in 1951, remained a classic textbook for many years and was last reprinted in 1972.

The most prolific university contributions to the Dalradian between the wars were undoubtedly by Glasgow, where Bailey clearly inspired both existing staff and students. His predecessor, J.W. Gregory, had published several accounts (Gregory, 1910, 1916, 1928, 1929, 1930) and the first overview of *Dalradian Geology* (Gregory, 1931), all of which presented an 'alternative' rationalization of the succession across the whole region. W.J. McCallien (1925, 1926, 1929) had already published on the Dalradian rocks of Kintyre and went on to collaborate with Bailey in Perthshire (Bailey and McCallien, 1937). A. Allison worked on the Tayvallich–Loch Awe area and it was in the discussion to his paper, in 1941, that Bailey had his final say on the gross structure of the South-west Grampian Highlands, after becoming Director of the Geological Survey. Among Bailey's students, S.M.K. Henderson (1938) was the first to identify the Aberfoyle Anticline, but it was J.G.C. Anderson who made a major contribution to the Dalradian of the Highland Border region, in addition to his PhD studies on igneous rocks of the western Grampian Highlands. He joined the Geological Survey in Scotland in 1937, just before its activities became focussed upon war-related resource evaluation, and hence he did little 'official' mapping in the Highlands. However, in his own time he covered large areas in the manner of his mentor, resulting in a series of papers between 1935 and 1956, the last being published after he was appointed to the chair in Cardiff in 1949.

Work on the Dalradian at this time at Cambridge University centred around C.E. Tilley and Gertrude Elles. This included the recognition of the Portsoy Thrust in the North-east Grampian Highlands (Elles, 1931) and the refining of Barrow's zones of regional metamorphism (Tilley, 1925). Studies of the metamorphism of basic igneous rocks in the Dalradian were also made in Cambridge (Phillips, 1930; Wiseman, 1934), complementing what was already known about the progressive metamorphism of pelitic rocks. Also of the Cambridge 'school' was J.F.N. Green, who was a student contemporary of Gertie Elles before embarking upon a non-geological career in the Colonial Office, pursuing his geological interests in his spare time and becoming president of both the Geologists' Association and the Geological Society. After acclaimed work in Pembrokeshire and the Lake District, he made a major contribution to the geology of Islay, though a later paper on broader aspects of the Dalradian of the South-west Grampian Highlands was criticised by both Bailey and Elles (Green, 1924, 1931). His interest in the Dalradian probably resulted from an association with Barrow, after the latter's move to the Geological Survey in England. Less well known is the PhD study of S.O. Agrell (1942) under the supervision of Frank Coles Phillips, an unpublished part of which involved the first petrofabric analysis of the Ben Vuirich Granite and its country rocks. They could not have known how important these fabrics would become in subsequent discussions on the timing of pre-Caledonian and Caledonian magmatic and tectonic events, but the conclusions reached accord remarkably well with current interpretations (Howarth and Leake, 2002).

By 1950, Bailey had retired from the Geological Survey but was still a considerable influence on many aspects of Highland geology. Read had moved to the chair at Imperial College, London, where he continued to publish on the North-east Grampian Highlands. He led many investigations into the Caledonian basic intrusions of the region and introduced the concept of the Banff Nappe as a largely allochthonous succession (Read, 1955). The latter view was however disputed by his colleagues John Sutton and Janet Watson, who made a brief diversion from their work on the Lewisian of the North-west Highlands to publish three papers on the crucial across-strike Dalradian section of the Banffshire coast (Sutton and Watson, 1954, 1955, 1956). Read became the authority of his day on the origin of granites, deployed many post-graduate students and researchers to all parts of the Scottish Highlands, and developed what was to become a major involvement in Dalradian and Caledonian igneous rocks of the west of Ireland. But undoubtedly one of his most momentous moves was to support Derek Flinn's studies of the Dalradian (and other rocks) of Shetland, which were initiated as a PhD under Read (Flinn, 1953) and continued for over 50 years (e.g. Flinn, 2007). Subsequently at Imperial College, John Knill combined structural geology in the Craignish–Kilmelfort area with some of the earliest sedimentological studies of deformed and metamorphosed rocks (Knill, 1959, 1960, 1963) and Brian Amos (1960) and Brian Hackman (Stewart and Hackman, 1973) applied sedimentology to the Bowmore Sandstone and Colonsay groups of Islay respectively.

In 1948, the chair in Liverpool passed to Robert Shackleton, who had developed an interest in the Dalradian of Connemara and Donegal whilst at Imperial College. In Liverpool, he also turned his attention to the Grampian Highlands, in particular the Highland Border region, where he worked with research students (Stone, 1957; Stringer, 1957). This led to the conclusion that the Aberfoyle Anticline, and hence the closure of the Tay Nappe, is downward facing in the Highland Border region, and stimulated a debate on the geometry and mechanism of emplacement of the nappe that continues to the present day. The resulting seminal publication is frequently cited as the first explanation of the concept of structural facing in polyphase terrains to facilitate understanding of the structural evolution of an area (Shackleton, 1958). Shackleton's tenure also saw the move to Liverpool of Derek Flinn, the PhD study of the Colonsay Group on Colonsay and Oronsay by A.D. (Sandy) Stewart (1960) and the start of John Roberts' investigations in the South-west Grampian Highlands (Roberts, 1963).

Meanwhile, in Glasgow, research on the Dalradian was continuing under the direction of Basil King, and later Don Bowes, notable students being Nick Rast around Schiehallion (PhD, 1956), Donald Ramsay in Glen Lyon (PhD, 1959), Ken Jones in the Ben More–Stob Binnein area (PhD Swansea, 1959) and Harry Convery in the Ben Ledi–Balqhidder area. Rast became a key foundation in a 'dynasty' that dominated university Dalradian research for the next forty years. He first took up a post in Aberystwyth, where he extended his own work eastwards across the Loch Tay Fault by supervising the research of Brian Sturt, south of Loch Tummel (1959), and Tony Harris, between Loch Tummel and Blair Atholl (1960). When Shackleton moved to Leeds in 1962, Rast took over most of the Dalradian research in Liverpool, supervising Jack Treagus south of Loch Rannoch (1964a) and Peter Thomas to the north in what was later to become known as the Geal-charn–Ossian Steep Belt (1965). Those studies were two of the earliest to concentrate on rocks below and around the Boundary Slide. He also supervised Martin Litherland around Glen Creran (1970), A.N. Basahel on Islay (1971), Duncan France around the Boundary Slide at Bridge of Orchy (1971) and Graham Borradaile in the northern Loch Awe Syncline (1972a). It was during this era that Rast and Litherland (1970) made the first attempt to correlate the Dalradian successions of the South-west Grampians and Lochaber with those of the Central Grampians, which ultimately fed into the first correlations across the whole

Grampian Terrane by Harris and Pitcher (1975). Wallace Pitcher, Shackleton's successor at Liverpool, whilst mostly pursuing his Caledonian interests in Donegal, was promoting an appraisal of Dalradian tillites that culminated in the comprehensive Geological Society memoir by Tony Spencer (1971). Numerous metamorphic aspects of the Dalradian of Scotland were also investigated by Mike Atherton, Mike Brotherton and John Mather (PhD, 1968), leading to a major review article (Atherton, 1977), and the metamorphic history of north-east Shetland was studied by Roger Key (PhD, 1972).

Rast left Liverpool in 1971 and was replaced by Tony Harris, who by then had worked on Dalradian rocks for the Geological Survey in the Elgin area and in the Highland Border, around Dunkeld. Harris took up several lines of Dalradian research, involving many research students, notably Peter Gower on the Loch Tay Limestone (1973), Harry Bradbury (1978) and Richard Smith (1980) on the Pitlochry–Blair Atholl district, Lindsay Parson around Fort Augustus (1982), Andrew Highton (1983) and Nick Lindsay (1988) on the problems surrounding the structural history and stratigraphical correlation of the Grampian Group and its migmatitic 'basement', and Phillip Rose on the emplacement and evolution of the Tay Nappe (1989). Harris, Bradbury and Smith were all involved in a contract with the Geological Survey to map Sheet 55E (Pitlochry, 1981). At the same time, Jack Treagus was developing his own research in Manchester, mainly in the Central Grampian Highlands and including collaborative work with John Roberts in Newcastle on the Loch Leven area and on the Banffshire coast. He directed research students in the Braemar area (Paul Upton, 1983), Glen Lyon (Phillip Nell, 1984) and the South-west Grampians (Charlie Bendall, 1995), and collaborated with Peter Thomas, by this time at the University of Strathclyde, on a new edition of Sheet 55W (Schiehallion, 2000), with accompanying memoir, for the Geological Survey.

In Cambridge, Tilley's influence upon metamorphic studies continued into the 1950s, introducing Henry Pantin to the basic meta-igneous rocks of Ben Vrackie (1952) and encouraging Graham Chinner to re-examine the pelitic gneisses of Glen Clova (1957). Chinner then went on to direct numerous studies, in particular on high-grade migmatitic rocks (e.g. John Ashworth, 1972; Eileen McLellan, 1983). He was also responsible for introducing Ben Harte to the south-east Grampians (1966), and Keith Watkins to the Balquhidder–Crianlarich area (1982). Ashworth and Harte both went on to expand their studies elsewhere.

Studies of contemporaneous igneous rocks were also taking place at Bristol University under Bernard Leake, whose main interest lay in Connemara but who supervised Peter van de Kamp on the Green Beds (1968) and collaborated with J.R. Wilson on the 'epidiorites' of Tayvallich (Wilson and Leake, 1972). After moving to take up the chair in Glasgow, Leake wrote a review of volcanism in the Dalradian (Leake, 1982). Meanwhile, in Edinburgh (see below), Colin Graham had started a major study of volcanic and subvolcanic basic meta-igneous rocks in the South-west Grampians (Graham, 1976) and had also contributed to a review (Graham and Bradbury, 1981). Several more-recent studies of Dalradian volcanic and volcaniclastic rocks and of magmatism in general have been linked in some way to BGS mapping projects (Goodman and Winchester, 1993;

Macdonald *et al.*, 2005; Pickett *et al.*, 2006; Macdonald and Fettes, 2007; Fettes *et al.*, 2011) and David Chew of Trinity College, Dublin has incorporated the geochemistry of metavolcanic rocks into wider studies of Dalradian tectonics (e.g. Chew *et al.*, 2009)..

In Edinburgh, Mike Johnson re-examined the structure and metamorphism of the Banffshire Dalradian sections, with the help of PhD studies by Vic Loudon (1963) and Doug Fettes (1968). He also wrote reviews of the Dalradian for the first three editions of *Geology of Scotland* (1965, 1983, 1991). Ben Harte expanded his interests, notably through his own work in the 'Tarffside Nappe' and other areas close to the Highland Border and through the PhD work of John Booth (1984) and Tim Dempster (1983). The latter's work on metamorphism of the Dalradian and particularly on its uplift history has been continued at Glasgow. Harte also supervised the study by Neil Hudson on Buchan-type metamorphism of pelites (1976), which led on to studies at Derbyshire College, later University of Derby, of calcsilicate metamorphism by Stuart Kearns (1989), pelitic migmatites by Tim Johnson (1999) and the Portsoy Shear-zone by Jim Carty (2001). Colin Graham started his study of basic meta-igneous rocks with a PhD in 1973 and subsequently expanded into studies of low- to intermediate-grade metamorphism and fluid movement in the South-west Grampians that have included PhD students Ken Greig (1987), Peter Dymoke (1989), Alasdair Skelton (1993) and Chris Thomas (1999).

Following the earlier studies at Liverpool and Imperial College, sedimentological understanding of the lower grade Dalradian rocks of the South-west Grampian Highlands was significantly advanced by the work of Roger Anderton, first as a PhD in Reading (1974), then at the University of Strathclyde, and culminating in a seminal review paper (Anderton, 1985). Subsequent notable sedimentological PhD studies have been those of Brian Glover (1989) and Chris Banks (2005), both on the Grampian Group of the Northern Grampians at the University of Keele, and Elaine Burt (2002) on the Southern Highland Group at Kingston University. At Keele, John Winchester's interest in the Dalradian had originally been through whole-rock geochemistry but broader structural and sedimentological aspects of the Grampian Group in particular have been pursued through a number of research students in the Northern Grampian area, Keith Whittles (1981), Paula Haselock (1982) and C.T. Okonkwo (1985). Subsequently, whilst at the University of Greenwich, Haselock collaborated with colleagues and the BGS to produce Sheet 73E (Foyers, 1996).

Much of the Dalradian research at Aberdeen University in the latter part of the 20th century centred around the Caledonian basic intrusions of the North-east Grampians and more-general mapping contracts with the BGS. The latter were initially set up by Iain Munro and Bill Ashcroft, with other staff such as Graham Leslie, Alan Crane, Sally Goodman and Maarten Krabbendam becoming involved subsequently, together with PhD students such as Ben Kneller (1988). The first map and memoir to be produced in this way was Sheet 77 (Aberdeen, 1982), and this was followed by 87W (Ellon, 1985), 65E (Ballater, 1995) and 56W (Glen Shee, 1999).

At Birmingham, Alan Wright worked particularly on the stratigraphy and whole-rock geochemistry of the Appin Group (Wright, 1988) and supervised A.H. Hickman, who produced a radical re-appraisal of the stratigraphy and structure of the crucial area between Glen Roy and Lismore (Hickman, 1975, 1978). Also at Birmingham, Ian Fairchild, following on from his PhD studies at Nottingham, made detailed mineralogical and geochemical studies of the dolomitic beds at the base of the Argyll Group on Islay and both he and Wright contributed to the compilation of Sheet 27 (North Islay, 1994) for the BGS. Meanwhile Bill Fitches, Alex Maltman and Roddy Muir in Aberystwyth were concentrating upon the Colonsay Group in south-west Islay and its relationship with the basement of Rhinns Complex, whilst M.R. Bentley (PhD, 1986) re-appraised the outcrops on Colonsay.

Later work at Glasgow University has been largely by Geoff Tanner and Tim Dempster, with significant discussion and counter argument on broader tectonic themes by Brian Bluck. Tanner turned to addressing several key issues in the Scottish Dalradian after a long involvement with the Dalradian of Connemara that started with Shackleton at Leeds. In a series of seminal papers since 1994, he has established the emplacement age of the Ben Vuirich Granite relative to the Grampian deformation and metamorphism (Tanner and Leslie, 1994; Tanner, 1995; Tanner *et al.*, 2006) and has confirmed the structural and stratigraphical continuity between the Southern Highland Group and the older parts of the Highland Border Complex (Tanner, 1995; Tanner and Pringle, 1999; Tanner and Sutherland, 2007). A collaboration with Peter Thomas has led to a classic detailed description of recumbent folds between Tyndrum and Glen Orchy (Tanner and Thomas, 2010) and structural investigations in the Highland Border area around Loch Lomond, Cowal and Bute are contributing to understanding the geometry and development of the Tay Nappe.

During the mid 20th century, Geological Survey work in the Highlands was almost entirely north-west of the Great Glen. The only Dalradian mapped was on the fringes of the Grampian Highlands on sheets 95 (Elgin), 39 (Stirling) and 48W (Perth). However, considerable data on the Dalradian of the Central Grampian Highlands was obtained as a result of logging tunnels and other excavations for new hydro-electric schemes, mostly by Scot Johnstone and Donald Smith. Sheet 38W (Ben Lomond) and parts of surrounding areas were revised in the early 1980s by Doug Fettes, John Mendum, and Bill Henderson, and then in 1982 the East Grampians Project set out to complete the revision mapping of the North-east Grampian Highlands. Key players were Doug Fettes, John Mendum, David Stephenson, David Gould, Chris Thomas, Graham Smith and Steve Robertson, aided by specialists in geophysical, geochemical and mineral surveys and by several university contract teams (see above). Some nineteen 1:50 000 sheets were produced over a twenty-year period. This was followed by the Monadhliath Project in 1986, staffed mainly by Frank May, Roger Key, Colin Clark, Martin Smith, Steve Robertson, Andrew Highton, Donald Smith and Richard Smith. This project aimed to complete the mapping of the Grampian Group and its 'basement' (i.e. the Dava and Glen Banchor subgroups = Badenoch Group) in the Northern Grampian Highlands, a significant part of which was still classed as 'primary survey'. The East Grampian Project completed the lithostratigraphical rationalisation and correlation of the Appin and Argyll groups between the established sequences in the Central Grampian Highlands and on the north coast and recognized several important shear-zones and long-lived crustal lineaments (Fettes *et al*., 1986, 1991). The whole-rock geochemistry of metacarbonate rocks proved to be a useful indicator of depositional environment and a correlation tool (Thomas, 1989) and pelitic rocks revealed a fascinating story of high-pressure metamorphic overprinting west of the Portsoy Lineament (Beddoe-Stephens, 1990). The most significant results to emerge from the Monadhliath Project have been the establishment of a coherent lithostratigraphy for the Grampian Group, linked to early Dalradian basin architecture, and the confirmation of basement–cover relationships in the Northern Grampians (e.g. Robertson and Smith, 1999; Smith *et al*., 1999).

Other work in the Grampian Highlands by the BGS that has provided invaluable background information to so many studies includes the regional gravity and aeromagnetic surveys (published in 1977 and 1978 respectively) and the regional stream-sediment surveys that formed the basis for geochemical atlases (Great Glen, 1987; Argyll, 1990; East Grampians area, 1992; Southern Scotland, 1993). Work for the Mineral Reconnaissance Programme, led mainly by Mike Gallagher, Graham Smith and Stan Coats was spectacularly successful in its identification of the stratabound barium materialization near Aberfeldy (e.g. Coats *et al*., 1984), and that provided the impetus for investigations in other areas such as Tyndrum, Duntanlich, Coire Kander and The Lecht. Apart from the baryte at Aberfeldy and Duntanlich and a gold prospect at Cononish, economic prospects have been disappointing but the investigations have contributed to the mapping programme and inspired a wealth of scientific spin-off studies.

More-recent mapping by the BGS has been on Sheet 38E (Aberfoyle, 2005) and work is ongoing on sheets 46W and 46E in the Bridge of Orchy–Killin area (mainly by Graham Leslie, Maarten Krabbendam, Richard Smith and Chris Thomas). Other recent work includes the dating of detrital zircons and Sm-Nd signatures of whole-rock as indicators of sediment provenance (e.g. Cawood *et al*., 2003), the search for orogenic unconformities, especially within the Argyll Group, that might correlate with possible examples in the west of Ireland (e.g. Dempster *et al*., 2002; Hutton and Alsop, 2004), and the ongoing modelling of the Tay Nappe and regional deformation mechanisms (Krabbendam *et al*., 1997). The identification of various glacial deposits within the sequence and their correlation with known global glaciations has led to much speculation (e.g. McCay *et al*., 2006) and this has been linked to global C-isotope profiles, largely by Tony Prave at St Andrews (Prave *et al*., 2009a, 2009b).

Radiometric dating of events that have affected Dalradian rocks has been carried out at the Scottish Universities Environmental Research Centre (SUERC, formerly SURRC) and at the Natural Environment Research Council’s Isotope Geology Laboratories (NIGL). At SUERC, Otto van Breemen, in collaboration with Mark Piasecki at Hull, produced the first crucial dates on pegmatites emplaced in slides that cut what they regarded as pre-Grampian Group basement (Piasecki and van Breemen, 1979a,b, 1983). Subsequent fieldwork has confirmed that relationship and more-modern high-precision zircon and monazite dates have been obtained by Steve Noble at NIGL, in collaboration with Euan Hyslop and Andrew Highton at the BGS (Noble *et al.*, 1996; Highton *et al.*, 1999). Other key dates, notably for the emplacement of the the pre-metamorphic Ben Vuirich Granite, and the North-east Grampian Basic Suite that was almost coeval with the peak of Grampian deformation and metamorphism, were produced initially under Robert Pankhurst at the forerunner to NIGL (Pankhurst, 1970; Pankhurst and Pidgeon, 1976). These have been repeated, together with dates of the Tayvallich volcanic rocks and mineral ages that plot late-tectonic cooling and uplift, using high-precision methods at SUERC and elsewhere. The key workers have been Alex Halliday, Graeme Rogers and Tim Dempster, in collaboration with projects at Glasgow and Edinburgh, who are responsible for virtually the whole temporal framework currently in use (Halliday *et al.*, 1989; Rogers *et al.*, 1989; Dempster *et al.*, 1995, 2002). The possibility of more-direct dating of Dalradian sedimentation has been raised by encouraging results of Re–`Os dating at Durham University (Rooney *et al.*, 2011).

Field excursion guides to the Dalradian have been published by Read (1960) and Treagus (2009). Individual excursions are described in several regional guides i.e. Arran (MacDonald and Herriot, 1983), Aberdeen area (Trewin *et al.*, 1987), Glasgow and Girvan (Lawson and Weedon, 1992), Fife and Angus (MacGregor, 1996). Excursions in the Grampian Group and its inferred basement, all formerly regarded as Moine, are included in the original excursion guide to Moine geology (Allison *et al.*, 1988) and a series of excursions to the Dalradian of the South-west Grampian Highlands, described by various authors, comprise a whole part issue of the *Scottish Journal of Geology* (volume 13, part 2, 1977).

1.2 GCR SITE SELECTION

D. Stephenson

Metamorphic rocks in the more-sparsely populated areas of Great Britain are on the whole less prone to damage than sequences in the more-developed areas. They are none the less vulnerable to large-scale activities, some long established and obvious, such as quarrying and landfill, and others related to more-recent exploitation of the rural landscape such as coastal defences, hydro-electric schemes, wind farms and power transmission lines.

The greatest threat is undoubtedly the possibility of large areas of rock being obscured by man-made constructions or large volumes being removed by excavations. Some of the harder and more-resistant lithologies are an important source of construction materials and are hence particularly vulnerable to large-scale commercial extraction. Uses are many and varied but as demand changes with time, new uses are constantly emerging, so that no rock can be considered absolutely safe from future exploitation. However, with careful management both disused and active quarries, road cuttings and other excavations can provide highly instructive exposures, especially in areas of poor natural exposure. On a smaller scale, fossils, minerals and fine detail of delicate features can be lost easily through injudicious hammering, for casual or commercial collecting or even for bona fide research purposes. Much of the value of the GCR sites is derived from their research potential, but sampling does need to be controlled carefully and there is a clear need for better dissemination of information about protected sites.

The GCR sites in this volume vary greatly in size and character. There are long coastal sections (e.g. *Kilchiaran to Ardnave Point*, *Rubha a'Mhail*, *West Tayvallich Peninsula*, *Cullen to Troup Head*, *Fraserburgh to Rosehearty*) as well as numerous smaller coastal exposures such as those on the Isles of Islay and Jura and on the mainland of the South-west Grampian Highlands. River sections dominate the inland areas (e.g. *River Leven Section*, *River Orchy*, *River E*, *Glen Ey Gorge*, *Bridge of Brown*, *Bridge of Avon*, *Kymah Burn*) but road cuttings provide valuable additional sites (*A9 and River Garry*, *The Slochd*). At many of these sites exposure approaches 100 percent. Some of the larger sites occupy upland areas and mountain summits (*Stob Ban*, *Ben Lawers*, *Aonach Beag and Geal-charn*, *Ben Alder*, *Ben Vuirich*, *Cairn Leuchan*), where large-scale structures can be demonstrated, commonly in three dimensions, or where key exposures protrude from otherwise poorly exposed terrain.

The Geological Conservation Review (GCR) aims to identify the most important sites in order that the scientific case for their protection and conservation is fully documented as a public record, with the ultimate aim of formal notification as 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, and in Scotland this is the responsibility of Scottish Natural Heritage. At the time of writing most, but not all, of the sites described in this volume have been notified. 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, many of them satisfy two and some fall into all three categories (Table 1.1), such as the *Garvellach Isles* site that displays a tillite of international importance for its detailed features as well as for its stratigraphical and chronological significance. In addition to the GCR sites, significant, well-exposed local successions and structural features may be designated as 'Regionally Important Geological/Geomorphological Sites' (RIGS) so that, even though such status carries no legal protection, their importance is at least recognized and recorded.

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'. The *Dalradian rocks of Scotland* comprise a single block. Within each block, sites fall into natural groupings, termed 'networks', which in this volume are based upon geographical areas (Figure

1.5). The boundaries between the areas follow significant stratigraphical or structural boundaries wherever possible and the Highland Border Region and North-east Grampian Highlands are well defined in this way. Boundaries between the South-west, Central and Northern Grampian Highlands are more arbitrary and to some extent reflect the areas of interest of particular groups of researchers or periods of research. The six networks, each represented by a single chapter, contain 85 sites, which are listed in Table 1.1 together with their principal reasons for selection.

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 those sites more difficult to maintain.

Although this volume is titled *Dalradian rocks*, the GCR sites that it contains illustrate not only the lithostratigraphy and sedimentology of the Dalradian rocks and their basement but also the structures and metamorphism that affect them as a result of the Caledonian Orogeny. Some sites have been selected specifically to illustrate just one of those aspects, but many illustrate two or more. A few have historical significance.

The overall *international importance* of the Dalradian Supergroup has already been discussed in a historical context, highlighting significant contributions to the understanding of the processes of deformation and metamorphism. These contributions are acknowledged in several GCR sites such as those at *Glen Esk* and along the north coast (e.g. *Fraserburgh to Rosehearty*), where metamorphic zones at different confining pressures were first established. The sites that illustrate Neoproterozoic glacial espisodes, most notably at the *Garvellach Isles* and *Caol Isla* continue to attract attention for the worldwide significance of their deposits, the ages of which are still controversial. The granite at the *Ben Vuirich* site has yielded valuable information on the timing of deformation and metamorphism during the Caledonian Orogeny and unique economic deposits of stratabound barium minerals represented by the *Craig an Chanaich to Frenich Burn* site are of undoubted international value.

Exceptional features, invaluable for research and/or teaching purposes, are exhibited at many, if not most, of the GCR sites in this volume. For example, a range of sedimentary structures are particularly well displayed at the *A9 and River Garry* and *River E* sites, and many sites have first-rate examples of specific features such as dewatering structures (*Caol Isla*), slump structures (*Lussa Bay*, *Kinuachdrach*, *Port Selma*), sandstone dykes (*Surnaig Farm*), debris flows (*Black Mill Bay*) and Bouma sequences (*Rubha na Magach*). World-class examples of tillites occur at the *Garvellach Isles* site, algal stromatolites at *Rubha a'Mhail*, and pseudomorphs after gypsum at *Craignish Point*. Many of the sites show minor fold structures but these are particular features at *Black Mill Bay*, *Fearnach Bay* and *Port Cill Maluaig*. Fold interference structures are seen at the *Creag nan Caisean–Meall Reamhar* site and classic variations in style of cleavage occur in the related sites at *Little Glen Shee*, *Craig a'Barns* and *Rotmell*. Various types of migmatite are splendidly exposed at the *Balnacraig, Dinnet* and *Cairnbulg to St Combs* sites. Pillow lavas are present at several of the sites that include metavolcanic rocks (*West Tayvallich Peninsula*, *Muckle Fergie Burn*, *Black Water*) but the most exceptional meta-igneous features are probably the enigmatic spinifex-like textures at the *Cunningsburgh* site.

The criterion of *representativeness* aims to ensure that all key stratigraphical units and the most significant structural features are represented. It is difficult to do this whilst keeping the number of sites within reason. However, all of the main stratigraphical features of the Dalradian succession (e.g. those shown on Figure 1.6) are represented by sites, as well as some near-contemporaneous igneous intrusions. Selected structures include major and minor folds from each of the main phases of deformation, principal dislocations (thrusts, slides and faults), shear-zones and high-strain zones. Barrovian and Buchan metamorphism are represented as well as the highest grade rocks in the Dalradian and examples of polyphase metamorphism.

Clearly it would be impossible to represent all along-strike regional variations of the stratigraphy, structure and metamorphism by GCR sites. However, an attempt has been made to include broad descriptions of such variations in appropriate chapter introductions, together with references to key publications. Hence, this volume does constitute a complete review of the Dalradian Supergroup and the deformational and metamorphic effects of the Caledonian Orogeny throughout the whole Grampian Terrane.

Metavolcanic rocks within the stratigraphical column provide time markers and hence are important targets for radiometric dating. Precise U-Pb zircon dates have been obtained from the Tayvallich Volcanic Formation at the top of the Argyll Group, which give much added value to the *West Tayvallich Peninsula* GCR site. Unfortunately, as yet there have been no suitable targets that would date the tillites at the base of the Argyll Group (e.g. *Garvellach Isles* GCR site) that constitute the other significant chronostratigraphical marker in the Dalradian succession. Intrusions are less-precise chronostratigraphical markers than lavas but the deformed granite represented by the *Ben Vuirich* GCR site has yielded a number of increasingly precise radiometric dates that, together with dates from the Portsoy Granite (*Cullen to Troup Head* GCR site), have set time limits to Argyll Group deposition and early phases of the Caledonian Orogeny. The Tayvallich and Ben Vuirich dates are at present two of the mainstays of late-Neoproterozoic and Caledonian chronology in the whole North Atlantic region. Key radiometric evidence for the age of the Badenoch Group basement rocks has come from metasedimentary rocks at *The Slochd* GCR site.

Some sites are important in more than just the context of Dalradian rocks, their deformation and metamorphism. In particular, the *Ardsheal Peninsula* is also a GCR site in the *Silurian and Devonian Plutonic Rocks* block, as the type-area for the Appinite Suite of small ultramafic to felsic intrusions

(Stephenson *et al*., 1999). The *Keltie Water* GCR site has profound implications for relationships between the Dalradian and the Highland Border Complex and needs to be considered along with two sites (*Leny Quarry* and *Lime Craig Quarry*), which are described in Volume 18 of the GCR series, *British Cambrian to Ordovician Stratigraphy* (Rushton *et al*., 1999).

The broader aspects of Dalradian regional geology are outlined in the various sections of this chapter, with variations applicable to each network described in the following chapter introductions. In some cases, sections of general discussion apply to two or more related sites and this has necessitated a slight change of format in the *Little Glen Shee*, *Craig a'Barns* and *Rotmell* site reports. The voluminous and widespread Caledonian igneous rocks that are emplaced within and upon the Dalradian rocks are described in the *Caledonian Igneous Rocks of Great Britain* GCR volume (Stephenson *et al*., 1999). For details of post-Dalradian rocks in the Grampian Highlands the reader is referred to *The Geology of Scotland* (Trewin, 2002) and the volume in the British Geological Survey's *British Regional Geology* series (Stephenson and Gould, 1995).

1.3 BASEMENT TO THE DALRADIAN BASINS

D. Stephenson

Our knowledge of the immediate basement to the Dalradian rocks of the Grampian Highlands is limited to outcrops on the islands of Islay and Colonsay in the south-west (the Rhinns Complex) and in parts of the Northern Grampian Highlands (the Badenoch Group, formerly known informally as the Dava and Glen Banchor successions) (Figure 1.1). The existence of an unmodified contact with the basement is difficult to demonstrate in either area, but a stratigraphical and orogenic unconformity can be inferred from omission and overstep of strata on a regional scale and from structural and metamorphic hiatuses. Where contacts are exposed they are commonly seen to coincide with zones of high strain and shearing.

The Rhinns Complex was once thought to be part of the Lewisian Gneiss Complex of the Hebridean Terrane. It is now regarded as part of an extensive tract of Palaeoproterozoic juvenile crust that includes the Ketilidian belt of southern Greenland and the Svecofennian belt of Scandinavia and may form a link between those two segments (Marcantonio *et al*., 1988; Muir *et al*., 1989, 1992; Park, 1994). It extends south-westwards at least to the island of Inishtrahull off the northern coast of Ireland and Bentley *et al.* (1988) proposed that the three outcrops define a small allochthonous Colonsay–western Islay Terrane, bounded by the Great Glen and Loch Gruinart faults. Subsequently, it has been suggested that it might also underlie much of the Grampian Highlands, where the isotopic signatures of Caledonian granites are consistent with derivation, at least in part, from comparable juvenile crust forming a block measuring at least 600 x 100 km to the south-east of the Great Glen Fault (Dickin and Bowes, 1991).

Regional gravity and magnetic evidence indicate the presence of a distinctively different, lower density, basement beneath the south-eastern part of the Grampian Highlands (i.e. beneath the Tay Nappe), which seems to be a continuation of the basement that underlies the Midland Valley of Scotland (Rollin, 1994; Trewin and Rollin, 2002). The geophysical evidence also indicates the existence of a different, high-density, basement beneath the Buchan Block of the North-east Grampian Highlands.

The Dava and Glen Banchor subgroups of the Badenoch Group in the Northern Grampian Highlands are somewhat younger sequences of mainly gneissose and locally migmatitic metasedimentary rocks, comparable in lithology to parts of the Moine Supergroup to the north-west of the Great Glen Fault, and showing evidence of having experienced at least some elements of a Neoproterozoic, Knoydartian orogenic event. Gneissose metasedimentary units in the Buchan Block have also been interpreted as part of a Proterozoic 'basement' to the Dalradian by some authors (Sturt *et al.*, 1977; Ramsay and Sturt, 1979), although this is not currently accepted (see the *Introduction* to Chapter 6).

1.3.1 Rhinns Complex

The Rhinns Complex crops out over an area of about 20 km^2 on the Rhinns of western Islay and as a very small inlier at the north end of Colonsay (Muir, 1990; Muir *et al.*, 1992, 1994a, 1994b) (see Figure 2.1). On Islay, granitic and syenitic gneisses were all affected by deformation and amphibolite-facies metamorphism prior to the intrusion of gabbro sheets and further intense multiple deformation (Wilkinson, 1907). The inlier on Colonsay covers only *c.* 0.3 km^2 and is largely obscured by blown sand (Cunningham Craig *et al.*, 1911). The exposures there are of quartzofeldspathic gneiss, much of it pegmatitic, with dark knots, streaks and layers of amphibolite. The metasyenites and metagabbros represent an alkaline igneous association and are characterized by major- and trace-element patterns similar to subduction-related igneous rocks generated in continental margins or island-arcs (Muir *et al.*, 1992, 1994a). Isotope studies have shown that they were emplaced as magmas consisting dominantly of juvenile material derived from a depleted mantle source.

In places the gneisses have suffered considerable crushing, mylonitization and metamorphic downgrading and have been intersliced with the overlying low-grade metasedimentary rocks of the Colonsay Group (Muir *et al.*, 1995). The intensity of the cataclastic and mylonitic effects increases as the overlying sequence is approached, but the actual contact is rarely seen. Where it is exposed, it is marked by a high-strain zone of phyllonitization and mylonitization. On Islay this is termed the Kilchiaran Shear-zone or Bruichladdich Slide.

Palaeoproterozoic U-Pb zircon ages obtained from metasyenites on Islay (1782 ± 5 Ma; Marcantonio *et al.*, 1988) and Inishtrahull (1779 ± 3 Ma; Daly *et al.*, 1991) have been interpreted as crystallization ages of the protolith. That is about the time that the Lewisian Gneiss Complex of the Hebridean Terrane was undergoing tectonothermal reworking during the Laxfordian Event (Mendum *et al.*, 2009). However, the stable isotope studies have shown that the Rhinns rocks are not reworked Archaean crust but are derived dominantly from juvenile mantle material, effectively ruling out any direct correlation with the Lewisian Gneiss Complex, in which there is no evidence for major addition of mantle material at *c.* 1800 Ma.

1.3.2 Badenoch Group

Large areas of middle amphibolite-facies, gneissose and locally migmatitic, psammite and semipelite in the Northern Grampian Highlands were originally regarded as stratigraphically equivalent to the surrounding psammitic rocks, and all were equated with the Moine succession north-west of the Great Glen Fault, being referred to generally as the 'Younger Moines' (e.g. Johnstone, 1975; Harris and Pitcher, 1975). Detailed mapping and radiometric age determinations in the 1970s led to a radical re-interpretation of the stratigraphical and structural significance of the migmatitic rocks. These became regarded as a distinct tectonostratigraphical unit, termed the 'Central Highland Division', and were viewed as an older basement to the adjacent 'Grampian Division' psammites (Piasecki and van Breemen, 1979a, 1979b; Piasecki, 1980; Piasecki and Temperley, 1988a). The traditional view that the Central Highland Division comprises migmatized versions of the adjacent rocks (though not by this time correlated with the Moine) was restated by Lindsay *et al.* (1989) and the matter remained unresolved for some time, with the generally gneissose parts of the succession regarded for convenience as a tectonothermal lithodemic unit termed the 'Central Highland Migmatite Complex' (Harris *et al.*, 1994; Stephenson and Gould, 1995; Highton, 1999). Recent mapping by the British Geological Survey (BGS) has shown that the migmatization is controlled generally by the lithology of the protolith, but has confirmed the existence of a basement–cover relationship and has mapped out the contact. 'Basement' successions have been documented in two geographically separate areas (see Figure 5.1) and these have been referred to informally as the Dava and Glen Banchor successions in recent publications (Robertson and Smith, 1999; Smith *et al.*, 1999; Strachan *et al.*, 2002). They have now been formalised as subgroups of the Badenoch Group. Additional small inliers occur in the Aviemore area at Kincraig and Ord Ban and enigmatic gneissose rocks in Gleann Liath, near Foyers, described by Mould (1946), could be a fault slice of a similar basement succession.

A series of ductile shear-zones, known collectively as the Grampian Shear-zone (formerly the Grampian Slide or Slide-zone), can be traced discontinuously throughout the outcrop of the Glen Banchor Subgroup and largely delimit the Dava Subgroup. The shear-zones have been variously interpreted as a deformed unconformity between basement and cover (Piasecki, 1980), a zone of tectonic interleaving of the Grampian Group with a migmatite complex (Highton, 1992; Hyslop and Piasecki, 1999), and a zone of distributed shear located entirely within the Badenoch Group (Smith *et al.*, 1999).

Many of the shear-zones incorporate a distinctive suite of syntectonic, foliated veins of pegmatitic granite and quartz, and it is believed that these segregations formed during early ductile shearing along the slides (Hyslop, 1992; Hyslop and Piasecki, 1999). Several dates were obtained by Rb-Sr methods on combined muscovite and whole rock, which cluster quite tightly around 750 Ma (Piasecki and van Breemen, 1979a, 1983). More-precise U-Pb analyses of monazites from such pegmatites have provided ages of 808 +11/−9 Ma and 806 ± 3 Ma, and a concordant age of 804 +13/−12 Ma has been obtained from the host mylonite matrix (Noble *et al.*, 1996). U-Pb dating of single zircon grains within kyanite-bearing migmatites has yielded an age of 840 ± 11 Ma (Highton *et al.*, 1999). These U-Pb dates provide a minimum age for the Badenoch Group and confirm that it was affected by a tectonothermal event, comparable in age to the Knoydartian that affected the Moine Supergroup of the Northern Highlands (Fettes *et al.*, 1986). No such dates have been obtained from rocks assigned to, or cutting, the Grampian Group, which record only later, Caledonian events, supporting the notion of an orogenic unconformity at or near to its base. Thus the rocks of the Badenoch Group are now regarded as forming the basement to Grampian Group depositional basins, and may possibly be comparable in age to the Moine Supergroup.

A full discussion of the basement–cover relationships and the evidence for a stratigraphical, structural and metamorphic break is given in the *Introduction* to Chapter 5 of the present volume.

1.4 DALRADIAN LITHOSTRATIGRAPHY

D. Stephenson

The Dalradian Supergroup is dominated by well-differentiated sequences of variably metamorphosed marine clastic sedimentary rocks and metacarbonate rocks. Some fluvial interludes are recognized in the earliest parts and localized metavolcanic rocks occur in the later parts. The aggregate total thickness of the succession adds up to at least 25 km, although the complete thickness was never deposited at one place. It is more likely that depocentres migrated south-eastwards with time and individual basins are unlikely to have accumulated more than 15 km of sediment.

The formal hierarchical lithostratigraphy of the supergroup is shown in Figure 1.6. This builds on the original division of the Dalradian into three groups by Harris and Pitcher (1975), with subsequent incorporation of the Grampian Group by Harris *et al.* (1978), and further rationalization and modification by Winchester and Glover (1988), Harris *et al.* (1994), Stephenson and Gould (1995) and Smith *et al.* (1999). The Grampian, Appin and Argyll groups are divided into subgroups. A suggestion by Banks and Winchester (2004) that the lowest subgroup of the Grampian Group should be elevated to group status as the Glenshirra Group has not been accepted here.

The two lower groups (Grampian and Appin groups) fall within the Cryogenian System/Period and the two higher groups (Argyll and Southern Highland groups) fall mainly within the Ediacaran System/Period but extend into the Middle Cambrian Series. Outcrops of the four groups are shown on Figure 1.1, which illustrates the overall younging from north-west to south-east. Subgroup outcrops are shown on the figures to acccompany the regional chapter introductions (Figures 2.1, 3.0, 4.1, 5.1, 6.1).

Similar sedimentary associations extend throughout the Grampian Highlands along a strike length of some 320 km. In fact in some parts of the succession, a remarkable stratigraphical consistency is preserved over the whole Dalradian outcrop from Connemara in the west of Ireland to the Banffshire coast, a distance of 700 km. A simple 'layer-cake' stratigraphy, in some cases allowing detailed correlation down to at least member level, is most apparent in the middle part of the Appin Group. That sequence, from the calcareous top part of the Lochaber Subgroup, through the whole of the Ballachulish Subgroup, to the basal metamudstones and metalimestones of the Blair Atholl Subgroup, is recognizable almost everywhere. In other parts of the Dalradian Supergroup, correlation between local successions is complicated by lateral facies changes, diachronous boundaries, local unconformities, non-sequences, tectonic discontinuities and changes in metamorphic grade. Many formations have only local extent but laterally persistent facies associations do allow broad correlations at subgroup level over most of the outcrop.

Certain key formations of distinctive lithology have been traced throughout the Grampian Highlands and, in some cases, through north-western Ireland. Most of these are highlighted on Figure 1.6. They provide lithostratigraphical markers and some have widespread chronostratigraphical significance. Foremost among the latter are the tillites (e.g. the Port Askaig Tillite Formation) that mark the base of the Argyll Group throughout most of its outcrop and record a major glacial event. Correlation with worldwide glaciations is currently a matter of debate but is taken here to be with the 635 Ma Marinoan global event (see p. xx [in Dating the Dalradian sedimentation]). The top of the Argyll Group is marked in the South-west Grampian Highlands and parts of Northern Ireland by large volumes of basic volcanic and subvolcanic rocks (e.g. the Tayvallich Volcanic Formation). These represent a major rift-related magmatic event during the early stages of development of the Iapetus Ocean that has been dated radiometrically at 600–595 Ma (see p. xx [in Dating the Dalradian sedimentation]). Other events, although readily recognizable in the lithostratigraphy, are probably more diachronous. These include transgressive flooding surfaces, such as those at the bases of the Ballachulish and Easdale subgroups, and basin shallowing events marked by calcareous lithologies at the tops of those two subgroups.

On the Shetland Islands, lithological associations are typical of the Dalradian as a whole. In particular, metalimestones and metamudstones in the middle of the succession suggest a broad correlation with the Appin and Argyll groups, and metavolcanic formations have been assumed to be broadly coeval with those at the top of the Argyll Group and in the Southern Highland Group. But, any detailed correlations with the Dalradian of mainland Scotland that have been suggested are extremely tenuous.

Correlations in parts of the succession are complicated by syn-depositional, possibly listric faulting (e.g. Anderton, 1985,

1988) and detailed field observations are now revealing previously undetected intrabasinal unconformities and periods of non-deposition. The scale and significance of such discontinuities is currently a matter of much debate, in some cases leading to speculation that major stratigraphical and orogenic breaks occur within the Dalradian successions of both Scotland and Ireland (Prave, 1999; Alsop *et al.*, 2000; Hutton and Alsop, 2004), though this has been challenged by Tanner (2005).

The original depositional thicknesses of sedimentary units are difficult to estimate due to tectonic thickening or thinning during polyphase folding and ductile shearing. And regional metamorphism not only obliterates original sedimentary features but can also change the lithological and mineralogical characteristics to such an extent that some lithostratigraphically equivalent units have been given different formation names in areas of differing metamorphic grade. However, the intensity of metamorphism and deformation varies considerably on a regional basis. In the South-west Grampian Highlands and in most of the Highland Border region, the middle to upper parts of the Dalradian succession have been affected only by low- to medium-grade metamorphism and are not strongly deformed. Hence, their basin architecture, sedimentological environment and depositional processes have been deduced with some confidence (e.g. Roberts, 1966a; Hickman, 1975; Anderton, 1976, 1979; Litherland, 1980; Burt, 2002). As a consequence of this detailed knowledge, most early reviews of Dalradian evolution were heavily biased towards interpretations from those areas (e.g. Knill, 1963; Harris *et al.*, 1978; Johnson, 1965, 1983, 1991; Anderton, 1982, 1985, 1988). In areas of higher grade metamorphism, interpretations of the original nature of the rocks are generally more difficult, although sedimentary structures are preserved to remarkably high grade in some psammitic rocks. These have enabled several sedimentological studies to be made, particularly in the Grampian Group (Winchester and Glover, 1988; Glover and Winchester, 1989; Glover, 1993; Banks, 2007) and sequence-stratigraphy has been applied to some extent in the lowermost parts (Glover and McKie, 1996; Banks, 2005).

For many years, the regional correlation of local formations within the Dalradian succession could not be attempted with any confidence and the first Grampian-wide lithostratigraphical scheme was that of Harris and Pitcher (1975). Since then most gaps in the mapping have been filled, correlations have been widened to at least subgroup level and most units have been formalized by inclusion in the BGS Lexicon of Named Rock Units (http://www.bgs.ac.uk/lexicon/lexicon_intro.html). However, despite attempts to rationalize the plethora of local names, historical uncertainties are still reflected by the fact that even key regionally recognized formations have different names in different areas. The name changes are usually confined to places where there is a break in continuous outcrop. For example, the major quartzite formation that dominates the Islay Subgroup is known variously as the Jura Quartzite, the Schiehallion Quartzite, the Creag Leacach Quartzite, the Kymah Quartzite and the Durn Hill Quartzite. A similar number of names are used for the same quartzite in Ireland.

Other relics of historical nomenclature persist in formal names that do not accord with accepted stratigraphical practice but have been adopted because the name is well established. Thus, for example, we have the Ballachulish Slate Formation immediately succeeding the Ballachulish Limestone Formation and both a Lower and an Upper Erins quartzite formation. In addition a few informal names remain, usually because a formal rank and correlation have yet to be established. These are placed in parentheses and not capitalized (e.g. the Stuartfield 'division' of the North-east Grampian Highlands). References to previous uses of the terms 'division' and 'group' are also parenthesized.

1.4.1 Grampian Group

The Grampian Group crops out over an area of approximately 4250 km^2 in a broad NE-trending area extending from Glen Orchy to near Elgin, with an isolated outcrop on the north coast around Cullen. It forms most of the Northern Grampian Highlands and large parts of the Central Grampian Highlands as defined in this volume (chapters 3 and 5). The group consists mainly of psammites and semipelites, with some quartzites, all at amphibolite-facies metamorphic grade. The coarse-grained siliciclastic Scatsta Group at the base of the Shetland Dalradian succession could well be a correlative, as could much of the Colonsay Group on Islay and Colonsay. It is also possible that the Bowmore Sandstone Group on Islay may be assigned to the Grampian Group. These problematical units are discussed separately below.

Regional mapping in the Northern Grampian Highlands has shown that deposition of the group occurred within a series of linked NE-trending basins bounded by major syndepositional faults and crustal lineaments (see Figure 5.2). Stratigraphical successions have been established in each of the main basins, although only the Corrieyairack Basin is known in detail, whilst the Cromdale and Strathtummel basins are still the subject of ongoing research. Correlation between the basins is tentative in parts. However, following the establishment of informal local stratigraphies (e.g. Thomas, 1980), an initial division into subgroups proposed by Winchester and Glover (1988) has now been expanded and adopted across the region (Glover and Winchester, 1989; Smith *et al.*, 1999; Banks, 2005). The three subgroups are characterized by different lithofacies associations and are interpreted to represent distinct phases of early and syn-rift extension followed by a protracted period of post-rift thermal subsidence (Glover *et al.*, 1995).

The nature of the contact between the gneissose and migmatitic basement of the Badenoch Group and the essentially non-gneissose lithologies of the Grampian Group is considered in some detail in the section on *Basement to the Dalradian Basins* and in the *Introduction* to Chapter 5.

For much of its length in the North-east and Central Grampian Highlands, the contact of the Grampian Group with the overlying Appin Group is defined tectonically by a regional high-strain zone of enigmatic origin and nature, known as the Boundary Slide-zone. However, to the south-west of the Schiehallion district the slide cuts up the succession so that a conformable Grampian–Appin group succession can be observed in places such as Glen Orchy and Kinlochleven and is inferred elsewhere. In those areas, the contact has been placed traditionally at the base of the Eilde Quartzite, now the base of the Loch Treig Schist and Quartzite Formation, although it is possible that unconformities exist locally (Winchester and Glover, 1988; Glover, 1993). A sedimentary transition is also recognized in the far north-east, where the boundary is rather arbitrarily defined to be above any major quartzite units.

The Grampian Group is geochemically distinctive and shares more characteristics with the Moine Supergroup of the Northern Highlands Terrane than it does with younger Dalradian groups. This is particularly noticeable in the regional geochemical maps, compiled from stream sediment data by the British Geological Survey (BGS) (Plant *et al.*, 1999; Stone *et al.*, 1999). The Moine Supergroup and Grampian Group are depleted in base elements such as Mg, Ni and Cu but are enriched in incompatible elements, Ba, K, La, Rb, Sr, U, and Zr, relative to later Dalradian sequences. In broad terms, this has been attributed to the change from dominantly psammitic sequences to more-mixed shelf and basin lithologies, which is reflected in a reduction in detrital minerals such as K-feldspar and an increase in marine clay minerals. Whole-rock analyses of the psammitic and semipelitic rocks are also chemically distinguishable from those in the overlying Appin Group and there are slight chemical differences between semipelites at different stratigraphical levels (Lambert *et al.*, 1982; Haselock, 1984; Winchester and Glover, 1988).

Throughout the sedimentation of the Grampian Group there was a constant supply of detritus from a hinterland of exposed quartzofeldspathic gneiss and granitic rock (Hickman, 1975; Glover and Winchester, 1989). This is particularly noticeable in pebbly beds of the Glenshirra Subgroup. Analysis of detrital zircon populations indicates source areas of Proterozoic rocks, with a marked absence of any Archean detritus (Cawood *et al.*, 2003). That study highlighted differences in provenance with time. In the Glenshirra Subgroup, populations are dominated by 1.8 Ga detritus with subsidiary 1.2 Ga detritus, suggesting that 'Rhinnian-type' basement was an important component of the source area at that time. Peaks at 2.0 Ga and 1.4 Ga characterize the Corrieyairack Subgroup, with progressive dilution by 1.1–0.9 Ga Grenvillian detritus in the more-mature sediments of the Glen Spean Subgroup. However, a study of detrital zircons and whole-rock Nd isotopes by Banks *et al.* (2007) revealed marked differences in provenance signatures between Grampian Group basins, which were attributed to sediment transport directions. Thus the Corrieyairack Basin contains voluminous 1.8 Ga detritus, inferred to have been derived from Ketilidian/Rhinian igneous basement in the Labrador region of Laurentia to the west, whereas the more easterly Strathtummel Basin was dominated by 1.0 – 0.9 Ga Grenvillian/Sveconorwegian sources in Baltica to the east. Further-travelled basin-axial deposition supplied a greater variety of late-Paleoproterozoic (1.8 – 1.6 Ga) and early Mesoproterozoic (1.6 – 1.4Ga) detritus to both basins.

1.4.1.1 Glenshirra Subgroup

The base of the Grampian Group is not seen in undisturbed contact with the underlying Badenoch Group rocks. The oldest exposed unit is the Glenshirra Subgroup, which has a type area in the core of the Glenshirra Dome in upper Speyside and in several fault- and shear-bounded inliers closer to the Great Glen Fault between Loch Lochy and Strath Errick (Haselock *et al.*, 1982; Okonkwo, 1988; May and Highton, 1997).

The subgroup comprises sequences, up to 2 km in thickness, of geochemically distinct, immature feldspathic psammite and beds of pebbly psammite and metaconglomerate. The metaconglomerates thicken and increase in abundance both up section and towards the Great Glen Fault. Abundant sedimentary structures are of a type indicative of deposition by traction currents in shallow marine environments with periodic influxes of fluviatile deposits (Banks and Winchester, 2004). The progressive westward thickening and coarsening of the strata imply the presence of a basin margin to the west or north-west, approximately coincident with the present trace of the Great Glen Fault.

Banks and Winchester (2004) argued that the largely sub-aerial environments of the Glenshirra Subgroup contrast so markedly with the deep-water marine environments of the succeeding Grampian Group sequences, that the Glenshirra should be afforded the status of a separate group.

1.4.1.2 Corrieyairack Subgroup

Around the Glenshirra Dome and in the upper reaches of the River Nairn, the Glenshirra Subgroup rocks are conformably overlain by a distinctive and regionally widespread succession of semipelite and striped semipelite and psammite. This marks the base of the overlying Corrieyairack Subgroup, which is the major component of the Grampian Group in the southern Monadhliath mountains (Haselock *et al.*, 1982; Okonkwo, 1988). The abrupt change to a semipelitic succession records a basin-wide flooding event heralding the start of a major period of widespread subsidence and rift-related extension (Banks, 2005).

There the basal semipelites are overlain by 4–5 km of siliciclastic rocks deposited by prograding turbidite complexes (Banks, 2005). Variations in sediment supply and source area are indicated by changes in the proportions of plagioclase and K-feldspar, whereas variations in bed thickness and form reflect depositional processes (Glover and Winchester, 1989; Key *et al.*, 1997). Overlying semipelites record a reduction in sand supply and the development of shelf conditions along the basin margins as recorded by the lateral thickness and facies changes. The youngest parts of the subgroup record a renewed influx of sand-dominated turbidites, deposited by extensive fan-lobe systems derived from the north-west. These pass southwards and eastwards in the Glen Spean and Drumochter areas into shelf environments with several units of distinctive quartzite (Glover and Winchester, 1989; Glover *et al.*, 1995; Robertson and Smith, 1999; Banks, 2005).

Throughout the subgroup, rapid local facies and thickness variations indicate contemporary tectonism and, together with the progressive overstep onto an interbasin high in the Glen Banchor area, they permit the tracing of outlines of former basin margins (Glover and Winchester, 1989; Robertson and Smith, 1999). Locally, as at Ord Ban and *Kincraig* near Aviemore, basement rocks of the Glen Banchor Subgroup are overlain directly by a condensed shallow-marine shelf sequence consisting of semipelite interbedded with calcsilicate rocks, thin quartzites, metacarbonate rocks and concordant sheets of amphibolite. These strata, previously assigned to the now defunct 'Ord Ban Subgroup' of Winchester and Glover (1988), are now redesignated as the Kincraig Formation. Comparable lithologies that constitute the Grantown Formation near Grantown-on-Spey (McIntyre, 1951; Highton, 1999) were also previously assigned tentatively to the 'Ord Ban Subgroup' but this formation includes metacarbonate rocks with a distinctly different lithogeochemical signature, more like those of the lower Appin Group (BGS unpublished data).

1.4.1.3 Glen Spean Subgroup

In all three major basins, the deep-water turbiditic rocks of the uppermost Corrieyairick Subgroup are conformably overlain by shallow-marine shelf sedimentary rocks of the Glen Spean Subgroup, consisting of a mature mixed sequence of semipelite and psammite with quartzites in the upper parts. Reduced subsidence and relative tectonic stability at this time are interpreted to represent post-rift thermal subsidence (Glover *et al*., 1995).

In the south-west of the Corrieyairack Basin, rocks of the subgroup were formerly known as the 'Eilde Flags'. Around Spean Bridge, the succession is approximately 4000 m thick (Winchester and Glover, 1991; Glover, 1993) but it thins southwards to about 100 m in the Kinlochleven area and on the Black Mount. A thin development also occurs in the south-east of the basin, on the flank of the Glen Banchor 'high'. Similar lithologies form a thick succession in the Strathtummel Basin, where a near-continuous section is exposed in the A9 road cuttings (see *Chapter 3*). There, the whole succession was formerly referred to as the 'Struan Flags', but Thomas (1980, 1988) described a 'Drumochter succession' of flaggy psammites and semipelites, overlain by a predominantly psammitic 'Strathtummel succession'. Those informal successions were designated as new 'Atholl' and 'Strathtummel' subgroups by Treagus (2000) and on the BGS 1:50 000 Sheet 55W (Schiehallion, 2000). However, they are almost certainly local equivalents of the Glen Spean Subgroup and will be referred to as such in the future. Shallow-water sedimentary structures are well preserved in many of the psammitic beds and these have been described in detail and interpreted by Banks (2007).

In the Cromdale Basin, the upper 2–3 km of Grampian Group strata are dominated by micaceous psammites and quartzites, which are assigned to the Glen Spean Subgroup. Shallow-water quartzites become dominant towards the top of the subgroup, in the Cromdale Hills, around Rothes and along the north coast at Cullen, where they pass conformably upwards into Appin Group successions.

1.4.2 Appin Group

The Appin Group was derived from a varied sequence of shelf sediments and comprises pelites, semipelites, quartzites, calcsilicate rocks, metalimestones and metadolostones, usually with rapid alternations of facies (Anderton, 1985; Wright, 1988). Local successions are easily established and the group has been divided into three subgroups. Lateral facies changes, thickness variations and local unconformities are well documented in several areas, but most formations and certain key beds can be traced over large distances and there is an overall general consistency of facies from Connemara in western Ireland to the Moray Firth coast. Correlations between local successions have thus been made with reasonable confidence throughout the Grampian Highlands (Harris *et al*., 1994, fig. 14; Stephenson and Gould, 1995, fig. 10), aided in some areas by detailed studies of the whole-rock geochemistry of a variety of lithologies. Such studies have been more successful in the Appin Group than in other parts of the Dalradian succession (Lambert *et al*., 1981; 1982; Hickman and Wright, 1983; Rock *et al*., 1986). Of particular use are the geochemical studies of metacarbonate units, some of which retain distinctive geochemical characteristics over considerable distances (Rock, 1986; Thomas, 1989, 1993).

Rocks of the Appin Group crop out over some 2100 km^2 in a relatively narrow outcrop extending throughout the Grampian Highlands over a strike length of 325 km (Figure 1.1). In the south-west a complete sequence, which continues up into the overlying Argyll Group, is recognized in the core of the Islay Anticline. Thick developments occur around Appin and in Lochaber, which are type areas for the two lowest subgroups, the Lochaber and Ballachulish subgroups. South-eastwards from Appin, rapid facies changes and considerable attenuation occur; higher parts of the group were either not deposited, or are cut out by unconformities, or have been excised by possible tectonic dislocation along the Boundary Slide-zone. As a result, only a condensed and possibly incomplete sequence of Lochaber Subgroup rocks is present from Glen Orchy to Glen Lyon. A more-complete although still condensed sequence, which passes up conformably into the Argyll Group, reappears to the north of Schiehallion and expands rapidly eastwards to Blair Atholl, the type area of the highest, Blair Atholl Subgroup. The complete sequence is then traceable north-eastwards to Braemar. To the north of the Cairngorm and Glengairn granite plutons a similar succession has been traced northwards to link with the succession on the Moray Firth coast. Appin Group strata also occur as outliers in narrow fold hinges in the Northern Grampian Highlands, both in the Glen Roy area, where they represent an extension of the Lochaber stratigraphy, and farther to the east in the Geal-charn–Ossian Steep Belt. On Shetland, a varied succession of siliciclastic and carbonate rocks, typical of the Appin and Argyll groups, occurs in the middle of the 'East Mainland Succession' and it is this Whiteness Group that most strongly suggests a correlation with the Dalradian of mainland Scotland.

The shallow-marine environment that dominated the Glen Spean Subgroup continued up into Appin Group times, when sedimentation occurred generally on a shallow tidal shelf, overlying crust that was gently subsiding due to lithospheric stretching (Anderton, 1985; Wright, 1988). Conditions fluctuated between an open marine oxidizing environment and stagnant euxinic lagoons to produce the alternating sandstone and black pyritic mudstone sequences (Figure 1.6). The overall lateral persistence of sedimentary facies suggests that similar processes of deposition were widespread and that supply of sediment remained constant. As in the preceding Grampian Group, this was from a north-western landmass, although palaeocurrent indicators show that sediment was distributed along the shelf by tidal longshore currents. In detail, a series of NE-trending basins might have developed, bounded by synsedimentary growth faults, such as those that have been identified in the Glen Creran–Loch Leven district (Hickman, 1975; Litherland, 1980).

1.4.2.1 Lochaber Subgroup

In many parts of the Grampian Highlands a sequence of semipelites and pelites with lenticular interbedded quartzites succeeds the underlying more-persistently psammitic rocks of the Grampian Group. This conformable relationship persists throughout much of the type area, between Port Appin and Glen Roy and in the mountainous ground around Kinlochleven. Elsewhere, significant stratigraphical omissions suggest the presence of local unconformities, such as around the Geal-charn–Ossian Steep Belt, where over 1200 m of strata are absent locally, possibly as a result of footwall uplift at a basin margin (Glover *et al*., 1995; Robertson and Smith, 1999). The subgroup is absent between Onich and Glen Spean, where the Ballachulish Subgroup is in direct contact with the Grampian Group along what was formerly interpreted as the Fort William Slide (Bailey, 1934, 1960) and subsequently re-interpreted as a localized unconformity (Glover, 1993). Between Glen Orchy and Braemar the Lochaber Subgroup is represented only by a highly condensed sequence within and above the Boundary Slide-zone but farther north a thick sequence, broadly comparable with that of the type area, rests conformably upon the Grampian Group.

In its type area, the Lochaber Subgroup has a maximum aggregate thickness of 4200 m (Hinxman *et al*., 1923; Bailey, 1934). Hickman (1975) defined type sections for some of the units within a continuous section along the River Leven and Loch Leven. Distinctive quartzite units are traceable over strike lengths of tens of kilometres, although they do taper out laterally and might be diachronous. Around Glen Coe and Kinlochleven there are three major quartzites (the Eilde, Binnein and Glen Coe quartzites), all of which thin north-eastwards towards Loch Treig, where the succession becomes dominantly semipelitic, and they taper out north of Glen Spean (Key *et al*., 1997). The quartzites become finer grained and less feldspathic towards the north-east, a mineralogical change that is reflected in their whole-rock chemistry (Hickman and Wright, 1983). Contacts between the quartzites and interbedded semipelites are commonly transitional over several metres with fine-scale interleaving of the two lithologies and consequently the alternating units are all classed as members within a single Loch Treig Schist and Quartzite Formation.

The upper part of the subgroup in its type area comprises a homogeneous sequence, up to 2200 m thick, of distinctive striped, greenish grey phyllitic or schistose semipelite and pelite with minor thin quartzites, termed the Leven Schist Formation. The pelites and semipelites are less feldspathic than those in the Grampian Group, and this is matched by distinct changes in the regional whole-rock chemistry and provenance (Lambert *et al*., 1982; Winchester and Glover, 1988; Stone *et al*., 1999). The uppermost strata become increasingly calcareous and contain thin beds of metalimestone in the Glen Spean area.

To the south-west, the upper part of the Lochaber Subgroup is exposed in the core of the Islay Anticline, where it consists of a lower quartzite unit with pebble beds containing extrabasinal granite clasts, and an overlying semipelitic unit which becomes more calcareous upwards, comparable to the Leven Schists (Rast and Litherland, 1970; Wright, 1988). However, south-east of the type area a tripartite division is recognized in which basal dark grey pelites and semipelites are overlain by striped semipelites with thin metacarbonate beds, which in turn are overlain by pale greyish green semipelites (Hickman, 1975; Litherland, 1980).

On the north-western edge of the Geal-charn–Ossian Steep Belt, between Ben Alder and Kingussie, semipelites and quartzites similar to those of the Loch Treig Schist and Quartzite Formation have been assigned to the lower part of the Lochaber Subgroup (Robertson and Smith, 1999). At the top of this succession is the Kinlochlaggan Boulder Bed, containing clasts of a variety of intra- and extrabasinal rock types including granite (Treagus, 1969, 1981; Evans and Tanner, 1996). These beds were formerly interpreted as tillites, deposited directly from ice-sheets, but the clasts are now thought to have originated as ice-rafted dropstones. Either way this is the earliest evidence for glacial activity in the Dalradian succession.

Between Glen Orchy and Braemar, thin developments of the Lochaber Subgroup have been recognized in condensed sequences, rarely exceeding a few hundred metres in thickness (Treagus and King, 1978; Roberts and Treagus, 1979; Upton, 1986; Treagus, 1987, 2000). The junction with the underlying Grampian Group lies within a zone of high strain, the Boundary Slide-zone, in which several formations are strongly attenuated or even excised locally along tectonic breaks. However, in some areas, there seems to be a continuous overall stratigraphical transition from the Grampian Group into the Lochaber Subgroup, as in the *Gilbert's Bridge* GCR site in Glen Tilt. The reduced thickness is not solely attributed to deformation in the slide-zone; there would seem to be considerable sedimentological thinning in this area, as there is in many of the succeeding Appin Group formations. Recognition of component formations is hampered by the highly tectonized state of lithological units such as the Beoil Schist Formation in the Schiehallion area and the Tom Anthon Mica Schist Formation south-west of Braemar. Calcareous Leven Schist-type lithologies occur in the Meall Dubh Striped Pelite Formation of the Schiehallion area and in the Glen Banvie Formation of Glen Tilt.

North of the granitic plutons that mark the Deeside Lineament, Grampian Group psammites are overlain conformably by micaceous psammites with thin quartzites and semipelites, passing up locally into slightly calcareous lithologies. The subgroup thickens markedly northwards, where the Findlater Flag Formation, passes transitionally upwards into calcareous psammites and semipelites locally termed the Pitlurg Calcareous Flag Formation and Cairnfield Calcareous Flag Formation.

Throughout its outcrop, the lower part of the subgroup records the continuation of relatively shallow marine conditions from Grampian Group times and the basal psammites, quartzites and pelites show close affinities with the Grampian Group. The major quartzites exhibit well-preserved shallow-water sedimentary structures, such as cross-bedding, grading, ripple-marks, slump and dewatering structures and have been interpreted generally as nearshore tidal sand bodies (Hickman, 1975; Wright, 1988). They probably represented periodic basin shoaling events in a delta that extended north-eastwards over a distance of about 40 km, with facies varying from proximal at Appin to distal at Glen Roy (Glover *et al*., 1995; Glover and McKie, 1996). Farther east, where the quartzites and associated psammites pass into semipelite, the complex facies variations reflect generally deeper water environments (Key *et al*., 1997). Gradually the coarse siliciclastic basin-fills gave way to widespread deep-water muddy sedimentation during the first of several marine transgressions that typify subsequent sedimentary cycles of the Appin and Argyll groups. In almost all areas, the highest beds of the subgroup are variably calcareous with tremolitic amphibole, and rare units of impure metacarbonate rock, heralding the more-persistent and more-widespread carbonate sedimentation of the Ballachulish Subgroup. They have been interpreted as reflecting the establishment of local lagoonal environments with seawater-precipitated magnesium-rich carbonate rocks and possible seasonal desiccation (Thomas, 1989; Stephenson, 1993). This broadly calcareous part of the succession is a useful stratigraphical marker.

1.4.2.2 Ballachulish Subgroup

This subgroup, more than any other in the Dalradian, exhibits a remarkable lateral continuity of lithological type; key elements of the sequence can be traced, almost on a bed-for-bed basis, from Connemara to the Moray Firth coast, attesting to widespread stability and relatively uniform subsidence at this time.

In most parts of the Grampian Highlands, the contact of the Lochaber Subgroup with the Ballachulish Subgroup is conformable; there is a transition from calcareous semipelites and tremolitic calcsilicate rocks to a background lithology of graphitic pelites with more-persistent discrete beds of metacarbonate rock that are commonly dolomitic. Notable exceptions occur between Onich and Glen Spean, where the basal Ballachulish Subgroup rests with local unconformity on the Grampian Group (Glover, 1993), and on the north-western edge of the Geal-charn–Ossian Steep Belt where, as a result of non-deposition and erosion on a longstanding footwall 'high', the upper part of the Ballachulish Subgroup oversteps the lower part and the entire Grampian Group to rest directly on the Badenoch Group (Robertson and Smith, 1999). In the Boundary Slide-zone, despite the highly attenuated successions, a complete stratigraphical transition can be recognized in most areas.

Five formations are recognized in the Lochaber–Appin area (Bailey, 1960; Hickman, 1975; Litherland, 1980). The Ballachulish Limestone Formation and Ballachulish Slate Formation together account for over 500 m of succession in the type area, around Ballachulish and Onich, but thin northwards around fold closures in the area of Glen Roy, where they are partly excised by slides (Key *et al.*, 1997). Phyllitic grey-green calcsilicate rocks, cream and grey metadolostones and dark bluish grey metalimestones define the lower formation within a background lithology of slaty and phyllitic graphitic pelites that become dominant upwards. Intercalations of graded psammite and quartzite on scales from a few millimetres to about a metre become numerous in the upper part of the pelites where they form the distinctively striped Appin Transition Formation. The succeeding Appin Quartzite Formation is about 300 m thick in its type area but it thins considerably to the north-east like the quartzites of the Lochaber Subgroup. This massive, clean, locally feldspathic quartzite is distinctive from other Dalradian quartzites throughout its strike length, and is characterized by sedimentary structures such as cross-bedding, ripple marks and graded bedding. The overlying Appin Phyllite and Limestone Formation consists of an alternating sequence of phyllitic and flaggy semipelites and psammites, metacarbonate rocks and thin quartzites. It attains a total thickness of up to 400 m in the type area. The metacarbonate rocks, which are more prevalent in the lower part, include several very distinctive lithologies, such as the pure white Onich Limestone and the aptly named 'tiger-rock' of Bailey (1960), which consists of regularly-spaced 5 to 10 cm layers of orange-weathering dolomitic carbonate and dark grey semipelite.

South-west of the type area, representatives of the Appin Quartzite and the Appin Phyllite and Limestone formations crop out on small islands in the Firth of Lorn, and still farther to the south-west, after a gap of 75 km, the subgroup crops out in the core of the Islay Anticline (Rast and Litherland, 1970).

To the south-east of Appin, the type succession thins rapidly across strike and marked facies changes occur (Litherland, 1980, figure 6). In Glen Creran the lower part of the sequence might be cut out by an unconformity and local non-sequences within the Appin Phyllite and Limestone Formation suggest some syndepositional tectonic control (Litherland, 1980). Farther to the south-east, beyond the Etive Pluton, the subgroup is absent. Small outliers of schistose calcareous rocks below the Boundary Slide-zone in the Bridge of Orchy area were formerly assumed to represent the Ballachulish Limestone (Bailey and Macgregor, 1912; Thomas and Treagus, 1968; Roberts and Treagus, 1979) but recent mapping by the Geological Survey has re-assigned them all to the Lochaber Subgroup. The remainder of the Appin Group succession is absent from this area, probably as a result of sedimentological factors with further tectonic attenuation in the Boundary Slide-zone.

The attenuated Ballachulish Subgroup re-appears north-eastwards as a condensed sequence totalling only 100 m at Errochty Water, but increases to 700 m in the Schiehallion area (Treagus and King, 1978; Treagus, 2000). The subgroup continues to the Loch Tay Fault at Foss where it is displaced north-eastwards to the Blair Atholl area (Pantin, 1961; Smith and Harris, 1976). It can then be traced in continuous outcrops north-eastwards to Braemar (Upton, 1986; Goodman *et al*., 1997; Crane *et al*., 2002). Throughout this continuous strike length of some 65 km the succession can be matched almost bed for bed with that in the type areas of Lochaber and Appin.

The subgroup is well developed to the north of the granitic plutons of the Deeside Lineament and the distinctive formations can be traced as far as the Keith area (see Chapter 6). However, the units become ill defined north of Keith, where marked facies changes probably reflect the original basin architecture. There, apart from a condensed sequence of metalimestone, graphitic pelite and quartzite around Deskford, and a thick sequence of graphitic pelite with thin basal metacarbonate rocks at Sandend Bay, much of the subgroup appears to be absent.

The base of the Ballachulish Subgroup marks a significant break from the siliciclastic rock-dominated successions of the Grampian Group and Lochaber Subgroup to the limestone–mudstone–sandstone facies associations of the higher parts of the Appin Group and much of the Argyll Group. It is interesting to note that this change coincides with the appearance of Archaean detrital zircon grains in the sediment load (Cawood *et al*., 2003). The limestones and graphitic mudstones of the lowest formations indicate a major marine transgression and widespread subsidence, with the progressive development of shallow, tidally influenced shelf sedimentation and anoxic lagoonal environments (Anderton, 1985; Wright, 1988). The more-persistent mudstones of the Ballachulish Slate Formation have been interpreted as prodelta clay deposits, and encroachment of upward-coarsening, fine quartz sands from the delta into deeper water produced the overlying sandstones such as the Appin Quartzite. A return to interbedded limestone, calcareous mudstone and siltstone deposition (the Appin Phyllite and Limestone Formation) indicates renewed transgression. Considerable along-strike continuity of facies is seen in all of the formations but the shelf must also have been relatively narrow to explain the rapid down-dip facies changes seen, for example, between Appin and Glen Creran (Litherland, 1980). The sporadic distribution of all of the formations, particularly in the NE-trending block between the Etive and Rannoch Moor plutons and the Bridge of Balgie Fault probably reflects non-deposition and/or erosion due to local uplift rather than tectonic excision.

1.4.2.3 Blair Atholl Subgroup

The Blair Atholl Subgroup maintains a generally constant lithology of dark pelites and metalimestones from Connemara to the Moray Firth, although local successions differ in detail, making bed-for-bed matching difficult. In some areas, notably Islay, the Blair Atholl district and parts of the North-east Grampian Highlands, the upper part of the subgroup is less pelitic with banded semipelites, micaceous psammites, metalimestones and metadolostones comprising a distinctive 'pale group'.

In the Ardsheal Peninsula of the Appin area, the Ballachulish Subgroup is seen to be overlain by some 300 m of dominantly slaty pyritiferous pelites and semipelites with minor dark-grey metalimestones and some more-psammitic beds, all comprising the Cuil Bay Slate Formation (Hickman, 1975). The pelites and semipelites pass upwards into the Lismore Limestone Formation, a 1 km-thick graphitic sequence of flaggy, banded, blue-grey metalimestones with thin pelite members, which forms the whole island of Lismore. It is also seen as an inlier in the core of the Loch Don Anticline in south-eastern Mull. Hickman (1975) has divided the formation into fifteen members and recognises several limestone–mudstone cycles. Slump folds and syndepositional breccias indicate periods of sediment instability along basin margins. Individual limestone formations are laterally persistent and contain ooids, stromatolites and lenticles of chert.

Owing to the south-westerly plunge of the major folds, any higher beds of the subgroup that might have been deposited in the Appin–Lismore area lie beneath the Firth of Lorn, but an extended sequence has been recognized in the Islay Anticline (Rast and Litherland, 1970). There, graphitic pelites and a metalimestone, equated with the Cuil Bay Slate and Lismore Limestone, are overlain by more pelites, semipelites and the distinctive, partly ooidal and stromatolitic, Lossit Limestone (Spencer, 1971) (see Chapter 2, *Introduction*).

To the south-east of the Appin area, in Glen Creran, the subgroup thins and facies changes similar to those in the underlying Ballachulish Subgroup result in a more-semipelitic succession (Litherland, 1980). Like its predecessor, the Blair Atholl Subgroup is absent eastwards from Glen Creran due to a presumed combination of sedimentary thinning and possible movement within the Boundary Slide-zone.

Strata of the Blair Atholl Subgroup reappear east of Loch Errochty in stratigraphical continuity with the Ballachulish Subgroup and a complete sequence, 250 to 350 m thick, is present between there and the Loch Tay Fault at Foss (Treagus and King, 1978; Treagus, 2000). A lower sequence of dark graphitic pelites and metalimestones is equated with the Cuil Bay Slate and Lismore Limestone and an overlying non-graphitic 'pale group' is generally composed of ribs of psammite and quartzite in a graded pelitic or semipelitic matrix. At the top of the subgroup is a pale cream-weathering dolomitic metalimestone, equated with the Lossit Limestone.

Across the Loch Tay Fault, around Blair Atholl, a similar continuous succession from the Ballachulish into the Blair Atholl subgroup has been demonstrated (Smith and Harris, 1976). This constituted the original type succession for the Blair Atholl 'series' (Bailey, 1925; Pantin, 1961). Thick beds of dark graphitic metalimestone in the lower part of the Blair Atholl Subgroup are a distinctive feature in this area and the main formations can be followed north-eastwards through the Glen Shee area almost to Braemar (Upton, 1986; Goodman *et al*., 1997; Crane *et al*., 2002).

North of the Deeside Lineament the Blair Atholl Subgroup consists mainly of semipelites, which are more-pelitic, graphitic and calcareous locally. A prominent thick metalimestone, the Inchrory Limestone Formation, occurs in its central part and minor metalimestones occur locally. The metalimestones thicken considerably around Fordyce and dominate the subgroup in the north coast section.

In many areas, the junction between the Ballachulish and Blair Atholl subgroups is taken at a fairly abrupt change from a background lithology dominated by semipelite and micaceous psammite to one dominated by graphitic pelite, marking a change to deeper de-oxygenated marine conditions. In contrast with the lateral stratigraphical continuity exhibited by the underlying strata, the greater variation seen between local successions might indicate deposition in a series of smaller basins. Basin margins are possibly marked by thinning of units and lateral changes of facies into coarser grained siliciclastic deposits (semipelites and micaceous psammites) and more-argillaceous limestones. Incomplete stratigraphical sequences in some areas might indicate that sediment supply periodically exceeded subsidence, so that emergence led to local non-deposition.

1.4.3 Argyll Group

The base of the Argyll Group as originally defined was marked by a tillite or a sequence of tillites, almost certainly deposited beneath ice sheets during a glacial event of restricted duration. The number of tillites and the character of the formations that contain them vary, but they are present throughout most of the Dalradian outcrop and hence constitute an important chronostratigraphical marker, not only in the British Isles but throughout the Caledonides. Unfortunately there are no obvious associated targets for direct radiometric dating and consequently there has been much debate as to with which of several dated global glacial events they might be correlated (see p. xx for a full discussion).

The group has been divided into four subgroups. The tillite-bearing sequence is followed by local carbonate successions, interpreted by some as 'cap carbonates', and by thick shallow-water shelf and deltaic quartzites of regional extent. Together, these constitute the oldest, Islay Subgroup, which marks the end of the stable shelf conditions that characterized Appin Group deposition. The succeeding Easdale, Crinan and Tayvallich subgroups are generally characterized by basin deposits, turbidites and unstable basin margin slump deposits, with only one widespread major shallow-water interlude, in the upper Easdale Subgroup. It is rarely possible to trace individual beds in the Easdale and Crinan subgroups for any great distance and correlations are made on the grounds of general similarity of facies. In contrast, for much of its outcrop the Tayvallich Subgroup is dominated by a calcsilicate- and carbonate-rock unit, which forms another of the principal marker bands of the Dalradian succession. The Argyll Group is also characterized by penecontemporaneous volcanic activity, evidence of which is found throughout the group but which reaches a maximum development in the Tayvallich Subgroup. This volcanism has provided the most-precise radiometric dates in the whole Dalradian succession (see p. xx). Further evidence for tectonic instability comes from widespread stratabound exhalative mineralization in the Easdale Subgroup, which includes economically significant sulphide and bedded baryte deposits near Aberfeldy.

Rocks of the Argyll Group crop out over an area of some 5700 km^2 (Figure 1.1). Extensive outcrops occur on Islay and Jura, and the type successions for all four subgroups are found in the South-west Grampian Highlands. Between the Etive Pluton and the Bridge of Balgie Fault, the Islay Subgroup, like much of the preceding Appin Group, is absent, although most of the younger units are continuous. Farther to the north-east a full succession is present through the Tummel Steep Belt to the Glen Shee area, with the higher units continuing to Deeside. In the North-east Grampian Highlands, west of the Portsoy Shear-zone, the lowest units have been traced intermittently to the north coast. East of the Portsoy Shear-zone, the higher parts of the group are believed to be present in an undivided gneissose sequence forming a horseshoe outcrop pattern around the Turriff Syncline. In Shetland, the absence of a tillite formation hampers identification of an Appin/Argyll group boundary, but the metalimestone-bearing upper part of the Whiteness Group is thought to be broadly equivalent to the Argyll Group of the mainland Dalradian.

In the Islay Subgroup, conditions of deposition on or close to an extensive continental shelf were similar to those of the preceding Appin Group. The Easdale Subgroup then records the onset of renewed instability with cycles of rapid basin deepening and variable lithofacies within a series of NE-trending basins. Locally thick clastic units indicate that sediment input kept pace with extension in some of the basins, and crustal rupturing allowed sub-marine volcanism to reach a climax in late Argyll Group time (Fettes *et al.*, 2011).

1.4.3.1 Islay Subgroup

This largely psammitic subgroup is dominated in most areas by a thick quartzite formation. The quartzite and the underlying basal tillite-bearing formation are persistent and distinctive, enabling a good correlation of beds from Connemara to the Moray Firth.

The basal Port Askaig Tillite Formation is one of the most obvious and readily recognized lithostratigraphical units within the Dalradian succession. In the type area on Islay and in the Garvellach Isles, the combined sequence could be up to 870 m thick, with up to 47 separate tillites recognized (Spencer, 1971, 1981). It consists of a sequence of metasandstones, metasiltstones, metaconglomerates, metadolostones and metadiamictites that have commonly been referred to informally as 'boulder beds'. These beds range from 0.5 m to 65 m in thickness and contain boulders up to 2 m in diameter. The lower beds contain clasts of dolostone, probably derived locally from within the formation or from the underlying Blair Atholl Subgroup. However, the higher beds contain clasts of granite and gneissose granite of extrabasinal origin (Fitches *et al.*, 1990). This division on the basis of clast content is also recognizable in metadiamictite sequences outwith the type area. The metadiamictites are generally regarded as tillites, deposited from grounded ice sheets, but isolated clasts in associated varved siltstones have been interpreted as dropstones from floating ice.

The succeeding Bonahaven Dolomite Formation includes metasandstones, metamudstones and impure dolomitic rocks with stromatolites and has been the subject of intense sedimentological, petrographical and geochemical studies (Hackman and Knill, 1962; Klein, 1970; Spencer and Spencer, 1972; Fairchild, 1980a, 1980b, 1985, 1991; Kessler and Gollop, 1988). Outcrops are restricted to north-east Islay, where the succession has been divided into four members, with a total thickness of up to 350 m.

The Jura Quartzite Formation (formerly also referred to as the Islay Quartzite) marks an abrupt change to a thick succession of cross-bedded and pebbly quartzites characteristic of a slightly deeper water tidal shelf environment (Anderton, 1976). The quartzites form almost all of the islands of Jura and Scarba and crop out on both limbs of the Islay Anticline on Islay. The thickest development of over 5000 m is on Jura from where the formation thins markedly along strike, to both the south-west and north-east (see Anderton, 1979, figure 1). Sedimentary structures imply dominant palaeocurrent flow directions towards the north-north-east throughout the formation, with a general change towards finer grained facies observed in the same direction.

Farther to the north-east in the Ardmucknish area, the Islay Subgroup is reduced in thickness to between 300 and 800 m (Litherland, 1980). The sequence there is similar to that of the type area in that it includes two dolomitic metadiamictites at the base, followed by dolomitic metacarbonate rocks and pebbly, cross-bedded quartzites. From Ardmucknish the subgroup increases in thickness across strike to between 4500 and 7000 m around Glen Creran, some 10 km to the east, where a distinctly different succession, consisting predominantly of flaggy and pebbly quartzites and semipelites with no metadiamictites, was termed the Creran succession by Litherland (1980). Graded turbidites and 'green beds' of possible volcaniclastic origin in the lower part of this succession are features which become more common in the subgroup in the North-east Grampian Highlands.

Eastwards from the Etive Pluton to the Bridge of Balgie Fault, the Islay Subgroup is not present. Rocks of the overlying Easdale and Crinan subgroups rest directly upon the Lochaber Subgroup with an intervening zone of highly strained rocks that have been interpreted as representing the Boundary Slide-zone (Roberts and Treagus, 1979). If rocks of the Islay Subgroup were not deposited in this area, it is necessary to invoke a fault-bounded structural 'high', separating rapidly subsiding basins on either side, to account for the great thicknesses observed in the adjoining areas. It is thought that non-deposition, contemporaneous erosion and resultant unconformities above such 'highs' might account for many gaps in local Islay Subgroup successions (Pantin, 1961; Harris and Pitcher, 1975; Harris *et al.*, 1994).

In the Schiehallion and Pitlochry areas, the Islay Subgroup is well developed, with a succession comparable with that of the type area (Bailey, 1925; Bailey and McCallien, 1937; Pantin, 1961; Harris, 1963; Treagus, 2000). The Schiehallion Boulder Bed Formation can be traced throughout most of the area, but is particularly well developed on the northern slopes of Schiehallion itself and is well exposed at the *Tempar Burn* GCR site. The lower part has a matrix of calcareous semipelite with only carbonate-rock clasts, whereas the upper part is more siliceous with large clasts of granite, syenite and quartzite. The overlying Schiehallion Quartzite Formation is typically massive and rarely cross-bedded. In the lower part, conglomeratic beds contain boulders of granite identical to those of the metadiamictites; dolomitic beds, consisting of tremolitic metalimestone and calcareous pelites, are well developed locally. Farther north-east, towards Braemar, thin developments of pebbly, granitic metadiamictite occur locally at the base of the massive Creag Leacach Quartzite Formation (Upton, 1986; Goodman *et al.*, 1997; Crane *et al.*, 2002).

To the north of the Deeside Lineament the lower part of the Islay Subgroup consists of two interdigitating and diachronous formations, the psammitic Ladder Hills Formation and the Nochty Semipelite and Limestone Formation. Thin beds of metadiamictite, typically underlain by a thin metadolostone, occur locally towards the top of the Ladder Hills Formation and within the lower units of the overlying Kymah Quartzite. Minor basic tuffs and pillow lavas occur locally. The Kymah Quartzite varies considerably in thickness between 10 m and 500 m, probably reflecting the influence of the underlying basin architecture. However, the whole subgroup is probably cut out structurally by the Portsoy Shear-zone to the west of Huntly. It re-appears close to the north coast as the Durn Hill Quartzite Formation, which overlies a psammitic formation characterized by the presence of metadiamictite (Spencer and Pitcher, 1968).

A dramatic climatic change that was possibly worldwide took place at the beginning of Argyll Group times. On page xx it is argued that this is most likely to be equated with the Marinoan glacial period at *c.* 635 Ma. Tillites were probably deposited on a shallow-marine shelf by up to seventeen successive pulses of grounded ice, possibly advancing from the south-east. Pre-existing intrabasinal sedimentary rocks were eroded by the glaciers and then covered by marine tills in which extrabasinal granitoid debris becomes increasingly common upwards. Isolated dropstones in varved siltstones infer local flotation of the ice sheet but large-scale deposition from ice rafts and reworking by downslope mass-flow, as suggested by Eyles and Eyles (1983), had been rejected by Spencer (1971). Periods of emergence and periglacial weathering between the glacial cycles are suggested by polygonal sandstone wedges, interpreted as ice wedges (Eyles and Clark, 1985). Beach conglomerates then heralded the start of a marine transgression followed by the next glacial advance. Dolomitic limestones with stromatolites, suggestive of warm water, were deposited during some of the interglacial periods, and on Islay, as in Donegal (McCay *et al.*, 2006), a sequence that includes dolomitic metacarbonate rocks has been interpreted as a ‘cap carbonate’ such as commonly occurs above tillite sequences of various ages worldwide. The paradox of having an ice sheet at sea level, followed immediately by warm-water carbonate precipitation in apparently low latitudes has so far eluded a completely satisfactory explanation.

After the final retreat of the ice, the cold climate conditions apparently ameliorated and shelf sedimentation resumed, resulting in the deposition of the widespread quartzite formations. Locally thick accumulations of psammite and quartzite indicate that sediment input kept pace with extension in a series of NE-trending basins. The closest shoreline remained north-west of Islay and Jura with at least 100 km of open sea to the south-east (Anderton, 1985). The change to a tidal, shallow-water environment was probably caused by a combination of source-area uplift and a tectonically induced marine transgression. This change in sedimentation is also marked by increasing volumes of Archaean detrital grains above the level of the tillite formations (Cawood *et al*., 2003). In some areas, thin but significant accumulations of volcaniclastic detritus and local pillow lavas could be early signs of basin instability that was soon to become widespread.

1.4.3.2 Easdale Subgroup

The base of this subgroup is marked in most places by a sharp change to finer grained rocks showing features typical of deep-water sedimentation and turbidity currents, with local incursions of coarse-grained mass-flow deposits. Higher parts of the subgroup are dominated by calcareous clastic rocks with local metacarbonate rocks, representing shallower water sedimentation. These general characteristics are preserved throughout the outcrop from Islay almost to the north coast and, although the detailed stratigraphy is less continuous than in preceding subgroups, individual units and some very distinctive sequences can be traced for up to 100 km.

Along the south-eastern coasts of Islay and Jura, the Jura Quartzite Formation is overlain by the Jura Slate, which constitutes the basal member of the Scarba Conglomerate Formation (Anderton, 1979). This formation is about 450 m thick, consisting of metamudstones that pass upwards into quartzite and metaconglomerate. Sedimentary structures such as graded beds with erosional bases suggest deposition from turbidity currents on a subsiding off-shore platform shelf. Farther north, on Scarba and adjoining islands, coarse debris flows are considered to have slumped downslope northwards into a fault-bounded basin. To the north of Scarba the debris flows and associated quartzites become finer-grained and thinner as they become interbedded with and pass upwards into the deeper water Easdale Slate Formation (Anderton, 1979, 1985). The Easdale Slate consists predominantly of graphitic, pyritic metamudstones, best developed on the islands of Seil and Luing where they have been quarried extensively for roofing slates. Thin beds of poorly graded metasandstones represent incursions of distal turbidites. Still farther north, in the Ardmucknish area, the Selma Black Slates and overlying Selma Breccia are interpreted as equivalent to the Jura Slate and Scarba Conglomerate. The overlying Culcharan Black Slates (200–500 m) and the graded, pebbly Culcharan Quartzite (200 m) were correlated with the Easdale Slate by Litherland (1980).

To the east of Ardmucknish, the Creran succession of Litherland (1980) is difficult to correlate with established Argyll Group successions elsewhere (see above). Anderton (1985) regarded the whole succession as typical of the Easdale Subgroup but Litherland (1987), whilst accepting the similarity of parts of the topmost Beinn Donn Quartzite Formation to the Killiecrankie Schist and Cairn Mairg Quartzite of Perthshire (see below), re-iterated his 1980 view that the whole succession is equivalent to the Islay Subgroup.

Throughout its strike length, the upper part of the Easdale Subgroup is dominated by a variably calcareous shallow-marine facies. In the South-west Grampian Highlands this facies is represented by three major formations, separated geographically and cropping out on different limbs of major folds but all broadly equivalent stratigraphically (Roberts, 1966a). On the north-west limb of the Loch Awe Syncline, the Easdale Slate passes upwards, locally via the 20 m-thick Degnish Limestone Formation, into the Craignish Phyllite Formation. The latter consists of abundant alternations of laminated phyllitic metamudstones, quartzites, metalimestones and pebbly metasandstones, with a total thickness of up to 4500 m. Many of the sediments were deposited on tidal flats and in subtidal environments with gypsum pseudomorphs, well preserved in the *Craignish Point* GCR site, that indicate periodical emergence. Above the Craignish Phyllite, cross-bedded, dark grey metalimestones, intercalated with metamudstones comprise the Shira Limestone and Slate Formation, which is a persistent local marker unit, up to 300 m thick. On Islay and Jura, on the south-eastern limb of the Islay Anticline, the Port Ellen Formation and its basal Kilbride Limestone Member consist of similar lithologies and occupy a similar stratigraphical position. There they are overlain by the Laphroaig Quartzite Formation.

On the south-eastern limb of the Loch Awe Syncline, and passing down into the core of the Ardrishaig Anticline, the upper part of the subgroup is represented by the Ardrishaig Phyllite Formation, overlain locally by the Shira Limestone. The Ardrishaig Phyllite is similar lithologically to the Craignish and Port Ellen phyllite formations but sedimentary structures are not so well preserved owing to a higher metamorphic grade. The amount of deformation makes estimates of thickness difficult but over 4000 m are recorded in places. On the south-eastern limb of the Ardrishaig Anticline, a diachronous, predominantly quartzitic unit with an apparent thickness of up to 5000 m, the Lower Erins Quartzite, replaces the upper part of the Ardrishaig Phyllite in Knapdale. There, the quartzite is succeeded by the dominantly pelitic Stornoway Phyllite Formation (with a more-graphitic and calcareous Stronachullin Phyllite Member locally). Towards the north-east, around upper Loch Fyne, the Ardrishaig Phyllite is overlain directly by the St Catherine’s Graphitic Schist, consisting of up to 200 m of graphitic metamudstones with thinly bedded metalimestones that are probably equivalent to the Shira Limestone. Minor ‘green beds’ of detrital volcanic material occur in the south-eastern parts of the

Ardrishaig Phyllite and Lower Erins Quartzite outcrop, and numerous basic sills could be near-contemporaneous with sedimentation.

The Easdale is the earliest subgroup in the Dalradian that can be traced continuously from the South-west Grampian Highlands through the Central Grampian Highlands to the Pitlochry area and beyond. Black slaty pelites overlain by Ardrishaig Phyllite-type lithologies in the area around Dalmally can be equated with both the Easdale Slate to the west and the Ben Eagach Schist to the east, hence providing a crucial link (Roberts and Treagus, 1975). Throughout this area, a common succession may be recognized above the Boundary Slide-zone which, with only local absences, consists of the Killiecrankie Schist–Carn Mairg Quartzite–Ben Eagach Schist–Ben Lawers Schist formations.

The Killiecrankie Schist Formation is a deep-water facies consisting dominantly of semipelite and pelite but with abundant intercalated psammite and pebbly quartzite and many concordant bands of amphibolitic metabasalt. Where there is no quartzite to represent the Islay Subgroup, as in most of the ground between Blair Atholl and Glen Shee, it is difficult to distinguish between the Killiecrankie Schist and the underlying Blair Atholl Subgroup, especially where the sequence is attenuated by tectonic slides, and the facies is probably continuous across the subgroup boundary (Goodman *et al*., 1997; Crane *et al*., 2002). The distinctive Carn Mairg Quartzite ranges from feldspathic, pebbly quartzite, to a psammitic metagreywacke and typically shows graded bedding. Locally it is absent and it is probably best regarded as the thickest and most extensive of many sandy turbidites that swept periodically into the fine-grained basin sediments now represented by the Killiecrankie and Ben Eagach schist formations.

The Ben Eagach Schist Formation can be traced almost continuously from north of Tyndrum eastwards to the Glen Shee area. It consists predominantly of distinctive graphitic pelites, with impersistent thin metalimestones and amphibolites. Most of the stratabound mineralization of the Argyll Group occurs in this formation, extending intermittently over a strike length of at least 90 km, from Loch Lyon to Loch Kander (Coats *et al*., 1984). Most notable is the 50 m-thick bed of baryte and celsian with sulphides around Ben Eagach and Farragon Hill, north of Aberfeldy, which has been mined commercially in recent times.

The Ben Lawers Schist Formation forms a wide continuous outcrop extending from Tyndrum to the Braemar area. North of Loch Tay it also occupies the core of the Ben Lawers Synform. The dominant lithology is a calcareous pelite or semipelite with some thin beds of quartzite and metalimestone. Hornblende-schists of metasedimentary origin are common, but chloritic ‘green beds’ of volcaniclastic origin and pods of basic and ultrabasic meta-igneous material are also recorded. A persistent zone of stratabound sulphide occurs near the top of the formation.

Above the Ben Lawers Schist, the top of the subgroup is marked by a variety of lithologies. In the Glen Lyon area, the Auchlyne Formation (formerly the Sron Bheag Schist) consists mainly of psammite, semipelite and possible volcaniclastic rocks with various calcsilicate rocks and metalimestones. East of the Loch Tay Fault the Farragon Volcanic Formation, a complex sequence of quartzite, psammite, metabasalt and volcaniclastic ‘green beds’ represents the earliest major volcanic episode in the Dalradian succession.

Only the upper formations of the subgroup can be traced with any confidence north-east of the Pitlochry area. In the Glen Shee–Braemar area, the Creag Leacach Quartzite of the Islay Subgroup passes up through a transition member of interlaminated quartzite and pelite into the graphitic Glas Maol Schist, which is correlated with the Ben Eagach Schist (Upton, 1986). Farther north-east, in the Ballater area, the subgroup consists mainly of psammite and semipelite, the Craig nam Ban Psammite Formation, in the lower part, with semipelite, calcsilicate rock, amphibolite and thin impure metalimestones, the Glen Girnock Calcareous Formation, equivalent to the Ben Lawers Schist, in the upper part (Smith *et al.*, 2002). The Meall Dubh Metabasite Formation, a unit of metabasalt and volcaniclastic rocks, occurs at the top of the subgroup in an equivalent position to the Farragon Volcanic Formation. Around the Ladder Hills, a more-typical Easdale Subgroup sequence consists of semipelite and psammite of the Culchavie Striped Formation, the Glenbuchat Graphitic Schist Formation and a sequence of calcareous semipelite and minor psammite with metalimestone and calcsilicate beds, termed the Badenyon Schist and Limestone Formation. Basic pillow lavas and tuffaceous beds of the Delnadamph Volcanic Member occur locally within the graphitic pelite and semipelite.

Still farther north, most of the succession above the Islay Subgroup is cut out by the Portsoy Shear-zone. Within and immediately to the east of the shear-zone, various local successions include Easdale-type facies but firm correlations with established successions are impossible. On the north coast, immediately west of the shear-zone, the subgroup is represented by a sheared and attenuated succession consisting of the Castle Point Pelite and Portsoy Limestone formations.

An initial shelf-deepening event at the start of the Easdale Subgroup is indicated by a rapid change to finer grained sediments showing features of deep-water sedimentation and turbidity currents, with a general tendency to become finer towards the east and north-east. Fault-controlled, steep shelf-slope sedimentation resulted in local incursions of very coarse-grained, mass-flow deposits, as seen in the Scarba Conglomerate Formation (Anderton, 1979, 1985). Marked along-strike facies changes indicate that, in contrast to the preceding Appin Group, deposition occurred within more-discrete fault-bounded marginal basins having a general north-east trend (Anderton, 1985, 1988). The interbasinal highs are marked by local thinning, facies changes, erosion or non-deposition; they commonly coincide with long-lasting major lineaments trending north-east or north-west (Fettes *et al.*, 1986; Graham, 1986). Syngenetic barium and base-metal mineralization has been attributed to ponding of exhalative brines in basins adjacent to active faults, which in turn controlled sea-water infiltration into buried sediments (Coats *et al.*, 1984).

Widespread shallow-water shelf and tidal-flat sedimentation returned during late Easdale Subgroup times due to infilling of the local basins with fine-grained sediment to produce, for example, the Craignish and Ardrishaig phyllites and the Ben Lawers Schist.

Although thin beds of volcaniclastic rock and local pillow lavas do occur in the Islay Subgroup, the first major volcanic episode in the Dalradian succession occurred in late Easdale Subgroup time and is represented by the Farragon Volcanic Formation, the Meall Dubh Metabasite Formation and the Delnadamph Volcanic Member. Taken together with the tendency towards unstable sedimentation and the slightly earlier syngenetic mineralization, these occurrences point to an increased extension in this part of Rodinia, possibly heralding the break up that led eventually to the separation of Laurentia and formation of the Iapetus Ocean (Fettes *et al.*, 2011).

1.4.3.3 Crinan Subgroup

Throughout its outcrop, this subgroup exhibits a relatively simple stratigraphy in which many local successions are dominated by a single thick formation. Sedimentation was generally of deep-water, turbiditic type with marked variations in thickness and diachronous facies changes. The Crinan Grit Formation of the South-west Grampian Highlands passes north-eastwards into the generally thinner-bedded and finer-grained Ben Lui Schist Formation of the Central Grampian Highlands. In most areas of the North-east Grampian Highlands, the Crinan and Tayvallich subgroups are difficult to separate; they crop out in a broad horseshoe of migmatitic and gneissose psammite and semipelite around the Turriff Syncline.

The Crinan Grit Formation, and its local equivalent the Ardmore Formation on the south-east coast of Islay, constitute the whole subgroup on both limbs of the Loch Awe Syncline (Knill, 1959; Roberts, 1966a; Borradaile, 1973, 1979). The base is probably diachronous and is interbedded locally with lithologies indistinguishable from the underlying Craignish Phyllite. In some areas a local unconformity is implied by a basal conglomerate. On the north-western limb of the syncline and around the head of Loch Awe, the subgroup consists of 100–550 m of white quartzite with thin beds of gritty psammite and interbedded green or grey phyllitic semipelite. Locally, thin metalimestones and slaty metamudstone units are present. A lens of pale green metatuff occurs near Craignish, and the overlying psammites have a more chloritic matrix, reflecting a volcaniclastic component. On the south-eastern limb of the syncline the thickness increases to over 3000 m with the incoming of many thick-bedded psammites containing angular fragments of detrital feldspar, mica and carbonate. Pebbly and conglomeratic quartzites increase towards the top of the formation and in places become the dominant lithology.

On the south-eastern limb of the Ardrishaig Anticline, the subgroup crops out in a continuous strip along the west coast of Kintyre and through Loch Fyne to the Central Grampian Highlands. In south Knapdale the lower part of the subgroup is represented by the Upper Erins Quartzite Formation, which lenses out to the north-east. Grey-green, phyllitic pelites and semipelites occur locally and pebbly quartzites, usually graded, become prevalent towards the top of the formation (Roberts, 1966a). Above the Upper Erins Quartzite, the Stonefield Schist Formation consists of schistose semipelite and pelite, with subordinate psammite and quartzite and numerous lenticular quartzose metalimestones. When traced north-eastwards, across Loch Fyne, this formation becomes dominantly pelitic and passes north-eastwards into the Ben Lui Schist Formation of the Central Grampian Highlands.

Around Tyndrum, the Ben Challum Quartzite Formation marks the base of the subgroup locally. It consists of up to 500 m of quartzite and micaceous semipelite with minor amphibolite of possible volcaniclastic origin and two bands of low-grade stratabound pyrite-chalcopyrite-sphalerite mineralization. There is a possible correlation with a zone of similar sulphide mineralization in the Upper Erins Quartzite in the Meall Mor area. The Ben Lui Schist Formation crops out continuously from Loch Fyne to Ben Vuirich, notably over wide areas on both limbs of the Ben Lawers Synform and including structural outliers on the lower limb of the Tay Nappe around Lochearnhead. The formation consists mainly of garnetiferous semipelite and graded psammite, although sparse hornblende-schist and impersistent beds of metalimestone have been recorded in the Killin area (Johnstone and Smith, 1965) and near Pitlochry (Sturt, 1961). At the base of the formation, between Tyndrum and Glen Lyon, is a zone up to 50 m thick containing lenticular bands of talcose or chloritic soft green schist containing lenses and pods of dolomite and magnesite with minor amounts of chromium, copper and nickel minerals. They probably represent sediments derived from the erosion of local ultramafic rocks, possibly of ophiolitic origin (Fortey and Smith, 1986; Power and Pirrie, 2000) but more-likely derived from subcontinental lithospheric mantle exposed during the development of extensional basins (Chew, 2001).

To the north-east of Pitlochry, the metamorphic grade of the Ben Lui Schist increases and the unit grades into migmatites that constitute the Duchray Hill Gneiss Member of Glen Isla and the equivalent Queen's Hill Gneiss Formation of Deeside (Read, 1927, 1928; see *Chapter 6, Introduction*). There, the formation also includes numerous bands of gneissose amphibolite that probably represent basic intrusions.

Generally gneissose and migmatitic semipelitic rocks that form a broad horseshoe outcrop around the Turriff Syncline, from mid-Donside to Fraserburgh have been assigned to the higher parts of the Argyll Group (Read, 1955; Harris and Pitcher, 1975; Harris *et al.*, 1994; Stephenson and Gould, 1995). Most are assumed to represent the Crinan Subgroup, although the Easdale and Tayvallich subgroups occur in some areas. Schistose and gneissose psammites and pelites of the Craigievar Formation in mid-Donside are considered to be equivalent to the psammites and semipelites of the Aberdeen Formation to the east and north-east (Munro, 1986). In the lower Ythan valley, gneisses of the Ellon Formation are distinguished from those of the Aberdeen Formation by their lack of regular lithological banding, their poor fissility and a foliated, streaky appearance (Read, 1952; Munro, 1986). To the north and east they grade into the structurally overlying Stuartfield 'division' of semipelite, pelite, psammite and metagreywacke. The upper part of this 'division' has a more coherent stratigraphy involving massive channel quartzites up to 500 m thick (e.g. the Mormond Hill Quartzite Member) and calcareous beds, and is termed the Strichen Formation. The calcareous beds have been taken to indicate that the formation spans the boundary between the Crinan and Tayvallich subgroups (Kneller, 1988).

Still farther north is the Inzie Head Gneiss Formation, which exhibits a wide range of relict metasedimentary lithologies with a general migmatitic appearance (Read and Farquhar, 1956), whereas on the west side of the Turriff Syncline, the Cowhythe Psammite Formation generally preserves original compositional banding with migmatization concentrated mainly in the semipelitic units (Read, 1923). Both of these formations are well represented by GCR sites described in Chapter 6.

The Crinan Subgroup marks a rapid shelf-deepening and basin-forming event. Well-developed grading, channelling and large-scale slump folding in the Crinan Grits are indicative of proximal turbidite deposits, which Anderton (1985) considered were deposited in submarine-fan channels flowing axially in a major NE-trending basin along the line of what is now the Loch Awe Syncline. As the grain size in the subgroup as a whole fines from south-west to north-east, a major input from the south-west seems likely. But the grain size also becomes finer from north-west to south-east, so that the Upper Erins Quartzite and the Stonefield Schist/Ben Lui Schist are all finer grained than the Crinan Grits. Many authors have regarded the finer grained beds as more distal turbidites, deposited in the same basin as the Crinan Grits (e.g. Harris *et al.*, 1978), but Anderton (1985) suggested that they were deposited in a separate parallel basin. Volcanic activity is not so evident as in the preceding Easdale Subgroup but reworked volcaniclastic deposits occur in the lower part of the subgroup and ultramafic rocks indicate the possible exposure of sub-continental lithospheric mantle somewhere in the basin (Chew, 2001). Slope instability with contemporaneous earthquakes as a result of intrabasinal faulting is suggested by the soft-sediment structures preserved in the Crinan Grits.

1.4.3.4 Tayvallich Subgroup

This subgroup is characterized by carbonate sequences, accompanied in the South-west Grampian Highlands by extensive basic volcanic rocks and subvolcanic sills. The Tayvallich Limestone and its lateral equivalents, the Loch Tay Limestone and Deeside Limestone, together constitute one of the most persistent marker bands of the Dalradian Supergroup, stretching from Donegal to the Banchory area (Gower, 1973). The youngest limestone of the Shetland Dalradian succession, the Laxfirth Limestone, is a possible equivalent. The basic volcanicity resulted in the thickest developments of volcanic and subvolcanic rocks seen in the Dalradian succession. However, this volcanicity is less extensive laterally than that of earlier, Easdale Subgroup times and Fettes *et al.* (2011) have speculated that it might have been associated with localized pull-apart basins on the rifted Laurentian margin, with the main full-scale rifting of the continental crust occurring outboard of the preserved Dalradian sequences.

In the Loch Awe Syncline and the subsidiary Tayvallich Syncline to the south-west, the Tayvallich Slate and Limestone Formation exhibits marked facies changes from north-west to south-east comparable to those in the underlying Crinan Subgroup. The overall thickness varies considerably, mainly due to variations in the amount of sedimentary and volcanic material. The formation reaches a maximum of 1200 m, but the total thickness of metalimestone is relatively constant, at about 100 m. On the north-western limb of the Loch Awe Syncline ooidal and graded, gritty metalimestones are interbedded with graphitic metamudstones. These lithologies probably represent shelf sedimentation. Coarse, slumped limestone-breccias, metaconglomerates and gritty metasandstones, all suggestive of an unstable shelf margin, attain maximum development along the axial zone of the syncline. On the south-eastern limb thinner lenses of limestone-breccia and metaconglomerate are interbedded with turbiditic metasandstone (Knill, 1963). Around the north-eastern closure of the Loch Awe Syncline, the upper part of the Tayvallich Slate and Limestone Formation includes the Kilchrenan Grit and the Kilchrenan Conglomerate members (Borradaile, 1973, 1977). The latter is a matrix-supported 'boulder bed', up to 30 m thick, consisting of well-rounded quartzite boulders in a matrix of gritty black metamudstone. It has been interpreted as a slump conglomerate (Kilburn *et al.*, 1965). In the south and west, the upper beds of metalimestone include several layers of volcaniclastic debris, including fragments of pillows, set in a carbonate matrix and the transition into the overlying Tayvallich Volcanic Formation is a complex interdigitation of metalimestone, clastic metasedimentary rocks and metavolcanic rocks.

Metavolcanic rocks occupy much of the core of the Loch Awe Syncline, with a smaller outcrop in the core of the Tayvallich Syncline. The Tayvallich Volcanic Formation consists of up to 2000 m of commonly pillowed basic lava, hyaloclastite and a variety of volcaniclastic volcanic rocks (Borradaile, 1973; Graham, 1976). Extrusion of the main volcanic pile was clearly sub-marine but away from the main centre of volcanicity, which corresponds to the axis of the Loch Awe Syncline, ash-fall tuffs suggest that volcanism evolved into a subaerial environment. Felsic tuffs have yielded U-Pb zircon ages of 601 ± 4 Ma (Dempster *et al.*, 2002).

The volcaniclastic rocks include breccias and waterlain pebbly deposits such as the Loch na Cille 'Boulder Bed' of the Tayvallich Peninsula (Gower, 1977). The possibility of a major stratigraphical break at this horizon has been proposed by Prave (1999) and Alsop *et al.* (2000) who pointed to the presence of cleaved clasts of metsedimentary rock with up to two deformational fabrics. Alternatively the clasts could merely represent the erosion of a significantly older metasedimentary source. This boulder bed has also been correlated tentatively with a younger tillite that has been recognized in the Dalradian of Donegal, which could represent the Varanger glaciations at *c.* 620–590 Ma (Condon and Prave, 2000).

Basic sills intrude the whole succession from the Craignish and Ardrishaig phyllites upwards; their total thickness attains 3000 m in places. These were originally thought to be contemporaneous with the lavas (Borradaile, 1973; Graham, 1976). However, in places they can be seen to have broken through limestone and developed pillowed margins within the unconsolidated sediments and overlying water, so that they might well be near-contemporaneous with their host sediments (Graham and Borradaile, 1984; Graham, 1986). A suite of NW-trending metabasalt dykes on Jura could represent feeders to the lavas and sills (Graham and Borradaile, 1984).

To the south-east of the Ardrishaig Anticline the subgroup is represented by the Loch Tay Limestone which maintains a thickness of around 100 m along strike from Campbeltown to Glen Doll (Bailey, 1925; Elles, 1926; Johnstone and Smith, 1965; McCallien, 1929; Roberts, 1966a; Crane *et al.*, 2002). Thinner developments are also present to the south-east of the main outcrop, at the base of structural outliers of Ben Lui Schist in the inverted limb of the Tay Nappe around Lochearnhead (Johnstone and Smith, 1965; Mendum and Fettes, 1985; Watkins, 1984). Throughout its strike length the formation consists of thick beds of crystalline metalimestone, locally with various schistose semipelites, calcsilicate rocks and psammites. Thin, graphitic metamudstones and metagreywackes are present locally and grading in all lithologies suggests a distal turbidite origin. Intrusive basic meta-igneous rocks are present throughout the outcrop, although there is no continuous volcanic sequence comparable with the Tayvallich Volcanic Formation.

The Loch Tay Limestone can be traced almost continuously north-eastwards as far as Glen Doll, beyond which the Water of Tanar Limestone Formation and Deeside Limestone Formation are probably lateral equivalents. The latter formations are composed largely of calcareous semipelite and psammite with calcsilicate rocks, amphbolite and only thin beds of impure metalimestone. Around the head of Glen Esk and in Middle Deeside the calcareous rocks are overlain by the dominantly psammitic Tarfside Psammite Formation, which is also assigned to the Tayvallich Subgroup on account of locally abundant calcsilicate and amphibolite beds (Harte, 1979).

North of Deeside, the gneissose units that are assigned generally to the Crinan Subgroup probably include some Tayvallich Subgroup rocks, as is indicated by the presence of calcsilicate and metalimestone beds. Notable examples are the calcareous upper parts of the Strichen Formation and its lateral equivalent on the north coast, the Kinnairds Head Formation. In the coast section to the west of the Turriff Syncline, the Tayvallich Subgroup is well defined by a 1200 m-thick sequence, termed the Boyne Limestone Formation, which includes the 200 m-thick Boyne Castle Limestone Member (Read, 1923; Sutton and Watson, 1955). Inland, the metalimestones can only be traced for some 2.5 km, making it difficult to define the Argyll–Southern Highland group boundary farther south.

However, in the Cabrach area, basaltic metavolcanic rocks occur within a turbiditic sequence of pelite, semipelite and pebbly psammite termed the Blackwater Formation (MacGregor and Roberts, 1963; Macdonald *et al.*, 2005). Since the formation appears to pass upwards into Southern Highland Group lithologies, the volcanic rocks have been correlated tentatively with the Tayvallich Volcanic Formation, with which they share some tholeiitic geochemical characteristics.

The change from the coarse siliceous Crinan Grits to massive carbonate beds with dispersed clastic carbonate containing siliciclastic material implies a major change and reduction of sediment source. Rapid lateral variations in facies and thickness and intercalations of graphitic metamudstone, associated with unconformities, overstep relations and pebbly beds indicate deposition of the metalimestones by low-density turbidity currents. They were therefore probably deposited in pre-existing Crinan Subgroup basins following a reduction in the supply of clastic sediment to the fringing shelves (Anderton, 1985).

1.4.4 Southern Highland Group

The Southern Highland Group consists of a *c.* 4 km-thick turbiditic sequence made up mainly of coarse-grained, poorly sorted metagreywacke with subordinate fine-grained metamudstone. Minor intercalations of metalimestone occur locally. Volcaniclastic 'green beds' are widespread at several levels, notably in the basal part of the group, there is one thick local development of basic lavas, and widespread thin 'brown beds' within metamudstones of the Highland Border have been interpreted as more-evolved ash-fall tuffs. The metasedimentary rocks are markedly more chloritic than those of the underlying Argyll Group, partly due to the generally lower metamorphic grade, but probably also reflecting the volcaniclastic input. They are also more feldspathic, with high-grade metamorphic and granitic rock fragments, suggesting a less-mature source area.

The group can be traced from County Mayo in western Ireland to the North-east Grampian Highlands. Much of its outcrop occurs in areas of gentle regional dip such as the Flat Belt of the Tay Nappe, so that its outcrop covers a wide area of some 4900 km^2. The main outcrop is a belt up to 34 km wide, extending along the whole south-eastern edge of the Grampian Highlands from the Mull of Kintyre to Stonehaven and Aberdeen (Chapter 4). A small outlier occurs in the core of the Loch Awe Syncline, and in the North-east Grampian Highlands the group occupies the broad core of the Turriff Syncline and a small outlier on the east coast around Collieston.

Although several local successions have been established, detailed correlations are seldom possible over any distance, as the general lateral and vertical persistence of turbidite facies means that there are few reliable stratigraphical marker beds. Green beds are useful locally, but metamudstone beds are probably highly diachronous. Correlations are further complicated by across-strike changes in metamorphic grade, which significantly alter the appearance of the rocks and have led to different names for units that are probably equivalent stratigraphically. Consequently no subgroups are recognized and in terms of thickness and uniformity of facies the whole group is comparable to a subgroup in other parts of the Dalradian succession.

In the core of the Loch Awe Syncline, the Tayvallich Volcanic Formation is overlain by up to 1100 m of chloritic gritty metasandstone and metamudstone, calcareous in parts, which together comprise the Loch Avich Grit Formation. The succeeding Loch Avich

Lavas Formation consists of 300 to 500 m of basaltic pillow lavas with no significant sedimentary intercalations (Borradaile, 1973).

In the main outcrop of the group south-west of Loch Lomond, the Loch Tay Limestone is succeeded by a typical, predominantly metagreywacke sequence (McCallien, 1929; Roberts, 1966a). The basal part of this sequence is the Glen Sluan Schist Formation, consisting of up to 500 m of pelitic turbidites, lithologically similar to the main part of the succession but separated from it by the Green Beds Formation. Here, the latter form a well-defined stratigraphical unit up to 1000 m thick, consisting of metagreywacke and fine-grained quartzite, interbedded with the well-foliated, green schists containing abundant chlorite and epidote. These lithologies become hornblende-schist at higher metamorphic grades. Lenses of obvious detrital material, pebbles of quartz and graded bedding indicate a sedimentary origin. The beds probably represent an influx of detrital basic volcanic material, a feature reflected in their chemistry and mineralogy (Phillips, 1930; van de Kamp, 1970). Mafic sheets within the formation represent contemporaneous shallow intrusions. The volcaniclastic components are interpreted as recording in part, the erosion of the nearby Loch Avich lavas, but could also have resulted from contemporaneous volcanism in the hinterland (Pickett *et al.*, 2006). This interpretation is not however strongly supported by the detrital zircon data, which are dominated by Archaean detritus (Cawood *et al.* 2003). Above the Green Beds in this area is the Beinn Bheula Schist Formation, which consists predominantly of fine-grained metagreywacke with lenticular developments of pebbly metasandstone and green metamudstone.

In the South-west Grampian Highlands, most of the Southern Highland Group outcrop lies on the inverted limb of the Tay Nappe, which is folded into the late broad Cowal Antiform. Consequently, the lower parts of the group are also exposed on the south-eastern limb of that fold. There the Beinn Bheula Schist passes stratigraphically downwards into the Dunoon Phyllite Formation (equivalent to the Glen Sluan Schist), with only local developments of green beds that are too sparse to warrant a formal formation. The Dunoon Phyllites lie within the complex hinge-zone of the Tay Nappe, which takes the form of a downward-facing (i.e. synformal) anticline known as the Aberfoyle Anticline. Consequently the rocks that crop out farther to the south-east, between the Dunoon Phyllites and the Highland Boundary Fault-zone, are regarded as younger than the phyllites and broadly equivalent to the Beinn Bheula Schist (Anderson, 1947a; Roberts, 1966a; Paterson *et al.*, 1990). In Cowal and Bute, these pebbly metasandstones with metaconglomerate and local metalimestone and metamudstone were fotrmerly known as the Bullrock Greywacke and Innellan 'group' and have now been united as the St Ninian Formation. In north Arran a similar synformal anticline structure exists, with the Loch Ranza Slate Formation occupying the core and the North Sannox Grits Formation on each limb.

To the north-east of Loch Lomond, boundaries between metagreywacke and metamudstone units are demonstrably diachronous. Hence, although the metamudstones generally occur in the cores of downward-facing anticlines, neither the local lithostratigraphical units nor the fold axes are likely to be continuous along the whole length of the Highland Border. Metamudstone in the core of the obvious main anticline in the Aberfoyle area is assigned to the Aberfoyle Slate Formation, whereas other metamudstone units, there and in the Callander area, are now recognized to be facies variations within younger metagreywacke. To the north-west of the Aberfoyle Anticline, throughout this area, the Southern Highland Group consists predominantly of rocks of turbiditic greywacke facies, most of which are assigned to the Ben Ledi Grit Formation (e.g. Mendum and Fettes, 1985). Green beds and basic intrusions are widespread at various horizons in the lower part of this formation, and in the area of the Trossachs these define a separate Loch Katrine Volcaniclastic Formation, underlain and overlain respectively by the Ardnandave and Creag Innich sandstone formations. Detrital sodic feldspar is common in many of the metasandstones between Loch Fyne and Loch Tay and a redistribution of sodium during metamorphism has given rise to many porphyroblastic albite-schists in the metamudstone units (Bowes and Convery, 1966; Watkins, 1983).

Correlation of lithostratigraphical units in the Highland Border Steep Belt to the south-east of the Aberfoyle Anticline, is more complex than previously supposed (Harris, 1962, 1972; Harris and Fettes, 1972; Tanner, 1995, 1997; Bluck and Ingham, 1997; Tanner and Sutherland, 2007). On that limb, the whole of the metagreywacke sequence was formerly known as the ‘Leny Grits’. Most of it is now assigned to the Ben Ledi Grit Formation, but in the Callander area, the upper part is the Keltie Water Grit Formation, which includes the Leny Limestone with its fossils of undoubted latest Early Cambrian age. This formation is now accepted to be in stratigraphical and structural continuity with the Ben Ledi Grits and thus provides the only reliable biostratigraphical age for the top of Dalradian Supergroup. A full discussion of the long-term debate concerning the affinities and significance of this unit and its relationship to adjoining fault slices of the Highland Border Complex can be found in Chapter 4.

To the north-east of Callander the south-eastern limb and hinge of the Aberfoyle Anticline are cut-out by the Highland Boundary Fault. Consequently in the Dunkeld area, the whole sequence in the Highland Border Steep Belt youngs to the north-west. Continuity of the Birnam Slate and Grit Formation (oldest) and the Dunkeld Grit Formation (youngest) with the Ben Ledi Grits is difficult to confirm and they could represent a higher stratigraphical level. In a similar structural position to the north-east are the Cairn Gibbs Psammite Formation of the Glen Shee area and the Rottal Schist Formation of Glen Clova but there too, stratigraphical continuity is uncertain.

To the east of the Loch Tay Fault, the lower parts of the Southern Highland Group, consisting dominantly of more-pelitic metagreywacke sequences, are exposed only along the north-western edge of its outcrop. Between Loch Tay and Glen Shee, these constitute the Pitlochry Schist Formation (Treagus, 2000), from Glen Shee eastwards the equivalent unit is the Mount Blair Psammmite and Semipelite Formation (Crane *et al*., 2002), and in the Glen Clova area this basal unit has been termed the Longshank Gneiss

Formation. Green beds are abundant at several stratigraphical levels but are notably absent north-east from Glen Clova. Soft, fine-grained, amorphous 'brown beds', up to 10 cm thick, have been identified at several localities over a distance of 96 km along strike, from the east side of Loch Lomond to near Fettercairn (Batchelor, 2004a, 2004b). Their chemistry and mineralogy suggests that they originated as mildly alkaline rhyolitic or trachytic tuff from a relatively distant source.

Farther to the north-east, stratigraphical continuity is interrupted by an extensive right-way-up sequence, which was assigned by Harte (1979) to the Tarfside Nappe, a major recumbent structure below the Tay Nappe. In that sequence a lower more-pelitic unit, the Glen Effock Schist Formation, passes upwards into the higher Glen Lethnot Grit Formation, characterised by beds of pebbly psammite, and hence a broad correlation is suggested with the Tay Nappe successions. On the east coast, north of Stonehaven, the sequence reverts to being upside down and has been assigned to the Glen Lethnot Grit on lithological criteria.

A transition from lagoonal calcareous silts and muds of the Argyll Group into turbidites that define the Southern Highland Group is well seen on both limbs of the Turriff Syncline. The turbiditic psammites with subordinate semipelites and pelites are referred to as the Whitehills Grit Formation on the western limb (Read, 1923; Sutton and Watson, 1955) and the Rosehearty and Methlick formations on the eastern limb (Read and Farquhar, 1956). In the core of the syncline the Macduff Formation is a finer grained, more-distal turbidite facies (Sutton and Watson, 1955). A more-persistent semipelitic facies to the south-west has been termed the Clashindarroch Formation. Around the closure of the syncline, in the Correen Hills, the Southern Highland Group is represented by the Suie Hill Formation, which consists dominantly of semipelite and gritty psammite with prominent pelite units. An eastward-younging sequence of turbiditic rocks on the east coast, north of Aberdeen, is termed the Collieston Formation and is assigned to the Southern Highland Group (Read and Farquhar, 1956; Munro, 1986). This predominantly psammitic graded sequence includes characteristic 'knotted' pelite containing andalusite and cordierite.

Some exotic boulders and pebbles in the higher exposed part of the Macduff Formation have been attributed to ice-rafting or debris flows linked to marine tills (Sutton and Watson, 1954; Hambrey and Waddams, 1981; Stoker *et al.*, 1999). Correlations with various glacial periods, some as young as Ordovician, have been suggested, though a correlation with the glacigenic deposit in the Southern Highland Group of Donegal (Condon and Prave, 2000) and the Varanger tillites (accepting their revised age of 620–590 Ma) seems to be the most likely on present evidence (see below).

In general character the clastic sediments of the Southern Highland Group are similar to those of the preceding Argyll Group and sedimentary structures are commonly preserved in immature turbidite-dominated sedimentary facies associations (Harris *et al.*, 1978; Anderton, 1980, 1985; Burt, 2002; Pickett *et al.*, 2006). Metagreywacke and metasandstone are typically coarse-grained, poorly sorted, graded, and are commonly composite. Bouma sequences have been identified in thin-bedded turbidites of the Macduff Formation. Some of the channels are asymmetrical with steep banks showing evidence of slumping and the bases of the coarser metasandstones commonly display large saucer-shaped loadcasts. Minor silty beds show small-scale cross-bedding.

These sediments mark a return to rapid basin deepening, which persistently stayed ahead of the sedimentary and volcanic fill. The sedimentary structures imply that the coarse-grained sediments were probably deposited in slope-apron or ramp settings with channels on the lower slopes and inner zones of major deep-water sub-marine fans, with the finer sediments being laid down as overbank deposits or as outer fan facies. Palaeocurrent directions and facies changes in the sequence all suggest a dominant flow towards the south-east with minor north-eastward and south-westward axial flows. Clasts of feldspar, high-grade metamorphic rocks and granitic rocks are more abundant than in earlier Dalradian turbidites, suggesting a newly emerged, less mature source area (Harris and Pitcher, 1975; Harris *et al.*, 1978), and Plant *et al.* (1984) and Anderton (1985) suggested that this could be due to stripping of a cover sequence in a north-western source area to reveal a granitoid basement.

The Loch Avich Lavas, the 'green beds' and the 'brown beds' represent a final phase of magmatism in the Dalradian basins, probably erupting from volcanic centres in the Loch Awe area, close to the source of the earlier Tayvallich lavas.

1.4.5 Units of uncertain stratigraphical affinity

Two metasedimentary units of uncertain affinity crop out on the Isle of Islay, where they are separated by the NNE-trending Loch Gruinart Fault, a possible splay from the Great Glen Fault (see *Chapter 2*). Both the Colonsay Group and the Bowmore Sandstone Group are thought to have been deformed and metamorphosed during the Grampian Event but they are separated tectonically from the Dalradian succession and direct correlations on lithological grounds are equivocal. There are significant differences between the early deformation histories of the Colonsay Group and the Dalradian, adding to speculation that western Islay and Colonsay might represent a separate terrane (e.g. Bentley *et al.*, 1988; Muir *et al.*, 1992).

1.4.5.1 Colonsay Group

The Colonsay Group crops out on Colonsay, Oronsay and the Rhinns of Islay. It consists of a 5.0–5.5 km-thick sequence of greenschist-facies, strongly deformed metasandstone and phyllitic metamudstone, with minor calcareous beds. The succession youngs generally towards the north-west and Stewart (1962a) and Stewart and Hackman (1973) divided the sequence into 18 lithostratigraphical units; the lower 10 on Islay and the upper 8 on Oronsay and Colonsay. It is possible that there is a slight overlap between the successions on Islay and Oronsay but Bentley (1988) thought that there might be a stratigraphical gap of up to a kilometre in thickness. Subsequently, Muir *et al.* (1995) have recognized that four formations in the lower part of Stewart and Hackman's Islay succession are in fact two formations repeated by folding, but they also identified a previously unrecorded formation (the Octofad Sandstone Formation) on the south-east coast of the Rhinns, which is the lowest preserved part of the group.

The lowest 650 m of the succession on Islay consist of feldspathic metasandstone and metamudstone, interpreted as representing delta-top sheet sands and interdistributary muds. These pass upwards on Islay into quartz-rich metagreywacke and metamudstone suggesting deeper water, delta-slope turbidite accumulation. These become increasingly distal as the succession youngs on to Oronsay and Colonsay, possibly reflecting basin deepening. The upper part of the succession on Colonsay shows a change back towards shallow-water, marine, mainly siliciclastic sedimentation but with several calcareous developments, notably the 1–5 m-thick (dolomitic) Colonsay Limestone. The topmost units possibly reflect the onset of renewed deepening. Several thin volcaniclastic layers have been identified from mineralogical and geochemical criteria, mainly in the upper part of the succession on Colonsay, by Batchelor (2011).

On Islay, the Colonsay Group is in sheared contact with gneisses of the Rhinns Complex. A perceived coarsening of facies and the presence of local conglomerates towards the contact led Wilkinson (1907) and Bentley (1988) to suggest that the contact is a sheared unconformity. However, for much of its length in the western and central Rhinns, the contact is marked by a 3–4 m-wide mylonite zone that cuts discordantly across four formations in the lower part of the group. It is therefore possible that an unknown thickness of the original sequence might be missing and Stewart and Hackman (1973) interpreted the contact as a major tectonic dislocation, which they termed the Bruichladdich Slide. However, on the south-east coast of the Rhinns, Muir *et al.* (1995) identified complex basement-cover interslicing, which extends into the Bruachladdich area, and hence they proposed that the simpler, single plane of dislocation in the central and western Rhinns would be more appropriately named the Kilchiaran Shear-zone. The contact at the north-eastern end of Colonsay was interpreted as a sheared unconformity by both Bentley (1988) and Fitches and Maltman (1984). However, the conglomeratic cover rocks there belong to the Kilchattan Formation, about 4 km above the base of the Colonsay Group succession on Islay, which would require a highly uneven basement topography.

For many years the Rhinns basement was thought to be Lewisian, and consequently the overlying Colonsay Group had been correlated with the Torridonian, until this was challenged by Stewart (1969, 1975). The presence of metalimestone in the upper part of the group suggested to Litherland (*in* Stewart and Hackman, 1973) that there could be a correlation with the Appin Group and this was supported by Rock (1985), who suggested that the chemistry of the Colonsay Limestone is similar to that of the Ballachulish Limestone. In fact the uppermost formations on Colonsay are lithologically similar to the laterally persistent Leven Schist to Appin Quartzite sequence of the Ballachulish type area. Such a correlation would imply that the underlying parts of the Colonsay Group are lateral equivalents of the Lochaber Subgroup and the Grampian Group. The main objection to a correlation with any part of the Dalradian has been on structural grounds, since the first phase of deformation seen in Colonsay Group rocks is not apparent in the undoubted Dalradian rocks of Islay (Borradaile, 1979; Fitches and Maltman, 1984). The matter is still not fully resolved but the distribution of U-Pb ages in detrital zircon and titanite does suggest a correlation with the Grampian Group (McAteer *et al.*, 2010).

1.4.5.2 Bowmore Sandstone Group

The Bowmore Sandstone Group is separated from both the Colonsay Group of western Islay and the Dalradian succession of eastern Islay by tectonic dislocations. The predominantly grey-brown, feldspathic sandstones have been divided into two formations, each exceeding 2 km in thickness (Amos, 1960). The lower, Laggan Sandstone Formation, consists of fine- to medium-grained sandstone with silty partings, and the upper, Blackrock Grit Formation, is mainly coarse-grained sandstone with pebbly beds. The rocks are tightly folded but the locally developed tectonic fabrics are weak and metamorphism is slight. However, younging indicators are rare.

The group has been correlated variously with the Moine, the Torridonian and the Dalradian (Fitches and Maltman, 1984, table 1). It is separated from an overlying Dalradian succession by the Loch Skerrols Thrust, and those workers who have regarded this as a major structure, possibly equivalent to the Moine Thrust, have correlated the Bowmore Sandstone mainly with the Torridonian, by analogy with the structure of the North-west Highlands (e.g. Johnstone, 1966; Stewart, 1969, 1975). Others have regarded the Loch Skerrols Thrust as a structure of local importance only and hence have proposed that the Bowmore Sandstone is more likely to be part of the Dalradian succession. Fitches and Maltman (1984) argued that it is the lateral equivalent of the Crinan Grits on the lower, inverted limb of the Islay Anticline.

1.5 STRUCTURE OF THE GRAMPIAN HIGHLANDS

D. Stephenson

Current structural interpretations of the Grampian Highlands are still based upon those proposed by C.T. Clough and E.B. Bailey, which drew upon the results of the primary mapping by the Geological Survey. In a series of papers, from 1910 to 1938, Bailey demonstrated that the rocks of the South-west and Central Grampian Highlands are disposed in large, Alpine-scale recumbent folds. He proposed that the long limbs of many of these folds are partly replaced by low-angled faults, termed 'slides', with postulated movements of several kilometres. Most of the major fold structures originally identified and named by Bailey are still recognized, and many of his slides exist as complex low-angled high-strain zones, some with tectonic dislocation and/or stratigraphical attenuation, but some have lost their original significance as major tectonic and stratigraphical boundaries.

Subsequent refinements to the Bailey model have involved careful consideration of the relative ages of the various structures, their relationships with each other, and hence the overall structural history of the area, which involves several phases of deformation. This history has been painstakingly pieced together and refined by a multitude of workers. Several alternative structural models have emerged but no single hypothesis can account satisfactorily for all of the observed features (see Stephenson and Gould, 1995 for examples). Various controversies have raged over the years but there has also been a remarkable amount of agreement and consensus on many aspects.

The overall structure of the Grampian Highlands is best illustrated by the dissected block diagram of Figure 1.7, which is based upon an original published by Peter Thomas in 1979 and not bettered since, though it was modified slightly by Stephenson and Gould (1995) and reproduced by Strachan *et al.* (2002).

The large-scale structures are most easily described and understood with reference to those of the South-west Grampian Highlands (Figure 1.7, block A), where the relatively simple fold geometry remains essentially as described first by Bailey (1910, 1922, 1934), despite subsequent re-interpretation by Roberts and Treagus (1977c), Hickman (1978) and Litherland (1982). There, the major folds are seen to diverge on either side of a central *Loch Awe Syncline* which, although composite, is characterized by open to close, upright, upward-facing folds that are generally regarded as F1. On either side of this syncline, the early folds become progressively overturned and verge to the north-west and south-east. To the south-east, the tight *Ardrishaig Anticline* is interpreted as the core of a large SE-facing nappe, the *Tay Nappe*, which dominates the overall structure of the south-eastern part of the Grampian Highlands throughout its strike length.

Throughout the Central Grampian Highlands, the core of the Tay Nappe is obscured within a zone of steeply dipping strata resulting from the refolding of co-axial F1 and F2 folds by near-upright F3 structures (the *Ben Lui Fold-complex* and the *Tummel* and *Cairnwell steep belts*). To the north-west of this zone, generally SE-dipping Appin and Argyll group strata are separated from the structurally underlying Grampian Group by a high-strain zone, which includes several planes of dislocation and has been termed the *Boundary Slide*. Beneath the Boundary Slide, major early folds still face south-east (e.g. those formerly known as the *Glen Orchy* and *Atholl nappes*) but farther to the north-west, a fundamental change in facing direction lies in the region of a 4 km-wide zone of upright, isoclinal folds known as the *Geal-charn–Ossian Steep Belt* (Figure 1.7, blocks C and D).

To the north-west of the Loch Awe Syncline is a stack of NW-facing early folds, including the *Islay Anticline*, *Appin Syncline*, *Beinn Donn Syncline* and *Ballachulish Syncline* (Bailey, 1934; Roberts and Treagus, 1977c). Similar NW-facing folds occur to the west of the Geal-charn–Ossian Steep Belt (Key *et al.*, 1997) and there is reasonable continuity of overall structure between Islay and Glen Roy. To the west, these folds of mainly Appin and Argyll group rocks overlie the Grampian Group.

In the following sections, each major structural domain of the Grampian Highlands is described firstly in the south-west and then progressively through to the north-east, with reference to the labelled blocks of Figure 1.7. The structure of the Dalradian terrane in the Shetland Islands is described in the introduction to Chapter 7.

1.5.1 The Tay Nappe

The Tay Nappe dominates the south-eastern part of the Grampian Terrane, in a 15–20 km-wide outcrop that extends from Kintyre to Stonehaven parallel to the Highland Boundary Fault (Figure 1.7, see also Figure 4.4). Throughout much of its outcrop, the nappe is parallel-sided and flat-lying. The erosion level is such that most of the outcrop constitutes part of the inverted limb, so that stratigraphical sequences are inverted. Structures underlying this inverted limb are seen only in the area of the Angus glens, where a largely right-way-up sequence has been interpreted as a separate *Tarfside Nappe* (Harte, 1979). Close to the Highland Boundary Fault, the Tay Nappe is bent downwards by a large monoform known as the *Highland Border Downbend* to form the *Highland Border Steep Belt* (see below). The hinge-zone of the nappe thus becomes downward facing as a synformal anticline, recognized in the South-west Grampian Highlands as the *Aberfoyle Anticline* (Shackleton, 1958). The south-eastern limb of this anticline is the only place where the original upper limb of the Tay Nappe is preserved.

In the South-west Grampian Highlands the inverted limb of the Tay Nappe has the general form of a broad arch, known as the *Cowal Antiform* (Figure 1.7, block A), although in some areas, at least, this late (?D4) antiform is more of an open chevron (see Figure 4.4, section A–A'). To the north-west of the Cowal Antiform, the core of the nappe is brought down below the level of erosion to crop out as the *Ardrishaig Anticline*. Here the fold limbs, primary axial planes and associated cleavages all dip steeply to the north-west and constitute part of the *Knapdale Steep Belt* (Roberts, 1974). This is the only area in which the core of the Tay Nappe is exposed.

North-east from Cowal, the crest of the late antiform flattens and the inverted lower limb of the Tay Nappe forms the *Flat Belt* which dominates so much of the South-eastern Grampian Highlands (Figure 1.7, blocks B, C and D). The width of the Flat Belt varies and is up to 18 km wide in Perthshire. There, Krabbendam *et al.* (1997) and Treagus (1999) have identified kilometre-scale isoclines and right-way-up sequences within the dominantly inverted limb. The north-western limit of the Flat Belt is defined by a zone of F1 and F2 folds with steeply SE-dipping axial surfaces, which must refold the hinge-zone of any major syncline originally underlying and complementary to the Tay Nappe (Roberts and Treagus, 1979). This zone is termed the *Ben Lui Fold Complex* in Figure 1.7 block B (after Cummins and Shackleton, 1955) but the zone widens north-eastwards in blocks C and D with the addition of many tight, upright folds of later generation (F2 and F3) to form the *Tummel Steep Belt* (see below).

Farther to the north-east, the amplitude of the Tay Nappe is considerably reduced (Figure 1.7, block E). In the Glen Esk area a broad late antiform, the *Tarfside Culmination*, exposes a wide zone of right-way-up strata, apparently beneath the Tay Nappe that has been assigned to the Tarfside Nappe. According to Harte (1979) the axial zone of the fold separating the two nappes has been replaced by a slide, the *Glen Mark Slide*. On the coast section north of Stonehaven, the Highland Border Downbend is well developed and a generally flat-lying inverted sequence is bent down and becomes overturned to the south-east, with downward-facing D1 structures (Booth, 1984; Harte *et al.*, 1987) (see Figure 4.33).

To the north of Aberdeen the Tay Nappe can no longer be identified with any certainty (Figure 1.7, block F). The rocks are mostly the right way up, possibly beneath the Tay Nappe, and it is not clear whether the inverted limb has been cut out by major thrusting, or whether, more simply, the nappe structures have a much smaller amplitude in this area (Harte *et al.*, 1984). However, in the coast section around Collieston the beds are regionally inverted and there are abundant small- to large-scale recumbent, isoclinal F1 folds with a maximum amplitude of about 1 km (Read and Farquhar, 1956; Mendum, 1987) (Figures 6.40. 6.41). These folds plunge gently to the north, face eastwards and may represent a subdued equivalent of the nappe (Ashcroft *et al.*, 1984).

Later (F3 and/or F4) NE-trending folds and other structures on both a major and a minor scale were imposed subsequently on the Tay Nappe. In addition to the Highland Border Downbend, broad, upright folds affect the north-western part of the Flat Belt (Figure 1.7, blocks B, C and D). Of these, the best developed are the Ben Lawers Synform (Treagus, 1964b, 2000) and its complementary, lower amplitude *Loch Tay* (or *Ben More) Antiform* to the south-east (Watkins, 1984; Harte *et al.*, 1984; Treagus, 2000). The somewhat tighter *Sron Mhor Syncline* may be of the same generation but it is closely associated with steeper structures to the north and was probably initiated as an earlier structure. The Collieston F1 folds are also refolded by a set of near-coaxial, tight folds which post-date porphyroblast growth and hence are assigned to D3.

1.5.1.1 The Highland Border Steep Belt and The Hinge-zone of the Tay Nappe

The existence of a belt of steeply dipping rocks along the Highland Border has long been known and was implicit in the early discussions of the area (Henderson, 1938; Anderson, 1947a; Stringer, 1957). However, it was Shackleton (1958) who used both sedimentary structures and cleavage-bedding relationships to demonstrate that the Aberfoyle Anticline is a downward-facing synformal anticline and interpreted it as the closure of the Tay Nappe. Subsequently, many detailed local studies have been made of key areas (from south-west to north-east: Simpson and Wedden, 1974; Paterson *et al.*, 1990; Mendum and Fettes, 1985; Stone, 1957; Harris, 1962, 1972; Harris and Fettes, 1972; Harte *et al.*, 1984; Booth, 1984).

Figure 4.4 shows a series of cross-sections along most of the Highland Border region. North-eastwards from the Cowal and Bute area, the Cowal Antiform passes into the Highland Border Downbend (or Monoform), a sharp monoclinal flexure, over which the Flat Belt of the Tay Nappe gives way to the Highland Border Steep Belt. North-east from Dunkeld, the steep belt is overturned so that sequences of formerly inverted rocks dip at around 60° to the north-west and are once more the right way up (Treagus *et al*., 1972; Harris and Fettes, 1972). The hinge-zone of the Tay Nappe was originally described as a single downward-facing anticline, but it has been shown subsequently to be more complex. For example, in the Ben Ledi area the hinge-zone consists of two major synforms, the *Aberfoyle Anticline* and the *Benvane Synform*, separated by the *Ben Ledi Antiform* (Mendum and Fettes, 1985). These structures are all inferred to be of D1 age, since minor D2 structures are not seen near the Highland Border in this area and only become overprinted on D1 farther to the north-west.

In the rocks of low metamorphic grade in the steep belt and in much of the adjacent parts of the Flat Belt, minor structures are very distinctive and are much influenced by lithology. Pelites develop axial planar slaty cleavages but in the psammites, which constitute most of the Southern Highland Group, spaced S1 pressure-solution cleavages fan around fold closures and are strongly refracted across lithological boundaries (see Figure 4.26). Subsequent deformation during D2 results in characteristic microlithons of S1 in the hinge-zones of minor F2 folds but flattens the spaced cleavage on more-highly strained limbs and induces a finely striped rock, so that it is difficult to recognize the multiple origin of the dominant foliation (Harris *et al*., 1976) (see Figure 4.29).

The Highland Border Downbend is not generally seen to refold D3 structures. However, Crane *et al.* (2002) described gentle NE-trending warps near Kirkmichael that do refold F3 folds and hence the downbend is confirmed as regional F4. Where downbend-related folds are present, they are usually accompanied by a strong crenulation cleavage, best seen in the more pelitic or strongly foliated rocks. This cleavage dips north-westwards at moderate to subvertical angles.

1.5.1.2 The Ben Lui Fold-complex, Tummel Steep Belt and Cairnwell Steep Belt

From Dalmally north-eastwards to Strathtummel, a zone of steeply-inclined strata intervenes between the Flat Belt of the Tay Nappe and the Boundary Slide. Since the axial plane of the anticlinal Tay Nappe appears to be above the level of erosion throughout this area, early workers considered that the underlying major syncline (the 'righting fold') must lie within this zone. An antiformal syncline around Ben Lui was termed the 'Ben Lui Fold' by Bailey (1922) who proposed that it is the F1 syncline beneath the Tay Nappe.

Subsequent work by Cummins and Shackleton (1955) supported Bailey's view, but a more detailed study by Roberts and Treagus (1964, 1975) showed that the folding is more complex. Beneath the F1 Ardrishaig Anticline, the *Ben Lui Fold-complex* consists of three recumbent folds with SE-dipping axial surfaces, the *Dalmally Syncline*, the *Ra Chreag Anticline* and the *Ben Lui Syncline*, all of which have been shown to be later, D2 (or possibly D3) structures. This tripartite structure has been traced north-eastwards, via the Balquhidder area (Watkins, 1984), to Glen Lyon (Roberts and

Treagus, 1979), beyond which the individual folds lose their identity and the structure is probably represented by the F2 *Ruskich Antiform* (Nell, 1984; Treagus, 1987, 1999). Many folds in the Schiehallion area and associated folds in Strathtummel with SE-dipping axial surfaces appear to belong to the same generation of F2 folds, which in places are seen to fold the axial planes of major F1 folds such as the *Beinn a Chuallich Folds* and the *Creag na h'Iolaire Anticline* (Roberts and Treagus, 1979; Treagus, 1987) (see Figure 3.3b).

A similar co-axial arrangement of steeply inclined F1, F2 and F3 folds occurs east of the Loch Tay Fault in the *Tummel Steep Belt* (Bradbury *et al*., 1979; Treagus, 1999, 2000) and can be traced north-eastwards towards Braemar, where it is known as the *Cairnwell Steep Belt* (Upton, 1986; Crane *et al*., 2002) (Figure 1.7, blocks C and D). These two steep belts are offset along the complex 5 km-wide NW-trending zone of large-scale F2 and F3 folds termed the *Carn Dallaig Transfer Zone* (Crane *et al*., 2002, figure 19). They are described in more detail in the *Introduction* to Chapter 6.

In the area around Schiehallion and Strathtummel (Figure 1.7, block C) the strata undergo a dramatic swing of strike which is a major feature of even small-scale maps (e.g. Figure 1.1). This displacement is caused by two large-scale, steeply plunging, north-trending, relatively late folds termed the *Errochty Synform* and the *Bohespic Antiform* (see Figure 3.43). Earlier authors assigned these folds to D3 or D4 (Rast, 1958; Thomas, 1980; Treagus, 1987), but Treagus (2000) gave them a local designation of De, being unable to state categorically whether they pre- or post-date the regional D3 phase. The tight synform and broad, open antiform have contrasting geometry. Such changes in fold geometry commonly occur at the junction of materials of contrasting competence; in this case the thick psammites of the Grampian Group and the multilayered pelites and quartzites of the Appin Group. A similar geometry occurs in other fold pairs that have symmetrical spatial relationships to the major NNE- to NE-trending Loch Tay, Bridge of Balgie and Tyndrum faults, and Treagus (1991) considered that there might be a relationship between ductile shearing, the late fold pairs and later brittle faults. The latest folds in this area, termed the Dt phase by Treagus (2000), strongly deform the Errochty Synform along NW-trending axes, the most important being the *Trinafour Monoform.*

1.5.2 The Boundary Slide-zone and possible related structures

The Boundary Slide can be traced almost continuously, as a zone of high strain and attenuation along the boundary between the Grampian and Appin groups, from Dalmally to Glen Tilt (Roberts and Treagus, 1977c) and then with less certainty, intermittently to Glen Rinnes (Stephenson and Gould, 1995). This zone of highly schistose or platy rocks varies in thickness from a few metres up to 2000 m, and includes several planes of dislocation. Significant displacement or tectonic excision of strata is difficult to prove in most areas but a considerable stratigraphical hiatus can be demonstrated. Indeed the whole succession from the Ballachulish Subgroup to the lower Easdale Subgroup is missing over some distance, between Dalmally and Glen Lyon (A.G. Leslie, pers. comm., 2007). Such a large hiatus most likely represents a major unconformity due to non-deposition, possibly over a fault-bounded basement 'high'. However, overlap can be demonstrated locally and attenuated sequences of the Lochaber and Ballachulish subgroups in the Schiehallion area mark the return to a complete succession towards the north-east (Treagus and King, 1978; Roberts and Treagus, 1979; Treagus, 1987, 1999, 2000). The sharp change in competence between the psammitic and quartzitic Grampian Group and lower parts of the Lochaber Subgroup and the more-variable overlying strata then probably acted as a locus for high strain, with or without localized shearing and displacement.

Originally interpreted as a major dislocation separating two major tectonostratigraphical units, the *Ballappel Foundation* and the *Iltay Nappe* (e.g. Bailey, 1922), the Boundary Slide has lessened in significance as a structural boundary in most current interpretations. However, there is no doubt that it does transgress the stratigraphy on a regional basis and local planes of dislocation within the slide-zone might result in a total displacement of up to several kilometres (Treagus, 1987). Individual slides truncate early isoclinal folds and there is no doubt that the slide-zone is folded by later structures. The strong platy or schistose fabric present throughout the zone was regarded by Treagus (1987) as an intense development of the main regional schistosity (S2) developed during nappe formation. Most of the slides within the zone occur on the short limbs of F2 folds and result in an overall movement, in a thrust sense, towards the north-west. This fact is clearly contrary to the overall concept of the dislocations as extensional slides (lags), but it may be that they were initiated as extensional structures during basin development (Soper and Anderton, 1984; Anderton, 1988) or during the formation of the primary nappes (Thomas, 1980) and were then re-activated in a reverse sense as thrusts during subsequent tectonism. The present sinuous trace of the slide reflects large-scale folding by later structures.

A Boundary Slide has been traced north-eastwards from Glen Tilt, through the Braemar area to the eastern end of the Cairngorm Granite (Upton, 1986), where its overall effect is much reduced. Farther north, zones of high strain, locally accompanied by slides, are common at or below the Grampian Group–Appin Group junction but towards the north coast, the boundary appears to represent a relatively undisturbed, rapid stratigraphical passage (see *Chapter 6, Introduction*). However, zones of shearing around the Grampian–Appin group boundary in Glen Rinnes can be projected north-eastwards towards a major shear-zone that can be traced for some 30 km at higher stratigraphical levels, to reach the coast between Sandend and Portsoy. This *Keith Shear-zone* appears to have excised parts of the Ballachulish Subgroup in places and between its multiple branches are several pods and lenses of deformed muscovite-biotite granite dated at *c.* 600 Ma (Barreiro, 1998). Hence this shear-zone, at least, must have been in existence soon after sedimentation, during the extensional events that permitted emplacement of the Ben Vuirich Granite, the Tayvallich volcanism and the associated rifting heralding the opening of the Iapetus Ocean (e.g. Kinny *et al.*, 2003b). Subsequent Grampian deformation of the granite sheets resulted in a top-to-north-west, thrust sense of movement.

1.5.3 Folds beneath the Boundary Slide: the former Glen Orchy and Atholl nappes and the Gaick Fold-complex

In the area around Glen Orchy and Dalmally, Thomas and Treagus (1968) and Thomas (1979) recognized three major isoclinal, recumbent folds beneath the Boundary Slide, the *Glen Lochy Anticline*, the *Beinn Udlaidh Syncline* and the *Beinn Chuirn Anticline*, which they regarded as F1 (Figure 1.7, block B). However, Roberts and Treagus (1975, 1977c) interpreted the uppermost, Beinn Chuirn Anticline, as a secondary F2 fold, associated with strong deformation along the Boundary Slide. More-recent fieldwork on the Beinn Udlaidh Syncline by Tanner and Thomas (2010) failed to find evidence of any earlier folding but thin sections clearly revealed a cleavage and metamorphism pre-dating the major folds, all of which were therefore re-assigned to D2. All of the isoclinal folds, together referred to by some authors as the *Glen Orchy Nappe*, face towards the south-east (i.e. in the same direction as the major nappes above the Boundary Slide). These folds are arched across the broad dome, of the *Glen Orchy Antiform*, so that they face upwards on the north-west side of the dome and downwards beneath the Boundary Slide on the south-east side. Tanner and Thomas (2010) refer to this late structure as the Orchy Dome and observe that it post-dates late crenulation cleavages and hence is of D4 age or younger. A similar structure to the Glen Orchy Antiform refolds three early isoclines farther to the north-east, in the Glen Lyon area (Figure 1.7, block C; Roberts and Treagus, 1979).

Still farther to the north-east, around Strathtummel and along the A9 road section, a stack of isoclinal recumbent folds face downwards to the south-east (Thomas, 1979, 1980). Their axial surfaces, limbs and dominant cleavage all steepen to the south-east and dip beneath the Boundary Slide (Figure 1.7, block D). These folds, most notably the *Meall Reamhar Synform*, *Clunes Antiform* and *Clunes Synform,* were originally interpreted as components of a large-scale, isoclinal F1 fold termed the *Atholl Nappe*, which was thought to lie beneath the Tay Nappe, the intervening syncline having been cut out by the Boundary Slide. However more-recent work has shown that the dominant major folds and cleavage belong to the D2 regional phase (Treagus, 2000). They all verge towards the north-west and hence are developed on what is essentially an extension of the lower, inverted limb of the Tay Nappe, from which they are separated by the Tummel Steep Belt of later, D3 and possibly D4, folding. The Boundary Slide marks the north-western limit of that steep belt but does not seem to disrupt either the stratigraphy or the overall structure to any significant degree. In places, an earlier, bedding-parallel S1 cleavage is recognized, rare tight, metre- to 10 metre-scale F1 folds do occur on similar axes to the F2 folds and the possibility of large-scale F1 folds cannot be excluded (Treagus, 2000). The later Errochty Synform (Fe phase, see above) refolds the F1 and F2 folds and becomes very tight in this area, where the hinge-zone passes into a high-strain zone of flaggy rocks, at least 3 km wide, called the *Dalnacardoch Banded Zone* (Thomas, 1979; Treagus, 2000).

Farther north, neither F1 nor F3 folds are recognized across a wide area dominated by a stack of flat-lying, isoclinal, kilometre-scale, south-facing F2 folds and termed the Gaick Fold-complex (Leslie *et al.*, 2006). Around the Pass of Drummochter, the F2 axial planes and cleavages of the flat belt are folded across the broad *Drummochter Dome*, now generally accepted as a late structure (D3 or D4 depending upon the author) analogous to the domes of Glen Orchy and Glen Lyon (e.g. Lindsay *et al.*, 1989). On the north-western limb of the dome, some complex F1/F2 interference patterns are observed at Crubenmore (Thomas, 1988). Beyond Drummochter, a progressive increase in D3 deformation leads to steepening north-western dips and eventually to a zone of open to close, upright F3 folds on the south-eastern flank of an inlier of 'basement' Badenoch Group rocks termed the Glen Banchor High (Robertson and Smith, 1999).

1.5.4 The Geal-charn–Ossian Steep Belt

To the north-west of the Glen Banchor High is a 2–4 km-wide zone, in which all the fold limbs and axial planes are steeply dipping (over 60°). This is the *Geal-charn - Ossian Steep Belt* of Thomas (1979), which can be traced for some 50 km from south-west of Loch Ossian to Kinlochlaggan (Robertson and Smith, 1999). It is most clearly defined in the south-west, where it affects upper Grampian Group and Appin Group strata (Figure 1.7, block D). To the north it widens and becomes more diffuse, affecting lower strata of the Grampian Group and the Glen Banchor Subgroup 'basement' succession. On its north-western side, the steep belt includes the *Kinlochlaggan Syncline*, which has a core of Appin Group strata and has long been regarded as a major isoclinal primary fold (Anderson, 1947b, 1956; Smith, 1968; Treagus, 1969).

Within the steep belt, upright, near-isoclinal coplanar F1 and F2 folds and fabrics (see Figure 5.4) are associated with ductile shear-zones and/or slides. Major recumbent folds face in opposite directions on either side, and the intense focussing of deformation into such a narrow zone led Thomas (1979) to interpret the steep belt as a fundamental root-zone from which the large-scale F1 nappes of the Grampian Highlands originally diverged. He therefore regarded it as comparable to, but at a lower structural level than, the Loch Awe Syncline in the South-west Grampian Highlands. The concept of a root-zone is no longer popular but more-recent work has confirmed the steep belt as a zone of primary upright deformation that separates two contrasting structural domains: the upright to steeply inclined NW-facing folds of the Loch Laggan–Glen Roy area to the west, and the gently inclined, SE-facing folds of the Drummochter–Strathtummel area to the south-east (Robertson and Smith, 1999). It probably formed as a result of its location adjacent to an original faulted rift-basin margin, where the strata became compressed against the rigid upstanding buttress of the Glen Banchor High (see Figure 5.32). F3 folds in the steep belt are comparable in orientation to F3 folds in the immediately adjacent domains and are characterized by an upright crenulation cleavage.

To the north of Kinlochlaggan, a zone of steeply inclined strata, thrust slices and intense deformation extends to the north-north-east through the Monadhliath mountains (Piasecki and van Breemen, 1983). However, many of the upright folds in this zone are interpreted as later, possibly F3 structures (Smith, 1968) and their relationship to the steep belt is uncertain.

1.5.5 NW-facing folds between Islay and Glen Roy

This area is dominated by large-scale recumbent NW-facing early folds that have been refolded by largely upright open to close later folds. The area between Appin and Glen Roy in particular is arguably the most intensively studied in the whole of the Scottish Dalradian, particularly in the well-exposed, cross-strike section along Loch Leven and Loch Eilde that is represented by several GCR sites in *Chapter 3*. The original interpretation of the regional structure by Bailey (1910) was based largely upon that section. It underwent several modifications, including a complete reversal of the order of stratigraphical succession and consequently the facing direction of the major folds. The final interpretation by Bailey (1934, 1960) has remained a sound basis for all subsequent work.

The two principal re-interpretations (Roberts and Treagus, 1977c; Hickman, 1978) both accepted much of the near-surface fold geometry proposed by Bailey (1934). However, they differed considerably in the way in which the folds were projected to depth and correlated across strike. There were also highly significant differences in the assignation of relative ages to individual folds, much of the evidence for which depends on the detailed observation and interpretation of minor structures. These contrasting models have been summarized by Stephenson and Gould (1995) and are illustrated in Figure 1.8. They are all commented upon in Chapter 3, but the descriptions there follow the Roberts and Treagus (1977c) model, which was based largely upon detailed studies in the Ardsheal Peninsula (Treagus and Treagus, 1971), around Ballachulish (Roberts, 1976) and around Kinlochleven (Treagus, 1974). It also drew upon the authors' experience in adjoining areas of the South-west Grampian Highlands (Thomas and Treagus, 1968; Roberts, 1974; Roberts and Treagus, 1975).

In the Loch Leven area, Bailey recognized three NW-facing recumbent isoclinal folds, each about 15 to 20 km in amplitude. From north-west to south-east and progressing structurally upwards these are the *Appin Syncline*, the *Kinlochleven Anticline* and the *Ballachulish Syncline*. On the lower limb of the Kinlochleven Anticline, demonstrably inverted strata of the Lochaber Subgroup crop-out over a cross-strike width of some 7 km to form what is known as the *Kinlochleven Inversion*. Bailey also recognized the existence of near co-axial upright 'secondary folds', such as the *Stob Ban Synform*, which refolds both the Kinlochleven Anticline and the Ballachulish Syncline, and additional F2 folds such as the *Kinlochleven Antiform* and *Blackwater Synform* that deform rocks of the Kinlochleven Inversion were recognised by Roberts and Treagus. The lower limbs of the two major synclines were considered by

Bailey to be largely replaced at an early stage in the deformation by tectonic slides: the *Fort William Slide* beneath the Appin Syncline and the *Ballachulish Slide* beneath the Ballachulish Syncline. However, the apparent excision of strata along the Fort William Slide, at least in this area, has been shown subsequently to be due to an unconformity in the lower part of the Appin Group (Glover, 1993).

Any fundamental departures from Bailey's regional interpretation have been refuted by contemporaneous and later researchers. In particular, Weiss and McIntyre (1957) concentrated entirely on small-scale structures, and by taking no account of the larger-scale structures or overall stratigraphy, failed to recognize any earlier recumbent folds. The concept of large-scale nappes was also completely rejected by Voll (1964) who explained the observed outcrop pattern in the critical Loch Creran area in terms of major facies changes. However, a later paper did recognize the Kinlochleven Inversion, and hence accepted the presence of recumbent folds (Kruhl and Voll, 1975).

Hickman (1978) re-interpreted many of the large-scale folds identified as primary by Bailey and by Roberts and Treagus, as secondary, F2 structures. Large-scale recumbent F1 folds were recognized only in the eastern part of the section, and in the north-western part of the section, the Appin Syncline and the *Tom Meadhoin Anticline* (the latter formerly regarded as the upward-facing hinge of the Kinlochleven Anticline) were re-interpreted as separate upright F2 folds. In many respects this model followed the interpretation of Bowes and Wright (1967, 1973), based upon detailed mapping in the Ardsheal peninsula, and was contested by Roberts and Treagus (1980).

A similar major fold geometry has been identified farther to the north-east, around Glen Spean and Glen Roy (Key *et al.*, 1997). There, large-scale recumbent F1 folds, correlated with the Treig Syncline and Kinlochleven Anticline, are refolded by co-axial upright F2 folds, including the Appin Synform, the Stob Ban Synform, the Inverlair Antiform and the Blackwater Synform (Figure 1.9). In this area, the Fort William Slide does seem to exist as a high-strain zone and has been traced around the closure of the Appin Syncline, but it dies out eastwards, where the Lochaber Subgroup appears to rest conformably on the Grampian Group.

Correlation of the major folds to the south-west of Loch Leven, into the area of Loch Creran and Benderloch, and onwards to the Islay Anticline and Loch Awe Syncline, has been the subject of much controversy. The Appin Syncline can be traced from Glen Roy through Ardsheal to Lismore where, according to Hickman (1978), the equivalent *Balygrundle Syncline* refolds an early isoclinal fold, confirming its F2 status. The Tom Meadhoin Anticline was correlated with the *Airds Hill Anticline* of Appin and Benderloch by both Roberts and Treagus (1977c) and Hickman (1978), but whereas the former regarded it as the hinge of the Kinlochleven Anticline, and hence an F1 fold, the latter regarded it as F2. The Ballachulish Syncline was correlated by Roberts and Treagus with the *Beinn Donn Syncline* of Loch Creran but its main trace is subsumed into a complex stack of slides farther to the east in Glen Creran (Bailey, 1960).

The Loch Creran area was described by Litherland (1982) almost entirely in terms of relatively upright F1 folds in a simple 'mushroom-like' structure. He recognized no secondary folds of regional extent, whereas Roberts and Treagus (1977c) concluded that several of the F1 folds are refolded by a continuation of the F2 Stob Ban Synform and Hickman (1978) interpreted some of the upright folds as F2.

Both the Islay Anticline and the Loch Awe Syncline were regarded by Bailey as secondary folds but almost all subsequent workers have interpreted them as primary (e.g. Cummins and Shackleton, 1955; Shackleton, 1958; Rast, 1963; Borradaile, 1973; Roberts, 1974; Roberts and Treagus, 1977c; Litherland, 1982). Roberts and Treagus correlated the Islay Anticline with the Airds Hill and Kinlochleven anticlines, and the Loch Awe Syncline with the Beinn Don and Ballachulish synclines. However, those correlations involve considerable deflections of the fold axial traces and Litherland (1982) suggested alternative, more-direct correlations. He correlated the Islay Anticline with the *Glen Creran Anticline*, and the Loch Awe Syncline with the *Beinn Sgulaird Syncline* of upper Glen Creran.

The correlation of major slides in the west of the Central Grampian Highlands has been the subject of much speculation, especially when they were thought to separate fundamental tectonostratigraphical units. On Islay, the Islay Anticline over-rides the Bowmore Sandstone along the *Loch Skerrols Thrust*, which was formerly equated with the Moine Thrust (Bailey 1917, 1922; Kennedy, 1946). Later authors projected the Loch Skerrols Thrust north-eastwards into the *Benderloch Slide* at Loch Creran, which Bailey (1922) had correlated directly across the Etive Pluton with the Boundary Slide of the Central Grampian Highlands, to form what was later to become known as the '*Iltay Boundary Slide*' (MacGregor, 1948; Rast, 1963). Subsequently, Rast and Litherland (1970) proposed that the Benderloch Slide could be extended north-eastwards beyond the Ballachulish Pluton to continue as the Ballachulish Slide (Figure 1.7, block B). The latter is folded around the closure of the F2 Stob Ban Synform and trends back southwards to Glen Etive, from where Roberts and Treagus (1977c), following Bailey, linked it across the Etive Pluton with a slide in the Dalmally area, to propose once again a single, continuous Boundary Slide. Whatever their connections and correlations might be, the slides in this western area are clearly folded by F2 folds. Hence their initiation and main movement must have been early, and Litherland (1982) suggested that the Benderloch Slide could have been a re-activated synsedimentary fault. However, intense local re-activation of slides in the Dalmally area is compatible with the dominant D2 movements elsewhere along the Boundary Slide (Roberts and Treagus, 1975).

1.5.6 Corrieyairack, Strathspey and the Monadhliath Mountains

Metasedimentary successions in this area of the Northern Grampian Highlands consist almost entirely of rocks of the Grampian Group and the Badenoch Group.

To the south-east and east of the Geal-charn–Ossian Steep Belt, structures are comparable to and share a common history of structural development with those described above in the overlying Atholl Nappe (Lindsay *et al.*, 1989). This structural continuity was used as an argument for including the Grampian Group in the Dalradian, in accord with the proposal of Harris *et al.* (1978), based largely on stratigraphical continuity.

To the west and north-west of the steep belt and its projected continuation, many of the major structures are downward continuations of those that affect higher structural and stratigraphical levels of the Dalradian to the south and south-west, and hence the phases of deformation are broadly comparable.

Semipelites and micaceous tops to graded psammitic beds in the Grampian Group commonly show an early schistosity, usually subparallel to or steeper than bedding, which is clearly folded by the major folds and is assumed to represent S1. In the area around Loch Killin and the Corrieyairack Pass, Haselock *et al.* (1982) also recognized stratigraphical repetitions and minor structures, which suggested the presence of major early isoclines, refolded by the major more-upright regional folds. A similar structural pattern was recorded in the area between the Corrieyairack Pluton and Loch Laggan by Okonkwo (1988). However, major F1 folds cannot be identified anywhere north-east of Glen Roy and the Strath Ossian Pluton (Key *et al.*, 1997).

These areas are dominated by near-upright NE-trending F2 folds that face to the north-west, such as the *Tarff Antiform-Synform pair*, the *Corrieyairack Synform* and the *Creag Mhor Anticline* (Haselock *et al.*, 1982; Key *et al.*, 1997; May and Highton, 1997). Their axes are typically gently inclined to subhorizontal, curvilinear and are associated with a prominent lineation. Farther east, in the upper Findhorn area, the major folds, such as the *Loch Laggan Anticline* and the *Loch Laggan - Monadhliath Syncline-complex*, become tight to isoclinal and, together with the Corrieyairack Syncline, were originally interpreted as primary structures (Anderson, 1956; Piasecki, 1975).

The earliest recognizable folds to affect most of the Grampian Group (F2) are associated locally with high-strain zones and slides, which are particularly abundant close to the contact with the 'basement' of the Badenoch Group (e.g. the *Lochindorb Shear-zone*). In the west, between Loch Lochy and Loch Tarff, the *Eilrig Shear-zone* brings younger Grampian Group rocks to rest upon the Glenshirra Subgroup (Phillips *et al.*, 1993; Key *et al.*, 1997). Microstructures indicate a consistent NW-directed sense of shear and the metamorphic state changes from amphibolite facies above to greenschist facies below the shear-zone. Phillips *et al.* (1993) suggested that this shear-zone might represent the surface expression of a major basal decollement or floor thrust to many of the structurally higher slides and shear-zones.

In places, the D2 structures are indistinguishable from those of similar-style F3 folds. However, in the area between Killin, Farr and upper Glen Kyllachy, D3 structures consist of near-upright open folds with axes generally trending around north–south (Piasecki, 1975; Haselock *et al.*, 1982) (see Figure 5.2b). Minor structures and fabrics of this phase dominate the area, overprinting and commonly obliterating the earlier structures.

A major structural feature of the Northern Grampian Highlands is ta 3–4 km-wide zone that extends almost normal to the Caledonian regional trend from the Foyers Pluton, through Kincraig, to the eastern end of the Cairngorm Pluton. Within this zone, bedding, foliation and F1 and F2 axial surface traces become south-east trending and the upright to sideways-facing folds verge towards the south-west. The change in trend of the major folds from north-east to south-east (see Figure 5.2b) was recognized and investigated in the area between Kincraig and Newtonmore by Whitten (1959) in a detailed petrofabric study of the minor structures, which concluded that the two trends represent a single generation of folds. Later NW-trending open domes (?F4) have a considerable influence on the local outcrop pattern, around Kincraig for example, and expose inliers of Badenoch Group basement. Hence Smith *et al.* (1999) have suggested that the SE-trending zone, which they termed the *Foyers–Cairngorm Lineament*, is founded upon a series of basement 'highs' (see Figure 5.2a), which influenced the orientation of fold axes within the shallow cover of Grampian Group strata.

To the south-west, between the Allt Crom Complex and the Corrieyairack Pluton, the broad arch of the post-D2 (?F3) Glenshirra Dome has a trace that swings from east to north-east (see Figure 5.19). The dome exposes an inlier of the Glenshirra Subgroup and both Haselock *et al.* (1982) and Okonkwo (1988) recognized a zone of high strain between it and the overlying Corrieyairack Subgroup, which they termed the *Gairbeinn Slide* and attributed to D1. However, recent investigations have concluded that the high strain is focused at the boundary between contrasting lithologies within a conformable succession and can be attributed to D2 (Smith *et al*., 1999).

1.5.6.1 Structures affecting the Badenoch Group

The tectonic relationships between the Grampian Group and the Badenoch Group have been discussed in detail elsewhere in this chapter. The current view advocates that the largely migmatitic Badenoch Group constitutes an older basement beneath a cover of Grampian Group metasedimentary rocks and consequently that they have undergone more phases of deformation and metamorphism (Piasecki and van Breemen, 1979a, 1979b, 1983; Piasecki, 1980; Piasecki and Temperley, 1988a; Smith *et al*., 1999).

1.5.6.1.1 The Grampian Shear-zone The boundary between the Grampian Group and the Badenoch Group was formerly taken at a complex zone of shearing and dislocation, up to 200 m in thickness, known then as the 'Grampian Slide' or 'Slide-zone' (Figure 1.7, blocks E and F). Minor slides occur locally both above and below this zone and the slides appear to anastomose on a regional scale. It is now thought that the major slides, and certainly those that contain syntectonic pegmatitic veins dated at c. 806 Ma, are all within the Badenoch Group. However, the effects of later shearing are thought to have extended structurally downwards from the Grampian Group into the basement rocks and hence the Neoproterozoic ductile slides in the Grampian Shear-zone were reworked strongly in places during the Grampian Event. The main reworking is regarded as D2 in the structural sequence identified in the Grampian Group, since the shear fabrics are parallel to the axial surfaces of near-isoclinal folds that fold an earlier fabric assumed to represent D1.

Individual shear-zones range from a few centimetres up to several tens of metres thick and are characterized by intense grain-size reduction, destruction of pre-existing gneissose and migmatitic foliations, attenuation of minor folds, and muscovite growth. They commonly follow lithological boundaries and movement is concentrated locally within pelitic units. A variety of kinematic indicators indicate a mainly top-to-the-north or -north-east sense of shear.

1.5.6.1.2 Structures below the Grampian shear-zone Most parts of the Badenoch Group are characterized by a penetrative gneissose fabric, which is folded by tight to isoclinal, recumbent folds. The gneissose fabric is generally concordant with broad compositional banding, which might represent original bedding. No major F1 folds have been recognized but rare intrafolial folds and local low-angle discordance between the gneissose fabric and compositional banding suggest that early large-scale recumbent structures do exist. This deformation is considered to be broadly coeval with middle- to upper-amphibolite-facies metamorphism and regional migmatization.

The early gneissose fabric of the Badenoch Group successions is crenulated and transposed by the S1 schistosity that affects the Grampian Group rocks, which is associated with a later generation of lit-par-lit migmatites in lithologies of suitable composition.

The outcrop pattern is controlled largely by intermediate-scale folds. In areas of low strain these structures are recumbent to reclined, with a well-developed axial planar crenulation cleavage. In areas of intense deformation the earlier gneissose fabric becomes transposed into the crenulation fabric to produce a new banding. A larger-scale recumbent fold in the Kincraig area, has a NNW-trending outcrop of Glen Banchor Subgroup rocks in its core; its axis trends north-east and it closes to the north-west. All of these folds were regarded by Piasecki (1980) and Piasecki and Temperley (1988a) as affecting only the basement rocks, but are now considered to be part of the D2 phase in the Grampian Group structural sequence. Several phases of later near-upright folding recognized locally in the basement by Piasecki (1980) were correlated with the later deformations in the Grampian Group.

1.5.7 The Banff and Buchan area

The Banff and Buchan area of the North-east Grampian Highlands is bounded to the west and south by major shear-zones and it is distinguished from the remainder of the Scottish Dalradian by different stratigraphical, metamorphic, igneous and geophysical features. The western boundary of this *Buchan Block* is marked by the *Portsoy—Duchray Hill Lineament*, a major tectonic and stratigraphical boundary with a long history of extensional, transtensional, compressional and transpressional activity, which can be traced from the north coast to the Glen Shee area (Fettes *et al.*, 1986, Goodman, 1994). Major stratigraphical discontinuities occur at the lineament (Fettes *et al.*, 1991) and marked differences in metamorphic history on each side indicate major westward overthrusting during the regional D3 event (Baker, 1987; Beddoe-Stephens, 1990). The lineament also appears to have acted as a pathway for magma at various times, influencing the emplacement of both basic and silicic sheet intrusions. The southern margin of the Buchan Block is more difficult to define. It extends at least as far as the granitic plutons of Deeside but farther south the stratigraphical and structural features merge with those of the Highland Border region through an imbricated zone of east–west-trending shear-zones.

Various zones of shearing and dislocation on the western margin of the Buchan Block have been used to define its limit (see Chapter 6, Introduction). On the eastern edge of the Cowhythe Psammite Formation outcrop, a zone of highly deformed rocks marks the position of the *Boyne Line* of Read (1955), which was interpreted as a major slide underlying his proposed Banff Nappe. From the western margin of the Cowhythe Formation, a sub-vertical zone of shearing and faulting extends through Portsoy westwards for over 1 km. This *Portsoy Shear-zone*, which can be traced inland in a general southerly direction to the Cabrach area, is the main surface expression of the northern section of the *Portsoy–Duchray Hill Lineament*.

To the west of the Portsoy–Duchray Hill Lineament, Appin and Argyll group rocks are involved in a series of NW-facing folds, which can be traced down sequence into the underlying Grampian Group. There would appear to be no equivalent to the Boundary Slide in the coast section, although high strain along this boundary does occur in Glen Rinnes, 40 km to the south-west. On the east side of the Buchan Block, recumbent folds which might be correlated with those of the Tay Nappe have been identified in sections around Collieston (see above). However, the Buchan Block is dominated by late, open, broad, upright folds with gently NNE-plunging axes, principally the *Turriff Syncline* and *Buchan Anticline*, within which the upper parts of the Dalradian succession occur in right-way-up sequences (see Chapter 6 for a full discussion).

Early interpretations regarded the Banff and Buchan Dalradian succession as part of an allochthonous, recumbent, SE-facing 'Banff Nappe' (Read, 1923, 1955; Read and Farquhar, 1956) and other authors have suggested that the nappe and its underlying gneissose 'basement' are all allochthonous (Sturt *et al.*, 1977; Ramsay and Sturt, 1979). However, current interpretations suggest that the structures are essentially autochthonous and that successions can be correlated, at least at subgroup level, with those farther to the south-west (see Chapter 6, *Introduction*).

Along the north coast the rocks exhibit locally complex folding with steep dips over much of the section, but regionally they are disposed in the form of a broad, open syncline, the Turriff Syncline. The western limb of the syncline is steep due to a related monoform, termed the *Boyndie Syncline* and to the east it passes into the broad Buchan Anticline. An inlier of gneissose rocks in the hinge of the anticline was thought by Read and Farquhar (1956) to be in the core of the Banff Nappe, which others have equated tentatively with the Tay Nappe (Treagus and Roberts, 1981; Ashcroft *et al*., 1984).

The attitude and style of the consistently upward-facing F1 folds varies according to structural level, being generally upright and open to close at the highest levels in the centre of the late Turriff Syncline and generally close to tight on both limbs, where they face to the north-west, contrary to Read's (1955) model of a SE-facing nappe. Post-D1 structures are restricted to lower structural levels and hence are seen only on the western and eastern limbs of the Turriff Syncline. D2 folds and fabrics are dominant locally, as in the area around Portsoy. The D3 deformation, which post-dates the peak of metamorphism, is represented by westerly verging, small- to medium-scale folds with limits that almost coincide with the andalusite isograd (Figure 6.3a). Larger-scale F3 folds are characteristically monoclinal, as in the Boyndie Syncline. The major Turriff Syncline and Buchan Anticline have been tentatively attributed to the D3 phase by most authors, although their overall open and upright character is more comparable with major D4 structures elsewhere.

One of the most striking features of both stratigraphical and structural maps of the Grampian Highlands is the 20 km-amplitude 'S'-shaped 'knee-bend' in the strata in the area between Braemar and Tomintoul (e.g. Figures 1.1, 1.7, block E, 6.1). The reasons for this major feature are obscure, since there are no obvious associated minor folds or cleavages developed. It is clearly a late structure, as all of the folds and dislocations in the area, including the Portsoy–Duchray Hill Lineament, are folded around it. Such a large-scale structure must reflect deep crustal weaknesses and might reflect crustal block movements in the later stages of the Caledonian Orogeny. It is curious that both axial traces of the 'Knee-bend' appear to be marked by E–W-trending lines of late-Caledonian granitic plutons, the southern one roughly coinciding with the Deeside Lineament.

1.5.8 Structural development of the Grampian Highlands

In most areas of the Grampian Highlands the structural development of the Dalradian has been explained in terms of three or four major episodes or phases of deformation (D1–4), all of which occurred during the Caledonian Orogeny. Pre-Caledonian events are recorded only in the Badenoch Group and the Rhinns Complex. During the first widespread Caledonian deformation (D1), close to tight major folds were initiated with a north-east–south-west axial trend. The D1 structures are widespread but were commonly transposed during later events and hence are difficult to detect except in the south-west and south-east. Metamorphism at this stage did not exceed greenschist facies. D2 structures affect almost all Dalradian strata except for those at the highest structural levels, close to the Highland Boundary Fault. During D2 the F1 folds were extensively modified, either by near-co-axial refolding or, at deeper levels, by simple shear on a regional scale. Much of the observed high strain and/or displacement along major slides can be attributed to the D2 phase, although the slides might have been initiated earlier, during D1 or as synsedimentary growth faults. A separate D3 phase of generally more-upright folding can be identified in most areas, except within about 5–10 km of the Highland Boundary Fault. It is broadly coincident with the peak of regional metamorphism and associated igneous intrusion, although it might be a little later in some areas, particularly in the north-east. Various late-tectonic phases overprint the composite foliations of the early nappes and the F2 and F3 fold-complexes. The most widespread, D4 structures are within the Highland Border Steep Belt and the Buchan Block but still-later phases occur locally. They are all separated from the earlier movements by a significant time gap and seem to be the result of a change in tectonic regime from ductile folding to basement fracture and block uplift, possibly coeval with but not necessarily resulting from the Scandian (Baltica–Laurentia) collision.

1.5.8.1 Early crustal shortening (D1)

The early regional syntheses of E.B. Bailey and others established that the Dalradian strata are disposed in large-scale recumbent folds or nappes that originated early in the deformational sequence. The mechanism of nappe development was not considered at that time, apart from an 'eddy' theory in which NW-directed movements in the lower structural levels are compensated by movements in the opposite direction at higher levels (Bailey, 1938). South-eastward gravity sliding of the higher nappes was proposed by Cummins and Shackleton (1955) and has subsequently been invoked by several authors in conjunction with various models (e.g. Bradbury *et al.*, 1979; Shackleton, 1979; Anderton, 1988) (Figure 1.10c). However, the first overall models involved the concept of a root-zone, from which nappes were expelled laterally in opposing directions (Sturt, 1961; Harris, 1963; Rast, 1963; Thomas, 1979, 1980) (Figure 1.10a). These were refined into models in which essentially upright major folds fanned outwards as 'mushroom' or 'fountain' structures above the root-zone and then 'collapsed' under gravity in a continuous process to produce the recumbent structures (Roberts and Treagus, 1977c, 1979; Nell, 1986; Treagus, 1987) (Figure 1.10b). The later models emphasized the importance of north-westerly directed movements, particularly on such structures as the Ballachulish and Boundary slides, possibly rising from a fundamental 'floor thrust' (Bradbury, 1985; Mendum and Fettes, 1985; Nell, 1986; L.M. Hall in Fettes *et al.*, 1986; Treagus 1987) (Figure 1.10d). Thus, despite the apparent dominance of the SE-facing Tay Nappe, overall movement in the Grampian Highlands was considered to be to the north-west, and hence the structural development of the whole Scottish Caledonides could be modelled as a complete entity from the Highland Border to the Moine Thrust Belt, where Caledonian structures over-ride the foreland (e.g. Coward, 1983; Fettes *et al.*, 1986). All of the above models have been summarized by Stephenson and Gould (1995, pp. 102–107), from where Figure 1.10 has been taken.

The overall concept of a root-zone and a 'mushroom' or upright 'fountain' of primary folds has fallen out of favour. Most authors find it difficult to imagine major nappes being expelled in this manner from such a narrow zone, either laterally or vertically, and root-like F1 folds are difficult to identify with any certainty in the complex steep belts (e.g. Shackleton, 1979; Coward, 1983). There is no direct evidence regarding the original attitude of the F1 folds (i.e. upright or recumbent) and current conflicting views are dependent upon how they are seen to relate in particular to the development of the Tay Nappe (see below).

1.5.8.2 Peak deformation (D2)

The history of development of the Tay Nappe is central to all interpretations of the overall evolution of the Grampian Highlands and is a matter of continuing discussion. It is possible that SE-facing folds, such as the Tay Nappe, originated as primary (D1) structures, in which case the F1 folds were most likely to have been recumbent and tight to isoclinal (e.g. Mendum and Fettes, 1985; Mendum and Thomas, 1997). However, other authors have considered that their current geometry and facing direction is a result of subsequent deformation during the D2 phase. Both backward gravitational collapse of an upright 'nappe fountain' (Roberts and Treagus, 1977a, 1977c; Treagus, 1987; Figure 1.10b) and large-scale isoclinal backfolding of an original NW-facing Tay Nappe (L.M. Hall in Fettes *et al.*, 1986; Figure 1.10d) have been suggested. New fold hinges formed by either of these mechanisms became F2 folds, such as the the Ben Lui Fold-complex, which has the overall effect of 'righting' the inverted limb of the Tay Nappe.

However, most authors now agree that the D2 deformation was almost continuous with D1 as part of a single progressive event and had a high simple-shear component. Nell (1986), Treagus (1987) and Anderton (1988) all suggested that the F2 folds were overturned towards the north-west at deep structural levels where they were associated with NW-directed simple shear along the Boundary Slide and related dislocations. At higher levels, the upright F1 folds became translated by SE-directed simple shear, also of D2 age, to produce the intense deformation of the inverted limb of the Tay Nappe in the Flat Belt as described by Harris *et al.* (1976) (echoes of the 'eddy' theory of Bailey, 1938).

Most current models for the development of the Tay Nappe invoke near-upright compressional F1 folds, the lower levels of which were subjected to top-to-the-south-east simple shear as a result of north-westward subduction beneath the Laurentian margin (e.g. Krabbendam *et al.*, 1997; Treagus, 1999; Rose and Harris, 2000). At higher levels the upright F1 folds were little affected by the D2 deformation, except that they might have developed a south-east vergence (P.W.G. Tanner, personal communication, 2008). They are preserved only in the Aberfoyle Anticline and equivalent folds in the Highland Border Steep Belt. At lower levels, the originally SE-facing limbs became the dominant long limbs of shear-folds, giving the impression of being part of a single inverted lower limb of a large-scale nappe (see Figure 1.11). Krabbendam *et al.* (1997)

estimated the structural thickness affected by the shear to be 4–5 km, with a displacement of 10–50 km.

In areas to the north-west of the Tay Nappe, the F1 folds were considerably modified by generally co-axial F2 folding, which is particularly well developed above the Boundary Slide and in the various steep belts. To the north-west of the Geal-charn–Ossian Steep Belt, NW-facing nappes, such as the Ballachulish Nappe, were refolded into upright folds such as the Stob Ban Synform. However, most of the F2 folds were originally recumbent and verged to the north-west. They are typically close to isoclinal and are almost always associated with the dominant foliation (S2), which varies from pressure-solution striping to crenulation, schistosity or gneissosity, depending on lithology, metamorphic grade and amount of strain. Extremely strong fabrics, some submylonitic, in high-strain zones on the attenuated limbs of large-scale F2 folds are continuous with the penetrative S2 fabrics, confirming the D2 affinities of major slides, most of which moved in a top-to-north-west thrust sense during this phase. The stacking produced by the D2 refolding and thrusting resulted in considerable crustal thickening that eventually led to the classic Barrovian metamorphism.

1.5.8.3 Waning deformation and peak metamorphism (D3)

The D3 deformation phase is dominated by more-upright structures that are particularly well represented in the various steep belts such as the Tummel Steep Belt. They formed under lower to middle amphibolite-facies conditions, and were associated with locally high temperatures producing minor granitic melts and pegmatitic segregations. The F3 folds clearly fold the dominant S2 fabrics and vary from open to tight, with moderately inclined to vertical axial planes. Axial planes and fold axes display highly variable orientations; in many places the F3 folds are co-axial with F2 folds, but elsewhere they developed at right angles, as in the Carn Dallaig Transfer Zone near Kirkmichael, and spectacular non-co-axial interference structures are seen in some areas.

1.5.8.4 Post-nappe deformation and uplift (D4 and later)

The later phases of Caledonian deformation were, with notable local exceptions, generally less intense and produced more-open, near-upright structures trending between east-north-east and north-east. These take the form of broad upright folds, chevron-style minor folds, crenulations and brittle structures; well-developed axial planar fabrics are generally seen only in hinge-zones. The numbering of later phases is frequently inconsistent and is complicated by local variations (see for example the scheme adopted by Treagus, 2000 to identify late phases in the area north of Schiehallion, which uses local letters rather than regional numbers). However, most authors are agreed upon the existence of a late, D4 phase that is associated with retrograde metamorphism.

The D4 phase probably included more than just one type of tectonic mechanism but most authors have attributed the initial, most widespread D4 deformation to the commencement of late-orogenic isostatic uplift (Watson, 1984; Harte *et al*., 1984; Mendum and Fettes, 1985; Dempster, 1985a). The scale, monoformal nature and lateral continuity of many of the earlier F4 folds, especially the Highland Border Downbend, suggest that they are controlled by a parallel series of major basement lineaments. Between these lineaments episodic uplift of crustal blocks at different rates generated the pattern of contrasting flat and steep belts which now dominates the south-eastern Grampian Highlands.

The Highland Border Downbend is the largest and most obvious D4 structure and is responsible for the downturning of the hinge-zone and part of the lower limb of the Tay Nappe into the Highland Border Steep Belt. The D4 deformation is also probably responsible for the steepening of major F2 and F3 fold limbs in the Knapdale, Tummel and Cairnwell steep belts. In the North-east Grampian Highlands, the Turriff Syncline, Buchan Anticline and other late NE- to NNE-trending open to close folds are regarded as D4, although they are often difficult to separate from D3 structures. Renewed movements at this time on major shear-zones such as the Portsoy Shear-zone, probably resulted in further disruption and re-orientation of intrusions of the North-east Grampian Basic Suite.

Minor folds and crenulation cleavages that overprint the earlier D4 major flexures locally, can be traced north-westwards across the Flat Belt, where they are seen to be related to broad, upright folds such as the Ben Lawers Synform (termed F3 by Treagus, 1987, 2000). These are taken to indicate a later D4 compressional phase which post-dates the earlier D4 uplift event. Roberts and Treagus (1977c, 1979) and Treagus (1987) also considered that the Drummochter and Glen Orchy domes are late-D4 compressional structures (i.e. their D3).

Other late major folds, such as the Bohespic Antiform and Errochty Synform, north of Schiehallion, which have a more north–south trend, were attributed to D4 (his D3) by Thomas (1979, 1980). They were considered to belong to a post-D4 phase (i.e. post his D3) by Treagus (1987) but were then re-interpreted as pre-dating D4 (his D3) by Treagus (2000). Whatever their relative age might be, they form part of a set of major north- to NNE-trending folds between the Ericht–Laidon and Loch Tay faults, which Treagus (1991) related to the initiation of sinistral movement on the faults. Refolding and overprinting by more-definitely later fabrics are generally only of local extent and tend to be small-scale, brittle open box folds and conjugate kink-zones. However, significant NW-trending flexures and monoforms affect the limbs of the Errochty Synform (Thomas, 1980; Treagus, 2000), and Roberts (1974) described a complex sequence of late structures from the South-west Grampian Highlands.

1.6 METAMORPHISM OF THE GRAMPIAN HIGHLANDS

D.J. Fettes and A.G. Leslie

The metamorphic grade expressed in the Dalradian rocks of the Grampian Highlands was initally referred to index minerals in pelitic rocks. Barrow (1893, 1912), working in the south-east of the Grampian Highlands, was the first to establish a zonal sequence in such rocks, indicative of progressive metamorphic grade. This scheme, slightly modified by Tilley (1925), became the classical Barrovian zones (chlorite → biotite → garnet → staurolite → kyanite → sillimanite). Subsequently, Read (1952) recognized a different style of metamorphism in the North-east Grampian Highlands, characterized by a progressive mineral sequence, which he termed the Buchan zones (biotite → cordierite → andalusite → sillimanite). The overall pattern of metamorphic zonation across the Grampian Highlands was established principally by Elles and Tilley (1930), Kennedy (1948), Chinner (1966), Dewey and Pankhurst (1970) and Winchester (1974) and comprehensive summaries of the metamorphic reactions that define the boundaries of the metamorphic zones were provided by Atherton (1977), Harte and Hudson (1979) and Hudson (1980). Although these workers all made use of zonation in pelitic and calc-silicate rocks, the metamorphic grade is more-generally illustrated by the broader concept of metamorphic facies, which is applicable to all lithologies (Fettes *et al.*, 1985; Harte, 1988). The basis of the correlation between the mineral zones and the range of facies was given by Fettes *et al*. (1985).

Read (1952) regarded the Barrovian and Buchan metamorphisms as quite separate events. However, Johnson (1962, 1963) demonstrated that the two metamorphisms were coeval relative to the deformation sequence, a conclusion subsequently supported by radiometric dates (Oliver *et al.*, 2000). Fettes *et al.* (1976) demonstrated that the Buchan zones are part of a progressive decrease in the pressure of metamorphism (or increase in the geothermal gradient) from the South-west to the North-east Grampian Highlands. The transition from the Barrovian to the Buchan areas was detailed by Harte and Hudson (1979), who defined a series of four zonal sequences reflecting decreasing pressure, namely: *Barrovian* (biotite → garnet → staurolite → kyanite → sillimanite), *Stonehavian* (biotite → garnet → chloritoid + biotite → staurolite → sillimanite, *West Buchan* (biotite → cordierite → andalusite → staurolite → kyanite) and *East Buchan* (biotite → cordierite → andalusite → sillimanite → sillimanite + K-feldspar). That is, the transition from Barrovian zonal sequences to Buchan sequences occurs both northwards along the Stonehaven coast and eastwards along the Banffshire coast. Strictly, the Buchan sequence as defined by Read (1952) is restricted to eastern Aberdeenshire. However, the term Buchan metamorphism is commonly used for the area of low-P/T type, that is the West Buchan and East Buchan sequences of Harte and Hudson (1979). Similarily the type area of Barrovian metamorphism is the Angus glens and eastern Perthshire, although the term is commonly used to describe the wider area of intermediate-P/T type (see below).

The above studies clearly indicate that the Buchan and Barrovian sequences are expressions of the variable pressure-temperature conditions, in both space and time, of the Grampian Event; the two sequences are broadly synchronous and are not separate or dissociated metamorphisms.

The metamorphic history of the Dalradian rocks on the Shetland Isles and its timing relative to Caledonian deformation is difficult to correlate with that of the Grampian Highlands and is discussed separately in the introduction to Chapter 7.

1.6.1 Distribution of facies

The distribution of metamorphic facies is shown in Figure 1.12. This shows the general increase in grade from greenschist facies in the South-west Grampian Highlands, north-eastwards through the epidote-amphibolite facies to predominantly amphibolite facies; greenschist-facies assemblages wedge out as two arms running, respectively, along the Highland Boundary and Great Glen faults. The greater part of the higher grade rocks lie in the lower amphibolite facies, characterized by kyanite + staurolite and andalusite + cordierite assemblages. In the Northern and North-eastern Grampian Highlands the rocks reach middle and upper amphibolite-facies conditions, characterized by sillimanite + muscovite and sillimanite + K-feldspar assemblages. Superimposed on the main metamorphic facies from Loch Tay to Kintyre is a regional zone marked by the development of late-stage albite porphyroblasts (Watkins, 1983).

Some earlier zonal maps differentiated areas of ‘migmatites’ (e.g. Dewey and Pankhurst, 1970; Fettes, 1979). These rocks are characterized by the presence of quartzofeldspathic lenses, pods or stringers and are generally associated with sillimanite-bearing amphibolite-facies rocks. Barrow (1912) originally considered the migmatites as the heat source for the metamorphism, a view echoed by Kennedy (1948) and Read (1955). However subsequent studies have shown that the ‘migmatites’ encompass a variety of products including coarse sillimanite gneisses and true anatectic melts (e.g. Atherton, 1977; Ashworth, 1976, 1979). These products were derived by a range of relatively high-grade metamorphic and metasomatic processes, and the presence or absence of ‘migmatites’ at the local scale is largely controlled by the chemical composition of the host lithologies. As such, ‘migmatites’ can be regarded as by-products of high-grade metamorphism with no direct significance in terms of the pattern of metamorphic facies.

The boundaries of the facies, or the regional isograd surfaces, are broadly flat lying over the greater part of the Northern and Central Grampian Highlands but steepen markedly against the Highland Boundary Fault, particularly in the east towards Stonehaven. This pattern of facies and facies boundaries led Kennedy (1948) to propose the concept of a ‘thermal anticline’ whose core is marked by the higher grade rocks and which plunges south-westwards. The distribution of the metamorphic facies is now generally considered to represent the peak conditions during the Grampian Event. Although there is evidence of a pre-Grampian (Knoydartian) regional metamorphic event in the Badenoch Group, no evidence of overprinting consistent with polyorogenic metamorphism has been identified in the facies pattern in Dalradian strata. No regionally significant areas of retrogressive metamorphism are present.

1.6.2 Age of metamorphism and relationship to ductile deformation

Elles and Tilley (1930) suggested that the metamorphism was broadly coeval with the early deformation, but that no metamorphism accompanied the later folds, which demonstrably fold the isograd surfaces. Later workers placed emphasis on the textural relationship between porphyroblast growth and deformational fabrics (e.g. Rast, 1958; Sturt and Harris, 1961; Johnson, 1962, 1963; Harte and Johnson, 1969). This work broadly showed that growth started during the early deformation and that the peak took place after the main nappe-forming or crustal thickening phases but before the later uplift phases, that is syn-D2 to late-D3 (Strachan *et al*, 2002). The late deformation was accompanied by only limited and localized retrogression, due to relatively rapid uplift of the succession.

A maximum age for the metamorphism is given by the age of the youngest rocks that have been affected, namely the top of the Trossachs Group, which Tanner and Sutherland (2007) gave as early Arenig (*c.* 477 Ma). The later stages of metamorphism in the North-east Grampian Highlands are given by a series of dates on syn- to late-metamorphic intrusions, such as the Strichen Granite (473 Ma, Oliver *et al.*, 2000), the Insch Pluton of the North-east Grampian Basic Suite (470 Ma, Dempster *et al.*, 2002) and the Aberdeen Granite (470 Ma, Kneller and Aftalion, 1987). A minimum age is given by dates from post-metamorphic granites such as Kennethmont at 457 Ma (Oliver *et al.*, 2008). This accords with dates of 473-465 Ma for garnet growth (roughly from syn-D2 to syn-D3) in Glen Clova given by Baxter et al. (2002). Baxter et al. further proposed that the peak conditions in the kyanite, sillmanite and garnet zones were effectively synchronous.

In the Northern Grampian Highlands, the age of the metamorphism has been given as 470–450 Ma based on U-Pb monazite ages by Barreiro (quoted by Phillips *et al.*, 1999).

Although conditions and exact timing varied across the Dalradian belt, in general metamorphism, that is porphyroblast growth, lasted about 10 Ma from *c.* 474 to *c.* 464 Ma, with peak conditions around 470 Ma. This accords with a date for peak conditions for Grampian tectonothermal events in Connemara in western Ireland of *c.* 470 Ma (Friedrich *et al.*, 1999).

In the Grampian Highlands the main metamorphism was rapidly followed by cooling and uplift, which had occurred by at least *c.* 460 Ma (Dempster, 1985a; Dempster *et al.*, 1995; Soper and Evans, 1997; Soper *et al.*, 1999; Oliver *et al.*, 2000). Dempster (1985a) further argued for significant uplift and cooling episodes at 460-440 Ma and 410-390 Ma.

1.6.3 Facies variations in space and time

Although the pattern of the Grampian metamorphism is broadly uniform throughout the Grampian Highlands there are significant variations. Fettes *et al.* (1976) documented an increase in geothermal gradient from the South-west to the North-east Grampian Highlands and P-T estimates have subsequently quantified those variations. Thus temperatures of *c.* 550°C were recorded for lower amphibolite-facies conditions across the Northern and North-east Grampian Highlands but at markedly different pressures in different areas: namely 9–10 kbar in the Schiehallion area (Baker, 1985), 7–8 kbar in western Aberdeenshire (Baker, 1985) and in the Monadhliath (Phillips *et al.*, 1999), 5–6 kbar in Angus (Dempster, 1985a; Zenk and Schulz, 2004), and 3–4 kbar in Banffshire (Beddoe-Stephens, 1990). In addition, Graham (1983) recorded pressures of 8–10 kbar for epidote-amphibolite-facies rocks in the South-west Grampian Highlands, whereas similar facies rocks in Buchan record pressures of 2–3 kbar (Hudson, 1985; Beddoe-Stephens, 1990). Although these figures indicate systematic variations across the Grampian Highlands there are also significant variations in style and timing at a local scale with marked kinks in the P-T-t loops. Harte (1988) categorized these variations into six regions characterized by different metamorphic and tectonic styles with their boundaries coincident in part with major lineaments (Ashcroft *et al.*, 1984; Fettes *et al.*, 1986).

1.6.3.1 South-west Region

This region encompasses the area south-west of the Cruachan Lineament (Graham 1986). This lineament separates a higher density block to the south-west, dominated by the thick succession of the mafic Tayvallich Volcanic Formation, from a lower density block to the north-east with a markedly lower abundance of mafic intrusive rocks. The lineament also marks the south-western limit of granitic plutons.

The region is characterized by greenschist-facies metamorphism with a thin spine of garnet-bearing epidote-amphibolite-facies rocks running through the centre. The biotite isograd swings through 90° across the Cruachan Lineament from a north-west trend to the north to a south-west trend to the south (Figure 1.12). The metamorphism is characteristically of a low-temperature–high-pressure type compared to that in the rest of the Grampian Highlands, with reported temperatures ranging from 410 to 530°C (in garnet-bearing rocks) and pressures in the range 8–10 kbar (Graham and Harte, 1985). A later retrogressive phase is associated with lower greenschist-facies conditions and pressures of *c.* 6 kbar. Graham (1986) attributed this distinctive style of metamorphism, particularly the absence of high-temperature assemblages, to the relatively low conductivity and low heat-production potential of the mafic rocks. He also noted that the peak of metamorphism in the region was closely associated with the early deformation and thus relatively earlier than in the other regions.

1.6.3.2 South Perthshire Region

This region lies between the Cruachan Lineament and the Portsoy–Duchray Hill Lineament and extends northwards from the Highland Boundary Fault to the Tummel Steep Belt. It encompasses the Highland Border Steep Belt and the Flat Belt of the Tay Nappe. The metamorphism is represented in classical Barrovian zones, reflecting a regional increase in grade to the north. The main porphyroblast growth took place after the nappe-forming movements, essentially post-D2 to syn/post-D3 (Bradbury, 1979; Watkins, 1985). Dempster (1985a) contrasted the presence of chloritoid + biotite assemblages in Perthshire with their absence from the Angus glens to the east (South-east Region), indicating slightly lower pressures of metamorphism than in the latter.

The zone of late-stage albite porphyroblast growth extends from this area into the South-west Grampian Highlands. Watkins (1983) noted that the albite porphyroblasts occur in the crests of regional F3 folds and attributed their origin to a late-stage metamorphic phase driven by dehydration fluids trapped in the fold crests. However, Dymoke (1989) suggested that the albite porphyroblasts were a prograde product initiated by a phase of D3 movements in rocks at temperatures still close to their maximum.

Elles and Tilley (1930) noted inverted metamorphic zones in the Balquidder area with garnet-zone overlying biotite-zone rocks. Watkins (1985) argued that, since porphyroblast growth post-dated the major nappe-forming movements in this region, the inversion could not be tectonic. He suggested that the inversion represented a negative thermal gradient, attributed to emplacement of relatively hot rocks at higher levels during the nappe formation. It is also possible however, that garnet crystallization was either inhibited in the biotite zone by bulk-rock compositional control or was subsequently retrogressed by late-stage fluid movement. Watkins (1985) argued though that retrogression was not a significant factor.

Dempster (1985a) studied the cooling ages recorded by a number of mineral species along two north–south transects of the Highland Border. In this region he noted differential and spasmodic uplift; over most of the transect the rocks show an initial slow cooling phase from the peak metamorphic conditions followed by a period of rapid uplift and cooling.

1.6.3.3 South-east Region

This region extends from the Highland Boundary Fault northwards to the River Dee, east of the Portsoy–Duchray Hill Lineament, and is the classical area of *Barrovian metamorphism* (Barrow, 1893, 1912; Tilley, 1925). However, in the east of the region, lower pressure chloritoid + biotite assemblages are present, both transitional to, and within, the area of *Stonehavian metamorphism* (Harte and Hudson, 1979, fig. 2).

The main porphyroblast growth occurred from syn-D2 to syn-D3 with a late phase of sillimanite growth slightly post-D3 (Harte and Johnson, 1969; McLellan, 1985). Throughout the region, the isograd surfaces trend broadly parallel to the Highland Boundary Fault and steepen markedly against it. Chinner (1978) suggested that the cause of the steepening was underthrusting by cold material, but Harte and Hudson (1979) attributed it partly to late folding but also to the presence of a tectonic boundary, roughly coincident with the Highland Boundary Fault; a subsiding basin to the south brought cold rocks into contact with the northern sequences at the time of metamorphism.

In a transect of this region, Dempster (1985a) deduced that the northernmost or structurally deepest rocks recorded the oldest cooling ages, indicating relatively rapid uplift. In contrast, rocks rotated into the Highland Border Steep Belt by late folds show evidence of very slow cooling. He suggested that the rapid uplift of hot rocks from depth might have resulted in heat transfer to adjacent blocks, thus prolonging or promoting metamorphism in those blocks.

1.6.3.4 North Perthshire Region

This region encompasses the Tummel Steep Belt and extends northwards across the Central Grampian Highlands to the Boundary Slide. The rocks in this region are steeply dipping, in contrast to the flat-lying aspect of those to the south in the Flat Belt of the Tay Nappe. Dempster and Harte (1986) noted that the Barrovian zones, which show a progressive increase in metamorphic grade across the Flat Belt, are poorly developed within the Tummel Steep Belt. This they attributed to continued porphyroblast growth in the northern region; porphyroblast growth in the Flat Belt took place between D2 and D3 and syn-D3, whereas in the Tummel Steep Belt growth continued post-D3. They further calculated that the later porphyroblast growth in the north was accompanied by a significant increase in ambient pressure conditions, rising from 7 kbar (at 550°C) in the earlier growth phase to 9 kbar (at 550°C) in the later. This pressure increase was attributed to D3 rotation and deeper burial of originally flat-lying strata in the Tummel Steep Belt, thus promoting continued porphyroblast growth.

Dempster (1985a) suggested that the region cooled rapidly to *c.* 300°C in the period 460–440 Ma; the fact that the rocks in the Tummel Steep Belt do not record a temperature rise consequent upon their burial was attributed to uplift shortly afterwards.

1.6.3.5 Buchan Region

This is essentially the area of *Buchan metamorphism* (Read, 1952), encompassing the *East Buchan* and *West Buchan* sequences of Harte and Hudson (1979). The area lies east of the Portsoy–Duchray Hill Lineament and north of the River Dee. The Buchan region hosts a significant number of syn- to late-metamorphic granites as well as intrusions of the 470 Ma North-east Grampian Basic Suite, a unique occurrence in the Scottish Dalradian. The area is relatively simple in structure; the D1 and D2 phases have not given rise to major nappe structures, zones of inversion or crustal thickening such as are seen in other regions. In addition, the only other deformational phase identified (D3) is manifested by a late crenulation cleavage that demonstrably post-dates the main porphyroblast growth. The area is characterized by high-temperature–low-pressure metamorphic conditions; Hudson (1985) estimated temperatures of *c.* 430°C, 490°C and 510°C for the cordierite, andalusite and staurolite isograds respectively. Pressure estimates are uncertain but were reported by Hudson as 2–3.5 kbar in the staurolite zone.

The North-east Grampian Basic Suite was intruded after the early deformation, broadly coeval with peak metamorphic conditions (Johnson and Stewart, 1960; Johnson, 1962, 1963; Fettes, 1970; Pankhurst, 1970). Droop and Charnley (1985) estimated inner aureole conditions of 700–850°C and 4–5 kbar (granulite-facies hornfelses), indicating an emplacement depth of *c.* 15–18 km. The main regional porphyroblast growth is, in general, difficult to separate from the thermal effects. However, the intrusions undoubtedly boosted ambient regional temperatures and gave rise, for example, to the upper amphibolite-facies sillimanite gneisses around the Huntly–Knock Intrusion (Ashworth, 1975). Harte and Hudson (1979) discussed the possibility of two generations of sillimanite crystallization, the first of regional metamorphic origin, the second related to the gabbroic intrusions, although concluding that both were most probably part of a regional prograde event.

The current position of the kyanite/andalusite isograd is close to the Portsoy–Duchray Hill Lineament. West of this however, there is a zone up to 10 km wide indicative of a pressure increase, where andalusite has inverted to kyanite (Chinner and Heseltine, 1979; Baker, 1985; Beddoe-Stephens, 1990). Beddoe-Stephens noted that pressure conditions east of the Portsoy–Duchray Hill Lineament in Buchan did not exceed 4.5 kbar but that rocks to the west record significantly higher pressures of 8–9 kbar in structurally lower strata. He calculated that a pressure increase of *c.* 2 kbar occurred across the lineament during porphyroblast growth, and that it was this increase that led to the inversion of the regional andalusite to kyanite; the pressure increase was attributed to overthrusting on the Portsoy Shear-zone. Dempster *et al.* (1995) subsequently suggested that the pressure increase might have reflected magmatic loading induced by intrusion of the basic rocks. However the question arises as to whether the intrusions had sufficient mass to produce the necessary overpressures.

Considerable movement occurred on a regional system of shear-zones subsequent to the main porphyroblast growth, deforming the basic igneous rocks, their aureoles and the Dalradian country rocks that were unaffected by gabbro intrusion (Ashcroft *et al.*, 1984). Kneller and Leslie (1984) demonstrated that shearing occurred in rocks at or close to their peak metamorphic conditions and led locally to crystallization of sillimanite (fibrolite) in rocks previously carrying andalusite + cordierite mineral assemblages; this crystallization was attributed to the percolation of hot fluids along the shear-zones.

1.6.3.6 Monadhliath Region

This region covers the remainder of the Grampian Highlands, coinciding broadly with the Northern Grampian Highlands as defined in this volume. It includes rocks assigned to the Badenoch Group and to the unconformably overlying Grampian and Appin group strata. The region contains such notable structural features as the Geal-charn–Ossian Steep Belt, the Eilrig Shear-zone, and the Grampian Shear-zone. The greater part of the area features amphibolite-facies assemblages, the exception being a strip of greenschist-facies rocks lying below the Eilrig Shear-zone (Figure 1.12; Phillips *et al.*, 1993). Phillips *et al.* (1999) reported a coherent metamorphic history across the region, with growth of biotite during D1 and kyanite early in D2. The general conditions for kyanite growth were given as 7–8 kbar and 500–600°C. In the northern part of the region, there was significant decompression during the later part of D2 resulting in conditions of 5–6 kbar and 585–695°C. This moved the rocks from the kyanite stability field into that of sillimanite. However, in the south of the region, no such changes have been observed and the rocks remained in the kyanite field. Phillips *et al.* (1993) suggested peak temperatures of 250°C for the greenschist-facies rocks below the Eilrig Shear-zone in contrast to 550°C for rocks above, suggesting that considerable crustal shortening affected the Grampian Group strata juxtaposed along the shear-zone.

Late-Neoproterozoic syntectonic porphyroblast growth and pegmatitic segregation is recorded in ductile shear-zones within the Badenoch Group and, locally, close to the contact with the younger Dalradian rocks (Hyslop, 1992; Hyslop and Piasecki, 1999). U-Pb monazite analyses from the pegmatites have provided high-precision ages of 808 +11/-9 Ma and 806 ± 3 Ma, and a concordant age of 804 +13/-12 Ma has been obtained from the host mylonite matrix (Noble *et al.*, 1996). More-recent U-Pb dating of single zircon grains within kyanite-bearing migmatites has yielded an age of 840 ± 11 Ma (Highton *et al.* (1999). Together, these data have been interpreted by Highton *et* al. as the effects, in the Badenoch Group rocks, of the high-grade metamorphism and migmatization that is associated with Knoydartian orogenesis farther west in the Moine Supergroup of the Northern Highlands Terrane.

In contrast, radiometric evidence for Neoproterozoic tectonothermal events has yet to be recorded in the succeeding Dalradian rocks. There is evidence of progressive overstep of various lithologies onto the older strata (Smith *et al.*, 1999; Robertson and Smith, 1999), and this, combined with $^{87}Sr/^{86}Sr$ isotopic signatures from the lowest Dalradian strata (Thomas *et al.*, 2004), provides evidence for a significant stratigraphical and tectonothermal break at the base of the Grampian Group. The Badenoch Group rocks have thus been interpreted as a Moine-like metasedimentary basement that was affected by the Knoydartian tectonothermal event prior to deposition of the overlying Grampian Group, which records only Grampian Event deformation and metamorphism.

1.6.4 Metamorphic Models

A great variety of models has been proposed to explain the pattern of metamorphism in the Grampian Highlands. These include the thermal effects of 'older granites' (Barrow, 1912), burial (Elles and Tilley, 1930), thermal zonation around a mountain root (Kennedy, 1948), uprising migmatite domes (Read and Farquhar, 1956), and self-generating heat in tectonically heated crust (Richardson and Powell, 1976). The latter is now generally accepted as an important cause, although it does not explain the very high heat flows in the area of least crustal thickening in Buchan. The high heat flow has been ascribed to deep-seated igneous masses (Harte and Hudson, 1979), and to lithospheric stretching that might have occurred during thermal relaxation immediately following Grampian arc accretion (Kneller, 1985). The latter concept is consistent with the extension necessary for intrusion of the gabbros and with the contrasting structural architecture.

Also within the Barrovian sequences of the south-east Grampian Highlands, several workers have noted the limited time-span of the metamorphism, the requisite rate of heating and the virtual synchroneity of porphyroblast growth in the different mineral zones, and have concluded that advective heat sources are essential (Baxter *et al*., 2002; Ague and Baxter, 2007; Lyubetskaya and Ague, 2010; Viete *et al*., 2011a, 2011b; Vorhies and Ague, 2011). Viete *et al.* (2011a, 2011b) argued for mid-crustal extensional shear-zones that focussed heat sources such as magmas and hot fluids, as well as generating heat through mechanical working; they suggested crustal thickening was not a significant factor. Vorhies and Ague (2011) argued for thermal relaxation of a thickened crust as a general factor in the Dalradian metamorphism but also for significant advective heat input in the Barrovian (*sensu stricto*) and Buchan regions, the heat input being facilitated by the numerous igneous intrusions and associated fluid flow. They noted the variation across the Dalradian belt, with the metamorphism in the South-west Grampian Highlands and western Perthshire being the product of a thickened crust with little or no additional heat source, whereas in the eastern Grampian Highlands (essentially the areas where the greatest temperatures were attained) crustal loading was significantly less and advective heat from igneous intrusions was the major factor in the metamorphism. Viete *et al*. (2011a, 2011b) and Vorhies and Ague (2011) noted spikes in the peak metamorphic conditions, for example the phases of sillimanite growth. This they ascribed to thermal pulses associated with the igneous intrusions.

These systematic changes along the Dalradian outcrop reflect variations in tectonism during the Grampian Event. In the south-west, compression and crust-thickening deformation was greater or lasted longer than in the north-east, where the later phases might have included a period of extension.

Following peak metamorphic conditions at around 470–467 Ma, the entire region was subject to differential and spasmodic uplift, resulting in rapid exhumation and cooling. Ague and Baxter (2007) also suggested that the cooling might have been hastened by the ingress of relatively cold fluids.

1.7 DATING THE DALRADIAN SEDIMENTATION

D. Stephenson

The age of the sediments that became the Dalradian Supergroup is poorly constrained. Fossils are rare, are poorly preserved, and where species have been identified they have a wide stratigraphical range. Tillites and other possible glacigenic deposits raise various possibilities of correlation with global glacial events. As yet few radiometric age determinations have been made on the undoubted interbedded volcanic rocks and most available dates relate to intrusions or later tectonothermal events.

1.7.1 Palaeontology

The palaeontology of the Dalradian was reviewed by Downie *et al.* (1971) and Downie (1975) and there have been few significant developments since then.

In the Appin Group, worm burrows recorded from quartzites by Peach and Horne, (1930) have subsequently been shown to be dewatering structures (Tanner, 1998a) but algal stromatolites have been demonstrated in the Lismore and Lossit limestones (Spencer and Spencer, 1972). The Lossit Limestone has also yielded oncoliths. None are of biostratigraphical value.

In the Argyll Group, the Bonahaven Dolomite Formation has yielded acritarchs and algal stromatolites (Hackman and Knill, 1962; Spencer and Spencer, 1972), including some which suggest a late-Neoproterozoic age (Downie, 1975). Fairchild (1977) recorded possible glauconitized microfossils, but a report by Brasier and McIlroy (1998) of metazoan faecal pellets was subsequently retracted (Brasier and Shields, 2000). The Easdale Slate contains long-ranging, Ediacaran to Cambrian acritarchs (Downie, 1975). Limestone clasts in the Selma Breccia contain oncoliths, catagraphs and other calcareous fossils, which have been assigned to the Ediacaran (Litherland, 1975). However, calcareous and burrowing algae that resemble Early Cambrian and younger forms are also present (Downie, 1975). Acritarchs from the Tayvallich Limestone, which were originally thought to be Early Cambrian (Downie *et al.*, 1971), are now known to have a longer range, extending back into the Ediacaran.

In the Southern Highland Group the search for fossils has concentrated upon the weakly deformed, greenschist-facies metamudstones and metalimestones of the Highland Border area and Turriff Syncline. The Macduff Formation has yielded rare burrows, a few acritarchs and more-widespread microfossils, which resemble highly altered chitinozoa. Downie *et al.* (1971) tentatively identified chitinozoa of early Ordovician, probably Llanvirn, age, and a single specimen of the Ordovician acritarch, *Veryhachium lairdii*, was identified by Molyneux (1998). However, failure to replicate this find and its unusually pristine state of preservation despite metamorphism to biotite grade cast doubt upon its origin. In fact all of these identifications remain controversial and have not gained general acceptance. Similarly, a record of Silurian graptolites by Skevington (1971) is now attributed to a sample labelling error. Possibly one of the most striking features of these generally low-grade rocks is their lack of macrofossils and trace fossils which has led several workers to suggest that they must all be of Neoproterozoic age.

The fossiliferous limestone of Leny Quarry near Callander, which contains latest Early Cambrian Pagetid trilobites (Pringle, 1940; Rushton *et al.*, 1999), is undoubtedly the most reliable palaeontological indicator of the age of the youngest Dalradian strata in Scotland. This outcrop was once regarded as part of the Highland Border Complex, in faulted contact with the Southern

Highland Group (Bluck *et al.*, 1984; Curry *et al.*, 1984). However, a detailed examination of key sections, and in particular that in the *Keltie Water* GCR site, near Callander, has resulted in a radical re-appraisal of the relationship between the Highland Border Complex and the Southern Highland Group (Tanner, 1995; Tanner and Pringle, 1999; Tanner and Sutherland, 2007). It is now accepted that there is both stratigraphical and structural continuity between the Southern Highland Group and the Keltie Water Grit Formation, which includes the Leny Limestone. The south-easterly younging sequence continues through rocks containing mid-Arenig fossils (Rushton *et al.*, 1999), but reports of supposed chitinozoa of younger, Caradoc–Ashgill age by Burton *et al.* (1983) and Curry *et al.* (1984) have now been discounted (Tanner and Sutherland, 2007). Thus, Dalradian sedimentation continued to at least Early Cambrian times and possibly through to Arenig times. The succession of Dalradian Supergroup plus at least part of the Highland Border Complex was then deformed as one, during the Llanvirn-Age Grampian Event.

1.7.2 Correlation of the Dalradian tillites and other possible glacigenic deposits

The tillites at the base of the Argyll Group constitute one of the most persistent stratigraphical markers throughout the length of the Dalradian outcrop. Traditionally they have been correlated with the Varanger tillites in Scandinavia, which had been dated by Rb-Sr methods on associated metasedimentary rocks at *c.* 653 Ma (Pringle, 1972). However, revised estimates for the age of the Varanger tillites (see below) now suggest that they are probably younger than the Tayvallich volcanic rocks at the top of the Argyll Group, necessitating a re-appraisal of the age of all possible glacigenic events represented in the Dalradian successions of Scotland and Ireland.

Prave (1999), Brasier and Shields (2000), Condon and Prave (2000) and McCay *et al.* (2006) have all proposed that the basal Argyll Group tillites can be correlated with the Ghubrah glaciation in the Oman, dated at 723 +16/-10 Ma (Brasier *et al.*, 2000), which is part of the Sturtian global glacial event. If however, as is argued below, the base of the Grampian Group is unlikely to be older than *c.* 750 Ma and might even be as young as *c.* 700 Ma, this correlation would allow little or no time for the accumulation of the Grampian and Appin groups. Even the localized Kinlochlaggan Boulder Bed, interpreted as containing glacially-rafted dropstones and thus recording the earliest glacial influence in the Dalradian, is assigned to the Lochaber Subgroup, is hence almost certainly younger than 720 Ma and cannot be correlated with the Sturtian event. The most likely scenario, based upon currently available worldwide data and proposed by Leslie *et al.* (2008), is that the basal Argyll Group tillites should be equated with the Ghaub glaciation in Namibia at *c.* 635 Ma (Hoffmann *et al.*, 2004), which is regarded as part of the Marinoan global event.

The younger, Southern Highland Group glacigenic dropstone deposits in Inishowen (Donegal, Ireland) and Macduff (North-east Grampian Highlands) could then probably be correlated with the Varanger tillites (now 620–590 Ma, Gorokhov *et al.*, 2001; Bingen *et al.*, 2005) and the Gaskiers Formation of Newfoundland (*c.* 580 Ma, Bowring *et al.*, 2003).

1.7.3 Radiometric dating and isotopic evidence

Age constraints on the initiation of Dalradian sedimentation are poor. The youngest detrital zircons in Dalradian rocks have yielded ages of 900 Ma (Cawood *et al.*, 2003; Banks *et al.*, 2007) and the Grampian Group must be younger than the 800 Ma pegmatites within the Badenoch Group that constitutes its basement. The youngest deformation event recorded within the Moine rocks to the north-west of the Great Glen Fault is *c.* 730 Ma (Tanner and Evans, 2003; Emery, 2005) and it is possible that this might also have affected the lithologically similar Badenoch Group rocks. However, there is no radiometric evidence for Neoproterozoic tectonothermal activity in the Grampian Group or higher parts of the Dalradian Supergroup, which record only Caledonian events. $^{87}Sr/^{86}Sr$ whole-rock isotope data from the oldest metacarbonate rocks of the Grampian Group are consistent with a global late-Neoproterozoic strontium sea-water signature younger than 800 Ma and possibly as young as *c.* 670 Ma (Thomas *et al.*, 2004). Given the mounting evidence for a significant stratigraphical and tectonothermal break at the base of the Grampian Group (Smith *et al.*, 1999), the current consensus is that the base is unlikely to be older than *c.* 750 Ma and sedimentation could have been initiated as late as *c.* 730–700 Ma (Leslie *et al.*, 2008).

Later parts of the Grampian Group have been shown to be stratigraphically continuous with the Lochaber Subgroup in several areas and in general there would then appear to be stratigraphical continuity throughout the Appin Group, with no obvious major tectonic breaks. There are no radiometric dates that cover this interval, which continued at least until the major glacial event at the base of the Argyll Group that could be correlated with global glaciations at *c.* 635 Ma (see above). The time interval represented by this marine glacial interval is not known, but no major unconformity is seen.

At the top of the Argyll Group, the Tayvallich magmatism has been reliably dated by high-precision U-Pb methods on zircons at 600–595 Ma (Halliday *et al.*, 1989; Dempster *et al.*, 2002).

Estimates of minimum radiometric ages for younger parts of the Dalradian depend upon the dating of post-sedimentary tectonothermal events, in particular granites that were intruded into the Dalradian succession and then experienced the same deformation and metamorphism.

Much attention has centred upon the Ben Vuirich Granite Pluton, near Pitlochry. For many years it was believed that this granite was intruded after at least some of the earlier phases of deformation of its Dalradian host rocks (Bradbury *et al.*, 1976; Rogers *et al.*, 1989; Tanner and Leslie, 1994). However, detailed investigations of hornfelsed country rocks and xenoliths within the granite have now suggested that the pluton was emplaced into a previously undeformed sedimentary sequence of the Blair Atholl Subgroup (Tanner *et al.*, 2006). S1 and S2 fabrics, previously thought by some to have been preserved only in the aureole and xenoliths, and hence to be related to Neoproterozoic events, can now be assigned to the mid-Ordovician Grampian Event. The 590 Ma age of intrusion, obtained by U-Pb dating of carefully selected zircons (Rogers *et al.*, 1989) and confirmed by ion-microprobe dates on individual zircons (Pidgeon and Compston, 1992), is now thought to be much closer to the age of sedimentation of the country rocks but prior to any significant tectonic deformation (Tanner *et al.*, 2006). Farther north, in the North-east Grampian Highlands, the Keith–Portsoy Granite was intruded as a number of separate lenticular sheets into Appin Group and lower Islay Subgroup rocks. Zircons from two separate lenses have yielded precise U-Pb intrusion ages of *c.* 600 Ma (Barreiro, 1998).

The Ben Vuirich and Keith–Portsoy granites, together with several other intrusions in both the Grampian and Northern Highlands terranes, comprise the 600–590 Ma Vuirich Suite, which has been shown to have an A-type chemistry (Tanner *et al.*, 2006). This rift-related granitic suite was broadly coeval with the 595 Ma Tayvallich basic magmatism that marks the top of the Argyll Group, and both suites were probably related to a major extensional event that was part of the break-up of the supercontinent of Rodinia, leading eventually to the formation of the Iapetus Ocean (Cawood *et al.*, 2001). Sedimentation of the upper parts of the Dalradian succession took place in marginal basins and on continental slopes resulting from this 'Iapetan Event'.

1.7.4 Conclusions

The detailed chronological interpretation is constantly changing as more and better radiometric dates become available and as other methods are developed, but a reasonable consensus is beginning to emerge.

The Badenoch Group successions must be older than the *c.* 800 Ma pegmatitic veins and mylonites that cut them and they might have been affected by the same 730 Ma tectonothermal event that has been recorded in the Moine successions of the Northern Highlands Terrane. The earliest Grampian Group sedimentation probably post-dates that late-Knoydartian Event, and strontium sea-water signatures of the oldest metacarbonate rocks suggest an age within the range 800–670 Ma. A current best estimate for the age of the basal Grampian Group is 730–700 Ma.

If the tillites at the base of the Argyll Group are correlated with the Marinoan glaciations at 635 Ma, close to the start of the Ediocaran Period, the Grampian and Appin groups together cover a maximum interval of *c.* 95 Ma in the late Cryogenian Period. As yet there is no evidence to enable any chronological subdivision of those groups. The top of the Argyll Group is well defined by the Tayvallich basic magmatism at 600–595 Ma, implying that the group spans some 40 Ma, all well within the Ediocaran.

Granites of the Vuirich Suite were intruded into lower Argyll Group successions at 600–590 Ma, whilst the uppermost Argyll Group and lowest Southern Highland Group sediments were being deposited and prior to any significant tectonic deformation or metamorphism.

It is now accepted by most workers that there is stratigraphical and structural continuity in the Southern Highland Group of the Highland Border region from the Ben Ledi Grit Formation through into the Keltie Water Grit Formation, and the Lower Cambrian Leny Limestone in particular (*c.* 515 Ma on current timescales). Therefore, the base of the Cambrian (at 542 Ma) must lie within the Southern Highland Group, though there is no obvious stratigraphical horizon where it may be located. Although this part of the succession has a total thickness of several kilometres, the general turbiditic nature of the sediments suggests relatively rapid accumulation, and it is difficult to imagine it taking some 80 Ma for them to accumulate. There are no obvious major tectonic breaks and significant stratigraphical hiatuses are difficult to recognize in these facies. It is also possible that sedimentation continued through to mid-Arenig time in the Trossachs Group (*c.* 477 Ma on current timescales).

However. the above model does allow time for the deformation and metamorphism to reach its peak at *c.* 470 Ma in the mid-Ordovician Grampian Event.

1.8 TECTONIC EVOLUTION OF THE DALRADIAN BASINS

D. Stephenson

For much of Proterozoic time, the crustal foundations of Scotland were part of a continental block that also incorporated parts of present-day North America and Greenland. At the beginning of Neoproterozoic time, this block was included within the large supercontinent of Rodinia, where it lay adjacent to blocks that later became the Baltic shield and South America (Figure 1.13). It was only towards the end of Neoproterozoic time that Rodinia became fragmented and the three blocks became respectively the separate continents of Laurentia and Baltica and part of Gondwana. However, many authors have used those names to refer to the respective blocks of continental crust, even prior to their development as separate continents.

Sedimentation of the lower parts of the Dalradian Supergroup recorded events that took place within Rodinia, with later sedimentation recording increased instability and eventual break-up that left Laurentia separated from Gondwana and Baltica by the newly formed Iapetus Ocean. The latest Dalradian sedimentation and volcanism took place in basins on the Laurentian margin of the ocean. Later plate movements, during Early Palaeozoic time, resulted in closure of the Iapetus Ocean and the Caledonian Orogeny. Much evidence for the sequence of orogenic events is recorded by the deformation and metamorphism of the Dalradian strata.

Good, recent overviews of the tectonic setting and evolution of this area are given by Holdsworth *et al.* (2000), Strachan *et al.* (2002) and Leslie *et al.* (2008), on which much of this account is based.

1.8.1 Palaeoproterozoic and Mesoproterozoic events

Little is known about the nature of the crust that was stretched and rifted to form the Dalradian basins. The few areas of basement rock that are exposed within the Grampian Terrane are mostly fault bounded and their tectonostratigraphical affinities are unclear (see above). Despite the present relatively close proximity of the Lewisian Gneiss Complex in the Northern Highlands and Hebridean terranes, there is no evidence for the presence of Archaean crust beneath the Dalradian. Archaean detritus is present throughout the higher parts of the succession (Cawood *et al.*, 2003), but the source has not been identified and could well be distant. However, large amounts of juvenile crust are known to have been generated by Palaeoproterozoic arc magmatism to the south of major Archaean cratons, in both the 'Laurentian' and 'Baltic' crustal blocks. Examples include the Ketilidian Belt (1900–1800 Ma) of Laurentia and the Svecofennian Province (1900–1850 Ma) of Baltica. The Rhinns Complex of Islay and Colonsay (*c.* 1780 Ma) is probably representative of a similar Palaeoproterozoic belt that might underlie much of the Dalradian.

Towards the end of the Mesoproterozoic Era, from *c.* 1100 to 950 Ma, a series of mountain belts was formed around the globe. It was this mountain building event, generally referred to as the Grenvillian after its type area in North America, that led to amalgamation of the supercontinent of Rodinia. Palaeomagnetic reconstructions generally place the crustal blocks that were to become Baltica, Laurentia and the South American sector of Gondwana adjacent to each other, with Scotland positioned close to the triple junction (e.g. Soper, 1994a, 1994b; Torsvik *et al.*, 1996; Dalziel, 1997; Holdsworth *et al.*, 2000) (Figure 1.14a). A Grenville Front is well established in eastern Canada (e.g. Indares and Dunning, 1997) and the effects of the Sveconorwegian Orogeny, of similar age, are widespread in south-western Sweden (Möller, 1998). However, in Scotland, evidence for Grenvillian orogenesis is sparse. It is restricted to the Glenelg–Attadale Inlier, in the Northern Highlands Terrane and the Outer Hebrides Fault-zone, in the Hebridean Terrane (Mendum *et al.*, 2009). The only pre-Grenvillian rocks in the Grampian Terrane, in the Rhinns Complex, show no evidence of Grenvillian reworking and hence it is concluded that the Grenville Front lay farther to the north, buried beneath the extensive cover of post-Grenville metasedimentary rocks.

1.8.2 Pre-Dalradian Neoproterozoic sedimentation and tectonothermal events

The Badenoch Group successions of the northern Grampian Highlands are now generally accepted as having been derived from sedimentary rocks that experienced a tectonothermal event at 840–800 Ma and hence pre-date the earliest Dalradian sediments, which show no evidence of such an event. The generally gneissose and migmatized lithologies yield little evidence of their origin but they undoubtedly comprise one of several thick sedimentary successions that were deposited on the 'Laurentian' crustal block of Rodinia towards the end of and immediately following the Grenvillian

Orogeny. Representative successions in the Northern Highlands Terrane are the Torridon Group (fluviatile) and the Moine Supergroup (fluviatile and shallow marine); sediments of both contain very few Archaean detrital zircons and it has been suggested that they were derived largely from erosion of the Grenvillian mountain belt (Rainbird *et al.*, 2001; Krabbendam *et al.*, 2008).

Outcrops of the Badenoch Group now lie close to those of the Moine Supergroup and they are comparable in lithology to parts of the Moine succession. Their present proximity is largely as a result of terrane assembly during the Caledonian Orogeny and hence direct correlations across the Great Glen Fault are not possible. However, their detrital zircons (Cawood *et al.*, 2003) have a similar age distribution to those of the Morar Group of the Moine and the Torridon Group (Karabbendam *et al.*, 2008) and their broad tectonic setting and age are probably comparable.

The age of the Moine is constrained by its youngest detrital zircons at *c.* 950 Ma (Kinny *et al.*, 1999; Friend *et al.*, 2003), and by later intrusions at *c.* 870 Ma (Friend *et al.*, 1997; Millar, 1999; Rogers *et al.*, 2001). The intrusions, of granitic sheets and tholeiitic basic rocks, constitute a bimodal igneous event, typical of an intracontinental rift setting (Ryan and Soper, 2001), and it probably represents the development of a failed rift between the 'Baltic' and 'Laurentian' crustal blocks.

The earliest known tectonothermal event in the Badenoch Group is recorded by a U-Pb age of *c.* 840 Ma on zircons within migmatites (Highton *et al.*, 1999) and from U-Pb ages of *c.* 806 Ma on monazites from pegmatites and their host mylonites (Noble *et al.*, 1996). [The pegmatites had previously yielded less-precise ages of *c.* 750 Ma by Rb-Sr methods (Piasecki and van Breemen, 1979a, 1983).] Those dates correlate well with numerous dates in the range 820–780 Ma on pegmatites and metamorphic minerals within the Moine which, together with a separate cluster of dates at 750–730 Ma, have been attributed to a major Knoydartian Orogeny (e.g. Rogers *et al.*, 1998; Tanner and Evans, 2003). The extent and nature of those events have been the source of much controversy. Soper and England (1995) envisaged that the Neoproterozoic evolution of the Scottish part of the Laurentian crustal block was dominated by rifting and extension, without any contractional orogenic events. However, by linking radiometric age dating with metamorphic pressure and temperature data, recent work has shown that at least some of the Knoydartian events are contractional (Vance *et al.*, 1998; Zeh and Millar, 2001; Tanner and Evans, 2003). Orogenic igneous activity occurred at *c.* 840–800 Ma in northern Norway (Daly *et al.*, 1991) and sinistral strike-slip motion between the 'Baltic' and 'Laurentian' crustal blocks at *c.* 800–750 Ma, as suggested by Park (1992), might have severed an original close association with the Knoydartian events of Scotland.

1.8.3 Late-Neoproterozoic Dalradian basins

The lithostratigraphy and sedimentology of the Dalradian Supergroup indicate periods of basin deepening and shallowing which, by analogy with Phanerozoic basins, have been attributed to multiple periods of lithospheric stretching, rifting and thermal subsidence. Early phases of rifting and subsidence, possibly from *c.* 730 Ma, took place within the supercontinent of Rodinia. Increasing instability, attributed to progressive lithospheric stretching, first produced a series of fault-bounded basins and eventually culminated in continental rupture, volcanicity and development of the Iapetus Ocean at *c.* 600 Ma (Figure 1.14b). The Grampian Terrane then became part of an extensive passive margin to the new continent of Laurentia, where turbiditic sedimentation continued for at least 85 Ma, and possibly until the early Ordovician (Figure 1.14c).

Several studies have addressed basin architecture and its influence on both the composition and shape of the sediment pile, factors that in turn have affected the morphology of some regional folds. In the Northern Grampian Highlands, basin margins within the Grampian Group and lower parts of the Appin Group can be identified from thickness and facies changes and overstep onto older strata (Glover *et al.*, 1995; Goodman *et al.*, 1997; Smith *et al.*, 1999; Robertson and Smith, 1999). In the South-west Grampian Highlands, Knill (1963), Borradaile (1979), Litherland (1980) and Anderton (1985) identified very rapid lateral facies and thickness changes in the Appin Group and lower parts of the Argyll Group, which imply that syndepositional faulting accommodated the deposition of the essentially shallow-water shelf deposits. Anderton (1985), in particular, envisaged this area of deposition to be divided into a series of NW-dipping fault blocks bounded by 'scoop-shaped' listric faults, which delimited individual basins (Figure 1.15). The faults might also have acted as controls for later sub-marine volcanic activity, and were eventually draped by rapidly deposited sub-marine fan deposits on a subsiding continental margin in Southern Highland Group times.

More-recent studies have concentrated on tracking the evolution and denudation history of the hinterland, through plotting the age distribution and frequency of detrital zircons obtained by Sensitive High-Resolution Ion Micro Probe (SHRIMP) analysis (e.g. Cawood *et al.*, 2003, 2007).

1.8.3.1 Early rifting

Rifting of the 'Laurentian' crustal block was probably initiated during the middle of the Cryogenian Period at some time after 730 Ma and lasted for about 60–70 Ma. Turbiditic sands and muds of the Grampian Group were derived from a hinterland to the west and north-west (Banks, 2005), with at least one basin receiving detritus from the east (Banks et al., 2007). Early models that envisaged a broad ensialic rift, opening north-eastwards to form a marine gulf (Winchester and Glover, 1988), were refined following the recognition of discrete intrabasinal highs separating a series of localized basins (e.g. Robertson and Smith, 1999; see Figure 5.2a). Those early (presumably failed) rift basins had been infilled by the time that deltaic and shelf sands prograded from the south and east across their margins in late Grampian Group and early Appin Group times. The sand- and mud-dominated sedimentary facies associations culminated with diminished sediment input into marginal offshelf to lagoonal, locally emergent, even evaporitic environments in Lochaber Subgroup time (Stephenson, 1993). Ages of detrital zircons show that the source areas throughout Grampian Group and earliest Appin Group sedimentation were dominated by late-Palaeoproterozoic to earliest-Neoproterozoic rocks, possibly from the Ketillidian and Grenvillian mountain belts, such as those that had supplied earlier Neoproterozoic successions in the Northern Highlands Terrane (Cawood *et al.*, 2003; Banks et al., 2007).

1.8.3.2 Post-rift thermal subsidence

Shallow-marine shelf sedimentary facies associations that dominate the remainder of the Appin Group are characteristic of post-rift thermal subsidence, which might have extended for c. 30–40 Ma until the end of the Cryogenian Period at c. 635 Ma. The base of the Ballachulish Subgroup is marked by a major transgression across a flooding surface, which saw the onset and development of wide-ranging and uniform sedimentary lithofacies (Figure 1.15a). Typically, deposition of dark anoxic limestone and mud is followed by shallowing upwards cycles of progradational clean-washed sands and shallow-water muds and limestones. Marine basins at this time were probably wide and shallow as evidenced by remarkably similar successions extending along strike across Ireland and Scotland. Renewed flooding resulted in further deposition of muds and limestones during Blair Atholl Subgroup time, before glacial diamictites were deposited during a major lowstand at c. 635 Ma. In the Central Grampian Highlands, some parts of these basins were interspersed with sediment-starved areas, now expressed by major stratigraphical omissions and subsequent overstep. The flooding at the base of the Ballachulish Subgroup introduced, or just preceded, the arrival of Archaean zircons in detritus and an apparent absence of Grenvillian ones.

1.8.3.3 Renewed rifting

Vigorous extension is recorded by renewed rifting in early-Ediacaran time. Sharply-defined thickness changes become apparent in the Islay Subgroup and are most-likely to have been fault controlled (Anderton, 1985). Instability is recorded by influxes of pebbly sands, debris-flow breccias and slump deposits in the Easdale Subgroup. Localized basaltic volcanic centres became a widespread feature for the first time (e.g. Goodman and Winchester, 1993; Fettes *et al.*, 2011) and synsedimentary exhalative mineralization affected some small basins. Within this increasingly unstable environment the upward-shallowing cyclical behaviour, recorded previously in the Appin Group, recurred briefly in late Easdale Subgroup time, with deposition of shallow-marine shelf sands, limestones and muds. It was only following this stage that the sediment-starved sectors in the Central Grampian Highlands were overstepped as a more rapidly foundering rift system evolved during Crinan Subgroup time (Figure 1.15b). A newly established trough received a deluge of immature siliciclastic sediment that became increasingly dominated by Archaean detritus.

1.8.3.4 Rift-drift transition; the Iapetan extensional event

The rifting of Rodinia during early-Ediacaran (Argyll Group) time eventually led to complete rupture of the continental crust and the formation of the Iapetus Ocean, as the new continents of Baltica and Gondwana drifted away from Laurentia (Soper, 1994b; Figure 1.14c). [Iapetus was the father of Atlas in Greek mythology.]

The timing of this rift-drift transition is generally considered to be tightly constrained by a sudden increase in magmatism at *c.* 600 Ma. Localized episodes of igneous activity had punctuated periods of basin deepening throughout Argyll Group time, but more-voluminous basic volcanism in the South-west Grampian Highlands dominated the Tayvallich Subgroup and eruption continued more-sporadically during deposition of the Southern Highland Group (Figure 1.15c). All of the Dalradian lavas have tholeiitic affinities similar to those formed at accreting oceanic plate margins (Graham and Bradbury, 1981), but the more-voluminous later eruptions show evidence of a more-enriched, deeper mantle source that was able to rise to higher levels as continental rupture progressed (Macdonald *et al.*, 2005; Fettes *et al.*, 2011). Anderton (1985) observed that the thickest volcanic sequences overlie areas of supposed greatest crustal attenuation and it might also be significant that the most-enriched magmas were erupted close to major structures such as the Cruachan and Portsoy lineaments. The Tayvallich basic volcanic rocks have been dated precisely at around 600–595 Ma (Halliday *et al.*, 1989; Dempster *et al.*, 2002), coeval with the foliated, mildly alkaline granites of Keith–Portsoy at 600 Ma and Ben Vuirich at 590 Ma (Rogers *et al.*, 1989). Together they define a major bimodal magmatic event, typical of an extensional rift environment (Tanner *et al.*, 2006).

The onset of the Iapetan extensional event is also recorded in the Northern Highlands Terrane, where a variety of igneous rocks were intruded into the Moine Supergroup between 610 and 590 Ma (e.g. Kinny *et al.*, 2003b). As in the Grampian Terrane, this magmatism was distinctly bimodal, with both basic and silicic intrusions, some with alkaline affinities, and all compatible with a continental rift setting.

The rifting was also heralded by basic (and possibly ultrabasic) volcanism in Shetland which, according to Flinn (2007), was followed very shortly afterwards by burial metamorphism. The metamorphism was boosted by high heat-flow through the stretched and thinned crust, prior to oceanic opening. As the Laurentian passive margin developed, the Dalradian strata become tilted (in the manner of present day 'seaward-dipping seismic reflectors'), were eventually rotated into a vertical orientation and suffered further metamorphism and granitic veining locally under the influence of permeating hydrous fluids. The upper part of the vertical 'slab' was then rotated further to form the inverted limb of a huge monocline that is the main structure of the Shetland Dalradian. Flinn's interpretation places this whole sequence of events in an extensional regime, related to Iapetus opening, some 100 Ma before the Grampian Event affected the Grampian Highlands, possibly overprinting and obscuring any earlier tectonothermal events in that region.

A major change to more-immature sediment, increasingly dominated by Archaean detritus, had already occurred at the base of the Crinan Subgroup. From that time onwards, Palaeoproterozoic zircons became less-abundant in the sediment load, suggesting that either any *c.* 1800 Ma Ketillidian/Rhinnian source had become isolated from the Dalradian basins by the Iapetan rifting or, more likely, that it had been buried by sedimentation (Leslie *et al*., 2008). During Tayvallich Subgroup time, volcaniclastic aprons built out from the volcanic centres and carbonate build-ups on the shelf were reworked into deeper water as redeposited metacarbonate rocks (Thomas *et al*., 2004). In Southern Highland Group time, as the Iapetus Ocean began to widen and the continental margin foundered, turbiditic submarine fans prograded from the margin into the trough and possibly extended along the trough axis, spilling out onto adjacent marginal platforms. Localized volcanic activity continued and volcaniclastic debris was reworked along the margin as 'green beds' (Pickett *et al*., 2006).

1.8.4 Cambrian to early Ordovician sedimentation

It is now generally accepted that deep-water turbiditic sedimentation on the Laurentian side of the Iapetus Ocean continued throughout the later parts of the Ediocaran Period at least until latest Early Cambrian time (*cf*. the Leny Limestone) and possibly into the early Ordovician (mid Arenig) (Tanner, 1995; Tanner and Pringle, 1999; Tanner and Sutherland, 2007; see the *Introduction* to Chapter 4). The younger rocks, currently assigned to the Highland Border Complex, occur only in fault-bounded slivers along the Highland Boundary Fault. They include pillow lavas and remnants of a fragmented ophiolite-complex that must have been obducted onto the margin of the Grampian Terrane at some stage during the Grampian Event (Tanner, 2007; see below).

Coeval with this upper Southern Highland Group–Highland Border Complex succession is the undeformed, non-metamorphosed Cambrian to mid-Ordovician succession of the Hebridean Terrane, described in GCR Volume 18 (Rushton *et al*., 1999). This sandstone and carbonate sequence (the Ardvreck and Durness groups) rests upon a remarkably planar basal unconformity and represents a major marine transgression onto a wide, shallow shelf on the subsiding Laurentian margin.

The two successions, together with their correlatives in East Greenland and north-west Newfoundland, formed subparallel sedimentary belts located along the continuous passive margin of Laurentia (Figure 1.14c). The shelf sequences were deposited on the landward side of the generally deeper water Dalradian-type lithologies that accumulated on the continental slope and rise. Oceanic crust is presumed to have existed to the south-east of the present Dalradian outcrop, where it might ultimately have been covered by progradation of the youngest sediments. All along the former margin, these two successions are now in much closer proximity than they were at their time of deposition due to the effects of crustal shortening during the Caledonian Orogeny.

Whether or not there was originally a continuous transition between them has been a matter of debate (e.g. Dewey, 1969; Bluck *et al.*, 1997; Leslie *et al.*, 2008). However, the ages of their detrital zircons are distinctly different (Cawood *et al.*, 2007), reflecting derivation from different sectors of the Laurentian margin. Palaeocurrent data suggests that the Dalradian sediments were supplied by currents from the south-west, along troughs parallel to the Laurentian shoreline (Anderton, 1985). These could have sampled Mesoproterozoic rocks of the Grenvillian mountain belt currently exposed in eastern Canada, which are not represented by zircon ages in samples from the Ardvreck Group. The sediments of the latter group were transported by currents flowing from the north-west, across the shelf and transverse to the shoreline (McKie, 1990), from a hinterland to the west composed almost entirely of Palaeoproterozoic and Archaean rocks.

1.8.5 The Caledonian Orogeny

The Iapetus Ocean reached its greatest width, of about 2000 km, during late Cambrian time at around 500 Ma. It then began to close rapidly due to the renewed convergence of Laurentia with Baltica and with a microcontinent called Avalonia that separated from Gondwana (Soper and Hutton, 1984; Pickering *et al.*, 1988; Soper *et al.*, 1992) (Figure 1.14d). The combined tectonic and magmatic effects of that convergence, leading eventually to continent–continent collision and subsequent uplift, constitute the Caledonian Orogeny. Prior to the more-recent opening of the North Atlantic Ocean, the resultant Caledonian mountain belt stretched continuously from the Appalachians, through Newfoundland and the British Isles to East Greenland and north-west Scandinavia (Figure 1.3). The western Caledonian Front can be followed from East Greenland, through the Moine Thrust Belt of north-west Scotland to Newfoundland, whilst the eastern front runs through Sweden and Norway. In southern Britain a complex Caledonian Front lies buried beneath younger strata.

Within this broad orogenic framework, many separate events have been identified, several of which have been given specific names. Of most relevance to the Dalradian are the mid-Ordovician peak of deformation and metamorphism, accompanied by localized basic magmatism and crustal melting, termed the Grampian Event, and a period of later folding, uplift and generation of huge volumes of largely silicic magma, during the Silurian, termed the Scandian Event. The Early- to Mid-Devonian Acadian Event, which was responsible for most of the deformation in northern England and Wales, might have been the cause of re-activation of the major bounding faults of the Scottish Highlands (Mendum and Noble, 2010).

The GCR sites in this volume represent Caledonian deformation and metamorphism in the Grampian Terrane. GCR volumes 3 (Treagus, 1992) and 34 (Mendum *et al.*, 2009) represent deformation and metamorphism elsewhere in Britain, and Volume 17 (Stephenson *et al.*, 1999) represents Caledonian magmatism throughout Britain.

1.8.5.1 The Grampian Event

The mid-Ordovician Grampian Event was the first collisional event to affect the Scottish part of the Laurentian margin, and was the first phase of the Caledonian Orogeny (Lambert and McKerrow, 1976). This event is now widely regarded as having been caused by the collision of an arc terrane against the passive margin (Dewey and Shackleton, 1984; van Staal *et al.*, 1998; Oliver, 2001; see Figures 1.14d and 1.16). In Scotland, there is only indirect evidence that an arc is buried beneath post-Ordovician sedimentary cover in the Midland Valley (Bluck, 1983, 1984) and might also occur at depth beneath part of the Highland Border region of the Grampian Highlands. However, parts of an early Cambrian to early Ordovician island arc, together with a suprasubduction ophiolite, are exposed in western Ireland (Dewey and Ryan, 1990). Most Grampian deformation and metamorphism in Scotland occurred in the Grampian Terrane. In the Northern Highlands Terrane, most deformation appears to be Knoydartian (see above) or Scandian (see below), but some significant Grampian tectonic and metamorphic effects have also been proved (Kinny *et al.*, 1999; Dallmeyer *et al.*, 2001; Rogers *et al.*, 2001; Emery, 2005). A comparable mid-Ordovician orogenic event in the Appalachians of eastern North America is known as the Taconic Event (Dewey and Shackleton, 1984).

In Cambrian and early Ordovician times, the Scottish sector of the Laurentian margin consisted of a shallow-water shelf that developed on the foreland of the Hebridean Terrane. This passed south-eastwards into the deep-marine turbidite basins of the Southern Highland Group (Figure 1.16a), where sedimentation was terminated in the mid Ordovician by crustal flexure and/or uplift associated with the Grampian Event (e.g. Soper *et al.*, 1999). The arc-continent collision is thought to have resulted in the obduction or overthrusting of exotic ophiolitic nappes (Figure 1.16b), accompanied by regional deformation and Barrovian metamorphism of the Dalradian rocks (Dewey and Shackleton, 1984; Dewey and Ryan, 1990; Chew *et al.*, 2010). The best-preserved ophiolite-complex occurs in north-east Shetland in two nappes that structurally overlie Dalradian rocks (Flinn and Oglethorpe, 2005). Another ophiolite-complex occurs in the Grampian Terrane at Clew Bay in Ireland and ophiolitic fragments form a discontinuous outcrop along the Highland Border from Bute to Stonehaven (Tanner, 2007). Ophiolites of similar age occur in the Midland Valley Terrane at Ballantrae and Tyrone.

Several authors have attributed the main Grampian deformation to the obduction of ophiolites (e.g. Dewey and Shackleton, 1984; Dewey and Mange, 1999; Dewey, 2005) and it has been common practice to regard their age of emplacement as marking the start of the Grampian Event. Although relatively precise radiometric dates are now available for the crystallization ages of some of the obducted material, attempts to date the time of obduction have so far proved more difficult and, in some cases, contradictory.

In Shetland, an Ar-Ar step-heating age of 498 ± 2 Ma from hornblende in the metamorphic sole of the lower nappe (Flinn *et al.*, 1991) is older than a U-Pb zircon crystallization age of 492 ± 3 Ma for a leucotonalite vein within the ophiolite (Spray and

Dunning, 1991). Nevertheless, Flinn and Oglethorpe (2005) concluded that the lower nappe was obducted at about 500 Ma, i.e. early in the Grampian Event. However, U-Pb monazite ages from pelites in the footwall of the ophiolite nappes have been considered to date the regional metamorphism at 462–451 Ma (Cutts *et al*., 2011). Leucotonalites associated with the Ballantrae ophiolite have yielded a U-Pb zircon age of 483 ± 4 Ma with a marginally younger K-Ar hornblende age of 478 ± 8 Ma on an amphibolite that is considered to date obduction (Bluck *et al*., 1980). Two Cambrian dates obtained from an amphibolite on Bute that have been claimed to date obduction of the Highland Border ophiolite (Dempster and Bluck, 1991) have been questioned by Tanner (2007). The latter, expanding upon a model first proposed by Henderson and Robertson (1982), argued that the Highland Border Ophiolite was obducted at a relatively late stage in the Grampian Event onto the upper limb of an already recumbent Tay Nappe (F1) and hence could not have been responsible for significant early deformation of the Dalradian. However, subsequent work has shown that the ophiolite is relatively early in age and was emplaced prior to D1 (Henderson *et al*., 2009), at around 490 Ma (Chew *et al*., 2010), and prior to the metamorphic peak at *c*. 470 Ma.

It seems reasonable to conclude that fragments of ophiolite were probably obducted at various times in different places during the Grampian Event. Possibly more-reliable indicators of the onset of arc–continent collision in the west of Ireland are U-Pb zircon dates of 489 ± 3.1 Ma and 487 ± 2.3 Ma obtained from leucotonalite boulders unequivocally derived from the Cambro-Ordovician arc (Chew *et al*., 2007). Nd isotope evidence indicates that these leucotonalites had assimilated significant amounts of Laurentian margin sediment and hence that subduction was underway by *c.* 490 Ma. The timing might have varied slightly along the Laurentian margin, particularly if the convergence was markedly oblique, and some authors have suggested that events occurred earlier in Ireland than Scotland.

In the Scottish sector, intra-oceanic obduction and accretion was probably under way by 480 Ma (Tremadoc–Arenig) time, with the Midland Valley Arc beginning to encroach upon the Laurentian margin (Bluck, 2001) (Figure 1.16a). The youngest rocks affected by Grampian deformation in the Highland Border region are at most *c.* 520 Ma (latest Early Cambrian; the Leny Limestone) and possibly as young as c. 475 Ma (mid Arenig; Tanner and Sutherland, 2007). But, by Arenig–Llanvirn time (470 Ma), several lines of evidence indicate that orogenesis was well under way and that the arc had been accreted onto the continental margin (Figure 1.16b).

The Grampian deformation culminated in the formation of major fold stacks or nappe complexes and associated zones of structural attenuation (Figure 1.16c). Structures associated with at least the major phases D1, D2 and D3 were formed at this time. The gross lateral continuity of the Dalradian lithostratigraphy precludes the existence of any large-scale thrusting at the present exposure level but a major zone of top-to-the-SE simple shear in the lower levels of the SE-facing and southerly directed Tay Nappe might reflect underthrusting of the arc beneath the Laurentian margin (Krabbendam *et al*., 1997).

Several suites of plutonic rocks were intruded into the Dalradian rocks of the North-east Grampian Highlands at *c.* 470 Ma, demonstrably during regional deformation and metamorphism. Precisely dated by U-Pb methods on minerals, these include the North-east Grampian Basic suite and two suites of diorite and granite (Kneller and Aftalion, 1987; Dempster *et al.*, 2002). Similar basic and silicic plutons were emplaced at *c.* 470 Ma during the peak of metamorphism in the west of Ireland (Friedrich *et al.*, 1999). These dates are consistent with U-Pb monazite ages of c. 470–450 Ma obtained from Grampian Group rocks of the Northern Grampian Highlands that are thought to date the peak of metamorphism (Phillips *et al.*, 1999).

General consensus is that the main collisional event was relatively short-lived, and its culmination is constrained in both Western Ireland and Scotland to an interval of c. 10 Ma between 475 and 462 Ma (Dewey and Mange, 1999; Friedrich *et al.*, 1999; Soper *et al.*, 1999; Oliver, 2001). It was followed by uplift and cooling as the metamorphic belt was unroofed, starting at *c.* 460 Ma and continuing through to early Silurian time. A range of mineral ages, determined by various methods on muscovite and biotite, suggest relatively rapid cooling through 500°C and 350°C between 470 and 440 Ma and slower cooling through 300°C between 460 and 430 Ma, depending on location within the orogen (Dempster *et al.*, 1995; Soper *et al.*, 1999; Oliver *et al.*, 2000).

Uplift and erosion dispersed Grampian-age metamorphic detritus across the accreted arc (or arcs) and into an accretionary wedge facing the narrowing Iapetus Ocean. In Scotland, such detritus appears in the sedimentary record of the Southern Uplands in the Caradoc Stage (Oliver, 2001). Later strike-slip displacements, which moved structural blocks and possibly whole terranes for considerable distances along the orogenic belt (see below), mean that detailed sediment-dispersal pathways cannot be determined. However, more complete data in the west of Ireland record progressive unroofing of an ophiolite complex during Arenig time, followed by exhumation of the metamorphic belt during the Llanvirn Age (Dewey and Mange, 1999).

1.8.5.2 The Scandian Event

The second main phase of the Caledonian Orogeny, termed the Scandian Event, occurred during early Silurian to Early Devonian time, between c. 435 and 400 Ma. It coincided with the final closure of the Iapetus Ocean, and the docking of Avalonia against Laurentia, but resulted mainly from the collision of Baltica with Laurentia (Coward, 1990; Dewey and Mange, 1999; Dallmeyer *et al.*, 2001; Kinny *et al.*, 2003a) (Figures 1.14 e and f). The effects of this event are widespread in the Northern Highlands Terrane and both west and east of the Walls Boundary Fault in Shetland, but are very limited in the Grampian Terrane, which must have been located some distance away from, and to the south of, the main collision zone (Figure 1.17a). An alternative view is that the Grampian Highlands might have formed a relatively rigid block entrained between contractional deformation zones at the leading edges of the obliquely colliding Laurentian and Baltican plates (Leslie *et al.*, 2008).

There is no specific evidence of regional deformation and metamorphism in the Grampian Terrane during the Scandian Event. Almost all of the major regional folds, including the Tay Nappe, had formed by now and the metamorphic peak was well past. However, the uplift and cooling at the end of the Grampian Event might have overlapped in time with Scandian deformation elsewhere and it is not clear how the major regional D4 deformation and subsequent localized phases are related to the overall tectonic pattern.

In contrast, Scandian nappe stacking dominates the structure of the Northern Highlands Terrane of Scotland and the East Greenland Caledonides. The most prominent structure ascribed to the Scandian Event in Britain is the Moine Thrust Belt, which forms the western Caledonian Front in Scotland. Thrusts within the belt are cut by syenites of the Loch Borralan Pluton, which have been dated at 430 ± 4 Ma (van Breemen *et al.*, 1979). However, dating of micas in the Moine Supergroup and mylonites that overlie the thrust belt has indicated that ductile deformation may have been occurring until *c.* 410 Ma (Dallmeyer *et al.*, 2001). Ductile deformation and thrusting also occurred farther to the east within the Moine rocks, and hence, in the Northern Highlands Terrane, the Scandian Event resulted in significant overall crustal shortening, probably in excess of 150 km. West-verging shears to the west of the Walls Boundary Fault in Shetland, including the Virdibreck Shear-zone responsible for emplacement of possible Dalradian rocks of the Queyfirth Group, have long been equated with the Moine Thrust Belt and hence can be regarded as Scandian.

East of the Walls Boundary Fault, the Upper Nappe of the Shetland Ophiolite-complex was emplaced by westward thrusting over the Lower Nappe, from which it is separated by an imbricate zone. Within the imbricate zone are siliceous metasedimentary rocks of Ordovician to Silurian age, derived by erosion of the Lower Nappe and Dalradian 'basement'. The thrusting was broadly coeval with emplacement of the Skaw Granite, which has been dated by Ar-Ar step heating of muscovite in its aureole at *c.* 425 Ma (Flinn and Oglethorpe, 2005). Hence the emplacement of the Skaw Granite, the westward thrusting of the Upper Nappe and the metamorphism of the Ordovician–Silurian sedimentary rocks can all be regarded as part of the Scandian Event. In a further development, Cutts *et al.* (2011) have attributed a marked contrast in P–T conditions between pelites directly below the Lower Nappe and those from deeper structural levels to an extensional tectonic break that excised at least 10 km of crustal section at some time after the peak of metamnorphism.

Flinn and Oglethorpe (2005) also attributed the west-verging Quarff Nappe to the Scandian Event. The presence of Scandian structures in eastern Shetland further emphasises the separation between the Scottish and Shetland Dalradian sequences. Prior to later sinistral movement along terrane boundaries (see below), Shetland was probably sited more-directly opposite the Norwegian sector of Baltica, where a Scandian fold-and-thrust belt with an opposite, easterly vergence marks the eastern Caledonian Front.

The final stages of closure of the Iapetus Ocean was achieved by subduction to the north-west beneath the Laurentian margin (e.g.

Dewey and Ryan, 1990), reversing the polarity of oceanic subduction, which had been towards the south-east beneath the Midland Valley Arc (Figure 1.16). It is generally accepted that the ocean had closed and the three continents had collided by the end of the Wenlock Epoch (e.g. Soper *et al.*, 1992). And it is at about that time, at *c.* 425 Ma, that large volumes of silicic magma were intruded into both the Grampian and Northern Highlands terranes, followed shortly afterwards by High-K calc-alkaline volcanism in the Grampian and Midland Valley terranes (424–410 Ma). The magmas were derived mainly from lower crustal sources, but there is also a significant background input of magma from the subcontinental lithospheric mantle, modified by contact with subducted oceanic crust, even after the continental collision (see the *Caledonian Igneous rocks of Great Britain* GCR volume; Stephenson *et al.*, 1999). The emplacement of the magmas implies that by this time the Grampian Terrane at least was being uplifted in an extensional regime and hence could not have been experiencing Scandian orogenic (i.e. compressional) forces.

1.8.5.3 Late Brittle Faulting, Terrane Assembly and Extensional Collapse

The main phase of Scandian ductile thrusting and folding was followed by sinistral strike-slip displacements along an array of NE-trending steep faults that dissect the Northern Highlands and Grampian terranes (Watson, 1984) (Figure 1.17). Strike-slip faults had already developed prior to and during the collision of Avalonia and Laurentia. However, the major sinistral movement was associated with the lateral translation of Baltica and Avalonia along the Laurentian margin that was probably continuous throughout late Silurian and into Early Devonian time. Those movements eventually resulted in juxtaposition of the Northern Highlands and Grampian terranes in more-or-less their current positions. According to some authors (e.g. Bluck, 2002), the Highland Border Ophiolite-complex was part of an exotic terrane that 'docked' with the Grampian Terrane during this strike-slip motion, and the Midland Valley Terrane reached its present position only in latest Devonian time (Bluck, 1984).

The most prominant faults are those that form the terrane boundaries; the linked Great Glen and Walls Boundary faults and the Highland Boundary Fault, along which hundreds of kilometres of displacement might have occurred. Seismic reflection studies show that the Great Glen Fault is coincident with a subvertical structure that extends to at least 40 km depth (Hall *et al.*, 1984), and isotopic signatures of mantle-derived magmas are different either side of the fault, suggesting that it has some expression in the upper mantle (Canning *et al.*, 1996, 1998). Geophysical studies have shown that the Highland Boundary Fault is broadly coincident with a change in lower crustal structure (Rollin, 1994) and various workers have speculated that this may correspond to the edge of the Laurentian craton (e.g. Soper and Hutton, 1984).

The timing and amount of movement along these faults are important for reconstructing some of the tectonic events in the later part of the Caledonian Orogeny (Harris, 1995). Although little is known about its pre-Silurian history, sinistral movement on the Great Glen Fault certainly occurred during the period between *c.* 430 Ma and *c.* 400 Ma (Stewart *et al.*, 1999). More specifically, Silurian displacement is indicated by the U-Pb zircon age of 428 ± 2 Ma of the Clunes Tonalite which is thought to have been emplaced during sinistral shear (Stewart *et al.*, 2001). The fault was re-activated around 400–393 Ma, as shown by evidence of sinistral transpression affecting the *c.* 400 Ma Rosemarkie Inlier leucogranite intrusions (Mendum and Noble, 2010). Late Emsian sedimentary rocks within the fault-zone are relatively undeformed and it therefore seems certain that intense deformation fabrics seen in Moine and Dalaradian rocks within the 3 km-wide fault-zone pre-date most Old Red Sandstone deposition (Stewart *et al.*, 1999). However, during Early and Mid Devonian time, alluvial fans were deposited along active fault scarps (Trewin and Thirlwall, 2002). Thus, lateral movement along the Great Glen and associated faults overlapped with, but outlasted, the Scandian Event. Post-Caledonian structures along the fault-zone (most notably associated with Mesozoic dextral movements) are invariably brittle in style (Stewart *et al.*, 1999).

The magnitude of early displacement along the Great Glen Fault is uncertain because there is no unambiguous correlation of pre-Devonian features across the fault. Estimates of sinistral movement based on correlations of various igneous and metamorphic features have ranged from 104 km (Kennedy, 1946) to 160 km (Winchester, 1974; Piasecki *et al.*, 1981). Latterly, the general consensus has been that sinistral displacements are unlikely to have exceeded 200–300 km. This is consistent with most palaeomagnetic estimates (Briden *et al.*, 1984) and the inferred offset of reflectors within the mantle lithosphere (Snyder and Flack, 1990). A comparable early sinistral offset of at least 100 km on the Walls Boundary Fault is based on the onshore geology of Shetland (Flinn, 1961) but apparent offsets of various offshore features have produced a variety of ambiguous and controversial estimates (e.g. Ritchie and Hitchen, 1993; Underhill, 1993). However, larger displacements are implied by tectonic reconstructions that place the Northern Highlands Terrane opposite Baltica during the Scandian collision, and Dewey and Strachan (2003) have suggested that at least 700 km of sinistral displacement must have occurred in order to explain the absence of Scandian deformation from the Grampian Terrane.

The Highland Boundary Fault is a high-angle reverse fault that eventually juxtaposed Dalradian rocks against Upper Devonian and Lower Carboniferous rocks of the Midland Valley Terrane. Much of the movement was therefore post Caledonian, although it seems likely that the reverse fault might have re-activated an older and more fundamental structure (Tanner, 2008). The full tectonic significance of the fault is uncertain. Late Silurian to Early Devonian sinistral displacements have commonly been assumed (e.g. Soper and Hutton, 1984; Hutton, 1987; Soper *et al.*, 1992) and studies of clasts within Old Red Sandstone sedimentary rocks led Bluck (1984) to conclude that major strike-slip movement continued until latest Devonian time. However, there is little direct evidence and other workers have argued against any major lateral displacements after the Grampian Event (e.g. Hutchison and Oliver, 1998; Oliver, 2001).

Within the Grampian Terrane, several related NE-trending faults occur mainly between the Great Glen and Loch Tay faults (see figures 1.1 and 3.1). Marked facies and thickness changes across these faults, particularly in the Central Grampian Highlands, suggest that they exerted an influence on Appin and early Argyll group sedimentation and defined basin margins in places. Treagus (1991) demonstrated an early phase of dip-slip movement with a cumulative downthrow to the east of *c.* 7 km, followed by sinistral strike-slip with a cumulative displacement of *c.* 23 km. Various lines of evidence suggest a late Silurian to Early Devonian age for the main strike-slip movements, which had a close temporal relationship with, and partly controlled the emplacement of, certain late-Caledonian plutons and dyke-swarms (Morris and Hutton, 1993; Jacques and Reavy, 1994). The intrusion of large volumes of silicic magma, starting at *c.* 425 Ma, suggests that by mid-Silurian time sinistral transtensional stresses had begun to replace oblique convergence and transpression.

Most of the strike-slip faults developed prior to the onset of Old Red Sandstone sedimentation and by Early Devonian time the Scottish sector of the Caledonian orogenic belt was undergoing extensional collapse (McClay *et al.*, 1986). Extensional dip-slip movements on many of the faults then led to the development of localized intermontane basins during the Early Devonian and more-extensive regional basins in Mid to Late Devonian time. Syndepositional deformation of Old Red Sandstone sedimentary rocks in the Orcadian Basin has been proposed by Seranne (1992), and shear fabrics in the Upper Nappe of the Shetland Ophiolite-complex and its underlying imbricate zone might also be related to this extensional phase and hence represent the youngest deformation to affect Caledonian metamorphic rocks (Cannat, 1989).

ACKNOWLEDGEMENTS

This volume is the combined work of 22 authors, listed with the paper titles, many of whom, in addition to their own site descriptions, have made valuable comments on other aspects of the work. Sadly, John Roberts and Steve Robertson both died during the early stages of preparation and their contributions have been completed by P.W.G. Tanner and M. Smith respectively. Peter Thomas died whilst the volume was being prepared for final submission. All three made major contributions to their own areas of the Dalradian outcrop and to our overall understanding of Grampian Highland geology.

The regional chapters containing the site reports have been compiled by their first-named authors and have been edited by D. Stephenson. Chapter 1 has been edited by P.W.G. Tanner and J.E. Treagus, and S.H. Treagus is thanked for additional comments on chapters 1 and 3. Overall compilation and editing was by D. Stephenson. The GCR editor was P.H. Banham and the referee was M.R.W. Johnson, who also provided valuable editorial suggestions. The Glossary and explanations of terminology were compiled by D.

Stephenson, J.R. Mendum, D. Millward, K.M. Goodenough and P.W.G. Tanner. The project was cofunded by the Joint Nature Conservation Committee (JNCC) and the British Geological Survey (BGS) and has been managed by N.V. Ellis for JNCC and D.J. Fettes and M. Smith for BGS.

The initial site selection and site documentation for the Dalradian block of the Geological Conservation Review was by S.J. Moorhouse. Since then, much new mapping and refined interpretation has taken place, and the site list has been revised, firstly by J.E. Treagus and subsequently through a panel consisting of R. Anderton, A.L. Harris, J.R. Mendum, J.L. Roberts, P.W.G. Tanner, R. Threadgould and J.E. Treagus. Additional sites to represent the Dalradian of Shetland were suggested by D. Flinn and F. May. The necessary amendments to the GCR documentation were greatly facilitated by R. Wignall (for Scottish Natural Heritage).

K.M. Goodenough and S.W. Horsburgh assisted with preliminary drafts of key maps and all diagrams were drafted for publication by S.C. White (JS Publications, Newmarket) and K.J. Henderson (BGS, Edinburgh). Photographs were scanned and prepared by B.M. McIntyre (BGS, Edinburgh). Photographs from the BGS collection are reproduced by kind permission of the Director, BGS © Natural Environment Research Council; all rights reserved (PR/23–27).

Several of the principal authors of this volume have been involved in the writing of other reviews of the Dalradian of Scotland and, inevitably, sections of introductory text have been adapted and updated from their contributions to those earlier works. In particular, large sections have been adapted from *British Regional Geology: the Grampian Highlands* (Stephenson and Gould, 1995) and some smaller sections have been adapted from a chapter in *The Geology of Scotland* (Strachan *et al.*, 2002) and from a recent review of the evolution of the north-east margin of Laurentia (Leslie *et al.*, 2008). The original sources of many key diagrams taken from these and other works are acknowledged in their captions.

The first complete draft of this volume was submitted to the JNCC in June 2009. In 2010, the JNCC terminated its involvement in Earth Science conservation and abandoned its contractual agreements to publish the remaining GCR volumes. So, the authors are greatly indebted to Diarmad Campbell, Chief Geologist Scotland for the BGS, for funding the drafting of remaining figures and to the Geologists' Association, for ensuring that this volume is published as a Special Issue of their Proceedings. We are particularly grateful to Neil Ellis of the JNCC for his efforts to secure a new publisher and to Professor James Rose, Editor in Chief of the PGA, for making it all happen.

Finally, on behalf of all of the site authors, we would like to record our thanks to the owners and managers of land and quarries who have allowed access to the sites, either during previous work or specifically for the GCR exercise.

BIBLIOGRAPHY

In this bibliography the arrangement is alphabetical by author surname for works by sole authors and dual authors. Where there are references that include the first-named author with others, the sole-author works are listed chronologically first, followed by the dual author references (alphabetically) followed by the references with three or more authors listed *chronologically*. Chronological order is used within each group of identical authors.

Agrell, S. O. (1942) 1. A petrological investigation of the adinoles at Dinas Head, Cornwall. 2. A petrofabric study of the Ben Vuroch granite and the adjacent schists in Perthshire. Unpublished PhD thesis, University of Cambridge.

Ahmed-Said Y. and Tanner P. W. G. (2000) P-T **conditions** during emplacement, and D2 regional metamorphism, of the Ben Vuirich Granite, Perthshire, Scotland. *Mineralogical Magazine,* **64**, 737–53.

Ague, J.J. & Baxter, E.F., 2007. Brief thermal pulses during mountain building recorded by Sr diffusion in apatite and multicomponent diffusion in garnet. Earth and Planetary Science Letters, 261, 500-516.

Allen, J. R. L. 1963. The classification of cross stratified units with notes on their origin. *Sedimentology*, **2**, pp. 93-114.

Allison, A. (1933) The Dalradian succession in Islay and Jura. *Quarterly Journal of the Geological Society, London*, **89**, 125–44.

Allison, A. 1941. Loch Awe succession and tectonics-Kilmartin-Tayvallich-Danna. *Quarterly Journal of the Geological Society, London*, **96**, 423–49.

Allison, I., May, F and Strachan, R.A. (1988) *An Excursion guide to the Moine Geology of the Scottish Highlands*. Scottish Academic Press for Edinburgh Geological Society and Geological Society of Glasgow.

Alsop, G.I. and Hutton, D.H.W. (1990) A review and revision of Dalradian stratigraphy in central and southern Donegal, Ireland. *Irish Journal of Earth Sciences*, **10**, 181–98.

Alsop, G.I., Prave, A.R., Condon, D.J. and Phillips, C.A. (2000) Cleaved clasts in Dalradian conglomerates: possible evidence for Neoproterozoic compressional tectonism in Scotland and Ireland? *Geological Journal*, **35**, 87–98.

Amos, B.J. (1960). The geology of the Bowmore district, Islay. Unpublished PhD thesis, University of London, Imperial College.

Anderson, E M. (1923). The geology of the schists of the Schiehallion district. *Quarterly Journal of the Geological Society of London*, **79**, 423–45.

Anderson, E M. (1951) *The Dynamics of Faulting*. (Second edition). (Edinburgh: Oliver and Boyd.)

Anderson, J. G. C., (1942) The stratigraphical order of the Dalradian schists near the Highland Border in Angus and Kincardineshire. *Transactions of the Geological Society of Glasgow*, **20**, 223–37.

Anderson, J.G.C. (1947a) The geology of the Highland Border, Stonehaven to Arran. *Transactions of the Royal Society of Edinburgh*, **61**, 479–515.

Anderson, J.G.C. (1947b) The Kinlochlaggan Syncline, southern Inverness-shire. *Transactions of the Geological Society of Glasgow*, **21**, 97–115.

Anderson, J.G.C. (1948) Stratigraphic nomenclature of Scottish metamorphic rocks. *Geological Magazine*, **85**, 89–96.

Anderson, J.G.C (1956). The Moinian and Dalradian rocks between Glen Roy and the Monadhliath Mountains, Inverness-shire. *Transactions of the Royal Society of Edinburgh*, **63**, 15–36.

Anderton, R. (1974) Middle Dalradian sedimentation in Argyll, with particular reference to the Jura quartzite, Scarba conglomerate and Craignish phyllites. Unpublished PhD thesis, University of Reading.

Anderton, R. (1975) Tidal flat and shallow marine sediments from the Craignish Phyllites, Middle Dalradian, Argyll, Scotland. *Geological Magazine*, **112**, 337–40.

Anderton, R. (1976) Tidal-shelf sedimentation: an example from the Scottish Dalradian. *Sedimentology*, **23**, 429–58.

Anderton, R. (1977) The Dalradian rocks of Jura. *Scottish Journal of Geology*, **13**, 135–42.

Anderton, R. (1979) Slopes, submarine fans and syn-depositional sedimentology of parts of the Middle and Upper Dalradian in the S.W. Highlands of Scotland. In *The British Caledonides - Reviewed* (eds. Harris, A. L., Holland, C. H. and Leake, B. E.), Geological Society, London, Special Publications, **8**.

Anderton, R. (1980). Distinctive pebbles as indicators of Dalradian provenance. *Scottish Journal of Geology,* **16**, 143–52.

Anderton, R. (1982) Dalradian deposition and the late Precambrian - Cambrian history of the N Atlantic region: a review of the early evolution of the Iapetus Ocean. *Journal of the Geological Society of London*, **139**, 421–31.

Anderton, R. (1985) Sedimentation and tectonics in the Scottish Dalradian. *Scottish Journal of Geology*, **21**, 407–36.

Anderton, R. (1988) Dalradian slides and basin development: a radical interpretation of stratigraphy and structure in the SW and Central Highlands of Scotland. *Journal of the Geological Society of London*, **145**, 669–78.

Arndt, N.T. and Nisbet, E.G. (editors) (1982) *Komatiites*. George Allen and Unwin, London.

Ashcroft W.A., Kneller B.C., Leslie, A.G. and Munro M. (1984) Major shear zones and autochthonous Dalradian in the northeast Scottish Caledonides. *Nature, London* **310**, 760–2.

Ashworth, J.R. (1972) Migmatites of the Huntly-Portsoy area, north-east Scotland. Unpublished PhD thesis, University of Cambridge.

Ashworth, J.R. (1975) The sillimanite zones of the Huntly–Portsoy area in the north-east Dalradian, Scotland. *Geological Magazine*, **112**, 113–224.

Ashworth, J.R. (1976) Petrogenesis of migmatites in the Huntly-Portsoy area, north-east Scotland. *Mineralogical Magazine*, **40**, 661–82.

Ashworth, J.R. (1979) Comparative petrography of deformed and undeformed migmatites from the Grampian Highlands of Scotland. *Geological Magazine*, **116**, 445–56.

Astin, T.R. and Rogers, D.A. (1991) 'Subaqueous shrinkage cracks' in the Devonian of Scotland re-interpreted. *Journal of Sedimentary Petrology*, **61**, 850–9.

Atherton, M.P. (1977) The metamorphism of the Dalradian rocks of Scotland. *Scottish Journal of Geology*, **13**, 331–70.

Atherton, M.P., and Brotherton, M.S. (1972) The composition of some kyanite-bearing regionally-metamorphosed rocks from the Dalradian. *Scottish Journal of Geology*, **8**, 203–13.

Atherton, M.P. and Ghani, A.A. (2002) Slab breakoff: a model for Caledonian, Late Granite syn-collisional magmatism in the ortho-tectonic (metamorphic) zone of Scotland and Donegal. *Lithos*, **62**, 65–85.

Bailey, E.B. (1910) Recumbent folds in the schists of the Scottish Highlands. *Quarterly Journal of the Geological Society of London*, **66**, 586–620.
Bailey, E. B. 1913. The Loch Awe Syncline (Argyllshire). *Quarterly Journal of the Geological Society of London*, **69**, 280–307.
Bailey, E.B. (1917) The Islay anticline (Inner Hebrides). *Quarterly Journal of the Geological Society of London*, **72**, 132–64.
Bailey, E.B. (1922) The structure of the South West Highlands of Scotland. *Quarterly Journal of the Geological Society of London*, **78**, 82–131.
Bailey, E.B. (1925) Perthshire tectonics: Loch Tummel, Blair Atholl and Glen Shee. *Transactions of the Royal Society of Edinburgh*, **53**, 671–98.
Bailey, E.B. (1930) New Light on Sedimentation and Tectonics. *Geological Magazine*, **67**, 77.
Bailey, E.B. (1934) West Highland tectonics: Loch Leven to Glen Roy. *Quarterly Journal of the Geological Society of London*, **90**, 462–523.
Bailey, E.B. (1938) Eddies in mountain structure. *Quarterly Journal of the Geological Society of London*, **94**, 607–25.
Bailey, E B. (1953). Facies changes versus sliding: Loch Leven, Argyll. *Geological Magazine*, **90**, 111–13.
Bailey, E.B. (1960) The geology of Ben Nevis and Glencoe and the surrounding country. (2nd edition). Memoir of the Geological Survey of Great Britain, Sheet 53 (Scotland).
Bailey, E.B., and McCallien, W. (1937). Perthshire tectonics: Schiehallion to Glen Lyon. *Transactions of the Royal Society of Edinburgh*, **59**, 79–118.
Bailey, E B, and MacGregor, M. 1912. The Glen Orchy Anticline, Argyllshire. *Quarterly Journal of the Geological Society of London*, Vol. 68, 164–179.
Bailey, E.B., and Maufe, H.B. (1916) The geology of Ben Nevis and Glen Coe and the surrounding country. (1st edition). Memoir of the Geological Survey of Great Britain, Sheet 53 (Scotland).
Bain, J.A., Briggs, D.A. and May, F. (1971) Geology and mineralogical appraisal of an extensive talc-magnesite deposit in the Shetlands. *Transactions of the Institute of Mining and Metallurgy*, **80**, B77–B84.
Baker, A.J. (1985) Pressures and temperatures of metamorphism in the eastern Dalradian. *Journal of the Geological Society of London,* **142**, 137–48.
Baker, A.J. (1987) Models for the tectonothermal evolution of the eastern Dalradian of Scotland. *Journal of Metamorphic Geology*, **5**, 101–18.
Baker, A.J., and Droop, G.T.R. (1983) Grampian metamorphic conditions deduced from mafic granulites and sillimanite-K-feldspar gneisses in the Dalradian of Glen Muick, Scotland. *Journal of the Geological Society of London,* **140**, 489–97.
Baldwin, C.T. and Johnson, H.D. (1977) The Dalradian rocks of Lunga, Luing and Shuna. *Scottish Journal of Geology*, **13**, 143–54.
Banks, C. J. (2005). Neoproterozoic Basin Analysis: a combined sedimentological and provenance study in the Grampian Group, Central Highlands, Scotland. Unpublished PhD Thesis, University of Keele.
Banks, C.J. (2007) Exceptional preservation of sedimentary structures in metamorphic rocks: an example from the upper

Grampian Group, Creag Stalcair, Perthshire. *Scottish Journal of Geology*, **43**, 9–14.

Banks, C.J. and J.A. Winchester (2004). Sedimentology and stratigraphic affinities of Neoproterozoic coarse clastic successions, Glenshirra Group, Inverness-shire Scotland. *Scottish Journal of Geology* **40**, 159–174.

Banks, C.J., Smith, M., Winchester, J.A., Horstwood, M.S.A., Noble, S.R. and Ottley, C.J. (2007) Provenance of intra-Rodinian basin-fills: the lower Dalradian Supergroup, Scotland. *Precambrian Research*, **153**, 46-64.

Barreiro, B.A. (1998) U-Pb systematics on zircon from the Keith and Portsoy granites, Grampian Highlands, Scotland. *NERC Isotope Geosciences Laboratory Report Series* No. **132.**

Barrow, G. (1893) On an intrusion of muscovite-biotite gneiss in the south-east Highlands of Scotland, and its accompanying metamorphism. *Quarterly Journal of the Geological Society of London,* **49**, 330–58.

Barrow, G. (1904) Moine gneisses of the east central Highlands and their position in the Highland sequence. *Quarterly Journal of the Geological Society of London*, **60**, 400–44.

Barrow, G. (1912) On the geology of Lower Deeside and the southern Highland border. *Proceedings of the Geologists' Association*, **23**, 274–90.

Barrow G. and Cunningham Craig E.H. (1912) The geology of the districts of Braemar, Ballater and Glen Clova. *Memoir of the Geological Survey of Great Britain*, Sheet 65 (Scotland).

Barrow, G, Grant Wilson, J S, and Cunningham Craig, E H. (1905). The geology of the country around Blair Atholl, Pitlochry and Aberfeldy. Memoir of the Geological Survey of Great Britain, Sheet 55 (Scotland).

Basahel, A.N. (1971) The Dalradian stratigraphy and structure of southern Islay, Argyll. Unpublished PhD thesis. University of Liverpool.

Batchelor, R.A. (2011) Geochemistry of Torridonian tuffs and contemporary phosphorites; potential for correlation of Torridonian sequences in NW Scotland. *Scottish Journal of Geology*, **47**, 133-142.

Baxter, E.F., Ague, J.J. and Depaolo, D.J. (2002) Prograde temperature-time evolution in the Barrovian type-locality constrained by Sm/Nd garnet ages from Glen Clova, Scotland. *Journal of the Geological Society, London*, **159**, 71–82.

Beddoe-Stephens B. (1990) Pressures and temperatures of Dalradian metamorphism and the andalusite-kyanite transformation in the northeast Grampians. *Scottish Journal of Geology* **26**, 3–14.

Bell, A. M. (1981) Vergence: an evaluation. *Journal of Structural Geology*, Volume 3, 197–202.

Bendall, C.A. (1995). A geochronological, structural and metamorphic study of rocks from the central and SW Dalradian of Scotland. Unpublished PhD thesis, University of Manchester

Bentley, M.R. (1986) The tectonics of Colonsay, Scotland. Unpublished PhD thesis, University of Wales, Aberystwyth.

Bentley, M.R. (1988). The Colonsay Group. *In* Winchester, J.A (ed.) *Later Proterozoic stratigraphy of the Northern Altlantic Regions.* Blackie and Son Ltd., London, 119–30.

Bentley, M.R., Maltman, A.J., and Fitches, W.R. (1988) Colonsay and Islay: a suspect terrane within the Scottish Caledonides. *Geology*, **16**, 26–8.

Bingen B., Demaiffe D. and van Breemen O. (1998) The 616 Ma old Egersund basaltic dyke swarm, SW Norway, and late Neoproterozoic opening of the Iapetus Ocean. *Journal of Geology,* **106**, 565–74.
Bingen, B., Griffin, W.L. Torsvik, T.H. and Saeed, A. (2005) Timing of late Neoproterozoic glaciation on Baltica constrained by detrital zircon geochronology in the Hedmark Group, south-east Norway. *Terra Nova*, **17**, 250–58.
Bliss, G.M. (1977) The micropalaeontology of the Dalradian. Unpublished PhD thesis, University of London, Imperial College.
Bluck, B.J. (1983) Role of the Midland Valley of Scotland in the Caledonian Orogeny. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* **74**, 119 –136.
Bluck, B.J. (1984) Pre-Carboniferous history of the Midland Valley of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **75**, 275–95.
Bluck, B.J. (2000) 'Where ignorance is bliss 'tis a folly to be wise' (Thomas Gray 1716–1761) – controversy in the basement blocks of Scotland. *Scottish Journal of Geology*, **36**, 97–101.
Bluck, B.J. (2001) Caledonian and related events in Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* **91**, 375–404.
Bluck, B.J. (2002) The Midland Valley Terrane. *In:* Trewin, N.H. (ed.) *The Geology of Scotland.* The Geological Society, London, 149–66.
Bluck, B.J. (2010) The Highland Boundary Fault and the Highland Boundary Complex. *Scottish Journal of Geology*, **46**, 113-124.
Bluck B.J. and Dempster T.J. (1991) Exotic metamorphic terranes in the Caledonides: tectonic history of the Dalradian block, Scotland. *Geology,* **19**, 1133–6.
Bluck B.J., Dempster T.J., and Rogers G. (1997) Allochthonous metamorphic blocks on the Hebridean passive margin, Scotland. *Journal of the Geological Society of London* **154**, 921–4.
Bluck, B.J., Gibbons, W. and Ingham, J.K. (1992). Terranes. 1–4 in Atlas of palaeogeography and lithofacies. Cope, J.C.W., Ingham, J.K., and Rawson, P.F. (editors). Geological Society of London Memoir, No. 13.
Bluck B.J., Halliday A. N., Aftalion M., and Macintyre R.M. (1980) Age and origin of the Ballantrae ophiolite and its significance to the Caledonian orogeny and Ordovician time scale. *Geology* **8**, 492–95.
Bluck, B.J. and Ingham, J.K. (1997) The Highland Border controversy: a discussion of "New evidence that the Lower Cambrian Leny Limestone at Callander, Perthshire belongs to the Dalradian Supergroup, and a reassessment of the 'exotic' status of the Highland Border Complex". *Geological Magazine*, **134**, 563–70.
Bluck B.J., Ingham J.K., Curry G.B., and Williams A. (1984) The significance of a reliable age from some Highland Border rocks in Central Scotland. *Journal of the Geological Society of London* **139**, 451–4.
Boersma, J.R. (1969) Internal structures of some tidal megaripples on a shoal in the Westerschelde estuary, the Netherlands. *Geologie on Mijnbouw*, **48**, 409–14.
Booth, J.E. (1984) Structural, stratigraphic and metamorphic studies in the SE Dalradian Highlands. Unpublished PhD thesis. University of Edinburgh.
Borradaile, G.J. (1970) The west limb of the Loch Awe syncline and the associated cleavage fan. *Geological Magazine*, **107**, 459–467.

Borradaile, G.J. (1972a) The structural and stratigraphic history of the Dalradian rocks of the Northern Loch Awe syncline, Argyllshire. Unpublished PhD thesis, University of Liverpool.

Borradaile, G.J. (1972b) Variably oriented co-planar primary folds. *Geological Magazine*, **190**, 89–98.

Borradaile, G. J. (1973) Dalradian structure and stratigraphy of the northern Loch Awe district, Argyllshire. *Transactions of the Royal Society of Edinburgh*, **69**, 1–21.

Borradaile, G.J. (1974). Bulk finite strain estimates from the deformation of Neptunian dykes. *Tectonophysics,* **22**, 127–39.

Borradaile, G.J. (1977) The Dalradian rocks of the northern Loch Awe district. *Scottish Journal of Geology*, **13**, 155–64.

Borradaile, G.J. (1979). Pre-tectonic reconstruction of the Islay anticline: implications for the depositional history of Dalradian rocks in the SW Highlands. In *The Caledonides of the British Isles–reviewed*. Harris, A L, Holland, C H, and Leake, B E (editors). Special Publication of the Geological Society of London, No. 8, pp. 229–38.

Borradaile, G.J. and Johnson, H.D. (1973) Finite strain estimates from the Dalradian Dolomitic Formation, Islay, Argyll, Scotland. *Tectonophysics*, **18**, 249–59.

Boué, A. (1820) *Essai Géologique sur l'Écosse*. Ve Courcier, Paris.

Bouma, A. H. (1962). *Sedimentology of some Flysch Deposits, a Graphic Approach to Facies Interpretation.* Elsevier Co. Amsterdam, 168 pp.

Bowden, A.J. (2007) Book review: MacCulloch's 1840 Geological Map of Scotland. *Scottish Journal of Geology*, **43**, 181–4.

Bowes, D.R. and Convery, H.J.E. (1966) The composition of some Ben Ledi grits and its bearing on the origin of albite schists in the south-west Highlands. *Scottish Journal of Geology*, **2**, 67–75.

Bowes, D.R. and Wright, A.E. (1967) The explosion breccia pipes near Kentallen, Scotland and their geological setting. *Transactions of the Royal Society of Edinburgh*, **67**, 109–43.

Bowes, D.R. and Wright, A.E. (1973) Early phases of Caledonian deformation in the Dalradian of the Ballachulish district, Argyll. *Geological Journal*, **8**, 333–44.

Bowring, S., Myrow, P., Landing, E., Ramezani, J. and Grotzinger, J. (2003) Geochronological constraints on Terminal Neoproterozoic events and the rise of metazoans. *Geophysical Research Abstracts* **5**, p13219.

Bradbury, H.J. (1978) Stratigraphic, structural, igneous and metamorphic history of the Dalradian rocks of the Ben Vrackie-Ben Vuirich district, Tayside, Scotland. Unpublished PhD thesis, University of Liverpool.

Bradbury, H.J. (1979) Migmatization, deformation and porphyroblast growth in the Dalradian of Tayside, Scotland. In *The Caledonides of the British Isles — Reviewed* Harris, A.L., Holland, C.H. and Leake, B.E. (eds). Geological Society, London, Special Publications, **8**, 351–6.

Bradbury, H.J. (1985) The Caledonian metamorphic core: an Alpine model. *Journal of the Geological Society of London*, **142**, 129–36.

Bradbury, H.J., and Harris, A.L. (1982) Low grade Dalradian sediments carrying spaced cleavage; Polyphase deformation of spaced cleavage. In *Atlas of deformational and metamorphic rock fabrics*. Borradaile, G J, Bayly, M B, and Powell, C McA (editors). Springer Verlag, Berlin, pp. 100–9.

Bradbury, H.J., Harris, A.L. and Smith, R.A. (1979). Geometry and emplacement of nappes in the Central Scottish Highlands. In *The Caledonides of the British Isles - reviewed*. (eds. Harris, A.L., Holland, C.H. and Leake, B.E.), *Special Publication of the Geological Society of London*, **8**, 213–20.

Bradbury H.J., Smith R.A. and Harris A.L. (1976) 'Older' granites as time-markers in Dalradian evolution. *Journal of the Geological Society, London,* **132**, 677–84.

Brasier, M.D., Ingham, J.K. and Rushton, A.W.A. (1992) Cambrian. 13–18 in Atlas of Palaeogeography and Lithofacies. Cope, J.C.W., Ingham, J.K. and Rawson, P. F. (editors). *Memoirs of the Geological Society, London,* **13**.

Brasier, M.D. and Mcilroy, D. (1998) Neonereites uniserialis from c. 600 Ma year old rocks in western Scotland and the emergence of animals. *Journal of the Geological Society, London*, **155**, 5–12.

Brasier, M.D. and Shields, G. (2000) Neoproterozoic chemostratigraphy and correlation of the Port Askaig glaciation, Dalradian Supergroup of Scotland. *Journal of the Geological Society, London*, **157**, 909–14.

Brasier, M.D., McCarron, G., Tucker, R., Leather, J., Allen, P. and Shields, G. (2000) New U-Pb zircon dates for the Neoproterozoic Ghubrah glacaiation and for the top of the Huqf Supergroup, Oman. *Geology*, **28**, 175–8.

Briden, J.C., Turnell, H.B. and Watts, D.R. (1984) British palaeomagnetism, Iapetus Ocean and the Great Glen Fault. *Geology* **12**, 136–9.

Burgess J.G, Graham, C.M. and Harte, B. (1981). Kyanite and chloritoid phyllites from the chlorite zone of the Scottish Highlands. *Journal of the Geological Society of London,* **138**, p. 634 (abstract).

Burt, C.E. (2002) Sedimentary environments and basin evolution of the upper Dalradian: Tayvallich Subgroup and Southern Highland Group. Unpublished PhD thesis, Kingston University.

Burton, C.J., Hocken, C., MacCallum, D. and Young, M.E. 1983. Chitinozoa and the age of the Margie Limestone of the North Esk. *Proceedings of the Geological Society of Glasgow* Vol. **124–125**, 27–32.

Cannat M. (1989) Late Caledonian northeastward ophiolite thrusting in the Shetland Islands, U.K. *Tectonophysics* **169**, 257–70.

Canning J.C., Henney P.J., Morrison M.A. and Gaskarth J.W. (1996) Geochemistry of late Caledonian minettes from northern Britain: implications for the Caledonian sub-continental lithospheric mantle. *Mineralogical Magazine* **60**, 221–36.

Canning, J.C., Henney, P.J., Morrison, M.A., Van Calsteren, P.W.C., Gaskarth, J.W. and Swarbrick, A. (1998) The Great Glen Fault: a major vertical lithospheric boundary. *Journal of the Geological Society, London*, **155**, 425–8.

Carty, J.P. (2001) Deformation, metamorphism, magmatism and fluid-flow in the Portsoy Shear Zone, N.E. Scotland. Unpublished PhD thesis, University of Derby.

Cawood, P.A., McCausland, P.J.A. and Dunning, G.R. (2001) Opening Iapetus: constraints from the Laurentian margin in Newfoundland. *Geological Society of America Bulletin*, **113**, 443–53.

Cawood, P.A., Nemchin, A.A., Smith, M. and Loewy, S. (2003). Source of the Dalradian Supergroup constrained by U-Pb dating of detrital

zircon and implications for the East Laurentian margin. *Journal of the Geological Society of London* **160**, 231–46.
Cawood, P.A., Nemchin, A.A., Strachan, R.A., Prave, A.R. and Krabbendam, M. (2007) Sedimentary basin and detrital zircon record along East Laurentia and Baltica during assembly and breakup of Rodinia. *Journal of the Geological Society, London,* **164**, 257–75.
Chew, D.M. (2001) Basement protrusion origin of serpentinite in the Dalradian. *Irish Journal of Earth Science*, **19**, 23-35.
Chew, D.M., Daly, J.S., Magna, T., Page, L.M., Kirkland, C.L., Whitehouse, M.J. and Lam, R. (2010) Timing of ophiolite obduction in the Grampian orogen. *Geological Society of America Bulletin*, **122**, 1787-1799.
Chew, D.M., Fallon, N., Kennelly, C., Crowley, Q. and Pointon, (2009) Basic volcanism contemporaneous with the Sturtian glacial episode in NE Scotland. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, **100**, 399-415
Chew, D.M., Graham, J.R. and Whitehouse, M.J. (2007) U-Pb zircon geochronology of plagiogranites from the Lough Nafooey (= Midland Valley) arc in western Ireland: constraints on the onset of the Grampian orogeny. *Journal of the Geological Society, London* Vol. **164**, 747–50.
Chinner, G.A. (1957) The metamorphic history of the Glen Clova district, Angus. Unpublished PhD Thesis, University of Cambridge.
Chinner, G.A. (1960) Pelitic gneisses with varying ferrous/ferric ratios from Glen Clova, Angus, Scotland. *Journal of Petrology*, **1**, 178–217.
Chinner, G.A. (1961) The origin of sillimanite in Glen Clova, Angus. *Journal of Petrology* Vol. **2**, 312–23.
Chinner, G.A. (1966) The distribution of pressure and temperature during Dalradian metamorphism. *Quarterly Journal of the Geological Society of London,* **122**, 159–86.
Chinner, G.A. (1978) Metamorphic zones and fault displacement in the Scottish Highlands. *Geological Magazine*, Vol. 115, 37–45.
Chinner, G.A. and Heseltine, F.J. (1979) The Grampian andalusite/kyanite isograd. *Scottish Journal of Geology*, Vol. 15, 117–127.
Coats, J.S., Pease, S.F. and Gallagher, M.J. (1984) Exploration of the Scottish Dalradian. 21–34 in *Prospecting in areas of glaciated terrain*. (London: Institution of Mining and Metallurgy.)
Coats, J.S., Smith, C.G., Gallagher, M.J., May, F., Fortey, N.J. and Parker, M.E. (1978) Stratabound barium-zinc mineralisation in Dalradian schist near Aberfeldy, Scotland: preliminary report. *Institute of Geological Sciences, Mineral Reconnaisance Programme Report* No. **26**.
Coats, J.S., Smith, C.G., Fortey, N.J., Gallagher, M.J., May, F. and McCourt, W.J. (1980) Stratabound barium-zinc mineralization in Dalradian schist near Aberfeldy. *Transactions of the Institution of Mining and Metallurgy (Section B: Applied Earth Science)*, **89**, 110–22.
Coats, J.S., Smith, C.G., Gallagher, M.J., May, F., McCourt, W.J., Parker, M.E. and Fortey, N.J. (1981) Stratabound barium-zinc mineralisation in Dalradian schist near Aberfeldy, Scotland: final report. *Institute of Geological Sciences, Mineral Reconnaissance Programme Report* No. **40**.
Collerson, K.D., Jesseau, C.W. and Bridgewater, D. (1976). Contrasting types of bladed olivine in ultramafic rocks from the

Archaean of Labrador. *Canadian Journal of Earth Sciences*, **13**, 442–50.

Collinson, J. (1994). Sedimentary deformational structures. pp. 95–125 *In* Maltman, A. (ed.). *The geological deformation of sediments.* Chapman and Hall.

Collinson, J.D. and Thompson, D.B. 1988. Sedimentary Structures. George Allen and Unwin, London. 207 pp.

Condon, D.J. and Prave, A.R. (2000). Two from Donegal: Neoproterozoic glacial episodes on the northeast margin of Laurentia. *Geology*, **28**, 951–4.

Cooper, M.R. and Johnston, T.P. (2004) Central Highlands (Grampian) Terrane. 9–24, in: Mitchell, W.I. (editor), *The Geology of Northern Ireland–Our Natural Foundation* (2nd edition). Geological Survey of Northern Ireland, Belfast.

Coward, M.P. (1983) The thrust and shear zones of the Moine Thrust Zone of NW Scotland. *Journal of the Geological Society of London* **140**, 795–811.

Coward, M.P. (1990) The Precambrian, Caledonian and Variscan framework to NW Europe. In *Tectonic Events Responsible for Britain's Oil and Gas Reserves*. Hardman, R.F.P. and Brooks, J. (eds) Geological Society, London, Special Publications, **55**, 1–34.

Craig G. Y., McIntyre D. B., and Waterston C. D. (1978) *James Hutton's Theory of the Earth: the lost drawings*. Scottish Academic Press, Edinburgh.

Crane A., Goodman S., Krabbendam M., Leslie A. G., Paterson I. B., Robertson S. And Rollin K. E. (2002) *Geology of the Glen Shee District.* Memoir of the British Geological Survey. Sheet 56W with parts of sheets 55E, 65W and 64E (Scotland).

Cummins, W.A. and Shackleton, R.M. (1955) The Ben Lui recumbent syncline. *Geological Magazine*, **92**, 353–62.

Cunningham Craig, E.H. (1904) Metamorphism in the Loch-Lomond District. *Quarterly Journal of the Geological Society, London*, **60**, 10–31.

Cunningham Craig, E.H. (2000) (written 1901). Explanation of Sheet 38 (Loch Lomond). Selected documents from the BGS Archives No 3. *British Geological Survey Technical Report* No. **WO/00/05**.

Cunningham Craig, E.H., Wright, W.B. and Bailey, E.B. (1911) The Geology of Colonsay and Oronsay with parts of Ross of Mull. *Memoir of the Geological Survey of Scotland*, Sheet 35 (Scotland).

Curry, G.B., Bluck, B.J., Burton, C.J., Ingham, J.K., Siveter, D.J. And Williams, A. (1984) Age, evolution and tectonic history of the Highland Border Complex, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **75**, 113–33.

Cutts, K.A., Hand, M., Kelsey, D.E. and Strachan, R.A. (2011) P–T constraints and timing of Barrovian metamorphism in the Shetland Islands, Scottish Caledonides: implications for the structural setting of the Unst ophiolite. *Journal of the Geological Society*, **168**, 1265-1284.

Dallmeyer, R.D., Strachan, R.A., Rogers, G., Watt, G.R. and Friend, C.R.L. (2001) Dating deformation and cooling in the Caledonian thrust nappes of north Sutherland, Scotland: insights from 40Ar/39Ar and Rb-Sr chronology. *Journal of the Geological Society of London* **158**, 501–12.

Daly, J.S., Muir, R.J. and Cliff, R.A. (1991) A precise U-Pb zircon age for the Inishtrahull syenitic gneiss, County Donegal, Ireland. *Journal of the Geological Society, London,* **148**, 639–42.

Dalziel, I.W.D. (1994) Precambrian Scotland as a Laurentia-Gondwana link: Origin and significance of cratonic promontories. *Geology*, **22**, 589-92.

Dalziel, I.W.D. (1997) Neoproterozoic-Paleozoic geography and tectonics; review, hypothesis, environmental speculation. *Geological Society of America Bulletin* **109**(1), 16-42.

Davidek, K., Landing, E., Bowring, S.A., Westrop, S.R., Rushton, S.A., Fortey, R.A. And Adrain, J. (1998) New Uppermost Cambrian U-Pb date from Avalonian Wales and age of the Cambrian-Ordovician boundary. *Geological Magazine*, **135**, 303-09.

Deer, W.A., Howie, R.A. and Zussman, J. (1992). *An Introduction to the Rock Forming Minerals,* 2nd ed. Longman Scientific and Technical, London.

Dempster, T.J. (1983) Studies of orogenic evolution in the Scottish Dalradian. Unpublished PhD thesis, University of Edinburgh.

Dempster, T.J. (1985a) Uplift patterns and orogenic evolution in the Scottish Dalradian. *Journal of the Geological Society of London,* **142**, 111-128.

Dempster, T.J. (1985b) Garnet zoning and metamorphism of the Barrovian type. *Contributions to Mineralogy and Petrology,* **89**, 30-8.

Dempster T.J. and Bluck B.J. (1991) The age and tectonic significance of the Bute amphibolite, Highland Border Complex, Scotland. *Geological Magazine* **128**, 77-80.

Dempster, T.J. and Harte, B. (1986) Polymetamorphism in the Dalradian of the Central Scottish Highlands. *Geological Magazine*, Vol. 123, 95-104.

Dempster, T.J., Hudson, N.F. and Rogers, G. (1995). Metamorphism and cooling of the NE Dalradian. *Journal of the Geological Society, London,* **152**, 383-90.

Dempster, T.J., Rogers, G., Tanner, P.W.G., Bluck, B.J., Muir, R.J., Redwood, S.D., Ireland, T.R. and Paterson, B.A. (2002) Timing of deposition, orogenesis and glaciation within the Dalradian rocks of Scotland: constraints from U-Pb zircon ages. *Journal of the Geological Society, London*, **159**, 83-94.

Dewey, H. and Flett, J.S. (1911) On some British pillow lavas and the rocks associated with them. *Geological Magazine*, **8**, 202-9, 240-8.

Dewey J. F. (1969) Evolution of the Appalchian/Caledonian orogen. *Nature, London* **222**, 124-9.

Dewey, J.F. (2005) Orogeny can be very short. *Proceedings of the National Academy of Sciences, USA* Vol. **102**, 15286-93.

Dewey, J.F. and Mange, M. (1999) Petrography of Ordovician and Silurian sediments in the western Irish Caledonides: tracers of a short-lived Ordovician continent-arc collision orogeny and the evolution of the Laurentian Appalachian-Caledonian margin. In: *Continental Tectonics* (edited by MacNiocaill, C. and Ryan, P. D.). *Geological Society, London, Special Publication*, **164**, 55-107.

Dewey, J.F. and Pankhurst, R.J. (1970) The evolution of the Scottish Caledonides in relation to their radiometric age pattern. *Transactions of the Royal Society of Edinburgh,* **68**, 361-89.

Dewey, J.F. and Ryan, P.D. (1990) The Ordovician evolution of the South Mayo Trough, Western Ireland. *Tectonics*, **9**, 887-903.

Dewey J.F. and Shackleton R.M. (1984) A model for the evolution of the Grampian tract in the early Caledonides and Appalachians. *Nature, London* **312**, 115-21.

Dewey, J.F. and Strachan, R.A. (2003) Changing Silurian-Devonian relative plate motion in the Caledonides; sinistral transpression to sinistral transtension. *Journal of the Geological Society, London*, **160**, 219–229.
Dickin, A.P. (1992). Evidence for an Early Proterozoic crustal province in the North Atlantic region. *Journal of the Geological Society, London*, **149**, 483–6.
Dickin, A.P., and Bowes, D.R. (1991) Isotopic evidence for the extent of the early Proterozoic basement of Scotland and northwest Ireland. *Geological Magazine*, **128**, 385–8.
Droop, G.T.R. (1987). A general equation for estimating Fe^{3+} concentrations in ferromagnesian silicates or oxides from microprobe analysis using stoichiometric criteria. *Mineralogical Magazine,* **51**, 431–55.
Droop G.T.R. and Charnley N. (1985) Comparative geobarometry of pelitic hornfelses associated with the Newer Gabbros: a preliminary study. *Journal of the Geological Society of London* **142**, 53–62.
Droop, G.T.R., Clemens, J.D. and Dalrymple, D.J. (2003) Processes and conditions during contact anatexis, melt escape and restite formation: the Huntley Gabbro complex, NE Scotland. *Journal of Petrology* Vol. **44**, 995–1029.
Donovan, R.N. and Foster, R.J. (1972). Subaqueous shrinkage cracks from the Caithness Flagstone Series (Middle Devonian) of north-east Scotland. *Journal of Sedimentary Petrology*, **42**, 309–17.
Downie, C. (1975) The Precambrian of the British Isles: Palaeontology. In *A Correlation of Precambrian Rocks in the British Isles* (eds. Harris, A.L., Shackleton, R.M., Watson, J.V., Downie, C., Harland, W.B. and Moorbath, S.). Special Report of the Geological Society of London, No. 6. Pp. 113–15
Downie, C. (1984) Acritarchs in British stratigraphy. Special Report of the Geological Society of London, No. **17**.
Downie, C., Lister, T.R., Harris, A.L. and Fettes, D.J. (1971) A palynological investigation of the Dalradian rocks of Scotland. *Report of the Institute of Geological Sciences*, No. 71/9.
Dymoke, P.L. (1989) Geochronological and petrological studies of the thermal evolution of the Dalradian, South-west Scottish Highlands. Unpublished PhD thesis, University of Edinburgh.

Eby G. N. (1992) Chemical subdivision of the A-type granitoids: petrogenetic and tectonic implications. *Geology,* 20, 641–4.
Edwards, M.B. (1986) Glacial Environments. 416–436 in: *Sedimentary Environments and facies* (Editor: H.G. Reading). Blackwell Scientific
Publications.
Elles, G.L. (1926) The geological structure of Ben Lawers and Meall Corranaich (Perthshire). *Quarterly Journal of the Geological Society of London*, **82**, 304–31.
Elles, G.L. (1931) Notes on the Portsoy coastal district. *Geological Magazine*, **68**, 24–34.
Elles, G.L. (1935) The Loch na Cille Boulder Bed and its place in the Highland succession. *Quarterly Journal of the Geological Society of London*, **91**, 111–49.
Elles, G.L. and Tilley, C.E. (1930) Metamorphism in relation to structure in the Scottish Highlands. *Transactions of the Royal Society of Edinburgh*, **56**, 621–46.

Ellis, D.J. and Green, D.H. (1979) An experimental study of the effect of Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria. *Contributions to Mineralogy and Petrology,* **71**, 13–22.
Ellis, N.V., Bowen, D.Q., Campbell, S., Knill, J.L., McKirdy, A.P., Prosser, C.D., Vincent, M.A. and Wilson, R.C.L. (1996) *An Introduction to the Geological Conservation Review*. Joint Nature Conservation Committee, Peterborough.
Emery, M. (2005) Polyorogenic history of the Moine rocks of Glen Urquhart, Inverness-shire. Unpublished PhD thesis, University of Portsmouth.
Evans, J.A., Fitches, W.R. and Muir, R.J. (1998) Laurentian Clasts in a Neoproterozic Tillite in Scotland. *Journal of Geology*, **106**, 361–9.
Evans, J.A, and Soper, N.J. (1997) Discussion on metamorphism and cooling of the NE Dalradian and U-Pb and Rb-Sr geochronology of magmatism and metamorphism in the Dalradian of Connemara, western Ireland. *Journal of the Geological Society, London*, **154**, 357–60.
Evans, R.H.S. and Tanner, P.W.G. (1996). A late Vendian age for the Kinlochlaggan Boulder Bed (Dalradian)? *Journal of the Geological Society, London*, **153**, 823–6.
Evans, R.H.S. and Tanner, P.W.G. (1997). Discussion on a late Vendian age for the Kinlochlaggan Boulder Bed (Dalradian): reply. *Journal of the Geological Society, London*, **154**, 917–19.
Eyles, C.H. (1988) Glacially - and tidally - influenced shallow marine sedimentation of the Late Precambrian Port Askaig Formation, Scotland. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **68**, 1–25.
Eyles, C.H. and Eyles, N. (1983) Glaciomarine model for upper Precambrian diamictiles of the Port Askaig Formation, Scotland. *Geology*, **11**, 692–6.
Eyles, N. and Clark, M. (1985) Gravity-induced soft-sediment deformation in glaciomarine sequences of the upper Proterozoic Port Askaig Formation, Scotland. *Sedimentology*, **32**, 789–814.

Fairchild, I.J. (1977) Phengite spherules from the Dalradian Bonnahaven Formation, Islay, Scotland: Glauconitized microfossils. *Geological Magazine*, **114**, 355–64.
Fairchild, I.F. (1980a) Sedimentation and origin of a Late Precambrian "dolomite" from Scotland. *Journal of Sedimentary Petrology*, **50**, 423–46.
Fairchild, I.J. (1980b) Stages in a Precambrian dolomitization, Scotland: Cementing versus replacement textures. *Sedimentology*, **27**, 631–50.
Fairchild, I.J. (1980c) The structure of NE Islay. *Scottish Journal of Geology*, **16**, 189–97.
Fairchild, I.J. (1985) Comment on 'Glaciomarine model for Upper Precambrian diamictiles of the Port Askaig Formation, Scotland'. *Geology*, **13**, 89–90.
Fairchild, I.J. (1985) Petrography and carbonate chemistry of some Dalradian dolomitic metasediments: preservation of diagenetic textures. *Journal of the Geological Society, London*, **142**, 167–85.
Fairchild, I.J. (1989) Dolomitic stromatolite-bearing units with storm deposits from the Vendian of East Greenland and Scotland: a case of facies equivalence. In *Caledonian and related Geology of Scandinavia* (ed. Gayer, R. A.), pp. Graham and Trotman, London, pp. 275–283.

Fairchild, I.J. (1991) Itinerary II: Topmost Islay Limestone (Appin Group), Port Askaig and Bonahaven Formations (Argyll Group) Port Askaig area, Islay. In *The Late Precambrian geology of the Scottish Highlands and Islands* (ed. Lister, C.J.) Geologists' Association Guide No. **44**, pp. 33–41.

Fairchild, I.J. (1993) Balmy shores and icy wastes: the paradox of carbonates associated with glacial deposits in Neoproterozoic times. *Sedimentology Review*, **1**, 1–16.

Ferry, J.M. and Spear, F.S. (1978) Experimental calibration of the partitioning of Fe and Mg between biotite and garnet. *Contributions to Mineralogy and Petrology,* **66**, 113–17.

Fettes, D.J., (1968). Metamorphic structures of Dalradian rocks in North East Scotland. Unpublished PhD thesis, University of Edinburgh.

Fettes, D.J. (1970) The structural and metamorphic state of the Dalradian rocks and their bearing on the age of emplacement of the basic sheet. *Scottish Journal of Geology*, Vol. 6, 108–118.

Fettes, D.J. (1971) Relation of cleavage and metamorphism in the Macduff Slates. *Scottish Journal of Geology*, **7**, 248–53.

Fettes, D.J. (1979) A metamorphic map of the British and Irish Caledonides. *In*: Harris, A.L., Holland, C.H. and Leake, B.E. (eds) *The Caledonides of the British Isles–Reviewed*. Geological Society, London, Special Publications, **8**, 307–21.

Fettes, D.J. and Desmons, J. (editors) (2007) *Metamorphic Rocks: a Classification and Glossary of Terms. Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Metamorphic Rocks.* Cambridge University Press, Cambridge

Fettes, D.J., Graham, C.M., Harte, B., and Plant, J.A. (1986a) Lineaments and basement domains; an alternative view of Dalradian evolution. *Journal of the Geological Society of London*, **143**, 453–64.

Fettes, D.J., Graham, C.M., Sassi, F.P., and Scolari, A. (1976) The lateral spacing of potassic white micas and facies series variations across the Caledonides. *Scottish Journal of Geology*, **12**, 227–36.

Fettes, D.J., Harris, A.L. and Hall, L.M. (1986b) The Caledonian geology of the Scottish Highlands. In *Synthesis of the Caledonian rocks of Britain*. Proceedings of the NATO Advanced Study Institute. Fettes, D J, and Harris, A L (editors). Reidel Dordrecht, pp. 303–34.

Fettes, D.J., Leslie A.G., Stephenson D., and Kimbell S.F. (1991) Disruption of Dalradian stratigraphy along the Portsoy Lineament from new geological and magnetic surveys. *Scottish Journal of Geology* **27**, 57–73.

Fettes, D.J., Long, C.B., Bevins, R.E., Max, M.D., Oliver, G.J.H., Primmer, T.J., Thomas, L.J. and Yardley, B.W.D., 1985. Grade and time of metamorphism in the Caledonide Orogen of Britain and Ireland. . 5 In, Harris, A.L.(ed), The Nature and Timing of Orogenic Activity in the Caledonian Rocks of the British Isles. Memoir of the Geological Society, London, 9.

Fettes, D.J., Macdonald, R., Fitton, J.G., Stephenson, D. and Cooper, M.R. (2011) Geochemical evolution of Dalradian metavolcanic rocks: implications for the break-up of the Rodinia supercontinent. *Journal of the Geological Society*, **168**, 1133-1146.

Fisk, S. (1986) An oxygen isotope study of siliceous rocks associated with stratabound mineralisation in Scotland and Ireland. Unpublished PhD thesis, University of Strathclyde.

Fitches, W. R. And Maltman, A. J. (1984) Tectonic development and stratigraphy of the western margin of the Caledonides: Islay and Colonsay, Scotland. *Transactions of the Royal Society of Edinburgh*, **75**, 365–82.

Fitches, W.R., Muir, R.J., Maltman, A.J. and Bentley, M.R. (1990) Is the Colonsay-west Islay block of SW Scotland an allochthonous terrane? Evidence from Dalradian tillite clasts. *Journal of the Geological Society, London*, **147**, 417-20.

Fitches, W.R., Pearce, J.A., Evans, J.A. and Muir, R.J. (1996) Provenance of the late Proterozoic Dalradian tillite clasts, Inner Hebrides, Scotland. In *Precambrian Crustal Evolution in the North Atlantic Region* (ed. Brewer, T. S.), pp. 367–77.

Flinn, D., (1953) Regional metamorphism and migmatisation in Delting, Shetland. Unpublished PhD thesis, University of London, Imperial College.

Flinn, D. (1954) On the time relations between regional metamorphism amd permeation in Delting, Shetland. *Quarterly Journal of the Geological Society of London*, **110**, 177–99.

Flinn, D. (1961) Continuation of the Great Glen Fault beyond the Moray Firth. *Nature, London*, **191**, 589–91.

Flinn, D. (1967) The metamorphic rocks of the southern part of the Mainland of Shetland. *Geological Journal*, **5**, 251–90.

Flinn, D. (1985) The Caledonides of Shetland. *In* Gee, D. G. and Sturt, B. A. (editors) *The Caledonide Orogen-Scandinavia and Related Areas*. John Wiley and Sons, Chichester. 1161–72.

Flinn, D. (1995) Formation of gneisses of migmatite and diatexite appearance in Yell, Shetland by solid-state grain growth recrystallisation. *Geological Journal*, **30**, 415–22.

Flinn, D. (1999) The Shetland Ophiolite. 31–33, 36–58 *In* Stephenson *et al*. (editors) *Caledonian Igneous Rocks of Great Britain*. Geological Conservation Review Series, No. **17**. Joint Nature Conservation Committee, Peterborough, UK.

Flinn, D. (2001) The basic rocks of the Shetland Ophiolite Complex and their bearing on its genesis. *Scottish Journal of Geology*, **37**, 79–96.

Flinn, D. (2007) The Dalradian rocks of Shetland and their implications for the plate tectonics of the northern Iapetus. *Scottish Journal of Geology*, Vol. **43**, 125–42.

Flinn, D. in press. Geology of Unst and Fetlar in Shetland. Memoir of the British Geological Survey, Sheet 131 (Scotland).

Flinn, D. and Moffat, D. T. 1985. A peridotitic komatiite from the Dalradian of Shetland. *Geological Journal*, **20**, 287-292.

Flinn, D. and Moffat, D.T. (1986) A reply to R. W. Nesbitt and L. A. Hartmann. *Geological Journal*, **21**, 207–9.

Flinn, D. and Pringle, I.R. (1976). Age of migmatisation in the Dalradian of Shetland. *Nature, London*, **259**, 299–300.

Flinn, D., Frank, P.L., Brook, M. and Pringle, I.R. (1979) Basement-cover relations in Shetland. In *The Caledonides of the British Isles–reviewed*. Harris, A.L., Holland, C.H. and Leake, B.E. (eds), Geological Society of London Special Publication No. 8, 109–15.

Flinn, D., May, F., Roberts, J.L. and Treagus, J.E. (1972). A revision of the stratigraphic succession of the East Mainland of Shetland. *Scottish Journal of Geology*, **8**, 335–343.

Flinn, D., Miller, J.A. and Roddam, D. (1991) The age of the Norwick hornblendic schists of Unst and Fetlar and the obduction of the Shetland ophiolite. *Scottish Journal of Geology* **27**, 11-19.

Flinn, D. and Oglethorpe, R.J.D. (2005). A history of the Shetland Ophiolite Complex. *Scottish Journal of Geology*, **41**, 141-8.

Fortey, N.J., Coats, J.S., Gallagher, M.J., Greenwood, P.G. and Smith, C.G. (1993) Dalradian stratabound baryte and base metals near Braemar, NE Scotland. *Transactions of the Institution of Mining and Metallurgy (Section B: Applied Earth Science)*, Vol. 102, B55-64.

Fortey, N.J. and Smith, C.G. (1986). Stratabound mineralisation in Dalradian rocks near Tyndrum, Perthshire. *Scottish Journal of Geology*, **22**, 377-93.

France, D.S. (1971) Structure and metamorphism of Moine and Dalradian rocks in the Grampians of Scotland near Beinn Dorain between Tyndrum and Moor of Rannoch. Unpublished PhD thesis, University of Liverpool.

Francis, E.H. (1982). Magma and sediment-1: Emplacement mechanisms of late Carboniferous tholeiitic sills in Northern Britain. *Journal of the Geological Society, London,* **139**, 1-20.

Friedrich, A.M, Hodges, K.V., Bowring, S.A. and Martin, M.W. (1999) Geochronological constraints on the magmatic, metamorphic and thermal evolution of the Connemara Caledonides, western Ireland. *Journal of the Geological Society, London*, **156**, 1217-30.

Friend, C.R.L., Kinny, P.D., Rogers, G., Strachan, R.A. and Patterson, B.A. (1997) U-Pb zircon geochronological evidence for Neoproterozoic events in the Glenfinnan Group (Moine Supergroup): the formation of the Ardgour granite gneiss, north-west Scotland. *Contributions to Mineralogy and Petrology* **128**, 101-13.

Friend, C.R.L., Strachan, R.A., Kinny, P.D. and Watt, G.R. (2003) Provenance of the Moine Supergroup of NW Scotland; evidence from geochronology of detrital and inherited zircons from (meta)sedimentary rocks, granites and migmatites. *Journal of the Geological Society, London* **160**, 247-57.

Gallagher, M.J., Smith, C.G., Coats, J.S., Greenwood, P.G., Chacksfield, B.C., Fortey, N.J. and Nancarrow, P.H.A. (1989) Stratabound barium and base-metal mineralisation in Middle Dalradian metasediments near Braemar, Scotland. *British Geological Survey, Mineral Reconnaisance Programme Report*, No. 104.

Ganguly, J. (1979) Garnet and clinopyroxene solid solutions, and geothermometry based on Fe-Mg distribution coefficient. *Geochemica and Cosmochemica Acta* **43**, 1021-9.

Garson, M.S, and Plant, J. (1973) Alpine Type Ultramafic Rocks and Episodic Mountain Building in the Scottish Highlands. *Nature Physical Science*, **242**, 34-8.

Geikie, A. (1865) *The scenery of Scotland viewed in connection with its physical geology (with a geological map by Sir Roderick I. Murchison and Archibald Geikie)*. Macmillan, London and Cambridge.

Geikie, A. (1897) Annual report of the Geological Survey of the United Kingdom and of the Museum of Practical Geology for the year ending December 31, 1896. In Appendix E from the 44th Report of the Department of Science and Art. (London: Her Majesty's Stationery Office.)

Gibbons, W. And Harris, A.L. (1994) A Revised Correlation of Precambrian rocks in the British Isles. *Special Reports, Geological Society, London, 22*.

Gillen, C. (1987) Huntly, Elgin and Lossiemouth. 149–160 in *Excursion Guide to the Geology of the Aberdeen area.* (editors N.H.Trewin, B.C. Kneller, and C. Gillen,). (Edinburgh: Scottish Academic press for Geological Society of Aberdeen).

Gillespie, M.R. and Styles, M.T. (1999). BGS rock classification scheme, Volume 1: Classification of igneous rocks, 2nd edition. *British Geological Survey Research Report*, **RR/99/6**

Glover, B.W. (1989). The sedimentology and basin evolution of the Grampian Group. Unpublished PhD Thesis. University of Keele.

Glover, B.W. (1993). The sedimentology of the Neoproterozoic Grampian Group and the significance of the Fort William Slide between Spean Bridge and Rubha Cuilcheanna, Inverness-shire. *Scottish Journal of Geology*, **29**, 29–43.

Glover, B.W. (1998). Sedimentology and lateral extent of the Glenshirra succession, Monadhliath Mountains, Scotland. *British Geological Survey Technical Report*, WA/98/23.

Glover B.W., Key, R.M., May, F., Clark, G.C., Phillips, E.R. and Chacksfield, B.C. (1995). A Neoproterozoic multi-phase rift sequence: the Grampian and Appin groups of the southwestern Monadhliath Mountains of Scotland. *Journal of the Geological Society of London*, **152**, 391–406.

Glover B.W. and McKie, T. (1996). A sequence stratigraphical approach to the understanding of basin history in orogenic Neoproterozoic successions: an example from the central Highlands of Scotland. In: *Sequence stratigraphy in British Geology* (eds. Hesselbo, S.P. and Parkinson, D.N.). *Geological Society of London*, Special Publication, **103**, 257–69.

Glover, B.W. and Winchester, J.A. (1989) The Grampian Group: a major Late Proterozoic clastic sequence in the central Highlands of Scotland. *Journal of the Geological Society, London*, **146**, 85–97.

Goodman, S (1991) The Pannanich Hill Complex and the origin of the Crinan Subgroup migmatites in the North-eastern and Central Highlands. *Scottish Journal of Geology,* **27**, 147–56.

Goodman, S. (1994) The Portsoy-Duchray Hill Lineament; a review of the evidence. *Geological Magazine* **131**, 407–15.

Goodman, S., Crane, A., Krabbendam, M. and Leslie, A.G. (1997) Correlation of lithostratigraphic sequences in a structurally complex area: Gleann Fearnach to Glen Shee, Scotland. *Transactions of the Royal Society of Edinburgh,* **87**, 503–13.

Goodman, S, and Lappin, M.A. (1996) The thermal aureole of the Lochnagar Complex: mineral reactions and implications from thermal modelling. *Scottish Journal of Geology,* 27, 159–72.

Goodman, S., Leslie, A.G., Ashcroft, W.A. and Crane, A. (1990) The geology of the central part of Sheet 65E (Ballater); contribution to the memoir. *British Geological Survey Technical Report* No. **WA/90/59**.

Goodman, S. and Winchester, J.A. (1993) Geochemical variations within metavolcanic rocks of the Dalradian Farragon Beds and adjacent formations. *Scottish Journal of Geology*, **29**, 131–41.

Gorokhov, M., Siedlecka, A., Roberts, D., Melnikov, N.N. and Turchenko, T.L. (2001) Rb–Sr dating of diagenetic illite in Neoproterozoic shales, Varanger Peninsula, northern Norway. *Geological Magazine*, **138**, 541–62.

Gould, D. (1997) The geology of the country around Inverurie and Alford. *Memoir of the British Geological Survey,* Sheets 76E and 76W (Scotland).

Gould, D. (2001) Geology of the Aboyne district. *Memoir of the British Geological Survey,* Sheet 66W (Scotland).

Gower, P.J. (1973) The Middle-Upper Dalradian Boundary with special reference to the Loch Tay Limestone. Unpublished PhD thesis, University of Liverpool.

Gower, P.J. (1977) The Dalradian rocks of the west coast of the Tayvallich peninsula. *Scottish Journal of Geology*, **13**, 125–33.

Gradstein, F.M., Ogg, J.G., and Smith, A.G., Agterberg, F.P., Bleeker, W., Cooper, R.A., Davydov, V., Gibbard, P., Hinnov, L.A., House, M.R., Lourens, L., Luterbacher, H.P., McArthur, J., Melchin, M.J., Robb, L.J., Shergold, J., Villeneuve, M., Wardlaw, B.R., Ali, J., Brinkhuis, H., Hilgen, F.J., Hooker, J., Howarth, R.J., Knoll, A.H., Laskar, J., Monechi, S., Plumb, K.A., Powell, J., Raffi, I., Röhl, U., Sadler, P., Sanfilippo, A., Schmitz, B., Shackleton, N.J., Shields, G.A., Strauss, H., Van Dam, J., van Kolfschoten, T., Veizer, J., and Wilson, D. (2004) *A Geologic Time Scale 2004. Cambridge University Press,* 589 pp.

Graham, C.M. (1976) Petrochemistry and tectonic significance of Dalradian metabasaltic rocks of the SW Scottish Highlands. *Journal of the Geological Society, London*, **132**, 61–84.

Graham, C.M. (1983). High-pressure greenschist to epidote-amphibolite facies metamorphism of the Dalradian rocks of the SW Scottish Highlands. *Geological Society Newsletter*, **12**, No. 4, 19.

Graham, C.M. (1986) The role of the Cruachan Lineament during Dalradian evolution. *Scottish Journal of Geology*, **22**, 257–70.

Graham, C.M. and Borradaile, G.J. (1984). The petrology and structure of Dalradian metabasic dykes of Jura: implications for Dalradian evolution. *Scottish Journal of Geology,* **20**, 257–70. *Same page range as previous ref?*

Graham, C.M. and Bradbury, H.J. (1981) Cambrian and late Precambrian basaltic igneous activity in the Scottish Dalradian: a review. Geological Magazine, **118**, 27–37.

Graham, C.M., Greig, K.M., Sheppard, S.M.F. and Turi, B. (1983) Genesis and mobility of the H_2O-CO_2 fluid phase during regional greenschist and epidote amphibolite facies metamorphism: a petrological and stable isotope study in the Scottish Dalradian. *Journal of the Geological Society, London*, **140**, 577–599.

Graham, C.M. and Harte, B. (1985) Conditions of Dalradian metamorphism. *Journal of the Geological Society, London,* **142**, 1–3.

Grant Wilson, J.S. (1882) Explanation of Sheet 97. Northern Aberdeenshire, Eastern Banffshire. *Memoir of the Geological Survey, Scotland*.

Grant Wilson, J.S. (1886) Explanation of Sheet 87, North-east Aberdeenshire and detached portions of Banffshire. Memoir of the Geological Survey, Scotland.

Grant Wilson, J.S., and Hinxman, L.W. (1890) Geology of central Aberdeenshire. *Memoir of the Geological Survey of Scotland,* Sheet 76 (Scotland).

Green, J.F.N. (1924) The structure of the Bowmore–Portaskaig District of Islay. *Quarterly Journal of the Geological Society, London*, **80**, 72 –105.

Green, J.F.N. (1931) The South-west Highland Sequence. *Quarterly Journal of the Geological Society of London* **87**, 513–550.

Gregory, J.W. (1910) Work for Glasgow geologists–the problems of the South-western Highlands. *Transactions of the Geological Society of Glasgow* **14**, 1–29.

Gregory, J.W. (1916) Pre-Cambrian of Scotland. *Handbuch der Regionaler Geologie*, III, Part I, 34–42.

Gregory, J.W. (1928) The geology of Loch Lomond. *Transactions of the Geological Society of Glasgow* **18**, 301–23.

Gregory, J.W. (1929) The Pre-Cambrian or Pre-Palaeozoic of Scotland. 28–42 in Evans, J. W. and Stubblefield, C. J. (editors) *Handbook of the geology of Great Britain*. Murby.

Gregory, J.W. (1930) The sequence in Islay and Jura. *Transactions of the Geological Society of Glasgow* Vol. **18**, 420–441.

Gregory, J.W. (1931) *Dalradian Geology: The Dalradian Rocks of Scotland and their Equivalents in other Countries*. Methuen, London.

Greig, K.M., (1987) Metamorphosed carbonates and fluid behaviour in the Dalradian of S.W. Argyll, Scotland. Unpublished PhD thesis, University of Edinburgh

Grieve, A. (1996) Ruskin and Millais at Glenfinlas. *The Burlington Magazine*, **138**, 228–234.

Gunn, A.G., Styles, M.T., Stephenson, D., Shaw, M.H. and Rollin, K. (1990) Platinum-group elements in ultramafic rocks of the Upper Deveron Valley, near Huntly, Aberdeenshire. *Mineral Reconnaissance Programme Report, British Geological Survey*, No. 115.

Gunn, W., Clough, C.T. and Hill, J.B. (1897) *The Geology of Cowal, including the part of Argyllshire between the Clyde and Loch Fyne*. Memoirs of the Geological Survey of Scotland, Sheets 29, 37 and 38.

Hackman, B.D. and Knill, J.L. (1962) Calcareous algae from the Dalradian of Islay. *Palaeontology*, **5**, 268–71.

Hall, A.J. (1993) Stratiform mineralisation in the Dalradian of Scotland. In *Mineralisation in the British Isles*. Pattrick, R.A.D., and Polya, D.A. (editors). Chapman and Hall, London, pp. 38–101.

Hall, J., Brewer, J.A., Matthews, D.H. and Warner, M. (1984) Crustal structure across the Caledonides from the WINCH seismic reflection profile: Influences on the evolution of the Midland Valley of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **75**, 97–109.

Halliday, A.N., Graham, C.M., Aftalion, M. and Dymoke, P. (1989) The depositional age of the Dalradian Supergroup: U-Pb and Sm-Nd isotopic studies of the Tayvallich Volcanics, Scotland. *Journal of the Geological Society, London*, **146**, 3–6.

Hambrey, M.J. (1983) Correlation of the Late Proterozoic tillites in the North Atlantic region and Europe. *Geological Magazine*, **120**, 209–32.

Hambrey, M.J. and Harland, W.B. (editors). (1981) *Earth's pre-Pleistocene glacial record*. Cambridge University Press, Cambridge.

Hambrey, M.J. and Harland, W.B. (1985) The Late Proterozoic glacial era. *Palaeogeography, Palaeoclimatology and Palaeoecology*, **51**, 255–72.

Hambrey, M.J. and Waddams, P. (1981) Glaciogenic boulder-bearing deposits in the Upper Dalradian Macduff Slates, northeastern Scotland. In *Earth's pre-Pleistocene glacial record*. Hambrey, M.J. and Harland, W.B. (editors). Cambridge University Press, Cambridge, pp. 571–5.

Harkness, R. (1861) On the rocks of the portions of the Highlands of Scotland south of the Caledonian Canal; and on their

equivalents in the north of Ireland. *Quarterly Journal of the Geological Society of London* **17**, 256–71.
Harris, A.L. (1960) Dalradian geology of an area between Pitlochry and Blair Atholl. Unpublished PhD thesis, University of Wales, Aberystwyth.
Harris, A.L. (1962) Dalradian geology of the Highland Border, near Callander. *Bulletin of the Geological Survey of Great Britain*, **19**, 1–15.
Harris, A.L. (1963). Structural investigations in the Dalradian rocks between Pitlochry and Blair Atholl. *Transactions of the Edinburgh Geological Society*, **19**, 256–278.
Harris, A.L. (1969) The relationships of the Leny Limestone to the Dalradian. *Scottish Journal of Geology*, **5**, 187–90.
Harris, A.L. (1972) The Dalradian rocks at Dunkeld, Perthshire. *Bulletin of the Geological Survey of Great Britain*, **38**, 1–10.
Harris, A.L. (1995) Nature and timing of orogenesis in the Scottish Highlands and the role of the Great Glen Fault. In *Current perspectives in the Appalachian-Caledonian Orogen*, Hibbard, J., van Stall, C.R. and Cawood, P.A. (editors) *Geological Association of Canada, Special Paper* **41**, 65–79.
Harris, A.L., Baldwin, C.T., Bradbury, H.J., Johnson, H.D. and Smith, R.A. (1978) Ensialic basin sedimentation: the Dalradian Supergroup. In *Crustal evolution in northwestern Britain,* Bowes, D R, and Leake, B E (editors)Special Issue of the Geological Journal No. 10 . Seel House Press, Liverpool, pp. 115–38
Harris, A.L., and Bradbury, H.J. (1977) Discussion of 'The evolution and transport of the Tay Nappe'. *Scottish Journal of Geology*, **13**, 81–3.
Harris, A.L., Bradbury, H.J. and McGonigal, N.H. (1976) The evolution and transport of the Tay Nappe. *Scottish Journal of Geology*, **12**, 103–13.
Harris, A.L. And Fettes, D.J. (1972) Stratigraphy and structure of Upper Dalradian rocks at the Highland Border. *Scottish Journal of Geology*, **8**, 253–64.
Harris, A.L., Fettes, D.J. And Soper, N.J. (1998a) Age of the Grampian event: a Discussion of "New evidence that the Lower Cambrian Leny Limestone at Callander, Perthshire, belongs to the Dalradian Supergroup, and a re-assessment of the "exotic" status of the Highland Border Complex". *Geological Magazine*, **135**, 575.
Harris, A.L., Haselock, P.J., Kennedy, M.J., Mendum, J.R., Long, J.A., Winchester, J.A. and Tanner, P.W.G. (1994). The Dalradian Supergroup in Scotland, Shetland, and Ireland, *In A Revised Correlation of the Precambrian Rocks of the British Isles* (eds. W. Gibbons and A.L. Harris), Geological Society, London, Special Report No. **22**, 33–53.
Harris, A.L., Parson, L.M., Highton, A.J. and Smith, D.I. 1981. New/Old Moine relationships between Fort Augustus and Inverness (Abstract). *Journal of Structural Geology*, **3**, 187–88.
Harris, A.L. and Pitcher, W.S. (1975) The Dalradian Supergroup. In *A Correlation of Precambrian Rocks in the British Isles.* (eds. Harris, A. L., Shackleton, R. M., Watson, J.V., Downie, C., Harland, W. B. and Moorbath, S.), Special Reports of the Geological Society, London, 6, pp. 52–75.
Harte, B. (1966) Stratigraphy, structure and metamorphism in the south-eastern Grampian Highlands of Scotland. Unpublished PhD thesis, University of Cambridge.

Harte, B., (1975) Determination of a pelite petrogenetic grid for the eastern Scottish Dalradian. *Yearbook of the Carnegie Institute, Washington*, **74**, 438-446.

Harte, B. (1979) The Tarfside succession and the structure and stratigraphy of the eastern Scottish Dalradian rocks. In *Special Publications, Geological Society, London, 8* (eds. Harris, A. L., Holland, C. H. and Leake, B. E.), pp. 221–28.

Harte, B. (1987) Glen Esk Dalradian, Barrovian metamorphic zones. In *Excursion Guide to the Geology of the Aberdeen area.* (editors N.H.Trewin, B.C. Kneller, and C. Gillen,). Scottish Academic press for Geological Society of Aberdeen, Edinburgh, p 193–210.

Harte, B. (1988) Lower Palaeozoic metamorphism in the Moine-Dalradian belt of the British Isles. In *The Caledonian—Appalachian Orogen*. Harris, A L, and Fettes, D J (editors). Special Publication of the Geological Society of London, No. 38, pp. 123–34.

Harte, B., Booth, J.E., Dempster, T.J., Fettes, D.J., Mendum, J.R. and Watts, D. (1984) Aspects of the post-depositional evolution of Dalradian and Highland Border Complex rocks in the Southern Highlands of Scotland. *Transactions of the Royal Society of Edinburgh*, **75**, 151–63.

Harte, B., Booth, J.E. and Fettes, D.J., (1987) Stonehaven to Findon: Dalradian Structure and Metamorphism. In *Excursion Guide to the Geology of the Aberdeen Area* (eds Trewin, N. H., Kneller, B. C. and Gillen, C.). Scottish Academic Press for Geological Society of Aberdeen, Edinburgh, pp. 211–26

Harte, B. and Dempster, T.J. (1987) Regional metamorphic zones: tectonic controls. *Philosophical Transactions of the Royal Society of London* Vol. **321**, 105–27.

Harte, B, and Hudson, N.F.C. (1979) Pelite facies series and the temperatures and pressures of Dalradian metamorphism in E Scotland. in The Caledonides of the British Isles–Reviewed. (eds. A.L. Harris, C.H. Holland, and B.E. Leake,) *Geological Society of London Special Publication,* **8**, pp 323–37.

Harte, B, and Johnson, M.R.W. (1969) Metamorphic history of Dalradian rocks in Glens Clova, Esk and Lethnot, Angus, Scotland. *Scottish Journal of Geology*, **5**, 54–80.

Haselock, P.J. (1982) The geology of the Corrieyairack Pass area, Inverness-shire. Unpublished PhD thesis, University of Keele.

Haselock, P.J. (1984) The systematic geochemical variation between two tectonically separate successions in the southern Monadhliaths, Inverness-shire. *Scottish Journal of Geology*. **20**, 191–205.

Haselock, P.J. and Gibbons, W. (1990). The Central Highland controversy: a traverse through the Precambrian metasediments of the Central Highlands of Scotland. *Episodes* **13**, 113–15.

Haselock, P.J. and Leslie, A.G. (1992). Polyphase deformation in Grampian Group rocks of the Monadhliath defined by a group magnetic survey. *Scottish Journal of Geology* **28**, 81–7.

Haselock, P.J., Winchester, J.A. and Whittles, K.H. (1982). The stratigraphy and structure of the southern Monadhliath Mountains between Loch Killin and upper Glen Roy. *Scottish Journal of Geology*, **18**, 275–90.

Heddle, M.F. (1878) Chapters on the mineralogy of Scotland. Chapter fourth - augite, hornblende and serpentinous change. *Transactions of the Royal Society of Edinburgh* **28**, 453–555.

Heddle M. F. (1901) *The mineralogy of Scotland*. D. Douglas, Edinburgh.

Henderson, S.M.K. (1938) The Dalradian Succession of the Southern Highlands. *Report of the meeting of the British Association for the Advancement of Science, Cambridge, 1938*, 424.

Henderson, W.G. and Robertson, A.H.F. (1982). The Highland Border rocks and their relation to marginal basin development in the Scottish Caledonides. *Journal of the Geological Society of London*, **139**, 433–50.

Henderson, W.G., Tanner, P.W.G. and Strachan, R.A. (2009) The Highland Border Ophiolite of Scotland: observations from the Highland Workshop field excursion of April 2008. *Scottish Journal of Geology*, **45**, 13–18.

Hibbert, S. (1822) *A Description of the Shetland Islands: comprising an account of their geology, scenary, antiquities and superstitions.* Constable and Co., Edinburgh.

Hickman, A.H. (1975) The stratigraphy of late Precambrian metasediments between Glen Roy and Lismore. *Scottish Journal of Geology*, **11**, 117–42.

Hickman, A H. (1978) Recumbent folds between Glen Roy and Lismore. *Scottish Journal of Geology*, **14**, 191–212.

Hickman, A.H. and Roberts, J.L. (1977). Discussion of the North Ballachulish Dalradian. *Journal of the Geological Society of London*, **133**, Part 3, 277–79.

Hickman, A.H. and Wright, A.E. (1983) Geochemistry and chemostratigraphical correlation of slates, marbles and quartzites of the Appin Group, Argyll, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **73**, 251–78.

Highton, A.J. (1986). Caledonian and pre-Caledonian events in the Moine south of the Great Glen Fault, Unpublished PhD thesis, University of Liverpool.

Highton, A.J. (1992). The tectonostratigraphical significance of pre-750 Ma metagabbros within the northern Central Highlands, Inverness-shire. *Scottish Journal of Geology* **28**, 71–6.

Highton, A.J. (1999). Solid Geology of the Aviemore District. *Memoir of the British Geological Survey,* Sheet 74E (Scotland).

Highton, A.J., Hyslop, E.K. and Noble, S.R. (1999).U-Pb zircon geochronology of migmatization in the northern Central Highlands: evidence for pre-Caledonian (Neoproterozoic) tectonmetamorphism in the Grampian Block, Scotland. *Journal of the Geological Society, London*, **156**, 1195–204.

Hill, J.B. (1899) On the progressive metamorphism of some Dalradian sediments in the region of Loch Awe. *Quarterly Journal of the Geological Society, London*, **40**, 470–93.

Hill, J.B. (1905) *The geology of mid-Argyll*. Memoirs of the Geological Survey, Scotland. Explanation of Sheet 37.

Hill, J. and Buist, D. (1994) A Geological Field Guide to the Island of Bute, Scotland. (editor Greensmith, J. T.) *Geologists' Association Guide,* No. **51**, 95 pp. Warwick Press.

Hinxman, L.W. (1896). Explanation of Sheet 75. West Aberdeenshire, Banffshire, parts of Elgin and Inverness. Memoir of the Geological Survey, Scotland.

Hinxman, L. W. and Anderson, E. M. (1915). The geology of Mid-Strathspey and Strathdearn, including the country between Kingussie and Grantown, Scotland*. Memoir of the Geological Survey, Scotland,* Sheet 74 (Scotland).

Hinxman, L. W., Carruthers, R. G. and Macgregor, M. (1923). The geology of Corrour and the Moor of Rannoch. *Memoir of the Geological Survey, Scotland,* Sheet 54 (Scotland).

Hinxman, L.W. and Grant Wilson, J.S. (1902) The geology of Lower Strathspey. Memoir of the Geological Survey, Scotland, Sheet 85 (Scotland).

Hoffmann, P.F., Condon, D.J., Bowring, S.A. and Crowley, J.L. (2004) U-Pb zircon date from the Neoproterozoic Ghaub Formation, Namibia: Constraints on Marinoan glaciation. *Geology*, **32**, 817–20.

Holdsworth, R.E., Woodcock, N. and Strachan, R. (2000) Geological Framework of Britain and Ireland. In *Geological History of Britain and Ireland* (edited by Woodcock, N. and Strachan, R.) Blackwell Science, Oxford.

Holland, C.H. and Sanders, I.S. (editors) 2009. *The Geology of Ireland* (2nd edition). Dunedin Academic Press, Edinburgh. 576 pp.

Howarth, R.J. and Leake, B.E. (2002) *The Life of Frank Coles Phillips (1902–1982) and the Structural Geology of the Moine Petrofabric Controversy*. Memoir of the Geological Society, London, **23**, 95pp.

Hudson, N.F.C. (1976) Mineral facies in pelitic rocks, with particular reference to the Buchan type metamorphism of north-eastern Scotland. Unpublished PhD thesis, University of Edinburgh.

Hudson, N.F.C. (1980) Regional metamorphism of some Dalradian pelites in the Buchan area, NE Scotland. *Contributions to Mineralogy and Petrology,* **73**, 39–51.

Hudson, N.F.C. (1985) Conditions of Dalradian metamorphism in the Buchan area. *Journal of the Geological Society of London*, **142**, 63–76.

Hutchison, A.R. and Oliver, G.J.H. (1998) Garnet provenance studies, juxtaposition of Laurentian marginal terranes and timing of the Grampian Orogeny in Scotland. *Journal of the Geological Society, London*, **155**, 541–50.

Hutton D.H.W. (1987) Strike slip terranes and a model for the evolution of the British and Irish Caledonides. *Geological Magazine* **124**, 405–425.

Hutton, D.H.W. and Alsop, G.I. (2004) Evidence for a major Neoproterozoic orogenic unconformity within the Dalradian Supergroup of NW Ireland. *Journal of the Geological Society, London*, **161**, 629–40.

Hutton, D.H.W. and Alsop, G.I. (2005) Discussion on evidence for a major Neoproterozoic orogenic unconformity within the Dalradian Supergroup of NW Ireland. *Journal of the Geological Society, London*, **162**, 221–4.

Hutton J. (1788) Theory of the Earth; or an Investigation of the Laws observable in the Composition, Dissolution, and Restoration of the Land upon the Globe. *Transactions of the Royal Society of Edinburgh* **1**, 209–304.

Hyslop, E. K. (1992). Strain-induced metamorphism and pegmatite development in the Moine rocks of Scotland. Unpublished PhD thesis, University of Hull.

Hyslop, E.K. and Piasecki, M.A.J. (1999). Mineralogy, geochemistry and the development of ductile shear zones in the Grampian Slide Zone of the Scottish Central Highlands. *Journal of the Geological Society, London*, **156**, 577–90.

Hyslop, E.K. and Pickett, E.A. (1999) Stratigraphy and magmatism in the uppermost Dalradian of the SW Scottish Highlands: A field excursion to Tayvallich, Loch Avich and Tarbert (Loch Fyne). *BGS Technical Report* **WA/99/73**.

Indares, A. and Dunning, G.R. (1997) Coronitic metagabbro and eclogite from the Grenville Province of western Quebec; interpretation of U-Pb geochronology and metamorphism. *Canadian Journal of Earth Sciences* **34**, 891–901.

Jacques J.M. and Reavy R.J. (1994) Caledonian plutonism and major lineaments in the SW Scottish Highlands. *Journal of the Geological Society, London*, **151**, 955–69.

Jamieson, T.F. (1861) On the structure of the south-west Highlands of Scotland. *Quarterly Journal of the Geological Society of London*, **17**, 133–45.

Jehu, T.J. and Campbell, R. (1917) The Highland Border rocks of the Aberfoyle District. *Transactions of the Royal Society of Edinburgh*, **52**, 175–212.

Johnson, M.R.W. (1962) Relations of movement and metamorphism in the Dalradians of Banffshire. *Transactions of the Edinburgh Geological Society*, **19**, 29–64.

Johnson, M.R.W. (1963) Some time relations of movement and metamorphism in the Scottish Highlands. *Geologie en Mijnbouw*, **42**, 121–42.

Johnson, M.R.W. (1965) Dalradian. In *The Geology of Scotland* (1st edition). Craig, G. Y. (ed.) Oliver and Boyd, Edinburgh. 117–60.

Johnson, M.R.W. (1983) Dalradian. In *Geology of Scotland* (2nd edition), Craig, G. Y. (ed.), Scottish Academic Press, Edinburgh, pp. 77–104.

Johnson, M.R.W. (1991) Dalradian. In *Geology of Scotland* (3rd edition). Craig, G. Y. (ed.) The Geological Society, London, pp. 125–60.

Johnson, M.R.W. and Harris, A.L. (1967) Dalradian–?Arenig relations in part of the Highland Border, Scotland, and their significance in the chronology of the Caledonian orogeny. *Scottish Journal of Geology*, **3**, 1–16.

Johnson, M.R.W. and Stewart, F.H. (1960) On Dalradian structures in north-east Scotland. *Transactions of the Edinburgh Geological Society*, **18**, 94–103.

Johnson T.E. (1999) Partial melting in Dalradian pelitic migmatites from the Fraserburgh–Inzie Head area of Buchan, northeast Scotland. Unpublished PhD thesis, University of Derby.

Johnson T.E., Hudson N.F.C. and Droop G.T.R. (2001a) Partial melting in the Inzie Head gneisses: the role of water and a petrogenetic grid in KFMASH applicable to anatectic pelitic migmatites. *Journal of Metamorphic Geology*, **19**, 99–118.

Johnson T.E., Hudson N.F.C. and Droop, G.T.R (2001b) Melt segregation structures within the Inzie Head gneisses of the northeastern Dalradian. *Scottish Journal of Geology*, **37**, 59–72.

Johnson T.E., Hudson N.F.C. and Droop G.T.R. (2003) Evidence for a genetic granite–migmatite link in the Dalradian of NE Scotland. *Journal of the Geological Society, London*, **160**, 447– 57.

Johnstone, G.S. (1966) British regional geology: the Grampian Highlands (3rd edition). HMSO, Edinburgh for Geological Survey and Museum.

Johnstone, G.S. (1975) The Moine Succession. In *A Correlation of Precambrian Rocks in the British Isles* (eds. Harris, A. L., Shackleton, R. M., Watson, J.V., Downie, C., Harland, W. B. and

Moorbath, S.) *Geological Society, London, Special Report*, **6**, 30–42.
Johnstone, G.S. and Smith, D.I. (1965) Geological observations concerning the Breadalbane Hydroelectric Project, Perthshire. *Bulletin of the Geological Survey of Great Britain*, **22**, 1–52.
Johnstone, G.S. and Wright, J.E. (1957) The Geology of the tunnels of the Loch Sloy hydroelectric scheme. *Bulletin of the Geological Survey of Great Britain*, **12**, 1–17.
Jones, K.A. (1959) The tectonic and metamorphic history of the Ben More—Am Binnein area, Western Perthshire. Unpublished PhD thesis, University of Wales, Swansea.

Kearns, S. (1989) Metamorphism of calc-silicate and related rocks from the Dalradian of N.E. Scotland. Unpublished PhD thesis, Derbyshire College of Higher Education.
Kennedy, M.J. (1975) The Fleur de Lys Supergroup: stratigraphic comparison of Moine and Dalradian equivalents in Newfoundland with the British Caledonides. *Journal of the Geological Society, London,* **131**, 305–10.
Kennedy W.Q. (1946) The Great Glen Fault. *Quarterly Journal of the Geological Society of London*, **102**, 41–76.
Kennedy, W.Q. (1948) On the significance of thermal structure in the Scottish Highlands. *Geological Magazine*, **85**, 229–34.
Kessler, L.G. and Gollop, I.G. (1988) Inner shelf/shoreface-intertidal transition, Upper Precambrian, Port Askaig Tillite, Isle of Islay, Argyll, Scotland. In *Tide Influenced Sedimentology, Environments and Facies* (eds. de Boer, P. L., van Gelder, A. and Nio, S. D.), Reidal, Dohdrecht, pp. 341–58.
Key, R.M., Clark, G.C., May, F., Phillips, E.R., Chacksfield, B.C. and Peacock, J.D. (1997). Geology of the Glen Roy district. *Memoir of the British Geological Survey*, Sheet 63W (Scotland).
Kilburn, C., Pitcher, W.S. and Shackleton, R.M. (1965) The stratigraphy and origin of the Portaskaig Boulder Bed series (Dalradian). *Geological Journal*, **4**, 343–60.
Kinny, P.D., Friend, C.R.L., Strachan, R.A., Watt, G.R. and Burns, I.M. (1999) U-Pb geochronology of regional migmatites in East Sutherland, Scotland; evidence for crustal melting during the Caledonian Orogeny. *Journal of the Geological Society, London*, **156**, 1143–52.
Kinny, P.D., Strachan, R.A., Friend, C.R.L., Kocks, H., Rogers, G. and Paterson, B.A. (2003a) U-Pb geochronology of deformed metagranites in central Sutherland, Scotland; evidence for widespread late Silurian metamorphism and ductile deformation of the Moine Supergroup during the Caledonian orogeny. *Journal of the Geological Society of London,* **160**, 259–69.
Kinny, P.D., Strachan, R.A., Kocks, H. and Friend, C.R.L. (2003b) U-Pb geochronology of late Neoproterozoic augen granites in the Moine Supergroup, NW Scotland: dating of rift-related, felsic magmatism during supercontinent break-up? *Journal of the Geological Society of London,* **160**, 925–34.
Klein, G.D.V. (1970) Tidal origin of a Precambrian quartzite - the Lower Fine-grained Quartzite (Middle Dalradian) of Islay, Scotland. *Journal of Sedimentary Petrology*, **40**, 973–85.
Klein, G.D.V. (1971) Tidal origin of a Precambrian quartzite - the Lower Fine-grained Quartzite (Middle Dalradian) of Islay, Scotland: Reply. *Journal of Sedimentary Petrology*, **41**, 886–9.

Kneller, B.C. (1985) Dalradian basin evolution and metamorphism. *Journal of the Geological Society of London*, **142**, 4 (abstract).
Kneller, B.C. (1987) A geological history of NE Scotland. 1–50. In *Excursion guide to the geology of the Aberdeen area*. Trewin, H.N., Kneller, B.C. and Gillen, C. (editors). Scottish Academic Press for Geological Society of Aberdeen, Edinburgh.
Kneller, B.C. (1988) The geology of part of Buchan. Unpublished PhD thesis, University of Aberdeen.
Kneller, B.C. and Aftalion M. (1987) The isotopic and structural age of the Aberdeen Granite. *Journal of the Geological Society of London* **144**, 717–21.
Kneller, B.C. and Leslie, A.G. (1984) Amphibolite facies metamorphism in shear zones in the Buchan area of NE Scotland. *Journal of Metamorphic Geology* **2**, 83–94.
Knill, J.L. (1959) Palaeocurrents and sedimentary facies of the Dalradian metasediments of the Craignish–Kilmelfort district. *Proceedings of the Geologists' Association*, **70**, 273–84.
Knill, J.L. (1960) The tectonc pattern in the Dalradian of the Craignish–Kilmelfort District, Argyllshire. *Quarterly Journal of the Geological Society of London*, **115**, 339–64.
Knill, J.L. (1963) A sedimentary history of the Dalradian Series. In *The British Caledonides.* (eds Johnson, M.R.W. and Stewart, F.H.). Oliver and Boyd, Edinburgh, pp. 99–121.
Krabbendam, M. and Leslie, A.G. (1996) Folds with vergence opposite to the sense of shear. *Journal of Structural Geology*, **18**, 777–81.
Krabbendam, M., Leslie, A.G., Crane, A. and Goodman, S. (1997) Generation of the Tay Nappe, Scotland, by large-scale SE-directed shearing. *Journal of the Geological Society, London*, **154**, 15–24.
Krabbendam, M., Prave, A.R. and Cheer, D.A. (2008) A fluvial origin for the Neoproterozoic Morar Group, NW Scotland; implications for Torridon–Morar Group correlation and the Grenville Orogen foreland basin. *Journal of the Geological Society, London,* **165**, 379–94.
Kruhl, J. and Voll, G. (1975) Large scale pre-metamorphic and pre-cleavage inversion at Loch Leven, Scottish Highlands. *Neues Jahrbuch für Mineralogie*, **2**, 71–8.
Kynaston, H. and Hill J.B. (1908) *The Geology of the country near Oban and Dalmally*. Memoir of the Geological Survey, Sheet 45 (Scotland).

Lambert, R.St. J. (1975) Discussion of Moine–Dalradian relationships in the River Leven. *Journal of the Geological Society of London,* **131**, 327–8.
Lambert, R.St.J., Holland, J.G. and Winchester, J.A. (1982) A geochemical comparison of the Dalradian Leven Schists and the Grampian Division Monadhliath Schists of Scotland. *Journal of the Geological Society of London*, **139**, 71–84.
Lambert, R.St.J. and McKerrow, W.S. (1976) The Grampian Orogeny. *Scottish Journal of Geology*, **12**, 271–92.
Lambert, R.St.J, Winchester, J.A. and Holland, J.G. (1981) Comparative geochemistry of pelites from the Moinian and Appin Group (Dalradian) of Scotland. *Geological Magazine*, **118**, 477–90.
Lawson, J. D. and Weedon, D. S. (editors) (1992) *Geological Excursions around Glasgow and Girvan*. Geological Society of Glasgow, Glasgow.

Leake, B.E. (1982) Volcanism in the Dalradian. In *Igneous rocks of the British Isles*. Sutherland, D. S. (editor). John Wiley and Sons, Chichester, pp. 45–50.

Leake, B.E. and Tanner, P.W.G. (1994) *The Geology of the Dalradian and Associated Rocks of Connemara, Western Ireland: a report to accompany the 1:63360 geological map and cross sections.* Royal Irish Academy, Dublin.

Lee, G.W. and Bailey, E.B. (1925) The pre-Tertiary geology of Mull, Loch Aline and Oban. Memoir of the Geological Survey of Great Britain, Sheet 44 (Scotland).

Leggo, P.J., Tanner, P.W.G. and Leake, B.E. (1969) Isochron study of Donegal Granite and certain Dalradian rocks of Britain. In *North Atlantic-geology and Continental Drift, a symposium* (ed. M. Kay), Memoir of the American Association of Petroleum Geologists, 12, pp. 354–62.

Le Maitre, R.W (editor) (2002). *Igneous Rocks: a Classification and Glossary of Terms; Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks*. Cambridge University Press, Cambridge, 236 pp.

Leslie, A.G., Chacksfield, B.C., Smith, M. and Smith, R.A. (1999). The Geophysical signature of a major shear zone in the Central Highlands of Scotland. *British Geological Survey Technical Report* No. **WA/99/32R.**

Leslie, A.G., Krabbendam, M. and Smith, R.A. (2006) The Gaick Fold Complex: large-scale recumbent folds and their implications for Caledonian structural architecture in the Central Grampian Highlands. *Scottish Journal of Geology*, **42**, 149–60.

Leslie, A.G., Smith, M. and Soper, N.J. (2008) Laurentian margin evolution and the Caledonian orogeny–a template for Scotland and East Greenland. In *The Greenland Caledonides: Evolution of the Northeast Margin of Laurentia.* Higgins, A.K., Gilotti, J.A. and Smith, M.P. (editors), Geological Society of America Memoir, **202**, 307–43.

Lindsay, N.G. (1988) Contrasts in Caledonian tectonics of the Northern and Central Highlands. Unpublished PhD thesis, University of Liverpool.

Lindsay, N.G., Haselock, P.J. and Harris, A.L. (1989). The extent of Grampian orogenic activity in the Scottish Highlands. *Journal of the Geological Society of London*, **146**, 733–5.

Litherland, M. (1970) The stratigraphy and structure of the Dalradian rocks around Loch Creran, Argyll. Unpublished PhD thesis, University of Liverpool.

Litherland, M. (1975) Organic remains and traces from the Dalradian of Benderloch, Argyll. *Scottish Journal of Geology*, **11**, 47–50.

Litherland, M. (1980) The stratigraphy of the Dalradian rocks around Loch Creran, Argyll. *Scottish Journal of Geology*, **16**, 105–23.

Litherland, M. (1982) The structure of the Loch Creran Dalradian and a new model for the SW Highlands. *Scottish Journal of Geology*, **18**, 205–25.

Loudon, T.V. (1963) The sedimentation and structure in the Macduff District of North Banffshire and Aberdeenshire. Unpublished PhD thesis, University of Edinburgh.

Lowe, D. R. 1976. Subaqueous liquified and fluidised sediment flows and their deposits. *Sedimentology*, **23**, pp. 285-308.

Lyubetskaya, T. and Ague, J.J., 2010. Modeling metamorphism in collisional orogens intruded by magmas: fluid flow and implications for Barrovian and Buchan metamorphism, Scotland. American Journal of Science, 310, 459-491.

McAteer, C.A., Daly, J.S., Flowerdew, M.J., Connelly, J.N., Housh, T.B. and Whitehouse, M.J. (2010) Detrital zircon, detrital titanite and igneous clast U-Pb geochronology and basement-cover relationships of the Colonsay Group, SW Scotland: Laurentian provenance and correlation with the Neoproterozoic Dalradian Supergroup. *Precambrian Research*, **181**, 21-42.
McCallien, W.J. (1925) Notes on the Geology of the Tarbet district of Loch Fyne. *Transactions of the Geological Society of Glasgow*, **17**, 233–63.
McCallien, W.J. (1926) The structure of South Knapdale (Argyll). *Transactions of the Geological Society of Glasgow*, **17**, 377–94.
McCallien, W.J. (1929) The metamorphic rocks of Kintyre. *Transactions of the Royal Society of Edinburgh*, **56**, 409-36.
Mccallien, W.J. (1938) The Geology of Bute. *Transactions of the Buteshire Natural History Society*, **12**, 84–112.
McCay, G.A., Prave, A.R., Alsop, G.I. and Fallick, A.E. (2006) Glacial trinity: Neoproterozoic Earth history within the British-Irish Caledonides. *Geology,* **34**, 909–12.
McClay, K.R. (1987) *The Mapping of Geological Structures*. Geological Society of London Handbook, Open University Press, Milton Keynes, 161 pp.
McClay K.R., Norton M.G., Cony P. and Davis G.H. (1986) Collapse of the Caledonian Orogen and the Old Red Sandstone. *Nature, London* **323**, 147–9.
MacCulloch, J. (1814) Remarks on several parts of Scotland which exhibit quartz rock, and on the nature and connexions of this rock in general. *Transactions of the Geological Society,* **2**, 450–87.
MacCulloch, J. (1819) *A description of the western islands of Scotland including the Isle of Man: comprising an account of their geological structure; with remarks on their agriculture, scenary and antiquities*. 3 volumes. Constable, London.
MacDonald, J.G. and Herriot, A. (1983) *Macgregor's excursion guide to the geology of Arran*. (3rd edition). Geological Society of Glasgow and University of Glasgow, Glasgow.
Macdonald, R. and Fettes, D.J. (2007) The tectonomagmatic evolution of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* **97**, 213–95.
Macdonald, R., Fettes, D.J., Stephenson, D. and Graham, C.M. (2005) Basic and ultrabasic volcanic rocks from the Argyll Group (Dalradian) of NE Scotland. *Scottish Journal of Geology*, **41**, 159-74.
MacGregor, A.G. (1948) British regional geology: the Grampian Highlands (2nd edition), HMSO for Geological Survey and Museum, Edinburgh.
MacGregor, A.R. (1996) Edzell and Glen Esk. 93–108 in *Fife and Angus Geology, an excursion guide* (3rd edition) by A.R. MacGregor, Pentland Press, Durham.
MacGregor, S.M.A. and Roberts, J.L. (1963) Dalradian pillow lavas, Ardwell Bridge, Banffshire. *Geological Magazine*, **100**, 17–23.
McIntyre, D.B. (1950) Lineation, boudinage and recumbent folding in the Struan Flags (Moine), near Dalnacardoch, Perthshire. *Geological Magazine*, **87**, 205–25.

McIntyre, D.B. (1951) The tectonics of the area between Grantown and Tomintoul (mid-Strathspey). *Quarterly Journal of the Geological Society of London*, **107**, 1-22.
McKenzie, D.P. and Bickle, M.J. (1988). The volume and composition of melt generated by the extension of the lithosphere. *Journal of Petrology*, **29**, 625–79.
McKie, T. (1990) Tidal and storm-influenced sedimentation from a Cambrian transgressive passive margin sequence. *Journal of the Geological Society, London*, **147**, 785–94.
Mackie, W. (1908) Evidence of contemporaneous volcanic action in the Banffshire schists. *Transactions of the Edinburgh Geological Society*, **9**, 93–101.
McLellan, E.L. (1983) Barrovian migmatites and the thermal history of the south-eastern Grampians. Unpublished PhD thesis, University of Cambridge.
McLellan, E.L., 1985. Metamorphic reactions in the kyanite and sillimanite zones of the Barrovian type area, Journal of Petrology, 26, 789-818.
Macnair, P. (1896) The altered clastic rocks of the Southern Highlands: their structure and succession. *Geological Magazine*, Decade 4, **3**, 167–174, 211–217.
Macnair, P. (1906) On the development of the great axial lines of folding in the Highland schists. *Proceedings of the Royal Philosophical Society of Glasgow* Vol. **37**, 129–xxx.
Macnair, P. (1908) *The Geology and Scenery of the Grampians and the Valley of Strathmore,* James MacLehose and Sons, Glasgow, 2 volumes, 256 pp.
Marcantonio, F., Dickin, A.P., McNutt, R.H. and Heaman, L.M. (1988). A 1880-million year old Proterozoic gneiss terrane in Islay with implications for crustal evolution of Britain. *Nature,* **335**, 62–64.
Mather, J.D. (1968) A geochemical, mineralogical and petrological study of rocks of lower greenschist facies from the Dalradian of Scotland. Unpublished PhD thesis, University of Liverpool.
May, F. (1970) Movement, metamorphism and migmatization in the Scalloway region of Shetland. *Bulletin of the Geological Survey of Great Britain*, **31**, 205–26.
May, F. and Highton, A.J. (1997) Geology of the Invermoriston district. *Memoir of the British Geological Survey*. Sheet 73W (Scotland).
Melezhik, V.A., Gorokhov, I.M., Kuznetsov, A.B. and Fallick, A.E. (2001). Chemostratigraphy of Neoproterozoic carbonates: implications for 'blind dating'. *Terra Nova*, **13**, 1–11.
Mendum, J.R. 1987. Dalradian of the Collieston coast section. 161–172 in *Excursion guide to the geology of the Aberdeen area*. Trewin, N H, Kneller, B C, and Gillen, C (editors). (Edinburgh: Scottish Academic Press for Geological Society of Aberdeen.)
Mendum, J.R., Barber, A.J., Butler, R.W.H., Flinn, D., Goodenough, K.M., Krabbendam, M., Park, R.G. and Stewart, A.D. (2009) *Lewisian, Torridonian and Moine rocks of Scotland*, Geological Conservation Review Series, No. **34**, Joint Nature Conservation Committee, Peterborough, 722 pp.
Mendum, J.R. and Fettes, D.J. (1985) The Tay nappe and associated folding in the Ben Ledi–Loch Lomond area. *Scottish Journal of Geology*, **21**, 41–56.

Mendum, J.R. and Noble, S.R. (2010) Mid-Devonian sinistral transpression on the Great Glen Fault: the rise of the Rosemarkie Inlier and the Acadian Event in Scotland. In *Continental tectonics and mountain building: the legacy of Peach and Horne*. (eds R.D. Law, R.W.H. Butler, R.E. Holdsworth, M. Krabbendam and R.A. Strachan), *Geological Society, London, Special Publication*, No. **335**, pp. 161-187.
Mendum, J.R. and Thomas, C.W. (1997) Discussion on the generation of the Tay Nappe, Scotland, by large-scale SE-directed shearing. *Journal of the Geological Society, London*, **154**, 581–3.
Miall, A. D. 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. *Earth Science Reviews*, **22**, pp. 261-308.
Miall, A. D. 1992. Alluvial Deposits. In: Walker, R. G. & James, N. P. (eds), Facies models – response to sea level changes. Geoscience Canada, pp. 119-1992.
Millar, I.L. (1999) Neoproterozoic extensional basic magmatism associated with the West Highland granite gneiss in the Moine Supergroup of NW Scotland. *Journal of the Geological Society, London* **156**, 1153–62.
Moffat, D.T. (1987) The serpentinized ultramafites of the Shetland Caledonides. Unpublished PhD thesis, University of Liverpool.
Moig, N.A.W. (1986) A structural study of the Dalradian rocks of the Banff coastal transect, NE Scotland. Unpublished PhD thesis, University of Dundee.
Moles, N.R. (1985a) Geology, geochemistry and petrology of the Foss stratiform baryte–base metal deposit and adjacent Dalradian metasediments, near Aberfeldy. Unpublished PhD thesis, University of Edinburgh.
Moles, N.R. (1985b) Metamorphic conditions and uplift history in central Perthshire: evidence from mineral equilibria in the Foss celsian-barite-sulphide deposit, Aberfeldy. *Journal of the Geological Society of London*, **142**, 39–52.
Möller, C. (1998) Decompressed eclogites in the Sveconorwegian (Grenvillian) Orogen of SW Sweden; petrology and tectonic implications. *Journal of Metamorphic Geology,* **16**, 641–56.
Molyneux, S.G. 1998. An upper Dalradian microfossil reassessed. *Journal of the Geological Society, London,* **155**, 740–743.
Morgan, W.C. (1966) The metamorphic history of the Dalradian rocks between Tomintoul and Loch Builg, Banfshire. Unpublished Ph D thesis, University of Aberdeen.
Morris, G.A. and Hutton, D.H.W. (1993) Evidence for sinistral shear associated with the emplacement of the early Devonian Etive dyke swarm. *Scottish Journal of Geology,* **29**, 69–72.
Mould, D.D.C.P. (1946) The geology of the Foyers 'granite' and the surrounding country. *Geological Magazine*, **83**, 249–65.
Muir, R.J. (1990) The Precambrian basement and related rocks of the southern Inner Hebrides, Scotland. Unpublished PhD thesis, University of Wales, Aberystwyth.
Muir, R.J., Fitches, W.R. and Maltman, A.J. (1989) An Early Proterozoic link between Greenland and Scandinavia in the Inner Hebrides of Scotland. *Terra Abstract*, **1**, 5.
Muir, R.J., Fitches, W.R. and Maltman, A.J. (1992). Rhinns Complex: a missing link in the Proterozoic basement of the North Atlantic region*. Geology,* **20**, 1043–6.
Muir, R.J., Fitches, W.R. and Maltman, A.J. (1994a). The Rhinns Complex: Proterozoic basement on Islay and Colonsay, Inner

Hebrides, Scotland, and on Inishtrahull, NW Ireland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **85**, 77–90.

Muir, R.J., Fitches, W.R., Maltman, A.J. and Bentley, M.R. (1994b) Precambrian rocks of the southern Inner Hebrides–Malin Sea region: Colonsay, west Islay, Inishtrahull and Iona. *In*: Gibbons, W. and Harris, A.L. (eds) *A revised correlation of Precambrian rocks in the British Isles*. Geological Society, London, Special Report **22**, 54–58.

Muir, R.J., Fitches, W.R. and Maltman, A.J. (1995). The Colonsay Group and basement-cover relationship on the Rhinns of Islay, Inner Hebrides. *Scottish Journal of Geology*, **31**, 125–30.

Munro, M. (1986) Geology of the country around Aberdeen. *Memoir of the British Geological Survey*, Sheet 77 (Scotland).

Munro, M. and Gallagher, J W. (1984) Disruption of the 'Younger Basic' masses in the Huntly–Portsoy area, Grampian Region. *Scottish Journal of Geology*, **20**, 361–82.

Murchison, R.I. (1851) On the Silurian rocks of the south of Scotland. *Quarterly Journal of the Geological Society of London*, **7**, 139–78.

Murchison, R.I. (1859) *Siluria: the History of the Oldest Known Rocks Containing Organic Remains, With a Brief Sketch of the Distribution of Gold Over the Earth*. 3rd edition. John Murray, London.

Murchison, R.I. and Geikie, A. (1861) On the altered rocks of the Western Islands of Scotland and the North-Western and Central Highlands. *Quarterly Journal of the Geological Society of London* **17**, 171- ??.

Mutti, E. and Normark, W.R. (1987) Comparing examples of modern and ancient turbidite systems: problems and concepts. In *Marine Clastic Sedimentology* (eds. Legget, J.K and Zuffa, G.G.), Graham and Trotman, pp.1–38.

Mykura, W. (1976) *British Regional Geology: Orkney and Shetland*. HMSO, Edinburgh for the Institute of Geological Sciences.

Nell, P.A.R. (1984) The geology of lower Glen Lyon. Unpublished PhD thesis, University of Manchester.

Nell, P.A.R. (1986) Discussion on the Caledonian metamorphic core: an Alpine model. *Journal of the Geological Society of London*, **143**, 723–8.

Nesbitt, R.W. and Hartmann, L.A. (1986) Comments on 'A peridotitic komatiite from the Dalradian of Shetland' by D. Flinn and D.T. Moffat. *Geological Journal*, **21**, 201–5.

Nicol, J. (1844) *Guide to the geology of Scotland: Containing an Account of the Character, Distribution and More Interesting Appearances of its Rocks and Minerals*. Oliver and Boyd, Edinburgh.

Nicol, J. (1852) On the geology of the southern portion of the peninsula of Cantyre, Argyllshire. *Quarterly Journal of the Geological Society of London*, **8**, 406–25.

Nicol J. (1863) On the geological structure of the Southern Grampians. *Quarterly Journal of the Geological Society of London* **19**, 180–209.

Noble, S.R., Hyslop, E.K. and Highton, A.J. (1996). High-precision U-Pb monazite geochronology of the *c.* 806 Ma Grampian Shear Zone and the implications for evolution of the Central Highlands of Scotland. *Journal of the Geological Society, London*, **153**, 511–14.

Okonkwo, C.T. (1985). The geology and geochemistry of the metasedimentary rocks of the Loch Laggan–Upper Strathspey area, Inverness-shire. Unpublished PhD thesis, University of Keele.

Okonkwo, C.T. (1988). The stratigraphy and structure of the metasedimentary rocks of the Loch Laggan–Upper Strathspey area, Inverness-shire. *Scottish Journal of Geology*, **24**, 21–34.

Oldroyd, D.R. and Hamilton, B.M. (2002) Themes in the early history of Scottish geology. In: Trewin N. H. (ed.) *The Geology of Scotland*. The Geological Society, London, pp. 27–43.

Oliver, G.J.H. (2001) Reconstruction of the Grampian episode in Scotland: its place in the Caledonian Orogeny. *Tectonophysics,* **332**, 23–49.

Oliver, G.J.H. (2002) Chronology and terrane assembly, new and old controversies. In *The Geology of Scotland* (edited by Trewin, N. H.) The Geological Society, London, 201–11.

Oliver, G.J.H., Chen, F., Buchwald, R. and Hegner, E. (2000) Fast tectonometamorphism and exhumation in the type area of the Barrovian and Buchan zones. *Geology*, **28**, 459–62.

Oliver, G.J.H., Simon, A.W., Wan, Y., 2008. Geochronology and geodynamics of Scottish granitoids from the late Neoproterozoic break-up of Rodinia to Palaeozoic collision. Journal of the Geological Society, London, 165, 661-674.

Pankhurst, R.J. (1970) The geochronology of the basic igneous complexes. *Scottish Journal of Geology*, **6**, 83–107.

Pankhurst, R.J. and Pidgeon, R.T. (1976) Inherted isotope systems and the source region prehistory of the early Caledonian granites in the Dalradian Series of Scotland. *Earth and Planetary Science Letters*, **31**, 58–66.

Pantin, H.M. (1952) Part 1: The petrology and structure of the Ben Vrackie epidiorite. Part 2: Some new observations on Dalradian stratigraphy and tectonics. Unpublished PhD thesis, University of Cambridge.

Pantin H.M. (1961) The stratigraphy and structure of the Blair Atholl–Ben a' Gloe area, Perthshire, Scotland. *Transactions of the Royal Society of New Zealand,* **88**, 597–622.

Park, R.G. (1992) Plate kinematic history of Baltica during the Middle to Late Proterozoic: a model. *Geology* **20**, 725–8.

Park, R.G. (1994) Early Proterozoic tectonic overview of the northern British Isles and neighbouring terrains in Laurentia and Baltica. *Precambrian Research,* **68**, 65–79.

Parson, L M. (1982) The Precambrian and Caledonian geology of the ground near Fort Augustus, Inverness-shire. Unpublished PhD thesis, University of Liverpool.

Paterson, I.B., Hall, I.H.S. and Stephenson, D. (1990) Geology of the Greenock district. Memoir of the British Geological Survey, Sheet 30W and part of Sheet 29E (Scotland).

Pattrick, R.A. and Treagus, J.E. (1996) Economic geology of the Schiehallion district, central highlands of Scotland. *British Geological Survey Technical Report* No. **WA/96/89**.

Peach, B.N. (1904) *Summary of Progress of the Geological Survey of the United Kingdom for 1903*, 69.

Peach, B.N. and Horne, J. (1930) *Chapters on the Geology of Scotland,* Oxford University Press, London.

Peach, B.N., Kynaston, B.A. and Muff, H.B. (1909) The geology of the seaboard of mid Argyll including the islands of Luing, Scarba, the Garvellachs, and the Lesser Isles, together with the northern part of Jura and a small portion of Mull. Memoirs of the Geological Survey of Scotland, Sheet 36.

Peach, B.N., Wilson, J.G.S., Hill, J.B., Bailey, E.B. and Grabham, G.W. (1911) The Geology of Knapdale, Jura and North Kintyre. Memoirs of the Geological Survey of Scotland, Sheet 28.

Peach, B.N. and Horne, J. (1930) *Chapters on the Geology of Scotland,* Oxford University Press, Oxford.

Peacock, J.D., Berridge, N.G., Harris, A.L. and May, F. (1968) The geology of the Elgin district. Memoir of the Geological Survey of Scotland, Sheet 95 (Scotland).

Phillips, E.R. (1996) The mineralogy and petrology of the igneous and metamorphic rocks exposed in the Macduff district (Sheet 96E), Northeast Scotland. British Geological Survey, Mineralogy and Petrology Technical Report, **WG/96/26**.

Phillips, E.R. and Auton, C.A. (1997) Ductile fault rocks and metamorphic zonation in the Dalradian of the Highland Border SW of Stonehaven, Kincardineshire. *Scottish Journal of Geology*, **33**, 83-93.

Phillips, E.R., Clark, G.C. and Smith, D.I. (1993) Mineralogy, petrology, and microfabric analysis of the Eilrig Shear Zone, Fort Augustus, Scotland. *Scottish Journal of Geology*, **29**, 143–58.

Phillips, E.R., Hyslop, E.K., Highton, A.J and Smith, M. (1999). The timing and P-T conditions of regional metamorphism in the Central Highlands. *Journal of the Geological Society, London,* **156**, 1183–93.

Phillips, F.C. (1930) Some mineralogical and chemical changes induced by progressive metamorphism in the Green Bed group of the Scottish Dalradian. *Journal of the Mineralogical Society*, **22**, 240–256.

Phillips, F.C. (1954) *The Use of Stereographic Projection in Structural Geology,* Arnold, London.

Phillips, W.E.A., Stillman, C.J. and Murphy, T. (1976) A Caledonian plate tectonic model. *Journal of the Geological Society of London*, **132**, 579–609.

Piasecki M.A.J. (1975) Tectonic and metamorphic history of the Upper Findhorn, Inverness-shire, Scotland. *Scottish Journal of Geology,* **11**, 87–115.

Piasecki, M.A.J. (1980). New light on the Moine rocks of the Central Highlands of Scotland. *Journal of the Geological Society of London,* **137**, 41–59.

Piasecki, M.A.J. and van Breemen, O. (1979a) A Morarian age for the "younger Moines" of central and western Scotland. *Nature, London*, **278**, 734–6.

Piasecki, M.A.J. and van Breemen, O. (1979b). The 'Central Highland Granulites': cover-basement tectonics in the Moine. In *The Caledonides of the British Isles - reviewed*. (editors. Harris, A.L., Holland, C.H. and Leake, B.E.*), The Geological Society of London*, Special Publications, **8**, 139–44.

Piasecki, M.A.J. and van Breemen, O. (1983) Field and isotopic evidence for a c. 750 Ma tectonothermal event in Moine rocks in the Central Highland region of the Scottish Caledonides. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **73**, 119–34.

Piasecki, M.A.J., van Breemen, O. and Wright, A.E. (1981) Late Precambrian geology of Scotland, England and Wales. In *Geology of the North Atlantic Borderlands,* Kerr, J.W. and Fergusson, A.J.

(eds). Memoir of the Canadian Society of Petroleum Geologists, **7**, 57–94.

Piasecki, M.A.J. and Temperley, S. (1988a). The Central Highland Division. *In*: Winchester, J.A. (ed) *Later Proterozoic stratigraphy of the Northern Atlantic regions*. Blackie, Glasgow and London, 46–53.

Piasecki, M.A.J. and Temperley, S. (1988b). The northern sector of the central Highlands. 51-68 in *An excursion guide to the Moine geology of the Scottish Highlands*. Allison, I, May, F, and Strachan, R A (editors). (Edinburgh: Scottish Academic Press for Edinburgh Geological Society and Geological Society of Glasgow.)

Pickering K.T., Bassett M.G., and Siveter D.J. (1988) Late Ordovician–early Silurian destruction of the Iapetus Ocean: Newfoundland, British Isles and Scandinavia: A discusion. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* **79**, 361–82.

Pickett, E.A. (1997) An introduction to the Green Beds of the Southern Highland Group: previous research and an account of preliminary work carried out in 1997. *British Geological Survey Technical Report* WA/97/92.

Pickett, E.A., Hyslop, E.K. and Petterson, M.G. (2006) The Green Beds of the SW Highlands: deposition and origin of a basic igneous-rich sedimentary sequence in the Dalradian Supergroup of Scotland. *Scottish Journal of Geology*, **42**, 43–57.

Pidgeon R.T. and Compston W. (1992) A Shrimp ion microprobe study of inherited and magmatic zircon from Scottish Caledonian granites. *Transactions of the Royal Society, Edinburgh: Earth Sciences,* **83**, 473–83.

Pitcher, W.S. and Berger, A.R. (1972) *The Geology of Donegal: a study of granite emplacement and unroofing*. Wiley-Interscience, New York, 435 pp.

Plant, J.A., Stone, P. and Mendum, J.R. (1999) Regional geochemistry, terrane analysis and metallogeny in the British Caledonides. In *Continental Tectonics*. MacNiocaill, C and Ryan, P.D. (editors), Geological Society, London, Special Publication No **164**, 109–26.

Plant, J.A., Watson, J.V. and Green, P.M. (1984) Moine–Dalradian relationships and their palaeotectonic significance. *Proceedings of the Royal Society*, **395a**, 185–202.

Powell, R. and Evans, J.A. (1983). A new geobarometer for the assemblage biotite-muscovite-chlorite-quartz. *Journal of Metamorphic Geology,* **1**, 331–6.

Power, M.R. and Pirrie, D. (2000) Platinum-group mineralization within ultramafic rocks at Corrycharmaig, Perthshire: implications for the origin of the complex. *Scottish Journal of Geology*, **36**, 143–50.

Prave, A.R. (1999) The Neoproterozoic Dalradian Supergroup of Scotland: an alternative hypothesis. *Geological Magazine*, **136**, 609–17.

Prave, A.R., Fallick, A.E., Thomas, C.W. and Graham, C.M. (2009a) A composite C-isotope profile for the Neoproterozoic Dalradian Supergroup of Scotland and Ireland. *Journal of the Geological Society*, **166**, 845-857.

Prave, A.R., Strachan, R.A. and Fallick, A.E. (2009b) Global C cycle perturbations recorded in marbles: a record of Neoproterozoic Earth history within the Dalradian succession of the Shetland Islands, Scotland. *Journal of the Geological Society*, **166**, 129-135.

Pringle, I.R. (1972) Rb-Sr age determinations on shales associated with the Varanger Ice Age. *Geological Magazine*, **109**, 465–72.

Pringle, J. (1940) The discovery of Cambrian trilobites in the Highland Border rocks near Callander, Perthshire (Scotland). *British Association for the Advancement of Science: Annual Report for 1939–40*, **1**, 252.

Pumpelly, R., Wolff, J.E. and Dale, T.N. (1894) Geology of the Green Mountains. *United States Geological Survey Memoir*, **23**, 1-157.

Rainbird, R.H., Hamilton, M.A. and Young, G.M. (2001) Detrital zircon geochronology and provenance of the Torridonian, NW Scotland. *Journal of the Geological Society, London,* **158**, 15–27.

Ramsay, D.M. (1959) Structure and metamorphism of Glen Lyon. Unpublished PhD thesis, University of Glasgow.

Ramsay, D.M. and Sturt, B.A. (1979) The status of the Banff Nappe. In *The Caledonides of the British Isles—reviewed*. Harris, A L, Holland, C H and Leake, B E (editors). Special Publication of the Geological Society of London, No. 8. 145–151

Ramsay, J.G. (1958) Moine—Lewisian relations at Glenelg, Inverness-shire. *Quarterly Journal of the Geological Society of London* **113**, 487–523.

Rast, N. (1956) Tectonics of Central Perthshire. Unpublished PhD thesis, University of Glasgow.

Rast, N. (1958) Metamorphic history of the Schiehallion complex, Perthshire. *Transactions of the Royal Society of Edinburgh*, **64**, 413–31.

Rast, N. (1963). Structure and metamorphism of the Dalradian rocks of Scotland. In *The British Caledonides.* (editors. Johnson, M.R.W. and Stewart, F.H.). Oliver and Boyd, Edinburgh, 123–42.

Rast, N. and Litherland, M. (1970) The correlation of the Ballachulish and Perthshire (Islay) successions. *Geological Magazine*, **107**, 259–72.

Read, H.H. (1919) The two magmas of Strathbogie and Lower Banffshire. *Geological Magazine* **56**, 364–71.

Read, H.H. (1923) The geology of the country around Banff, Huntly, and Turriff, Lower Banffshire and north-west Aberdeenshire. *Memoir of the Geological Survey, Scotland.* Sheets 86 and 96 (Scotland).

Read, H.H. (1927) The igneous and metamorphic history of Cromar, Deeside. *Transactions of the Royal Society of Edinburgh,* **55**, 317–53.

Read, H.H. (1928) The Highland Schists of middle Deeside and east Glen Muick. *Transactions of the Royal Society of Edinburgh,* **55**, 755–72.

Read, H.H. (1933). On quartz-kyanite rocks in Unst, Shetland Islands, and their bearing on metamorphic differentiation. *Mineralogical Magazine,* **23**, 317–28.

Read, H.H. (1934) The metamorphic geology of Unst in the Shetland Islands. *Quarterly Journal of the Geological Society of London* **90**, 637–88.

Read, H.H. (1935) *British Regional Geology: the Grampian Highlands* (1st edition). HMSO for Geological Survey and Museum, Edinburgh.

Read, H.H. (1936) The stratigraphical order of the Dalradian rocks of the Banffshire coast. *Geological Magazine*, **73**, 468–75.

Read, H.H. (1937) Metamorphic correlation in the polymetamorphic rocks of the Valla Field Block, Unst, Shetland Islands. *Transactions of the Royal Society of Edinburgh*, **59**, 195–221.
Read, H.H. (1952) Metamorphism and migmatisation in the Ythan Valley, Aberdeenshire. *Transactions of the Edinburgh Geological Society*, **15**, 265–79.
Read, H.H. (1955) The Banff nappe: an interpretation of the structure of the Dalradian rocks of north-east Scotland. *Proceedings of the Geologists' Association*, **66**, 1–29.
Read, H.H. (1960) North-east Scotland: the Dalradian. Geologists' Association Guide, **31**. Benham and Co., Colchester.
Read, H.H. and Farquhar, O.C. (1956) The Buchan Anticline of the Banff Nappe of Dalradian rocks in north-east Scotland. *Quarterly Journal of the Geological Society of London*, 112, 131–56.
Richardson, S.W. and Powell, R. (1976) Thermal causes of the Dalradian metamorphism in the Central Highlands of Scotland. *Scottish Journal of Geology*, **12**, 237–68.
Ritchie, J.D. and Hitchen, K. (1993) Discussion on the location and history of the Walls Boundary fault and Moine thrust north and south of Shetland. *Journal of the Geological Society, London*, **150**, 1003–8.
Roberts, J.L. (1959) Fold Structures in the Dalradian Rocks of Knapdale, Argyllshire. *Geological Magazine*, **94**, 221–9.
Roberts, J.L. (1963) The Dalradian of the southwest highlands of Scotland. Unpublished PhD thesis, University of Liverpool.
Roberts, J.L. (1966a) Sedimentary affiliations and stratigraphic correlation of the Dalradian rocks in the South-west Highlands of Scotland. *Scottish Journal of Geology*, **2**, 200–23.
Roberts, J.L. (1966b) The formation of similar folds by inhomogeneous plastic strain, with reference to the fourth phase of deformation affecting the Dalradian rocks in the southwest Highlands of Scotland. *Journal of Geology*, **74**, 831–55.
Roberts, J.L. (1974) The structure of the Dalradian rocks in the SW Highlands of Scotland. *Journal of the Geological Society of London*, **130**, 93–124.
Roberts, J.L. (1976) The structure of the Dalradian rocks in the north Ballachulish district of Scotland. *Journal of the Geological Society of London*, **132**, 139–54.
Roberts, J.L. (1977a) The evolution and transport of the Tay Nappe: Discussion. *Scottish Journal of Geology*, **13**, 79–80.
Roberts, J.L. (1977b) The Dalradian rocks of Rosneath and South-east Cowal. *Scottish Journal of Geology*, **13**, 101–11.
Roberts, J.L. (1977c) The Dalradian rocks of Knapdale and North Kintyre. *Scottish Journal of Geology*, **13**, 113–124.
Roberts, J.L. and Sanderson, D.J. (1974) Oblique fold axes in the Dalradian rocks of the Southwest Highlands. *Scottish Journal of Geology*, **9**, 281–96.
Roberts, J.L. and Treagus, J.E. (1964) A reinterpretation of the Ben Lui Fold. *Geological Magazine*, **101**, 512–16.
Roberts, J.L, and Treagus, J.E. (1975) The structure of the Moine and Dalradian rocks in the Dalmally district of Argyllshire, Scotland. *Geological Journal*, **10**, 59–74.
Roberts, J.L, and Treagus, J.E. (1977a) The Dalradian rocks of the South-west Highlands-Introduction. *Scottish Journal of Geology*, Vol. 13, 87–99.
Roberts, J.L. and Treagus, J.E. (1977b) The Dalradian rocks of the Loch Leven area. *Scottish Journal of Geology*, **13**, 165–184.

Roberts, J.L. and Treagus, J.E. (1977c) Polyphase generation of nappe structures in the Dalradian rocks of the Southwest Highlands of Scotland. *Scottish Journal of Geology.* **13**, 237–254.
Roberts, J.L, and Treagus, J.E. (1979) Stratigraphical and structural correlation between the Dalradian rocks of the SW and Central Highlands of Scotland. 199–204 in The Caledonides of the British Isles–reviewed. Harris, A.L., Holland, C.H., and Leake, B.E.(editors). Special Publication of the Geological Society of London. 8.
Roberts, J.L, and Treagus, J E. (1980) The structural interpretation of the Loch Leven area. *Scottish Journal of Geology*, **16**, 73–5.
Robertson, S. (1991) Older granites in the south-eastern Scottish Highlands. *Scottish Journal of Geology,* **27**, 21–6.
Robertson, S. (1994) Timing of Barrovian metamorphism and 'Older Granite' emplacement in relation to Dalradian deformation. *Journal of the Geological Society of London,* **151**, 5–8.
Robertson, S. (1999) BGS Rock Classification Scheme Volume 2: Classification of metamorphic rocks. *British Geological Survey Research Report*, **RR 99–02.**
Robertson, S. and Smith, M. (1999) The significance of the Geal charn—Ossian Steep Belt in basin development in the Central Scottish Highlands. *Journal of the Geological Society, London,* **156**, 1175–82.
Rock, N.M.S. (1985) A compilation of analytical data for metamorphic limestones from the Scottish Highlands and Islands, with lists of BGS registered samples, and comments on the reproducibility and accuracy of limestone analyses by different analytical techniques. *Mineralogical and Petrological Report British Geological Survey*, No. 85/5.
Rock, N.M.S. (1986) Chemistry of the Dalradian (Vendian–Cambrian) metalimestones, British Isles. *Chemical Geology*, **56**, 289–311.
Rock, N.M.S., Macdonald, R. and Bower, J. (1986) The comparative geochemistry of some Highland pelites (Anomalous local limestone-pelite successions within the Moine outcrop; II). *Scottish Journal of Geology,* **22**, 107–26.
Rogers, G., Dempster, T.J., Bluck, B.J. and Tanner, P.W.G. (1989) A high precision U-Pb age for the Ben Vuirich Granite: implications for the evolution of the Scottish Dalradian Supergroup. *Journal of the Geological Society, London*, **146**, 789–98.
Rogers, G., Hyslop, E.K., Strachan, R.A., Paterson, B.A. and Holdsworth, R.A. (1998) The structural setting and U-Pb geochronology of the Knoydartian pegmatites of W Inverness-shire: evidence for Neoproterozoic tectonothermal events in the Moine of NW Scotland. *Journal of the Geological Society, London,* **155**, 685–96.
Rogers, G., Kinny, P.D., Strachan, R.A., Friend, C.R.L. and Patterson, B.A. (2001) U-Pb geochronology of the Fort Augustus granite gneiss, constraints on the timing of Neoproterozoic and Paleozoic tectonothermal events in the NW Highlands of Scotland. *Journal of the Geological Society, London,* **158**, 7–14.
Rogers, G. and Pankhurst, R.J. (1993) Unravelling dates through the ages: geochronology of the Scottish metamorphic complexes. *Journal of the Geological Society, London*, **150**, 447–64.
Rollin, K.E. (1994) Geophysical correlation of Precambrian rocks in northern Britain. In *A Revised Correlation of Precambrian Rocks in*

the British Isles. Gibbons, W. and Harris, A.L. (eds.) Geological Society, London, Special Report, **22**, 65–74.
Rooney, A.D., Chew, D.M. and Selby, D. (2011) Re – Os geochronology of the Neoproterozoic – Cambrian Dalradian Supergroup of Scotland and Ireland: implications for Neoproterozoic stratigraphy, glaciations and Re – Os systematics. *Precambrian Research*,
Rose, P.T.S. (1989) The emplacement of the Tay Nappe Scotland. Unpublished PhD thesis, University of Liverpool.
Rose, P.T.S. and Harris, A.L. (2000) Evidence for the lower Palaeozoic age of the Tay Nappe; the timing and nature of Grampian events in the Scottish Highland sector of the Laurentian margin. *Journal of the Geological Society, London*, **157**, 789–98.
Rushton, A.W.A., Owen, A.W., Owens, R.M. and Prigmore, J.K. (1999) British Cambrian and Ordovician stratigraphy, Geological Conservation Review Series No. **18**, Joint Nature Conservation Committee, Peterborough.
Russell, M.J., Hall, A.J., Willan, R.C.R., Allison, I., Anderton, R., and Bowes, G. (1984) On the origin of the Aberfeldy celsian+barite+base metals deposits, Scotland. In *Prospecting in areas of glaciated terrain*, 1984. Institution of Mining and Metallurgy, London, pp. 159–170.
Ryan, P.D. and Soper, N.J. (2001) Modelling anatexis in intra-cratonic basins: an example from the Neoproterozoic rocks of the Scottish Highlands. *Geological Magazine*, **138**, 577–588.
Ryan, P.D., Soper, N.J., Snyder, D.B., England, R.W. and Hutton, D.H.W. (1995) The Antrim – Galway Line: a resolution of the Highland Border Fault enigma of the Caledonides of Britain and Ireland. *Geological Magazine*, **132**, 171–184.

Saha, D. (1989) The Caledonian Loch Skerrols Thrust, SW Scotland: Microstructure and Strain. *Journal of Structural Geology*, **11**, 553–568.
Schermerhorn, L.J.G. (1974) Late Precambrian mixtites: glacial and/or non-glacial? *American Journal of Science*, **274**, 673–824.
Schermerhorn, L.J.G. (1975) Tectonic framework of Late Precambrian supposed glacials. In *Ice Ages: Ancient and Modern* (eds. Wright, A.E. and Moseley, F.), proceedings of the Inter-University Geological Congress (University of Birmingham) (1974), *Geological Journal* special issue No. 6, 242–247.
Scott, R.A. (1987) Lithostratigraphy, structure and mineralization of the Argyll Group Dalradian near Tyndrum, Scotland. Unpublished PhD thesis, University of Manchester.
Scott, R.A., Pattrick, R.A.D., and Polya, D.A. (1991) Origin of sulphur in metamorphosed stratabound mineralization from the Argyll Group Dalradian of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 82, 91–98.
Scott, R.A., Polya, D.A., and Pattrick, R.A.D. (1988) Proximal Cu + Zn exhalites in the Argyll Group Dalradian, Creag Bhocan, Perthshire. *Scottish Journal of Geology*, Vol. 24, 97–112.
Seranne, M. (1992) Devonian extensional tectonics versus Carboniferous inversion in the northern Orcadian basin. *Journal of the Geological Society, London*, **149**, 27–37.
Shackleton, R. M. 1958. Downward-facing structures of the Highland Border. *Quarterly Journal of the Geological Society, London*, **113**, 361–392.
Shackleton, R.M. (1979) The British Caledonides: comments and summary. 299–304 in The Caledonides of the British Isles—

reviewed. Harris, A L, Holland, C H, and Leake, B E (editors). Special Publication of the Geological Society of London, No. 8.

Shearman, D.J. and Smith, A.J. (1985) Ikaite, the parent mineral of jarrowite-type pseudomorphs. *Proceedings of the Geologists' Association*, **96**, 305–314.

Sibson, R.H. (1977) Fault rocks and fault mechanisms. *Journal of the Geological Society, London*, Vol 133, 191–213.

Simpson, A. and Wedden, D. (1974) Downward-facing structures in the Dalradian Leny Grits on Bute. *Scottish Journal of Geology*, **10**, 257–267.

Skelton, A.D.L. (1993) Petrological, geochemical and field studies of fluid infiltration during regional metamorphism of the Dalradian of the SW Scottish Highlands. Unpublished PhD thesis, University of Edinburgh.

Skelton, A.D.L., Bickle, M.J. and Graham, C.M. (1997) Fluid-flux and reaction rate from advective-diffusive carbonation of mafic sill margins in the Dalradian, southwest Scottish Highlands. *Earth and Planetary Science Letters,* **146**, 527–539

Skelton, A.D.L., Graham, C.M. and Bickle, M.J. (1995) Lithological and structural constraints on regional 3-D fluid flow patterns during greenschist facies metamorphism of the Dalradian of the SW Highlands. *Journal of Petrology*, **36**, 563–586.

Skevington, D. (1971) Palaeontological evidence bearing on the age of the Dalradian deformation and metamorphism in Ireland and Scotland. *Scottish Journal of Geology*, Vol. **7**, 285–288.

Smallwood, J.R. (2007) Maskelyne's 1774 Schiehallion experiment revisited. *Scottish Journal of Geology*, Vol. **43**, 15–31.

Smith, A.J. and Rast, N. (1958) Sedimentary dykes in the Dalradian of Scotland. *Geological Magazine* **95**, 234 –240.

Smith, C.G., Gallagher, M.J., Coats, J.S. and Parker, M.E. (1984) Detection and general characteristics of stratabound mineralization in the Dalradian of Scotland. *Transactions of the Institution of Mining and Metallurgy (Section B: Applied Earth Science)*, Vol. 93, B125–133.

Smith, C.G., Gallagher, M.J., Grout, A., Coats, J.S., Vickers, B.P., Peachey, D., Pease, S.F., Parker, M.E. and Fortey, N.J. (1988) Stratabound base-metal materialisation in Dalradian rocks near Tyndrum, Scotland. *Mineral Reconnaissance Programme Report, British Geological Survey*, No. **93**.

Smith, C.G., Goodman, S. and Robertson, S. (2002) Geology of the Ballater district. Memoir of the British Geological Survey, Sheet 65E (Scotland).

Smith, M., Robertson, S. and Rollin, K.E. (1999) Rift basin architecture and stratigraphical implications for basement-cover relationships in the Neoproterozoic Grampian Group of the Scottish Caledonides. *Journal of the Geological Society, London,* **156**, 1163–1173.

Smith, R.A. (1980) The Geology of the Dalradian rocks around Blair Atholl, Central Perthshire, Scotland. Unpublished PhD thesis, University of Liverpool.

Smith, R.A. and Harris, A,L. (1976) The Ballachulish rocks of the Blair Atholl District. *Scottish Journal of Geology*, Vol. 12, 153–157.

Smith, T.E. (1968) Tectonics in Upper Strathspey, Inverness-shire. *Scottish Journal of Geology*, **4**, 68–84.

Snyder, D.B. and Flack, C.A. (1990) A Caledonian age for reflectors within the mantle lithosphere north and west of Scotland. *Tectonics*, **9**, 903–922.
Soper N.J. (1994) Was Scotland a Vendian RRR junction? *Journal of the Geological Society, London,* 151, 579–582.
Soper N.J. (1994) Neoproterozoic sedimentation on the northeast margin of Laurentia and the opening of Iapetus. *Geological Magazine,* 131, 291–299.
Soper, N.J. and Anderton, R. (1984) Did the Dalradian slides originate as extensional faults? *Nature, London*, Vol. 307, 357–360.
Soper, N.J. and England, R.W. (1995) Vendian and Riphean rifting in NW Scotland. *Journal of the Geological Society, London* **152**, 11–14.
Soper, N.J. and Evans, J.A., 1997. Discussion on metamorphism and cooling of the NE Dalradian. Journal of the Geological Society, London. 154, 357-360.
Soper N.J. and Hutton D.H.W. (1984) Late Caledonian sinistral displacements in Britain: Implications for a three-plate collision model. *Tectonics* **3**, 781–794.
Soper, N.J., Ryan, P.D. and Dewey, J.F. (1999) Age of the Grampian Orogeny in Scotland and Ireland. *Journal of the Geological Society, London* **156**, 1231–1236.
Soper N.J., Strachan R.A., Holdsworth R.E., Gayer R.A. and O'Greiling, R.O. (1992) Sinistral transpression and the Silurian closure of Iapetus. *Journal of the Geological Society, London* **149**, 871–880.
Spear, F.S. (1993) *Metamorphic phase equilibria and pressure-temperature-time paths.* Mineralogical Society of America.
Spencer, A.M. (1971) Late Precambrian glaciation in Scotland. Memoir of the Geological Society of London, No. 6.
Spencer, A.M. (1981) The late Precambrian Port Askaig Tillite in Scotland. In Earth's pre-Pleistocene glacial record (eds. Hambrey, M. J. and Harland, W. B.), pp. 632–636. Cambridge University Press, Cambridge.
Spencer, A.M. (1985) Mechanisms and environments of deposition of Late Precambrian geosynclinal tillites: Scotland and East Greenland. *Palaeogeography, Palaeoclimatology and Palaeoecology*, 51, 143–157.
Spencer, A.M. and Pitcher, W.S. (1968) Occurrence of the Port Askaig Tillite in north-east Scotland. *Proceedings of the Geological Society of London*, No. 1650, 195–198.
Spencer, A.M. and Spencer, M. (1972) The Late Precambrian/Lower Cambrian Bonnahaven Dolomite of Islay and its stromatolites. *Scottish Journal of Geology*, 8, 269–282.
Spray J.G. and Dunning G.R. (1991) A U/Pb age for the Shetland Islands oceanic fragment, Scottish Caledonides: evidence from anatectic plagiogranites in "layer 3" shear zones. *Geological Magazine* **128**, 667–671.
Stephenson, D. (1993) Amphiboles from Dalradian metasedimentary rocks of NE Scotland: environmental inferences and distinction from meta-igneous amphibolites. *Mineralogy and Petrology*, Vol. 49, 45–62.
Stephenson, D., Bevins, R.E., Millward, D., Highton, A.J., Parsons, I., Stone, P. and Wadsworth, W.J. (1999) Caledonian Igneous rocks of Great Britain. *Geological Conservation Review Series* No.**17**. Joint Nature Conservation Committee, Peterborough. 648pp.

Stephenson, D. and Gould, D. (1995) *British regional geology: the Grampian Highlands* (4th edition). HMSO for the British Geological Survey, London.

Stewart, A.D. (1960) On the sedimentary and metamorphic history of the Torridonian, and the later igneous intrusions of Colonsay and Oronsay. Unpublished PhD thesis, University of Liverpool.

Stewart, A.D. (1962) On the Torridonian sediments of Colonsay and their relationship to the main outcrop in north-west Scotland. *Liverpool and Manchester Geological Journal* **3**, 121–156.

Stewart, A.D. (1969) Torridonian rocks of Scotland reviewed. *In* Kay, M. (ed.) *North Atlantic-Geology and Continental Drift, a symposium*. Memoir of the American Association of Petroleum Geologists **12**, 595–608.

Stewart, A.D. (1975) 'Torridonian' rocks of western Scotland. In: *A correlation of Precambrian rocks in the British Isles* (eds. Harris, A. L., Shackleton, R. M., Watson, J.V., Downie, C., Harland, W. B. and Moorbath, S.) *Geological Society, London, Special Report*, **6**, 43–51.

Stewart, A.D. and Hackman, B.D. (1973) Precambrian sediments of Islay. *Scottish Journal of Geology,* **9**, 185–201.

Stewart, M., Strachan, R.A. and Holdsworth, R.E. (1999) Structure and early kinematic history of the Great Glen fault zone, Scotland. *Tectonics* **18**, 326–342.

Stewart, M., Strachan, R.A., Martin, M.W. and Holdsworth, R.E. (2001) Constraints on early sinistral displacements along the Great Glen Fault Zone, Scotland; structural setting, U-Pb geochronology and emplacement of the syn-tectonic Clunes Tonalite. *Journal of the Geological Society, London* **158**, 821–830.

Stoker, M.S., Howe, J.A. and Stoker, S.J. (1999) Late Vendian-?Cambrian glacially influenced deep-water sedimentation, Macduff Slate Formation (Dalradian), NE Scotland. *Journal of the Geological Society, London,* **156**, 55–61.

Stone, M. (1957) The Aberfoyle Anticline, Callander, Perthshire. *Geological Magazine*, **94**, 265–276.

Stone, P., Plant, J.A., Mendum, J.R. and Green, P.M. (1999) A regional geochemical assessment of some terrane relationships in the British Caledonides. *Scottish Journal of Geology,* **35**, 145–156.

Strachan, R.A. (2000) The Grampian Orogeny: Mid-Ordovician arc—continent collision along the Laurentian margin of Iapetus. *In*: Woodcock, N.H. and Strachan, R.A. (eds) *Geological History of Britain and Ireland*. Blackwell Science Ltd, 88–106.

Strachan, R.A., Harris, A.L., Fettes D.J. and Smith, M. (2002) The Northern Highland and Grampian terranes. In: Trewin N. H. (ed.) *The Geology of Scotland*. (4th edition) The Geological Society, London, pp. 81–148.

Strachan, R.A. and Holdsworth, R.E. (2000) Proterozoic sedimentation, orogenesis and magmatism on the Laurentian Craton (2700–750 Ma). In: *Geological history of Great Britain and Ireland* (edited by Woodcock, N. and Strachan, R. A.) Blackwell Science. Oxford, 52–72.

Stringer, P.J. (1957) Polyphase deformation in the Upper Dalradian rocks of the Southern Highlands of Scotland. Unpublished PhD thesis, University of Liverpool.

Stupavsky, M., Symons, D.T.A. and Gravenor, C.P. (1982) Evidence for metamorphic remagnetisation of the upper Precambrian tillite in the Dalradian Supergroup of Scotland. *Transactions of the Royal Society of Edinburgh*, **73**, 59–65.

Sturt, B.A. (1959) Studies in the metamorphic rocks of the Loch Tummel district, Perthshire. Unpublished PhD thesis, University of Wales, Aberystwyth.

Sturt, B.A. (1961) The geological structure of the area south of Loch Tummel. *Quarterly Journal of the Geological Society of London*, Vol. 117, 131–156.

Sturt, B.A. and Harris, A.L. (1961) The metamorphic history of the Loch Tummel area. *Liverpool and Manchester Geological Journal*, Vol. 2, 689–711.

Sturt, B.A., Ramsay, D.M., Pringle, I.R. and Teggin, D.E. (1977) Precambrian gneisses in the Dalradian sequence of NE Scotland. *Journal of the Geological Society of London*, Vol. 134, 41–44.

Sutton, J. and Watson, J.V. (1954) Ice-borne boulders in the Macduff Group of the Dalradian of Banffshire. *Geological Magazine*, Vol. 91, 391–398.

Sutton, J. and Watson, J.V. (1955) The deposition of the Upper Dalradian rocks of the Banffshire coast. *Proceedings of the Geologists' Association*, Vol. 66, 101–133.

Sutton, J. and Watson, J.V. (1956) The Boyndie syncline of the Dalradian of the Banffshire coast. *Quarterly Journal of the Geological Society of London*, Vol. 112, 103–130.

Tanner, P. W. G. 1992. Rosneath Peninsula and Loch Long. In *Geological excursions around Glasgow and Girvan* (eds. Lawson, J. D. and Weedon, D. S.), pp. 159–185. Geological Society of Glasgow.

Tanner, P. W. G. 1995. New evidence that the Lower Cambrian Leny Limestone at Callander, Perthshire, belongs to the Dalradian Supergroup, and a reassessment of the 'exotic' status of the Highland Border Complex. *Geological Magazine*, **132**, 473–483.

Tanner, P. W. G. 1996. Significance of the early fabric in the contact metamorphic aureole of the 590 Ma Ben Vuirich Granite, Perthshire, Scotland. *Geological Magazine*, **133**, 683–695.

Tanner, P. W. G. 1997. The Highland Border controversy: Reply to a Discussion of 'New evidence that the Lower Cambrian Leny Limestone at Callander, Perthshire, belongs to the Dalradian Supergroup, and a reassessment of the 'exotic' status of the Highland Border Complex'. *Geological Magazine*, **134**, 565–570.

Tanner, P. W. G. 1998a. Interstratal dewatering origin for polygonal patterns of sand-filled cracks: a case study from Late Proterozoic metasediments of Islay, Scotland. *Sedimentology*, **45**, 71–89.

Tanner, P W G. 1998b. Age of the Grampian event: Reply to a Discussion of 'New evidence that the Lower Cambrian Leny Limestone at Callander, Perthshire belongs to the Dalradian Supergroup, and a reassessment of the 'exotic' status of the Highland Border Complex'. Geological Magazine, Vol. **135**, 575–579.

Tanner, P. W. G. 2005. Discussion on evidence for a major Neoproterozoic orogenic unconformity within the Dalradian Supergroup of NW Ireland. *Journal of the Geological Society, London*, **162**, 221–224.

Tanner, P.W.G. 2007. The role of the Highland Border Ophiolite in the ~ 470 Ma Grampian Event, Scotland. *Geological Magazine* Vol. **144**, 597–602.

Tanner, P.W.G. 2008. Tectonic significance of the Highland Boundary Fault. *Journal of the Geological Society, London* Vol. **165**, 915–921.

Tanner, P.W.G. and Bluck, B.J. (2011) Discussion of 'The Highland Boundary Fault and the Highland Boundary Complex' by B.J. Bluck *Scottish Journal of Geology* **46**, 113-124. *Scottish Journal of Geolgy*, **47**, 89-93.

Tanner, P. W. G. and BLUCK, B. J. 1999. Current controversies in the Caledonides. *Journal of the Geological Society, London*, **156**, 1137–1141.

Tanner, P. W. G. and Evans, J. A. 2003. Late Precambrian U-Pb titanite age for peak regional metamorphism and deformation (Knoydartian Orogeny) in the western Moine, Scotland. *Journal of the Geological Society, London* **160**, 555–564.

Tanner, P. W. G. and Leslie, A. G. 1994. A pre-D2 age for the 590 Ma Ben Vuirich Granite in the Dalradian of Scotland. *Journal of the Geological Society, London*, **151**, 209–212.

Tanner P. W. G., Leslie A. G. and Gillespie M.R. 2006. Structural setting and petrogenesis of a rift-related intrusion: the Ben Vuirich Granite of the Grampian Highlands, Scotland. *Scottish Journal of Geology,* Vol. **42**, 113–136.

Tanner, P. W. G. and Pringle, M. 1999. Testing for a terrane boundary within Neoproterozoic (Dalradian) to Cambrian siliceous turbidites at Callander, Perthshire, Scotland. *Journal of the Geological Society, London*, **156**, 1205–1216.

Tanner, P.W.G. and Sutherland, S. 2007. The Highland Border Complex, Scotland: a paradox resolved. *Journal of the Geological Society, London*, **164**, 111–116.

Tannner, P.W.G. and Thomas, P.R. (2010) Major nappe-like D2 folds in the Dalradian rocks of the Beinn Udlaidh area, Central Highlands, Scotland. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*. **100**, 371-389.

Temperley, S. (1990). The Late Proterozoic to Early Palaeozoic geology of the Glen Banchor area in the Monadhliath Mountains of Scotland, with particular reference to deformation in Knoydartian shear zones and the Caledonian Central Highland steep belt. Unpublished PhD thesis, University of Hull.

Thomas, C W. 1989. Application of geochemistry to the stratigraphic correlation of Appin and Argyll Group carbonate rocks from the Dalradian of northeast Scotland. *Journal of the Geological Society of London*, Vol. 146, 631–647.

Thomas, C. W. 1993. Sources of Rare Earth elements in Appin Group limestones, Dalradian, north-east Scotland. *Mineralogy and Petrology* Vol. **49**, 27–44 .

Thomas, C.W. (1995). The geochemistry of metacarbonate rocks from the Monadhliath Project area. *British Geological Survey Technical Report*. WA/95/40/R.

Thomas, C. W. (1999). The isotope Geochemistry and Petrology of Dalradian Metacarbonate Rocks, Unpublished PhD thesis, University of Edinburgh.

Thomas, C.W. and Aitchison (1998). Application of logratios to the statistical analysis of the geochemistry of metamorphosed limestones from the Northeast and Central Highlands of Scotland: the case for Appin Group correlations. *British Geological Survey Technical Report*, WA/98/03.

Thomas, C W, Aitken, A M, Pickett, E P, Mendum, J R, Hyslop, E K, and Petterson, M.P. in press. Geology of the Aberfoyle District. Sheet Description for the British Geological Survey, 1:50 000 Series Sheet 38E (Scotland).

Thomas, C. W., Graham, C. M., Ellam, R.M. and Fallick, A. E. (2004). $^{87}Sr/^{8}6Sr$ chemostratigraphy of Neoproterozoic Dalradian limestones of Scotland: constraints on depositional ages and timescales. *Journal of the Geological Society, London* **161**, 223-243.

Thomas, C.W., Smith, M. and Robertson, S. (1997). The geochemistry of Dalradian metacarbonate rocks from the Schiehallion District and Blargie, Laggan: implications for stratigraphical correlations in the Geal Charn–Ossian Steep Belt. *British Geological Survey Technical Report,* WA/97/81.

Thomas, P R. 1965. The structure and metamorphism of the Moinian rocks in Glen Garry, Glen Tilt, and adjacent areas of Scotland. Unpublished PhD thesis, University of Liverpool.

Thomas, P R. 1979. New evidence for a Central Highland Root Zone. 205–211 in The Caledonides of the British Isles –Reviewed. Harris, A L, Holland, C H, and Leake, B E (editors). Special Publication of the Geological Society, No. 8.

Thomas, P R. 1980. The stratigraphy and structure of the Moine rocks north of the Schiehallion Complex, Scotland. *Journal of the Geological Society of London*, Vol. 137, 469–482.

Thomas, P R. 1988. A9 road section—Blair Atholl to Newtonmore. 39–50 in *An excursion guide to the Moine geology of the Scottish Highlands*. Allison, I, May, F, and Strachan, R A (editors). (Edinburgh: Scottish Academic Press for Edinburgh Geological Society and Geological Society of Glasgow.)

Thomas, P R, and Treagus, J E. 1968. The stratigraphy and structure of the Glen Orchy area, Argyllshire, Scotland. *Scottish Journal of Geology*, Vol. 4, 121–134.

Thomson, J. 1877. On the geology of the Island of Islay. *Transactions of the Geological Society of Glasgow*, **5**, 200–222.

Tilley, C.E. (1925) A preliminary survey of metamorphic zones in the southern Highlands of Scotland. *Quarterly Journal of the Geological Society of London*, Vol. 81, 100–110.

Tollo R. P., Aleinikoff J. N., Bartholomew M. J. and Rankin D. W. 2004. Neoproterozoic A-type granitoids of the central and southern Appalachians: intraplate magmatism associated with episodic rifting of the Rodinian supercontinent. *Precambrian Research,* 128, 3–38.

Torsvik, T. H., Smethurst, M. A., Meert, J. G., Van der Voo, R., McKerrow, W. S., Brasier, M. D., Sturt, B. A. and Walderhaug, H. J. 1996. Continental break-up and collision in the Neoproterozoic and Palaeozoic–a tale of Baltica and Laurentia. *Earth Science Reviews* **40**, 229–258.

Treagus, J. E. 1964a. The structural and metamorphic history of an area of Moine and Dalradian rocks south of Loch Rannoch, Perthshire. Unpublished PhD thesis, University of Liverpool.

Treagus, J E. 1964b. Notes on the structure of the Ben Lawers Synform. *Geological Magazine*, Vol. 101, 260–270.

Treagus, J.E. (1969). The Kinlochlaggan Boulder Bed. *Proceedings of the Geological Society of London*, **1654**, 55–60.

Treagus, J E. 1974. A structural cross-section of the Moine and Dalradian rocks of the Kinlochleven area, Scotland. *Journal of the Geological Society of London*, Vol. 130, 525–544.

Treagus, J.E. (1981). The Lower Dalradian Kinlochlaggan Boulder Bed, Central Scotland. In: *Earth's pre-Pleistocene glacial record.* (editors. Hambrey, J.M. and Harland, W.B.), Cambridge University Press, 637–639.

Treagus, J E. 1987. The structural evolution of the Dalradian of the Central Highlands of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 78, 1-15.

Treagus, J E. 1991. Fault displacements in the Dalradian of the Central Highlands. *Scottish Journal of Geology*, Vol. 27, 135–145.

Treagus, J. E. (editor). 1992. *Caledonian Structures in Britain South of the Midland Valley*, Geological Conservation Review Series No. **3**. London: Chapman and Hall.

Treagus, J.E. (1997) Discussion on a late Vendian age for the Kinlochlaggan Boulder bed (Dalradian). *Journal of the Geological Society, London,* **154**, 917-919.

Treagus, J E. 1999. A structural reinterpretation of the Tummel Belt and a transpressional model of evolution of the Tay Nappe in the Central Highlands of Scotland. *Geological Magazine*, Vol. 136, Pt 6, 643–660.

Treagus, J. E. 2000. The Solid Geology of the Schiehallion District. Memoir of the British Geological Survey. Sheet 55W (Scotland).

Treagus, J.E. 2009. The Dalradian of Scotland. *Geologists' Association Guide* No. **67**. 202pp.

Treagus, J E, and King, G. 1978. A complete Lower Dalradian succession in the Schiehallion district, central Perthshire. *Scottish Journal of Geology*, Vol. 14, 157–166.

Treagus, J E, Pattrick, R A D, and Curtis, S F. 1999. Movement and mineralization in the Tyndrum fault zone, Scotland and its regional significance. *Journal of the Geological Society, London*, Vol. 156, 591–604.

Treagus, J E. and Roberts, J L. 1981. The Boyndie Syncline, a D1 structure in the Dalradian of Scotland. *Geological Journal*, Vol. 16, 125–135.

Treagus, J E, Talbot, C J, and Stringer, P. 1972. Downward-facing structures in the Birnam Slates, Dunkeld, Perthshire. *Geological Journal*, Vol. 8, 125–128.

Treagus, J E, and Treagus, S H. 1971. The structures of the Ardsheal peninsula, their age and regional significance. *Geological Journal*, Vol. 7, 335–346.

Treagus, J E, and Treagus, S H. 1981. Folds and the strain ellipsoid; a general model. *Journal of Structural Geology*, Vol. 3, Pt 1, 1–17.

Trewin, N. H. (editor) 2002. *The Geology of Scotland*. (4th edition) The Geological Society, London. 576 pp.

Trewin, N.H., Kneller, B.C. and Gillen, C. (1987) *Excursion Guide to the Geology of the Aberdeen area*. (Edinburgh: Scottish Academic Press, for Geological Society of Aberdeen).

Trewin, N.H. and Rollin, K. 2002. *In:* Trewin, N.H. (ed.) *The geology of Scotland.*(4th edition) The Geological Society, London, 1-25.

Trewin, N.H. and Thirlwall, M.F. 2002. Old Red Sandstone. In: Trewin N. H. (ed.) *The Geology of Scotland*. (4th edition) The Geological Society, London, pp. 213–249.

Tyrrell, G.W. 1921. Some points in petrographic nomenclature. *Geological Magazine* Vol. **58**, 494-502.

Underhill, J.R. 1993. Discussion on the location and history of the Walls Boundary fault and Moine thrust north and south of Shetland. *Journal of the Geological Society, London,* **150**, 1003-1008.

Upton, P.S., 1983. A stratigraphic, structural and metamorphic study of the lower and middle Dalradian, between Braemar and the Spittal of Glenshee, N.E. Scotland. Unpublished PhD thesis, University of Manchester.
Upton, P S. 1986. A structural cross-section of the Moine and Dalradian rocks of the Braemar area. *Report of the British Geological Survey*, Vol. 17, No. 1, 9–19.

Van Breemen, O., Aftalion, M. and Johnson, M. R. 1979. Age of the Loch Borrolan complex, Assynt and late movements along the Moine Thrust Zone. *Journal of the Geological Society of London* **16**, 489-495.
Van de Kamp, P.C. 1968. Origins of para-amphibolites. Unpublished PhD thesis, University of Bristol.
Van de Kamp, P C. 1970. The Green Beds of the Scottish Dalradian Series: geochemistry, origin and metamorphism of mafic sediments. *Journal of Geology*, Vol. 78, 281–303.
Van Staal, C. R., Dewey, J. F., McKerrow, W. S. and MacNiocaill, C. 1998. The Cambrian–Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, southwest Pacific-type segment of Iapetus. In: *Lyell: the Present is in the Past* (edited by Blundell, D. J. and Scott, A. C.). *Geological Society, London, Special Publication*, **143**, 199–242.
Vance, D., Strachan, R. A. and Jones, K. A. 1998. Extensional versus compressional settings for metamorphism: Garnet chronometry and pressure—temperature—time histories in the Moine Supergroup, northwest Scotland. *Geology* **26**, 927–930.
Viete, D.R., Forster, M.A. and Lister, G.S. (2011) The nature and origin of the Barrovian metamorphism, Scotland: $^{40}Ar/^{39}Ar$ apparent age patterns and the duration of metamorphism in the biotite zone. *Journal of the Geological Society, London*, **168**, 133-146.
Viete, D.R., Hermann, J., Lister, G.S. and Stenhouse, I.R. (2011) The nature and origin of the Barrovian metamorphism, Scotland: diffusion length scales in garnet and inferred thermal time scales. *Journal of the Geological Society, London*, **168**, 115-132.
Viete, D.R., Richards, S.W., Lister, G.S., Oliver, G.J.H. and Banks, G.J. (2010) Lithospheric-scale extension during Grampian orogenesis in Scotland. in Law, R.D., Butler, R.W.H., Holdsworth, R.E., Krabbendam, M. and Strachan, R.A. (editors) *Continental Tectonics and Mountain Building: the Legacy of Peach and Horne*. Geological Society, London, Special Publications, **335**, 121-160.
Viljoen, M. J and Viljoen, R. P. 1969. Evidence for the existence of a mobile extrusive peridotite magma from the Komati Formation of the Onverwacht Group. *Geological Society of South Africa, Special Publication* No. 2, 87–112.
Vogt, T. 1930. On the chronological order of deposition in the Highlands. *Geological Magazine*, **67**, 68–76.
Voll, G. 1960. New work on Petrofabrics. *Liverpool and Manchester Geological Journal*, **2**, 503–567.
Voll, G. 1964. Deckenbau und fazies im Schottischen Dalradian. *Geologische Rundschau*, Vol. 53, 590–612.
Vorhies, S.H. and Ague, J.J. (2011) Pressure – temperature evolution and thermal regimes in the Barrovian zones, Scotland. *Journal of the Geological Society, London*, **168**, 1147-1166.

Wain, A. (1999). The petrography and metamorphic evolution of metabasic rocks from the Lower Dalradian of the Central Highlands area. *British Geological Survey Technical Report* No. **WA/99/13**.

Watkins, K.P. 1982. The structure and metamorphism of the Balquhidder—Crianlarich region of the Scottish Dalradian. Unpublished PhD thesis, University of Cambridge.

Watkins, K P. 1983. Petrogenesis of Dalradian albite porphyroblast schists. *Journal of the Geological Society of London*, Vol. 140, 601–618.

Watkins, K P. 1984. The structure of the Balquhidder–Crianlarich region of the Scottish Dalradian and its relation to the Barrovian garnet isograd surface. *Scottish Journal of Geology*, Vol. 20, 53–64.

Watkins, K.P. 1985. Geothermometry and geobarometry of inverted metamorphic zones in the W. Central Scottish Dalradian. *Journal of the Geological Society of London,* **142**, 157–165.

Watson, J. V. 1984. The ending of the Caledonian Orogeny in Scotland. *Journal of the Geological Society of London* **141**, 193–214.

Weiss, L E, and McIntyre, D B. 1957. Structural geometry of Dalradian rocks at Loch Leven, Scottish Highlands. *Journal of Geology*, Vol. 65, 575–602.

Wells, P. R. A. and Richardson, S. W. 1979. Thermal evolution of metamorphic rocks in the Central Highlands of Scotland. *In* Harris, A. L., Holland, C. H. and Leake, B. E. (editors), *The Caledonides of the British Isles–reviewed*. Geological Society of London Special Publication No. 8, published by Scottish Academic Press, Edinburgh, 339–344.

Whalen J. B., Currie J. L. and Chappell B. W. 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology,* **95**, 407–419.

Whitten, E H T. 1959. A study of two directions of folding; the structural geology of the Monadhliath and mid-Strathspey. *Journal of Geology*, Vol. 67, 14–47.

Whittles, K.H. 1981. The geology and geochemistry of the area west of Loch Killin, Inverness-shire. Unpublished PhD thesis, University of Keele.

Wilkinson, S. B. 1907. The geology of Islay. Memoirs of the Geological Survey of Scotland, Sheets 19 and 27, and parts of 20.

Willan, R. C. R., and Coleman, M L. 1983. Sulphur isotope study of the Aberfeldy barite, zinc, lead deposit and minor sulfide mineralization in the Dalradian metamorphic terrain, Scotland. *Economic Geology*, Vol. 78, 1619–1656.

Williamson, D. H., 1953. Petrology of chloritoid and staurolite rocks north of Stonehaven, Kincardineshire. *Geological Magazine*, 90, 353–361.

Williamson, W O. 1935. The composite gneiss and contaminated granodiorite of Glen Shee, Perthshire. *Quarterly Journal of the Geological Society of London*, Vol. 91, 382–422.

Wilson, J.R. and Leake, B.E. 1972. The petrochemistry of the epidiorites of the Tayvallich Peninsula, North Knapdale, Argyllshire. *Scottish Journal of Geology* **8**, 215–252.

Winchester, J.A. 1974. The zonal pattern of regional metamorphism in the Scottish Caledonides. *Journal of the Geological Society of London,* **130**, 509–24.

Winchester, J.A. and Glover, B.W. (1988). The Grampian Group, Scotland. In: *Later Proterozoic stratigraphy of the Northern Atlantic region.* (editor Winchester, J.A.). Blackie, Glasgow and London, 146–161.

Winchester, J.A. and Glover, B.W. (1991). Grampian Group: Pitlochry—Loch Laggan—Glen Spean. In: *The Late Precambrian Geology of the Scottish Highlands and Islands*. (editors Hambrey, M.J., Fairchild, I.J., Glover, B.W., Stewart, A.D., Treagus, J.E. and Winchester, J.A.). Geologists' Association Guide No. **44**, 66–85.

Wiseman, J D H. 1934. The central and south-west Highland epidiorites: a study in progressive metamorphism. *Quarterly Journal of the Geological Society of London*, Vol. 90, 354–417.

Wood, D.S. 1964. Some structures in the Dalradian pillow lavas of the Tayvallich Peninsula, Argyll. *Geological Magazine,* **101**, 481

Woodcock, N. and Strachan, R. 2000. *Geological History of Britain and Ireland*. Blackwell Science, Oxford.

Wright, A.E. 1976. Alternating subduction direction and the evolution of the Atlantic Caledonides *Nature, London* **264**, 156.

Wright, A. E. 1988. 15. The Appin Group. In *Later Proterozoic Stratigraphy of the Northern Atlantic Regions* (editor Winchester, J. A.), pp. 177–199. Blackie.

Yardley B. W. D. (1989) *An introduction to metamorphic petrology*. Longman, Harlow.

Yardley, B.W.D. and Valley, J.W. 1997. The petrologic case for a dry lower crust. *Journal of Geophysical Research*, **106 B6**, 12173–12185.

Zeh, A. and Millar, I. L. 2001. Metamorphic evolution of garnet-epidote-biotite gneiss from the Moine Supergroup, Scotland, and geotectonic implications. *Journal of Petrology* **42**, 529–554.

Zenk, M. and Schulz, B. 2004. Zoned Ca-amphiboles and related P-T evolution in metabasites from the classical Barrovian metamorphic zones in Scotland. *Mineralogical Magazine*, **68**, 769-786.

Glossary and terminology

G.1 Geochronology

The time-scale and chronostratigraphical names used throughout this volume are from *A Geologic Time Scale 2004* (Gradstein *et al*., 2004). Wherever possible, interpretations of age are based upon the most recent radiometric dates, which are almost always by U-Pb analysis of zircons or, rarely, monazites. Determinations by other radiometric methods provide additional information but are interpreted with more caution or are included for historical interest.

G.2 Lithological nomenclature

The nomenclature of metamorphic rocks in this volume broadly follows the recommendations of the British Geological Survey's Rock Classification Scheme (Robertson, 1999). It also draws upon some parts of the Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Metamorphic Rocks (Fettes and Desmons, 2007). However, the nature of the GCR is such that the site reports draw heavily upon previous literature, to which the reader is frequently referred. Hence, some more-radical changes in nomenclature that would make comparison with previous work confusing have been avoided.

Historically in the Grampian Highlands, the names used to describe units of metasedimentary rock have been dependent upon metamorphic grade and the ease with which primary sedimentary features can be identified. Thus in the South-west Grampian Highlands, where metamorphic grade is generally low, many authors have used sedimentary rock terms (e.g. mudstone, siltstone, sandstone), with or without the prefix 'meta'. In an ideal world this would be the preferred scheme. However, where the rocks are more metamorphosed, the terms pelite, semipelite, psammite and quartzite have been used to represent argillaceous to arenaceous clastic protoliths. Use of the latter scheme, first proposed by Tyrrell (1921), is almost unique to the British Isles, has not been recommended by the IUGS (Fettes and Desmons, 2007), and will almost certainly be phased out in the future. Some attempt has been made to rationalize the two 'schemes', at least within individual chapters of this volume, but total consistency has proved to be impractical for various pragmatic reasons.

Some commonly used names have been abandoned because they are no longer approved in any modern-day sedimentary-rock scheme. For example, the term 'grit', beloved of Highland geologists since the earliest days, becomes 'pebbly sandstone' or 'microconglomerate' under this regime, and 'arkose' becomes 'feldspathic sandstone'.

Regardless of metamorphic grade, relatively pure metacarbonate rocks consisting essentially of recrystallized carbonate minerals are referred to as 'metalimestone' or 'metadolostone'. The term 'marble' is rarely found in modern descriptions and tends to be used as an informal general term for a decorative metacarbonate rock. Calcsilicate rocks represent originally impure calcareous (or magnesian) carbonate rocks and contain a high proportion of calcium-magnesium-silicate minerals such as tremolitic amphibole, grossular garnet, epidote, zoisite and idocrase. Such rocks grade into metasedimentary 'para-amphibolites'.

The textural terms 'slate', 'phyllite', 'schist' and 'gneiss' have commonly been used as rock names and are still approved by the IUGS and BGS schemes for use where the nature of the protolith is uncertain. However, they impart no information about the composition of the rock and hence the preferred terminology restricts their use to textural qualifiers, giving priority to root names based upon composition e.g. 'slaty metamudstone' or 'slaty pelite', rather than 'pelitic slate'. This principal has been followed throughout this volume wherever possible.

Restrictions on the use of non-approved rock names do not apply to lithostratigraphical names, into which they are commonly incorporated by historical precedence and in order to maintain consistency (e.g. Ballachulish Slate Formation, Ben Ledi Grit Formation).

The terminology of igneous rocks follows the IUGS-approved scheme of Le Maitre et al. (2002), with slight modifications following the BGS Rock Classification Scheme of Gillespie and Styles (1999). Metamorphosed igneous rocks are classified, wherever possible, by adding the prefix 'meta' to the name of their protolith (eg. metabasalt, metadolerite, metagranite). Where the protolith cannot be identified, general descriptive terms such as 'hornblende schist' or 'amphibolite' are used. The term 'epidiorite', formerly used for various metamorphosed basic rocks has been abandoned.

For the names of minerals, the reader is referred to standard textbooks.

G.3 Nomenclature and numbering of structures related to phases of deformation

Identifiable episodes of deformation have been termed D1, D2, D3 etc. in order of decreasing age. Folds that can be related to specific deformation phases are numbered F1, F2, F3 etc. Corresponding cleavages and other planar structures are numbered S1, S2, S3 etc. and primary bedding is numbered S0. Lineations are likewise numbered L1, L2, L3 etc.

However, not all of the deformation episodes are necessarily developed in all areas and, even within individual areas, the multiplicity of workers has resulted in differences in numbering of structural events. Consequently inconsistencies in the nomenclature of structural phases are common when comparing detailed studies of separate areas. Authors undertaking regional syntheses have attempted to solve this problem by disregarding phases of deformation whose effects can be shown to be of local extent only. The regional phases are then numbered to produce a sequence of major events recognizable over wide areas and accepted by most authors. Thus, for example, the sequence D1 to D3 identified in the regional synthesis of the South-west Highlands by Roberts and Treagus (1977c), differs numerically from that used in detailed, more local studies within the same area by Roberts (1974; 1976) and Treagus (1974). The issue of local fold phases that are difficult to date or seem to be additional to the regional phases was addressed by Treagus (2000) by the use of lower case letters, such as De and Dt to represent Errochty and Trinafour fold phases respectively in the Schiehallion area. Even with this rationalization, problems still exist on a regional scale with the result that different nomenclatures have been applied by various authors.

One major problem arises from a variation in the number of recognizable major phases across the Tay Nappe. D1 and D2 are widespread events recognized by most authors. However, a D3 event, responsible for refolding of the Tay Nappe in the Tummel Steep Belt, for example, becomes difficult to distinguish farther to the north-west. Consequently, workers in the Central Grampian Highlands and southern parts of the Northern Grampian Highlands, such as Roberts and Treagus (1977c; 1979), Thomas (1979; 1980) and Treagus (1987) recognized only D1 and D2 as definite nappe-forming and nappe-modifying events and later upright folds such as the Ben Lawers Synform, termed by them D3, were regarded as part of a post-nappe phase. Workers in areas to the south-east (e.g. Harris *et al.*, 1976; Bradbury *et al.*, 1979; Harte *et al.*, 1984; Mendum and Fettes, 1985) recognized three nappe forming or modifying events (D1, D2, D3) and hence their main late-tectonic phase, responsible in particular for the Highland Border Downbend, is D4. It is still not clear whether structures such as the Ben Lawers Synform correlate with D3 or D4 structures father to the south-east but the D1–D4 nomenclature is more generally applicable and hence will be adopted in this volume unless stated otherwise.

G.4 Use of the stereographic projection

The equal-area stereographic projection, whose use in structural geology was popularized by Coles Phillips (1954), remains the best tool for representing the orientation of planes and lines in three-dimensional space. Although it is possible to project planes and lines onto either the lower or the upper surface of a sphere, it has become conventional to use only the lower hemisphere; the equal-area projection of that hemisphere onto a two-dimensional plane is known as a stereogram or stereoplot.

On the stereogram, a plane is represented by a great circle, and a lineation by a point; if many planes are to be plotted they are best recorded as poles (a pole is a line drawn at right angles to the plane that uniquely defines the dip, dip direction, and strike of the plane)(Figure G.1a). Plotting of the two main geometrical features of minor folds, the axial plane and hinge, is illustrated in Figure G.1b.

In areas of tilted or folded strata, the pattern defined by the poles to bedding, for example, most commonly forms one of two distinctive patterns. Either the points cluster in a single group (a point distribution), or they are spread out along a great circle path and define a girdle (Figures G.1c and G.1d). A cluster represents the variation in orientation of a single surface or horizon, for which the computed mean is commonly quoted, together with the number of observations (N). In the case of the girdle, a best-fit great circle for the dataset is computed (i.e. the plane containing the poles to the bedding; Figure G.1d), with the pole to this plane giving the attitude of the major fold axis.

G.5 Glossary

This glossary aims to provide simple explanations of all but the most elementary geological terms used in Chapter 1 and in the Introduction and Conclusions sections of site descriptions. It also includes many of the more important terms encountered in other sections of the volume. *The explanations are not intended to be comprehensive definitions, but concentrate instead on the way in which the terms are used in this volume*. Bold type indicates a further glossary entry.

A-type: refers to an igneous rock, usually a granite, with **alkaline** characteristics; an alkali granite.

Accretion: used in a tectonic context to describe the process whereby sections of usually oceanic crust become attached to the margin of a craton or pre-existing terrane during plate collision.

Acritarch: hollow organic walled microfossils of uncertain biological affinities, but most might be algal cysts.

Agglomerate: a **pyroclastic** rock with predominently rounded **clasts** greater than 64 mm in diameter.

Alkaline: describes igneous rocks that contain more sodium and/or potassium than is required to form feldspar and hence contain, or have the potential to contain (i.e. in the **norm**), other alkali-bearing minerals such as feldspathoids, alkali pyroxenes and alkali amphiboles.

Allochthonous: describes a body of rock that has been transported from where it was originally formed to its present position by tectonic processes.

Alluvial: **proximal** terrestrial depositional environments containing a spectrum of **mass-flow** (debris-flow) and stream-flow (**fluvial**) deposits.

Amphibolite: a dark-green rock composed largely of amphibole, typically hornblende, possibly with some plagioclase. Most amphibolites are metamorphosed **mafic** igneous rocks (ortho-amphibolites), but some are metamorphosed calcareous sedimentary rocks (**para-amphibolites**).

Amygdale: a gas bubble cavity in an igneous rock that has been infilled later with minerals.

Anatexis: describes partial melting of a pre-existing rock

Anticline: a fold in which the oldest strata lie in the core of the fold, irrespective of whether the fold closes upwards, downwards or sideways.

Antiform: a fold with **limbs** that converge upwards (upward closing), either in strata where the direction of **younging** in the stratigraphical sequence is not known, or where the strata have been previously inverted so that the fold is an upward-closing syncline. In areas of multiphase folding, all upward closing post-F1 folds should strictly be termed antiforms because of the likely presence of both upward- and downward-facing earlier structures.

Aphyric: textural term, applied to igneous rocks that lack relatively large, conspicuous crystals (**phenocrysts**) compared with the grain size of the groundmass (or non-**porphyritic**).

Aplitic: describes relatively finer grained areas, or typically veins, usually of **felsic** material, within an igneous rock

Appinitic: describes coarse-grained **ultramafic** and **mafic** igneous rocks, characterized by the presence of abundant hydrous **mafic** minerals, particularly amphibole, and by distinctive whole-rock geochemistry.

Ash-fall tuff: lithified **pyroclastic** fall deposit with grain size less than 2 mm in diameter.

Augen: large, generally ovoid crystals within a foliated matrix. The foliation wraps around the augen to give a characteristic texture. (From German for 'eyes'.)

Autochthonous: describes a body of rock that formed approximately in its present position in contact with its basement.

Axial planar cleavage or **foliation**: a **cleavage** or **foliation** that is orientated parallel to the **axial plane** of a fold or set of folds.

Back-arc basin: the region adjacent to a **subduction**-related **island arc**, on the opposite side of the arc from the trench and subducting plate. Stresses in the back-arc region are typically extensional.

Basement: The oldest rock units recognized in a given area; usually a complex of metamorphic and/or igneous rocks that underlies a sedimentary or metasedimentary succession.

Basic: describes igneous rocks relatively rich in the 'bases' of early chemistry (MgO, FeO, CaO, Fe_2O_3); silica (SiO_2) is relatively low (nominally 45 – 52%).

Basin (i.e. sedimentary basin): a region of prolonged subsidence of the Earth's surface.

Bedding: a feature of sedimentary rocks, in which planar or near-planar surfaces known as bedding planes indicate successive depositional surfaces formed as the sediments were laid down.

Biostratigraphy: the stratigraphical subdivision of sedimentary or metasedimentary rocks based on their fossil content.

Blastomylonite: a type of **mylonite** in which **porphyroclasts** and matrix have undergone recrystallization, normally synchronous with the deformation.

Boudinage: the process whereby a competent bed or layer surrounded by less competent layers is subject to extension and separates into 'boudins', which have the cross-section appearance of a 'string of sausages', separated by the less competent material.

Breccia: rock composed of angular and subangular broken fragments greater than 2 mm in diameter; can be volcanic, sedimentary or **fault**-related.

Brittle fault: a **fault** that has developed at low enough temperatures and pressures that the rocks adjacent to the fault have become broken and ground up by **cataclasis**, rather than undergoing recrystallization (contrast with **ductile**).

Buckle fold: fold formed in response to end loading of a competent layer, e.g. bed, vein, igneous sheet.

Calc-alkaline: describes a suite of igneous rocks, characterized chemically by the steady decrease in iron content relative to silica during evolution of the magma; typical of magmas generated at destructive plate margins during **orogenesis**.

Calcsilicate: referring to calcium- and/or magnesium-silicate minerals, or to metamorphic rocks that are rich in those minerals but contain few or no carbonate minerals.

Cataclasis: fine-scale brecciation, fracturing, crushing and rotation of mineral grains under **brittle** conditions, without significant chemical reconstitution. A cataclastic rock has no foliation.

Chert: a microcrystalline or cryptocrystalline sedimentary rock composed dominantly of silica.

Chevron fold: a fold with an angular **hinge** and near-planar **limbs**, the limbs commonly being of approximately equal length (symmetrical).

Chronostratigraphy: the correlation and subdivision of sedimentary and volcanic rock units and their metamorphosed equivalents on the basis of their relative ages. The hierarchy of chronostratigraphical units is erathem, series, system and stage, which correspond to the geological time units era, period, epoch and age.

Clast: a fragment in a rock.

Cleavage: plane of incipient parting in a rock, produced by the preferred alignment of platy minerals such as mica in response to confining pressure during deformation and accompanying low-grade metamorphism.

Coaxial: describes parallel linear structures, especially fold axes and related **lineations** arising from different phases, plunging by the same amount and towards the same direction.

Comagmatic: describes igneous rocks that are considered to have been derived from the same parent **magma**, or at least from the same source region, at the same time and under identical physical and chemical conditions.

Complex: a large-scale spatially related assemblage of mixed rock units (igneous, metamorphic and sedimentary), with complicated inter-relationships, various ages and diverse origins.

Concretion: a hard, compact mass, commonly spheroidal or ovoid, in a sedimentary rock, formed by precipitation of a cementing mineral (commonly carbonate) around a nucleus during deposition or more commonly during subsequent burial and **diagenesis**.

Conglomerate: a sedimentary rock with a significant proportion of **clasts** greater than 2 mm in diameter, set in a finer-grained groundmass (normally sandstone or siltstone). The clasts are typically rounded to subangular pebbles, cobbles and boulders.

Country rock: rock that has been intruded by an igneous rock or replaced by a mineral vein etc.

Crenulation cleavage: a type of **spaced cleavage** developed by the microfolding (crenulation) of an earlier **cleavage** or **schistosity**.

Cross-bedding: a structure in sedimentary rocks, notably sandstones, that was formed due to current action by the migration of ripples or dunes on the sediment surface. Cross-bedding can be formed in **alluvial**, tidal or aeolian environments.

Crust: The outermost layer or shell of the Earth, above the **mantle**. It consists of two parts: a **basic** layer, which forms the oceanic crust and underlies the continents at depth; and a layer of dominantly **silicic** rocks, which forms the thickest, upper part of the continental crust.

Crustal shortening: compression of the **crust** resulting in shortening on a regional scale, normally in the plane of the earth's surface.

Culmination: highest point on a structural surface or linear structural feature, where the dip or plunge reverses its direction.

Cumulate: an igneous rock formed by the accumulation of crystals in a magma chamber.

Depleted mantle: **mantle** that has been depleted in **incompatible elements**, through **partial melting**.

Detrital zircon: a zircon crystal within a sedimentary deposit or rock. Detrital zircons can be dated by **radiometric dating** methods to provide information about the age of their source rocks. Hence, they can provide a maximum age limit for deposition of the sedimentary unit.

Dextral: the sense of **strike-slip** displacement along a **fault** that has had right lateral movement; i.e. to an observer standing on one side of the fault, the rocks on the other side appear to have been displaced to the right.

Diagenesis: the process of consolidation, mineral growth, recrystallization and other processes leading to lithification of unconsolidated sediment to form rock.

Diamictite: a sedimentary rock that consists of a fine-grained matrix with much coarser clasts, such as pebble-bearing mudstones and matrix-supported conglomerates. Diamictites show poor or no sorting and are commonly, but not exclusively, of glacial origin.

Diatexite: rock that has been almost, but not completely, melted, commonly with only refractory minerals remaining.

Distal: far from the source.

Dolerite: medium-grained rock of basaltic composition; used herein as a synonym of microgabbro.

Dolostone: a carbonate-rich sedimentary rock largely composed of the mineral dolomite (calcium-magnesium carbonate).

Ductile: a type of deformation that occurs at relatively high temperature and/or pressure, where the rocks deform by distributing the strain smoothly throughout the deforming mass, typically by recrystallization and grain boundary migration processes.

Dyke: a body of igneous rock emplaced as a steep, generally near-vertical sheet, and normally discordant to the structure of its host rocks.

Enclave: an inclusion; one rock type enclosed within another.

Epidiorite: An obsolete term, widely used in the Grampian Highlands, for fine- to medium-grained basic meta-igneous rocks at medium to high grades of metamorphism, where the mineralogy becomes comparable to that of a diorite i.e. hornblende plus plagioclase of andesine composition.

Euhedral: describes a mineral grain, such as a **phenocryst**, with well-formed crystal faces.

Extensional tectonics: the term used for tectonic processes where the **crust** is under extension, for example in an orogenic collapse or continental rift setting.

Extrusive: refers to igneous rocks that have been extruded onto the Earth's surface, rather than being intruded beneath the surface (**intrusive**).

Facies: the characteristic features of a rock unit, including rock type, mineralogy, texture and structure, which together reflect a particular sedimentary, igneous or metamorphic environment and/or process.

Facing: the direction towards which a rock unit, layer or structure youngs. Facing can be applied to folds, cleavages and even faults. A fold faces in the direction normal to its axis, along the axial surface and towards the younger beds (Figure G.2).

Fault: A fracture or zone of fractures in the Earth's **crust** across which the rocks have been displaced relative to each other.

Felsic: describes light-coloured minerals (*fe*ldspar/*fe*ldspathoid and *silica*) or an igneous rock containing abundant proportions of these minerals; the opposite of **mafic**.

Felsite: a field term for glassy and fine-grained **felsic** igneous rocks.

Fluvial: describes a depositional system related directly to stream-flow deposition (i.e. rivers and streams), within a more-general **alluvial** system.

Fold axial plane: see **fold axial surface**.

Fold axial surface: the surface that joins the hinge lines of a fold occurring in successive folded surfaces (Figure G.3). Where the surface is planar or near-planar, it is commonly referred to as an **axial plane**.

Fold axis: strictly describes an abstract feature i.e. the line that when moved parallel to itself generates a fold. It is also used to describe the feature derived from a stereographic projection (i.e. a pi-axis). However, it is commonly used loosely as a synonym for **fold hinge** (Figure G.3).

Fold hinge: the trace of the fold **axial surface** (or axial plane) on a folded surface. Measured in the field as the line along which a change occurs in the amount and/or direction of dip of a folded surface; the area with the smallest radius of curvature (Figure G.3).

Fold limb: the part of the fold between one hinge and the next; the area with a larger radius of curvature (Figure G.3).

Fold interference pattern/structure: the complex geometry created where early folds have themselves been deformed and re-orientated by later folds.

Foliation: the planar arrangement of textural and mineralogical components within a rock. In metamorphic rocks, generally formed during deformation and metamorphism of the pre-existing bedding or other primary fabric.

Footwall: the block of rock immediately below any non-vertical **fault**, **thrust** or **slide**.

Foreland: the stable region in front of an orogenic belt, which has not been significantly affected by the deformation and metamorphism. The rocks in the orogenic belt are normally thrust and overfolded towards the foreland.

Gneiss: Coarse-grained metamorphic rock with a compositional layering known as gneissose layering, typically defined by paler coloured quartz- and feldspar-rich layers and darker coloured layers of **mafic** minerals. Gneisses are formed by segregation and mineral growth during metamorphism at high grades.

Graben: an elongate down-faulted crustal block commonly bounded by two normal **faults** or fault systems and with a marked topographic expression. A half-graben is bounded on one side by a **fault** or fault system.

Graded bedding: describes a bed in a sedimentary rock that has a progressive change in particle size from top to bottom. Most common is a sequence with coarse grains at the bottom and fining upwards.

Granofelsic: refers to a recrystallized, medium- to coarse-grained quartzofeldspathic rock, commonly a **psammite**, with little or no foliation or lineation.

Greywacke: a coarse-grained and poorly sorted sedimentary rock composed of angular to subangular fragments in a sandy, silty or clayey matrix. Normally deposited from turbidity currents.

Hangingwall: the block of rock immediately above any non-vertical **fault**, **thrust** or **slide**.

Hinge-zone: the zone around a **fold hinge**.

Hornfels: a well-baked, hard, splintery rock resulting from thermal (contact) metamorphism.

Hyaloclastite: A **pyroclastic** rock composed of angular fragments of glass, formed when **magma** is rapidly quenched and shattered on entering water.

Hydrothermal: describes the reaction of hot water with rocks, resulting in changes in mineralogy and chemistry (cf. **metasomatism**).

Imbricate zone: consists of slices of rock displaced by successive **thrust faults** within a **thrust belt**, which commonly form a structure like stacked roof tiles.

Incompatible elements: trace elements that are not readily accepted into the crystal structure of common rock-forming minerals during the crystallization of **magma** and hence are concentrated preferentially into the remaining liquid. They are also concentrated in the first liquids produced during **partial melting**.

Inlier: strictly, an area of older rocks enclosed within a sequence of younger rocks. Where the sequences are inverted, or where boundaries between the distinct sequences are all structural dislocations (especially low-angle **thrust faults** or **slides**), the term 'structural inlier' is commonly used, irrespective of the relative ages.

Intermediate: applied to an igneous rock that is transitional between **silicic** and **basic** (i.e. SiO_2 between 52% and 63%).

Intrafolial: literally "within the foliation"; a term used to describe isolated, tight to **isoclinal** folds that typically have **axial planes** parallel to the **foliation** of the rock. The folds generally affect only a few layers of the rock succession and can even be confined to a single layer.

Intrusive: refers to igneous rocks that have been intruded into older rocks beneath the Earth's surface, rather than being extruded onto the surface (**extrusive**).

Island Arc: a chain of islands formed largely of volcanic rocks and volcaniclastic sedimentary rocks, commonly with a core of associated plutonic rocks, that formed above a **subduction zone**.

Isoclinal fold: a fold with parallel **limbs**.

Joint: a fracture in a rock across which there has been no noticeable displacement.

Juvenile: applied to material that has been derived directly from the melting or **partial melting** of **crust** or **mantle**.

Keratophyre: an altered fine- to medium-grained **felsic** igneous rock (originally a trachyte or microsyenite), consisting essentially of albite with minor chloritized **mafic** minerals.

Kink fold: a fold with planar **limbs** and a markedly angular **hinge**.

Lamination: very fine layering.

Lamprophyre: mineralogically and geochemically distinctive group of largely medium-grained igneous rocks characterised by abundant **phenocrysts** of **mafic** minerals, with **felsic** minerals largely confined to the groundmass. Allied to coarse-grained **appinitic** rocks.

Lava: molten rock at the Earth's surface (contrast with **magma**).

Lee (side): the steep slope of a ripple or dune bedform where sediment 'avalanches' from the top.

Leuco: prefix to denote a *relatively* light-coloured variant of a rock-type.

Leucocratic: *absolute* term to describe light-coloured igneous rocks based upon the modal proportions of **mafic** minerals being within the range 0 – 35%.

Leucosome: Lighter coloured, igneous-looking layers composed of **felsic** minerals in a **migmatite**, formed by segregation from or **partial melting** of the original rock.

Limestone: a sedimentary carbonate rock consisting largely of the mineral calcite (calcium carbonate).

Lineation: a linear structure in a rock; any linear fabric element. It can result from a number of processes including aligned mineral growth, intersection of cleavage and bedding, minor folding, stretching, or fault movement.

Listric: refers to a **normal fault** whose dip decreases downwards.

Lithosphere: the outer layer of the solid Earth, including the **crust** and upper part of the **mantle**, which forms tectonic plates.

Lithostratigraphy: the stratigraphical subdivision and correlation of sedimentary and volcanic rock units and their metamorphosed equivalents based on their lithology, stratigraphical position and affinities. Units are named according to their perceived rank in a formal hierarchy, namely supergroup, group, formation, member and bed. The fundamental unit is the formation.

Mafic: describes dark-coloured minerals, rich in *ma*gnesium and/or iron (*F*e), **or** an igneous rock containing substantial proportions of these minerals, mainly amphibole, pyroxene or olivine; the opposite of **felsic**.

Magma: molten rock beneath the Earth's surface.

Mantle: part of the interior of the Earth, beneath the **crust** and above the core.

Mass-flow: the transport, down slope under the force of gravity, of large, coherent masses of sediment, tephra or rock; commonly assisted by the incorporation of water, ice or air.

Megacryst: a large crystal, occurring within an igneous rock or more rarely a metamorphic rock, which is notably larger than the surrounding minerals in the groundmass or matrix.

Mélange: a chaotic rock unit, characterized by the lack of internal continuity of contacts between component blocks and including fragments of a wide range of composition and size.

Meta-: prefix added to any rock name (lithology) to indicate that it has been metamorphosed e.g. metabasalt is a metamorphosed basalt.

Metamorphic aureole: an area of rocks around an igneous intrusion that has undergone metamorphism due to the increased temperatures created by the intrusion of **magma**. Also commonly referred to as a **thermal aureole** or simply an aureole.

Metamorphic facies: an expression of a specific range of metamorphic conditions, in particular temperature and pressure, as determined from sets of mineral assemblages (Figure G.4). Unlike **metamorphic zones**, which relate to specific lithologies, metamorphic facies are applicable to all lithologies, although their names are derived from mineral assemblages in rocks of basaltic composition.

Metamorphic grade: widely used to indicate relative conditions of metamorphism; either as informal references to low, medium or high grade, with increase in temperature and/or pressure; or related to a specific **metamorphic zone** e.g. biotite-grade, sillimanite-grade etc.

Metamorphic isograd: in theory, any line connecting points of equal **metamorphic grade**, but in practise usually marks the incoming during **prograde** metamorphism of a key mineral, especially one that characterizes a **metamorphic zone**.

Metamorphic zone: an area or volume defined by the presence of a metamorphic index mineral or set of minerals in rocks of a specified composition (e.g. in metamudstones or in basic meta-igneous rocks).

Metasomatism: the process of chemical change and mineralogical replacement due to the introduction of different elements through fluid circulating in the rocks.

Micro: prefix added to the name of any coarse-grained igneous rock to indicate a medium-grained variety e.g. microgabbro is a medium-grained rock of gabbroic mineralogy.

Microfossil: a fossil that is of such a size that it can only be identified by use of a microscope.

Microlithon: in **spaced cleavage**, microlithons are the tabular to lenticular, millimetre- to centimetre-thick rock domains that lie between the cleavage domains. They are generally quartz and feldspar rich and either lack cleavage or have only poor cleavage development.

Mid-ocean ridge basalt (MORB): type of **tholeiitic** basalt, generated at mid-ocean ridges. A world-wide, voluminous basalt type widely used as a fundamental standard for comparative geochemistry.

Migmatite: a partially melted layered rock having an overall metamorphic appearance, generally consisting of light-coloured layers (**leucosome**) of igneous-looking **felsic** minerals, and darker layers (melasome), richer in **mafic** minerals.

Monoform: large- or medium-scale fold with one steep and one shallow-dipping limb in a sequence in which the way up of the beds is not known. Similar to monocline, where the way up is known.

Mudstone: a clastic sedimentary rock composed of very fine-grained clay and silt particles (grain size < 0.032 mm).

Mullion: an architectural term, adopted to describe a combination of **lineations** and **fold hinges**, which appear as a series of centimetre- to metre-scale columnar structures on the surface of a bed or layer.

Mylonite: A coherent, thinly layered rock, formed in a zone of intense **ductile** deformation where pre-existing grains in the rock have been deformed, recrystallized, and reduced to a grain size of 0.05 mm or less.

Nappe: a large recumbent fold or a coherent body of rock, with its margins bounded by **thrust faults** or **shear-zones**, either of which has been moved a considerable distance from its original location. (see also **allochthonous**).

Normative composition: a theoretical mineralogical composition of an igneous rock obtained by recalculation of the whole-rock chemical composition; useful for classification purposes and for comparison with experimental studies of **magma** crystallization.

Normal fault: an extensional high-angle **fault** (dip over 45°) on which the **hangingwall** has moved downwards relative to the **footwall**.

Obduction: the overriding/overthrusting of oceanic **crust** on to the leading edge of continental **lithosphere** during plate collision.

Ophiolite: an ordered sequence of related **ultramafic** rocks, gabbros, sheeted **dykes** and basalt **lavas** that originated through the generation of oceanic **crust**.

Orogenesis: crustal thickening following the collision of tectonic plates and resulting in magmatism, folding, thrusting and accretion, leading to regional uplift and mountain building. A period of orogenesis may be referred to as an orogenic event or as an orogeny, and the resulting area of rocks affected by these processes constitutes an orogenic belt.

Orthogneiss: a **gneiss** with an igneous **protolith**.

Orthoquartzite: a clastic sedimentary rock composed originally almost exclusively of quartz sand (over 90% quartz).

Outlier: strictly, an area of younger rocks completely surrounded by older rocks. Where the sequences are inverted (as in the Flat Belt of the Tay Nappe), or where an upper unit of restricted outcrop lies upon a low-angle **thrust fault** or **slide**, the term 'structural outlier' is commonly used, irrespective of the relative ages.

Palaeocurrent: a wind or water current direction that existed at the time of deposition of sedimentary rocks, and that can be inferred from sedimentary structures.

Palaeogeography: the study of the configurations of continents and oceans and their physical geography during geological history.

Palaeomagnetism: the variation in the Earth's magnetic field over time. When rocks that contain magnetic minerals are deposited, the orientation of the Earth's magnetic field is locked within the rocks and can be used to study the movement of tectonic plates.

Para-amphibolite: an **amphibolite** with a sedimentary **protolith**.

Paragneiss: a **gneiss** with a sedimentary **protolith**.

Partial melting: the incomplete melting of a rock to produce a **magma** that differs in composition from the parent rock.

Passive margin: a continental margin formed following rifting and continental rupture that is not the site of convergent tectonic processes. Passive margins generally contain marine sedimentary sequences.

Pegmatite: a very coarsely crystalline igneous-textured rock, typically a vein, **dyke** or sheet but also as irregular patches. Most commonly the minerals are **felsic** but used strictly the term has no mineralogical connotation.

Pelite: used here, and historically in the Scottish Highlands, for a rock, rich in mica, which formed by metamorphism of a sediment rich in clay minerals (a metamudstone).

Phenocryst: a crystal in an igneous rock that is larger than those of the groundmass, usually having crystallized at an earlier stage.

Phyllite: describes a rock with a strong **cleavage**, intermediate in texture between **slate** and **schist**, characterized by growth of new sericite, chlorite and locally biotite. Most commonly applied to **pelites** and **semipelites** but in theory can be applied to any **protolith**.

Phyllonite: a very platy type of **mylonite**, formed by deformation and recrystallization of rocks rich in mica and chlorite.

-phyric: as in 'plagioclase-phyric', a **porphyritic** rock containing **phenocrysts** of plagioclase.

Picrite: a magnesium-rich igneous rock (MgO greater than 18%), generally appearing as an olivine- and/or pyroxene-rich variety of a gabbro, dolerite or basalt.

Pillow lava: subaqueously erupted **lava**, usually basaltic in composition, comprising an accumulation of smooth pillow shapes produced by rapid chilling.

Plunge: the orientation of a **fold hinge/axis** or other linear structure, expressed as its angle below the horizontal (measured in degrees in a vertical plane) and its azimuth or compass direction.

Pluton: an intrusion of igneous rock, generally of kilometre-scale or larger, that has been emplaced at depth in the Earth's **crust**.

Porphyritic: textural term for an igneous rock in which larger crystals (**phenocrysts**) are set in a finer grained or glassy groundmass.

Porphyroblast: a newly grown mineral in a metamorphic rock that is significantly larger than most minerals in the matrix.

Porphyroclast: a relict, resistant, large crystal or rock fragment within a foliated rock. Common in **mylonites** where the rock has had its overall grain size reduced by deformation processes.

Porphyry: a field term for an igneous rock that contains **phenocrysts** within a fine-grained groundmass of indeterminate composition; usually preceded by a mineral qualifier indicating the type of **phenocryst** present; e.g. feldspar porphyry.

Prograde: metamorphism during which the temperature and/or pressure is progressively increasing. See **retrograde**. Also used to describe the advance of a sedimentary feature such as a delta.

Protolith: the source rock from which a new rock was formed, either by metamorphism to form a metamorphic rock, or by melting to form an igneous rock.

Proximal: near to the source.

Psammite: used here, and historically in the Scottish Highlands, for a rock, rich in quartz and feldspar with some micas, formed by metamorphism of a sandstone (a metasandstone or meta-arenite).

Pseudomorph: a replacement product, usually crystalline and consisting of one or more minerals, that retains the distinctive original shape of the parent crystal.

Ptygmatic fold: normally a single layer or vein, tightly folded in a lobate manner in a less-competent schistose matrix.

Pyroclastic: describes unconsolidated deposits and rocks that form directly by explosive ejection from a volcano.

Quartzite: used here, and historically in the Scottish Highlands, for a rock composed largely of quartz grains, formed by metamorphism of a pure sandstone (a meta-orthoquartzite).

Radiometric dating: Measuring the age of rocks using the rate of decay of radioactive isotopes contained within minerals in the rock. Sometimes referred to as isotopic dating.

Recumbent fold: an overturned fold with a near-horizontal **axial plane**.

Restite: the material remaining after **partial melting**.

Retrograde: metamorphism in which minerals that formed at relatively high temperature and/or pressure are converted to those characteristic of lower grades.

Rift: a defined area of crustal extension and thinning, typically bounded by **normal faults**. A rift may eventually rupture the continental **crust**, allowing the development of new oceanic **lithosphere**, to become an ocean. A failed rift is one in which extension has been insufficient to produce oceanic material.

Rift basin: a depositional **basin** resulting from crustal extension.

Rift–drift transition: the evolution of a continental **rift** into a **passive margin** following the development of new oceanic **lithosphere**.

Rodding: a type of **lineation**, formed by elongate structures that are monomineralic and not formed from the original rock, most commonly of quartz.

S-type: refers to an igneous rock, usually a granite, that formed by the **partial melting** of sedimentary or metasedimentary rocks.

Sandstone: a clastic sedimentary rock made up mainly of quartz and feldspar, between 0.032 and 2 mm in grain size.

Schist: a foliated metamorphic rock with a **schistosity**. A textural term that can be combined with compositional or mineralogical terms to specify the type of schist.

Schistosity: the subparallel alignment of grains, most commonly of micas, but also of other minerals, e.g. hornblende, talc, etc., to form a tectonic **foliation**, enabling the rock to split readily into thin flakes or laminae.

Selvedge: marginal zone to a rock mass having a distinctive feature or composition. Commonly refers to the fine-grained margin of an intrusion or to a concentration of **mafic** minerals adjacent to **leucosomes** in **migmatites** and migmatic rocks.

Semipelite: used here, and historically in the Scottish Highlands, for a metasedimentary rock, with roughly equal amounts of siliciclastic grains (quartz and feldspar) and micas, which formed from a sedimentary rock dominantly composed of silt.

Serpentinization: the hydrothermal alteration of **ultramafic** rocks in which the **mafic** minerals are replaced by a range of hydrous secondary minerals, collectively known as serpentine.

Serpentinite: a rock dominantly composed of serpentine-group minerals.

Shearing: Deformation of a rock body by the sliding or translation of one part relative to another part, in response to an applied stress. The deformation can be **brittle** or **ductile** dependent on the strain rate, temperature, pressure, presence of fluids, rock mineralogy, etc. Shearing can occur across a single fault-plane, across **shear-zones**, or it can affect kilometre-thick rock sequences.

Shear-zone: a near-planar zone of intense **shearing**, with deformation generally by **ductile** processes.

Sheath fold: a fold with a tubular shape in three dimensions, resulting from the marked variation in the **plunge** of the **fold axis** through some 180°. In cross-section on two-dimensional surfaces sheath folds are commonly manifest as closed ovoid structures.

SHRIMP: refers to 'Sensitive High-Resolution Ion MicroProbe'. An in-situ method of measuring isotope concentrations in polished thin sections or polished sections of rocks.

Silicic: used to describe igneous rocks rich in silica (SiO_2 more than 63%). Preferred alternative to traditional term 'acid'.

Siliciclastic: describes a sedimentary or metasedimentary rock composed dominantly of clasts of silicate minerals.

Sill: a tabular body of igneous rock, originally intruded as a subhorizontal sheet and generally concordant with the **bedding** or **foliation** in the **country rocks**.

Siltstone: a clastic sedimentary rock made up of silt-sized grains (between 0.004 and 0.032 mm).

Sinistral: the sense of **strike-slip** displacement along a **fault** that has had left lateral movement; i.e. to an observer standing on one side of the fault, the rocks on the other side appear to have been displaced to the left.

Slate: describes a fine-grained rock with a very strong, very regular, closely spaced penetrative **cleavage**, enabling it to be split into thin parallel sheets (slates). Most commonly applied to **pelites** and **semipelites** but in theory can be applied to any **protolith**.

Slickenside: Linear grooves and ridges formed on a **fault** plane as rocks move against each other.

Slide: strictly any **fault** making a very low angle with original **bedding** but nowadays used almost exclusively for extensional faults (lags), commonly on the long upper limbs of **recumbent folds** and excising elements of the succession. A lag is the opposite of a compressional **thrust fault**.

Spaced cleavage: a type of **foliation** defined by closely spaced micaceous cleavage surfaces, or less commonly fractures (termed cleavage domains), that divide the rock into a series of fine-scale quartzofeldspathic tabular bodies (termed rock domains). Includes **crenulation cleavage**. In rocks of low metamorphic grade, spaced cleavage is commonly the result of pervasive pressure-solution processes.

Spilite: a pervasively altered basalt, commonly in a sub-marine environment, due to conversion of the plagioclase to albite, together with other hydrous mineralogical changes.

Steatite: a massive, typically pale grey-green, fine-grained rock consisting largely of the magnesium silicate minerals talc and magnesite.

Stereoplot: stereographic projection of structural data. Also known as a sterogram. See Figure G.1 and accompanying text.

Stoss (side): the gentle, up-current side of a ripple or dune beform. See also **lee** side.

Strike-slip: a term used to describe a **fault** on which the sense of movement is parallel to the strike of the fault.

Subduction: the process of one lithospheric plate descending beneath another during plate convergence. Subduction occurs along a narrow belt, termed a subduction zone. Where an oceanic plate is subducted beneath a continental plate, a trench is formed.

Supercontinent: A large landmass that forms from the convergence of multiple continents. Such supercontinents have formed at various periods in the geological record, e.g. Rodinia in Mesoproterozoic times.

Syncline: a fold in which the youngest strata lie in the core of the fold, irrespective of whether the fold closes downwards, upwards or sideways.

Synform: a fold with **limbs** that converge downwards (downward closing), either in strata where the direction of **younging** of the stratigraphical sequence is not known, or where the strata have been previously inverted so that the fold is a downward-closing anticline. In areas of multiphase folding, all downward closing post-F1 folds should strictly be termed synforms because of the likely presence of both upward- and downward-facing earlier structures.

Tectonothermal event: an event in which rocks are heated and metamorphosed at depth in the crust due to tectonic processes; most commonly as a result of **orogenesis**.

Terrane: a fault-bounded body of oceanic or continental **crust** having a geological history that is significantly distinct from that of contiguous bodies.

Tholeiitic: describes a suite of silica-oversaturated igneous rocks, characterized chemically by strong iron enrichment relative to magnesium during the early stages of evolution of the **magma**; formed in extensional within-plate settings, at constructive plate margins, and in **island arcs**.

Thermal aureole: see **metamorphic aureole**.

Thermal relaxation: in a zone of rifting, upwelling **mantle** rises beneath the base of the **crust**, which becomes stretched and thinned. Following the end of rifting, this hot mantle material will gradually cool and contract, causing subsidence over a wider area, and generating a thermal relaxation **basin**.

Thrust fault: a compressional reverse **fault** making a low-angle (less than 45°) with original **bedding** and placing older rocks over younger rocks, repeating elements of the succession. Typically occurs on the short lower limbs of **recumbent folds.** The opposite of an extensional lag or **slide.**

Thrust belt: a zone where a series of **thrust faults** crop out at the Earth's surface marking a major area of translation linked to an orogenic belt.

Tillite: a lithified glacial till ('boulder clay').

TIMS: refers to 'Thermal Ionization Mass Spectrometry' (also known as 'Isotope Dilution Thermal Ionization Mass Spectrometry' or ID-TIMS). A method of measuring isotope concentrations involving grain selection (usually zircon or monazite) and dissolution in acid.

Trace fossil: a sedimentary structure that was formed by a living organism.

Transcurrent: describes predominantly horizontal relative movement across a large-scale, steeply dipping **fault** or **shear-zone** (see also **strike-slip**).

Transgression: the spread or extension of the sea over land areas, commonly due to a relative sea-level rise.

Transpression: crustal shortening as a result of oblique compression across a **transcurrent fault** or **shear-zone.**

Transtension: crustal extension as a result of oblique tension across a **transcurrent fault** or **shear-zone** leading to localised **rifts** or **basins.**

Tuff: a **pyroclastic** rock derived from volcanic ash and made up of fragments with average grain size less than 2 mm.

Turbidite: a clastic sedimentary rock formed by deposition from a **turbidity current.**

Turbidity current: an underwater, gravity-controlled, density flow laden with suspended sediment, which produces a characteristic graded sedimentary unit showing a range from sand and gravel at the base to silt and mud at the top.

U-Pb dating: measurement of the amounts of lead daughter products that result from the decay of various isotopes of uranium to calculate a radiometric age for a rock. Zircon and monazite are the common minerals dated. See **SHRIMP** and **TIMS.**

Ultrabasic: describes an igneous rock with a silica content less than that of **basic** rocks (less than 45% SiO_2).

Ultramafic: describes an igneous rock in which dark-coloured, **mafic** minerals (amphibole, pyroxene, olivine) comprise more than 90% of the rock.

Unconformity: a contact between two rock units of significantly different ages, representing a significant gap in the geological time record.

Vergence: direction of relative movement or rotation of layers in an asymmetrical fold pair. Also the direction of overturning of folded layers, e.g. towards the south. (Figure G.3).

Vesicle: a gas bubble cavity, usually in a **lava** or shallow intrusion.

Volcaniclastic: generally applied to a clastic rock containing mainly material derived from volcanic activity, but without regard for its origin or environment of deposition (includes rocks formed directly by explosive eruption from a volcano, and sedimentary rocks containing transported volcanic debris).

Xenolith: a rock fragment that is alien to the igneous rock in which it is found. Commonly refers to blocks of country rock included within intrusions.

Younging: the demonstration of the direction in a sedimentary or volcanic sequence in which younger strata can be found.

Figure 1.1 General bedrock geology of the Grampian Highlands and Inner Hebrides south-east of the Great Glen Fault, showing the outcrops of Dalradian groups and major faults. Adapted from Stephenson and Gould (1995) and the BGS 1:625 000 scale Bedrock Geology map (UK North, 2007).
BBF Bridge of Balgie Fault, ELF Ericht-Laidon Fault, GDF Glen Doll Fault, GF Garabal Fault, GLF Gleann Liath Fault, LTF Loch Tay Fault, MF Markie Fault, PBF Pass of Brander Fault, RF Rothes Fault, SF Sronlairig Fault, TF Tyndrum Fault.

Figure 1.2 Terrane map of the northern British Isles showing the outcrop of the Dalradian Supergroup in the Grampian Terrane of Scotland and Ireland and in Shetland. Adapted from the BGS 1:500 000 scale Tectonic map of Britain, Ireland and adjacent areas (1996) and the BGS 1:625 000 scale Bedrock Geology map (UK North, 2007).

Figure 1.3 Distribution of ancient continental fragments and Caledonian orogenic belts around Britain and Ireland prior to the opening of the North Atlantic Ocean in Palaeogene time (after Holdsworth *et al*., 2000).

Figure 1.4 Edward Battersby Bailey in a typical field pose. Note the mode of dress: shabby jacket with various pieces of equipment tied on with string; shorts, worn in all weather and all seasons; lack of socks (they would only get wet); shoes (not boots), with holes in the toes (legend has it that he would deliberately cut the toes out of new shoes in order that the water could run out). Other legends tell that first thing every morning he would stand in a stream so that he didn't worry about getting his feet wet for the rest of the day and then eat his packed lunch so that he didn't have to carry it and waste time eating it later. After mapping and interpreting huge areas of the Grampian Highlands for the Geological Survey and then as Professor of Geology at Glasgow University, he became Director of the Geological Survey (1937–1945) and was knighted in 1945. (Photo: BGS No. P 225785, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Figure 1.5 Divisions of the Grampian Highlands as used in this volume and locations of GCR sites, numbered as in Table 1.1.

Figure 1.6 Overall Dalradian stratigraphy with interpreted depositional environments, water depth and subsidence history, based mainly on successions in the western and south-western parts of the Grampian Highlands and Inner Hebrides. Representative formations are from the Corrieyairack, Laggan and Glen Spean areas (Grampian Group), the Lochaber area (Appin Group) and Islay, Jura and Kintyre (Argyll and Southern Highland groups). After Anderton (1985) and Strachan and Holdsworth (2000).

Figure 1.7 Block diagram of major structures in the Grampian Highlands. Brittle faults, major mafic and ultramafic intrusions and minor intrusions are not shown. Sections A, B, C and D were adapted from an original by P.R. Thomas (1979) and incorporated in an overall model in Stephenson and Gould (1995).
AS Appin Syncline, BA Bohespic Antiform, BAS Ballachulish Slide, BCH Beinn a'Chuallich folds, BDS Beinn Don Syncline, BES Benderloch Slide, BLA Beinn na Lap Antiform, BLS Ben Lawers Synform, BOS Boundary Slide, CIA Creag na h'Iolaire Anticline, CS Corrieyairack Syncline, DD Drumochter Dome, ES Errochty Synform, FWS Fort William Slide, GCA Glen Creran Anticline, GMS Glen Mark Slide, GS Grampian Slide, HBD Highland Border Downbend, HBS Highland Border Steep Belt, KA Kinlochleven Anticline, OSB Geal-charn–Ossian Steep Belt, SBS Stob Ban Synform, SMS Sron Mhor Synform, TMA Tom Meadhoin Anticline, TSB Tummel Steep Belt.

Figure 1.8 Contrasting interpretations of the structure of the classic section along Loch Leven by different authors (after Stephenson and Gould, 1995).

- **(a)** Bailey (1934)
- **(b)** Roberts and Treagus (1977b, 1977c): revised stratigraphical correlations and drastically revised projections at depth
- **(c)** Hickman (1978): primary folds are identified only in the eastern part of the section

AS Appin Syncline, BAS Ballachulish Slide, BS Ballachulish Syncline, BWS Blackwater Synform, FWS Fort William Slide, KA Kinlochleven Anticline, KAF Kinlochleven Antiform, MA Mamore Anticline/Antiform, MS Mamore Syncline, SBS Stob Ban Synform, TMA Tom Meadhoin Anticline, TS Treig Syncline.

Figure 1.9 Cross-section to illustrate the structure in the Glen Roy and Glen Spean area; a north-eastern continuation of the structures shown in Figure 1.8 (after Key *et al.*, 1997).

Figure 1.10 Alternative models for the structural development of the Grampian Highlands (after Stephenson and Gould, 1995). Individual stages are not numbered (D1, D2 etc.) to avoid confusing and unintentional time correlations between the models but all show deformation up to and including the post-nappe D4 phase.

- **(a)** Root-zone and 'mushroom' models: final stage adapted from Thomas (1980)
- **(b)** Nappe fans/'fountains': adapted from Roberts and Treagus (1977a, 1977c) and Treagus (1987)

(c) Gravity sliding of rootless nappes: adapted from Shackleton (1979)

(d) North-westward movement and backfolding: from model of Hall in Fettes *et al*. (1986)

Stipple Grampian Group, BAS Ballachulish Slide, BLF Ben Lui Fold-complex, BOS Boundary Slide, FWS Fort William Slide, OSB Geal-charn–Ossian Steep Belt, SBS Stob Ban Synform, TN Tay Nappe.

Figure 1.11 Model for the evolution of the Tay Nappe (after Krabbendam *et al*., 1997).

(a) Lower levels of upright F1 folds are subjected to top-to-the-south-east D2 shearing. The position of the older part of the Highland Border Complex is highly speculative.

(b) F3 folding steepens structures in the north-west; the F4 Highland Border Downbend results in the Highland Border Steep Belt to the south-east, which consequently includes outcrops of downward-facing F1 folds and the limit of D2 deformation.

HBD Highland Border Downbend.

Figure 1.12 Distribution of metamorphic facies within the Grampian Highlands, as adapted from Fettes *et al*. (1985) by Stephenson and Gould (1995) and Strachan *et al*. (2002).
B Balquidder, C Cairngorms, D Deeside, ESZ Eilrig Shear-zone, M Monadhliath, S Schiehallion, TSB Tummel Steep Belt.

Figure 1.13 Reconstruction showing the positions of Baltica, Amazonia and Laurentia, prior to the break-up of the supercontinent of Rodinia and formation of the Iapetus ocean in late Neoproterozoic time (after Soper, 1994b). Arrows indicate the relative movements of the continental blocks during subsequent rifting.
A–C western margin of Appalachian–Caledonian orogenic belt, G Greenland, N Newfoundland, S Scotland.

Figure 1.14 Global palaeogeographical reconstructions from the mid Neoproterozoic to the mid Silurian. Modified after Torsvik *et al*. (1996) and Holdsworth *et al*. (2000).

(a) The supercontinent Rodinia at *c*. 750 Ma. The Grenvillian orogenic belts that welded the Rodinia continent together are indicated in black. Rifting has commenced between Laurentia and East-Gondwana.

(b) Late Neoproterozoic, *c*. 600–580 Ma. Rifting between the continents of Laurentia, Baltica and the Amazonia sector of West Gondwana. See Figure 1.13 for the situation immediately prior to this.

(c) Late Neoproterozoic–Cambrian, *c*. 550–540 Ma. The Iapetus Ocean is at its widest. Clastic and carbonate deposition occurs along the southern margin of Laurentia.

(d) Mid Ordovician, *c*. 470 Ma. Iapetus is in the process of closing. Collision of oceanic and microcontinental arcs with Laurentia, e.g. the Midland Valley Terrane, results in the Grampian Event in Scotland and the Taconic Event in North America.

(e) Early Silurian, *c*. 440 Ma, Continental terranes that have spalled off Gondwana, notably Avalonia, collide with Laurentia as the Iapetus Ocean closes and the Rheic Ocean widens. The start of the Scandian Event.

(f) Mid Silurian, *c.* 425 Ma. Final closure of Iapetus and Tornquist oceans. Collision of Baltica with the Greenland sector of Laurentia gives rise to the main Scandian Event (435–425 Ma).
MVT Midland Valley Terrane, SP South Pole.

Figure 1.15 Schematic cross-sections to show the progressive development of the rifted Laurentian margin in Scotland during a) late Appin Group time b) Crinan Subgroup time and c) Southern Highland Group time (after Anderton, 1985). Basaltic volcanic rocks and intrusions are shown in black (in c only).

Figure 1.16 A possible tectonic model for the Grampian Event in Scotland, which is here attributed to the collision of an intra-oceanic subduction zone and island arc (now possibly forming the basement to the Midland Valley Terrane) with the margin of Laurentia during closure of the Iapetus Ocean (Strachan, 2000 after Dewey and Ryan, 1990 with modifications to text to reflect more-recent evidence for the timing of events).

Figure 1.17 Reconstruction of the final stages of the Caledonian Orogeny with multiple plate collisions and re-alignments in mid Silurian to Early Devonian time (after Soper *et al.*, 1992).

(a) Wenlock–Ludlow, *c.* 420 Ma. The Iapetus Ocean has almost closed as Eastern Avalonia converges with Baltica.

(b) Lochkovian, *c.* 400 Ma. The Rheic Ocean has closed as Armorica collides with Eastern Avalonia and strike-slip re-alignment of terranes occurs between Laurentia and Baltica (the Acadian Event). Farther south, Iberia is converging with Armorica prior to collision in Mid Devonian time.

GGF Great Glen Fault, HBF Highland Boundary Fault, MTB Moine Thrust Belt.

Figure G.1 Simplified examples of the use of the equal-area stereographic projection (lower hemisphere) to represent geological structures:

(a) representation of a bedding plane as a great-circle trace and as a pole.

(b) representation of a fold hinge line (fold axis) as a point, lying on the axial plane (great circle).

(c) example of a point distribution, defined by poles to gently dipping beds, mean dip = 05°.

(d) example of a girdle distribution of poles to bedding, with a best-fit great circle, and its pole (fold axis).

Figure G.2 Diagram to illustrate the concept of 'facing' direction of folds, introduced by Shackleton (1958) as a means to describe the structural 'way-up' of strata. Shackleton defined 'facing' geometrically as 'the direction normal to the fold axis, along the axial plane, and towards the younger beds'. Thus a synclinal synform is described as 'upward facing', whereas an anticlinal (i.e. inverted) synform is 'downward facing'. Asymmetrical and recumbent folds have a sideways component of facing which is an important descriptive parameter, and which has commonly been used to infer the direction of tectonic transport.

Figure G.3 Fold terminology:

(a) single inclined fold pair illustrating the basic fold nomenclature (from McClay, 1987);

(b) fold train showing the change from upright to recumbent fold and the concept of an enveloping surface (from McClay, 1987);

(c) terms to describe the tightness of folds (from McClay, 1987);

(d) Asymmetrical minor folds showing Z, S and M symmetry and their typical relationship to larger scale antiformal and synformal structures (from McClay, 1987);

(e) Fold profile showing direction of vergence of an asymmetrical fold (from Bell, 1981);

(f) Geometry of coaxially refolded folds showing F1 and F2 major folds and related minor fold structures. Note how minor F1 folds change vergence across F1 fold axial traces but maintain a consistent vergence across the F2 fold axial traces, whilst changing their facing from upwards to downwards. Minor F2 folds change their vergence across the F2 axes (after Bell, 1981);

(g) Geometry of orthogonally refolded folds. Note that both F1 and F2 folds change vergence across F2 fold axes but not facing direction (arrows indicate facing direction of F1 folds) (after Bell, 1981).

Figure G.4 Pressure/Depth–Temperature diagram showing the fields of metamorphic facies (Yardley, 1989) Abbreviations: a-e-albite-epidote, hbl–hornblende, hfls–hornfels, preh-pump-prehnite-pumpellyite, px–pyroxene.

Table 1.1 Dalradian rocks of Scotland: GCR networks and site selection criteria.

Table 1.1 Dalradian rocks of Scotland: GCR networks and site selection criteria.

Site name **GCR selection criteria**

South-west Grampian Highlands Network, Chapter 2

1 Garvellach Isles	Representative of Port Askaig Tillite. Some of the best examples of large- and small-scale sedimentary features in tillites formed from floating icebergs. Internationally important exposures of Neoproterozoic glacial deposit with major chronostratigraphical implications.
2 Caol Isla, Islay	Representative of lower part of Bonahaven Dolomite. Internationally important section showing transition from tillite into possible cap carbonate, with exceptional examples of tidal sedimentary structures.
3 Rubha a' Mhail, Islay	Representative of upper part of Bonahaven Dolomite, with exceptional examples of algal stromatolites and associated sedimentary structures.
4 Kilnaughton Bay, Islay	Representative of transition from shallow-water sands of Jura Quartzite into deeper water muds and gravity-flow deposits of Scarba Conglomerate. Pebbles are good strain indicators. Unusual occurrence of kyanite in greenschist-facies rocks.
5 Lussa Bay, Jura	Representative of Scarba Conglomerate with spectacular examples of sedimentary slump structures.
6 Kinuachdrach, Jura	Representative of Scarba Conglomerate with spectacular examples of sedimentary scour and slump structures and evidence of actual slump scar.
7 Surnaig Farm, Islay	Representative of Laphroaig Quartzite with spectacular examples of sandstone dykes.
8 Ardbeg, Islay	Representative of tightly folded and metamorphosed metadolerite sill. Notable for unusual presence of stilpnomelane.
9 Ardilistry Bay, Islay	Representative of greenschist-facies metadolerite sill. Notable for basal layer of metapyroxenite.
10 Black Mill Bay, Luing	Representative of Easdale Slate, including a debris-flow deposit. Exceptional examples of minor structures resulting from two deformational episodes.
11 Craignish Point	Representative of Craignish Phyllite containing spectacular pseudomorphs after gypsum and other sedimentary structures.
12 Fearnach Bay	Representative of Craignish Phyllite in a more-highly metamorphosed and deformed state than at Craignish Point. Splendid first-generation minor structures on NW limb of F1 Loch Awe Syncline.

13 Kilmory Bay	Representative of Ardrishaig Phyllite and base of Crinan Grit, with clear sedimentary structures indicating younging. Demonstrates relationship between major and minor fold structures in core of F1 Loch Awe Syncline.
14 Port Cill Maluaig	Representative of Ardrishaig Phyllite. Excellent examples of two phases of minor folds on SE limb of F1 Ardrishaig Anticline. F2 folds have strongly curved hinges.
15 Strone Point	Representative of Ardrishaig Phyllite. Minor structures of a single phase (D1) within the Strone Point Anticline illustrate the geometry of the major F1 Ardrishaig Anticline.
16 Kilchrenan Burn and Shore	Representative of a slump deposit transported from an unstable shelf into deeper water just prior to Tayvallich volcanism. Deformed pebbles are good indicators of strain during D1 deformation.
17 West Tayvallich Peninsula	Representative of Tayvallich Slate and Limestone and Tayvallich Volcanic formations, including controversial Loch na Cille Boulder Bed. Many sedimentary and volcanic features including excellent pillow lavas. Has provided only reliable radiometric dates from upper part of Dalradian, which are of great chronostratigraphical value.
18 South Bay, Barmore Island	Representative conformable section in Knapdale Steep Belt, from top of Crinan Subgroup through into Southern Highland Group, including Loch Tay Limestone and Green Beds.
19 Loch Avich	Type locality of Loch Avich Grit and Loch Avich Lavas formations. Youngest lavas in Dalradian succession.
20 Bun-an-Uillt, Islay	Representative of Bowmore Sandstone Group. Excellent, and only, exposure of Loch Skerrols Thrust.
21 Kilchiaran to Ardnave Point, Islay	Representative of lithologies and structures in lower part of Colonsay Group. Best exposure of Kilchiaran Shear-zone.

Central Grampian Highlands Network, Chapter 3

22 River Leven Section	Representative section from top of Grampian Group into Appin Group demonstrating continuity of both sedimentation and small-scale tectonic structures.
23 Nathrach	Representative of Binnein Schist and Binnein Quartzite. Minor structures yield important information on geometry of major folds from two phases of deformation.
24 Rubha Cladaich	Representative of Glen Coe Quartzite, Binnein Schist and Binnein Quartzite. Well-preserved sedimentary and tectonic structures on glaciated surfaces. Together with Nathrach, provides evidence for three generations of major folds.

25 Tom Meadhoin and Doire Ban	Clarifies succession from Binnein Quartzite to Ballachulish Slate. Exposes hinge of F1 Kinlochleven Anticline, re-orientated by major F2 folding, and Ballachulish Slide.
26 Stob Ban	Magnificent exposures of hinges of major F1 Ballachulish Syncline and F2 Stob Ban Synform.
27 St John's Church, Loch Leven	Representative section across the F1 Ballachulish Syncline, with rare exposure of Ballachulish Slide on lower limb.
28 Onich Dry River Gorge and **29 Onich Shore Section**	Together these sites provide a representative section through Ballachulish Slate, Appin Quartzite and Appin Phyllite and Limestone formations in F1 Appin Syncline. Sedimentary structures provide clear evidence of younging. Minor folds and cleavage indicate age, position and shape of the major fold.
30 Ardsheal Peninsula	Representative of formations from Appin Transition to Cuil Bay Slate in complete section across F1 Appin Syncline. Excellent examples of minor F1 folds and evidence of later deformation.
31 South Coast, Lismore Island	Type locality of Lismore Limestone Formation. Excellent D1 and D2 minor structures in core of F1 Appin Syncline.
32 Camas Nathais	Exceptional exposure of Benderloch Slide, representative of major ductile fault in Grampian Terrane that might have originated during sedimentation.
33 Port Selma, Ardmucknish	Representative of Selma Breccia. Exceptional example of sedimentary slump breccia. Contains rare Dalradian microfossils.
34 River Orchy	Representative section from top of Grampian Group into Appin Group demonstrating continuity of both sedimentation and tectonic history. Exceptional demonstrations of relationship of minor structures to major early fold.
35 A9 Road Cuttings and River Garry Gorge	Almost continuous section through Grampian Group of Strathtummel Basin. Excellent examples of sedimentary structures, major and minor F2 folds and significant late folds.
36 Creag nan Caisean – Meall Reamhar	Representative of Bruar and Tummel Quartzite formations. Excellent sedimentary younging evidence and interference structures in minor folds. Exhibits both limbs of F2 Meall Reamhar Synform.
37 Meall Dail Chealach	Representative of major late kink fold, the Trinafour Monoform. Refolded earlier structures including post-D2 Errochty Synform.
38 Strath Fionan	Representative section of condensed sequence from top of Grampian Group to top of Ballachulish Subgroup, demonstrating continuity of both sedimentation and tectonic history. Unusual preservation of sedimentary structures in highly strained rocks.
39 Tempar Burn	Representative of Schiehallion Boulder Bed. Internationally important exposure of

	Neoproterozoic glacial deposit with major chronostratigraphical implications.
40 Allt Druidhe	Representative section across Boundary Slide-zone, which here excises several hundred metres of succession. Unusual small-scale structures.
41 Slatich	Rare continuous exposures across hinge-zone of major F2 fold, the Ruskich Antiform. Unusual occurrence of small-scale F1 folds and all affected by later, F4 minor structures. Representative of Ben Lawers Schist, Farragon Volcanic and Ben Lui Schist formations.
42 Ben Lawers	Type locality of major, post-nappe, F4 Ben Lawers Synform with D1 and D2 minor structures. Representative of Ben Eagach Schist, Ben Lawers Schist, Ben Lui Schist and Loch Tay Limestone formations.
43 Craig an Chanaich to Frenich Burn	Principal exposures of a unique, metamorphosed and deformed body of stratiform baryte, barium silicate and sulphides that has been extracted commercially and is of international importance.
44 Auchtertyre	Exceptional example of stratabound sulphide mineralization in Ben Challum Quartzite Formation. Minor folds with curved hinges.
45 Ben Oss	Major splay of Tyndrum Fault, representative of major system of NE-trending sinstral faults. Exceptional examples of features associated with major faults.

Highland Border Region Network, Chapter 4

46 Ardscalpsie Point	Representative continuous section across top limb of F1 Tay Nappe. Exposes branch of Highland Boundary Fault. Representative of St Ninian Formation with excellent sedimentary structures.
47 Cove Bay to Kilcreggan	Only well-exposed coastal section across closure of F1 Tay Nappe, with evidence from clear minor structures. Reference section for Dunoon Phyllites. Representative of Bullrock Greywacke and Beinn Bheula Schists.
48 Portincaple	Hinge-zone of F4 Highland Border Downbend with minor structures from 4 major episodes of deformation. Representative of Beinn Bheula Schists.
49 Bealach nam Bo	Excellent varied examples of volcaniclastic 'green beds'. Representative of Loch Katrine Volcaniclastic and Creag Innich Sandstone formations. Exhibits simple D1 minor structures with some modification during D2.
50 Duke's Pass	Representative of Aberfoyle Slates and Ben Ledi Grits in core of Aberfoyle Anticline. Exhibits clear unmodified D1 minor structures in south, with D2 structures developing to north.
51 Keltie Water, Callander	Major historical and continuing national importance in debate over stratigraphical and structural continuity across boundary between

<table>
<tr><td></td><td colspan="2">Southern Highland Group and Highland Border Complex, once regarded as a possible terrane boundary. Representative of Ben Ledi Grit and Keltie Water Grit formations, the latter with definitive Early Cambrian fossils nearby.</td></tr>
<tr><td>52 Little Glen Shee</td><td rowspan="3">These three sites together display the geometry of the downbent hinge-zone of the flat-lying Tay Nappe, the largest, most significant major recumbent fold in the whole of Great Britain. Excellent examples of sedimentary structures, pressure-solution cleavage development, cleavage refraction, bedding/cleavage and cleavage/cleavage relationships.</td><td>Representative of lowest stratigraphical level and highest structural level in original F1 Tay Nappe. Hence lowest metamorphic grade, with well-preserved sedimentary structures. D1 minor structures in Highland Border Steep Belt, unmodified by later events. Historical area where downward-facing folds first demonstrated.</td></tr>
<tr><td>53 Craig a' Barns</td><td>Representative of higher stratigraphical level and lower structural level in original F1 Tay Nappe. Hence sedimentary characteristics and D1 structures considerably modified by D2 structures. Unique exposures of hinge of F4 Highland Border Downbend.</td></tr>
<tr><td>54 Rotmell</td><td>Representative of inverted Flat Belt of F1 Tay Nappe. Rocks at lowest structural level in original nappe, hence higher metamorphic grade (garnet-bearing) and strongly modified by D2 deformation. Evidence for emplacement of nappe by D2 translation to SE.</td></tr>
<tr><td>55 Glen Esk</td><td colspan="2">Internationally recognized type area for the 6 zones of Barrovian-type regional metamorphism in pelitic rocks. Index minerals all visible in hand specimen.</td></tr>
<tr><td>56 Garron Point to Muchalls</td><td colspan="2">Most north-easterly continuous section across downbent hinge-zone of F1 Tay Nappe. Excellent examples of structures from 3 deformational events (D1, D2 and D4). Historical locality where downward-facing folds first demonstrated.</td></tr>
</table>

Northern Grampian Highlands Network, Chapter 5

57 An Suidhe, Kincraig	Historical site where relationships between Grampian Group and pre-Dalradian basement first described. Now regarded as major orogenic unconformity. Representative of basement Glen Banchor Subgroup and carbonate-bearing Kincraig Formation at local base of Dalradian. Basement cut by major shear-zone with syntectonic pegmatitic veins, dated elesewhere.
58 The Slochd	Historical site where undeformed unconformity at

	base of Dalradian is now re-interpreted as sheared. Spectacular examples of migmatitic metasedimentary rocks in basement Dava Subgroup and syntectonic pegmatitic veins within Grampian Shear-zone. Isotopic evidence for 840 Ma zircon growth in basement rocks.
59 Lochan Uaine	Excellent example of a high-strain zone separating two distinct metasedimentary units, one gneissose and the other non-gneissose with good sedimentary structures. Representative of Ruthven Semipelite and Gairbeinn Pebbly Psammite formations, once thought to be Moine and Dalradian respectively but now both assigned to Grampian Group.
60 Blargie Craig	Representative of Laggan Inlier, including basement Glen Banchor Subgroup and cover of Grampian and Appin group. One of few places where basement–cover contact is exposed, here with most of Grampian Group omitted stratigraphically over a basement 'high'.
61 River E	Excellent preservation of wide range of fluvial and alluvial sedimentary structures in low-strain core of F2 antiform. Representative of lowest rocks in Dalradian succession (Glen Buck Pebbly Psammite).
62 Garva Bridge	Type area of Glenshirra Subgroup, including fluvial environments rarely seen in later Dalradian successions. Good evidence for basin geometry and depositional environment.
63 Rubha na Magach	Representative of Loch Laggan Psammite, dominant formation of Corrieyairack Subgroup. Low deformation preserves excellent Bouma sequences, deposited by turbidity currents near centre of basin.
64 Kinloch Laggan Road A86	Type locality for Kinlochlaggan Boulder Bed of Lochaber Subgroup. Ice-rafted dropstones are earliest recorded glacial influence in Dalradian succession.
65 Allt Mhainisteir	Representative complete section across Appin Group, Kinlochlaggan succession in Geal-charn–Ossian Steep Belt. Exposes Inverpattack Fault, major splay off regional NE-trending sinistral faults.
66 Aonach Beag and Geal-charn	Spans Geal-charn–Ossian Steep Belt, with excellent 3D exposures of tight upright folds, including Kinlochlaggan Syncline. Illustrates contrasting fold geometry between basin and footwall 'high'.
67 Ben Alder	Representative of F2 and F3 fold structures changing from steep to gently inclined SE of Geal-charn–Ossian Steep Belt, in Grampian Group strata on edge of Strath Tummel Basin.

North-east Grampian Highlands Network, Chapter 6

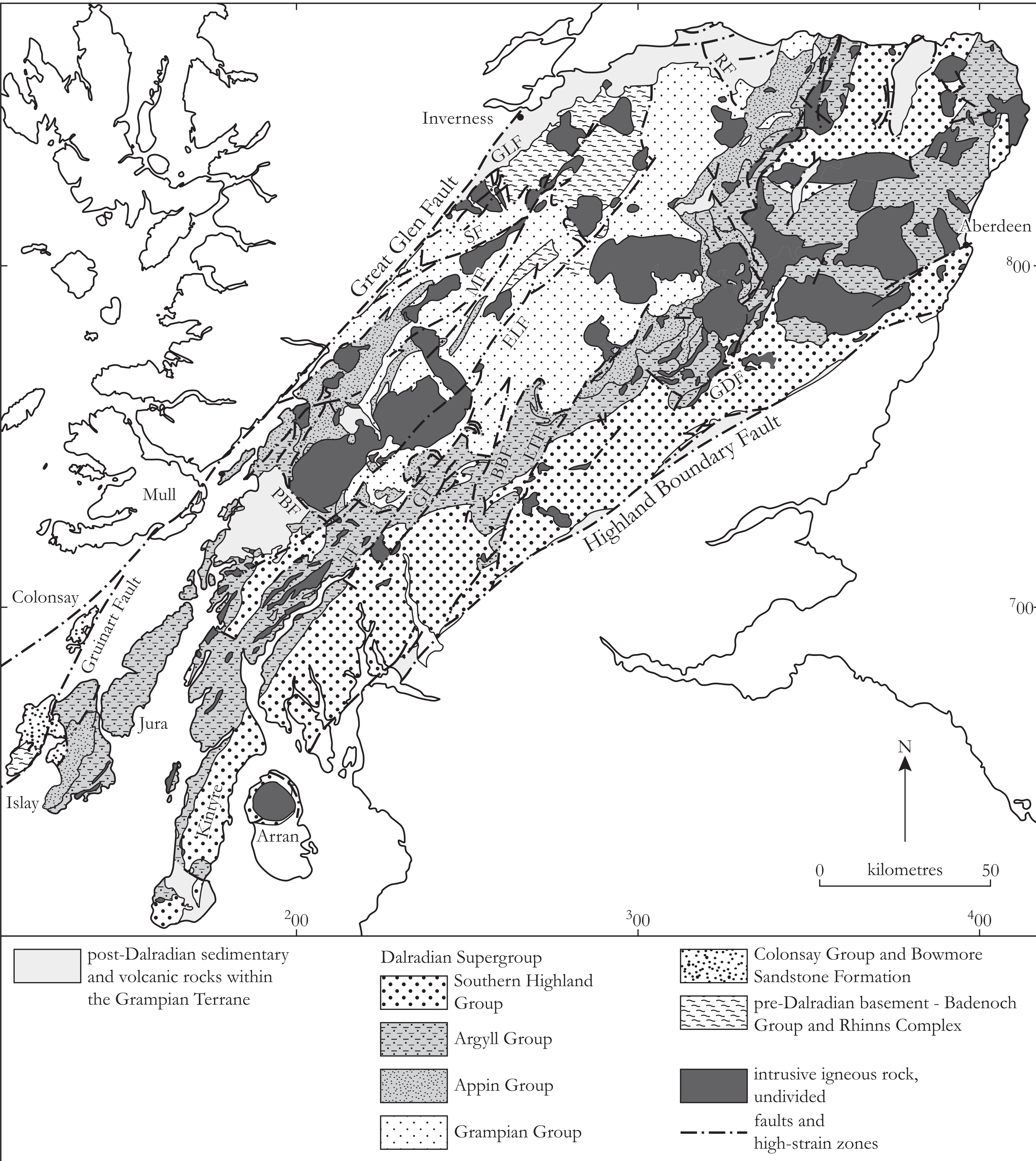
68 Ben Vuirich	Type example of *c.* 600 Ma Vuirich Granitic Suite with high-precision radiometric date. Nationally important for minimum age of Blair Atholl Subgroup. Internationally important for maximum age of Caledonian deformation in Grampian Highlands. Key exposures of xenoliths and hornfels preserve weak earlier fabric of uncertain origin.
69 Gilbert's Bridge, Glen Tilt	Historically important representative section across Boundary Slide, high-strain zone at junction between Grampian and Appin groups.
70 Glen Ey Gorge	Representative section across Boundary Slide, high-strain zone at junction between Grampian and Appin groups.
71 Cairn Leuchan	Represents most-extreme regional metamorphic conditions seen in Scottish Dalradian, recorded in both metasedimentary and basic meta-igneous rocks. Evidence for timing of sillimanite growth and two generations of migmatite.
72 Balnacraig, Dinnet	Displays many classical features of migmatization of metasedimentary rocks as result of partial melting, possibly enhanced by intrusion of basic magma. Features include granitic leucosomes, xenoliths of refractory material and large crystals of sillimanite.
73 Muckle Fergie Burn	Representative sequence of metadiamictites of glacial origin near base of Argyll Group. Succeeding pillow lavas are earliest basic igneous activity in Dalradian succession.
74 Bridge of Brown	Demonstrates transition from Grampian Group into Appin Group, with no tectonic dislocation (c.f. Boundary Slide elsewhere). Representative succession from topmost Glen Spean Subgroup to top of Lochaber Subgroup.
75 Bridge of Avon	Representative condensed succession from base of Ballachulish Subgroup to Blair Atholl Subgroup. Records typical shallow-marine transgression and regression.
76 Kymah Burn	Type section of Ladder Hills Formation and representative of Nochty Semipelite and Limestone and Kymah Quartzite formations that together comprise Islay Subgroup in this area. Thin basaltic lava and tuff units are present. Spectacular section through large-scale refolded fold.
77 Black Water	Representative section through Blackwater Formation, including thickest, most-extensive sequence of metavolcanic rocks in NE Grampian Highlands. Features metapicrites, pillow lavas and fragmental rocks in turbiditic environment.
78 Auchindoun Castle	Representative of Mortlach Graphitic Schist Formation, including basal Dufftown Limestone. Pelites contain exceptionally clear examples, with possible international value, of andalusite, pseudomorphed by kyanite due to later increase in pressure west of Portsoy

	Lineament.
79 Cullen to Troup Head	Longest continuous section across strike of Dalradian, from topmost Grampian Group to highest preserved Southern Highland Group. Complete transect from low to high structural level and high to low metamorphic grade, with a major dislocation and metamorphic hiatus at Portsoy Lineament. 600 Ma Portsoy Granite and boulder bed high in succession are age markers.
80 Fraserburgh to Rosehearty	Representative of Buchan Block, with its distinctive structural history, lacking major D1 nappe structures. International type section of regional low-pressure–high-temperature Buchan metamorphism. Exposes transition from partly calcareous Tayvallich Subgroup into Southern Highland Group.
81 Cairnbulg to St Combs	Representative of Inzie Head Gneiss Formation in core of Buchan Anticline. Spectacular range of low-pressure–high-temperature migmatites produced by partial melting, possibly associated with dioritic intrusions at peak of metamorphism.
82 Collieston to Whinnyfold	Representative of Collieston Formation, with well-preserved turbiditic sedimentary structures. Large-scale recumbent syncline might be north-eastern extension of Tay Nappe.

Shetland Network, Chapter 7

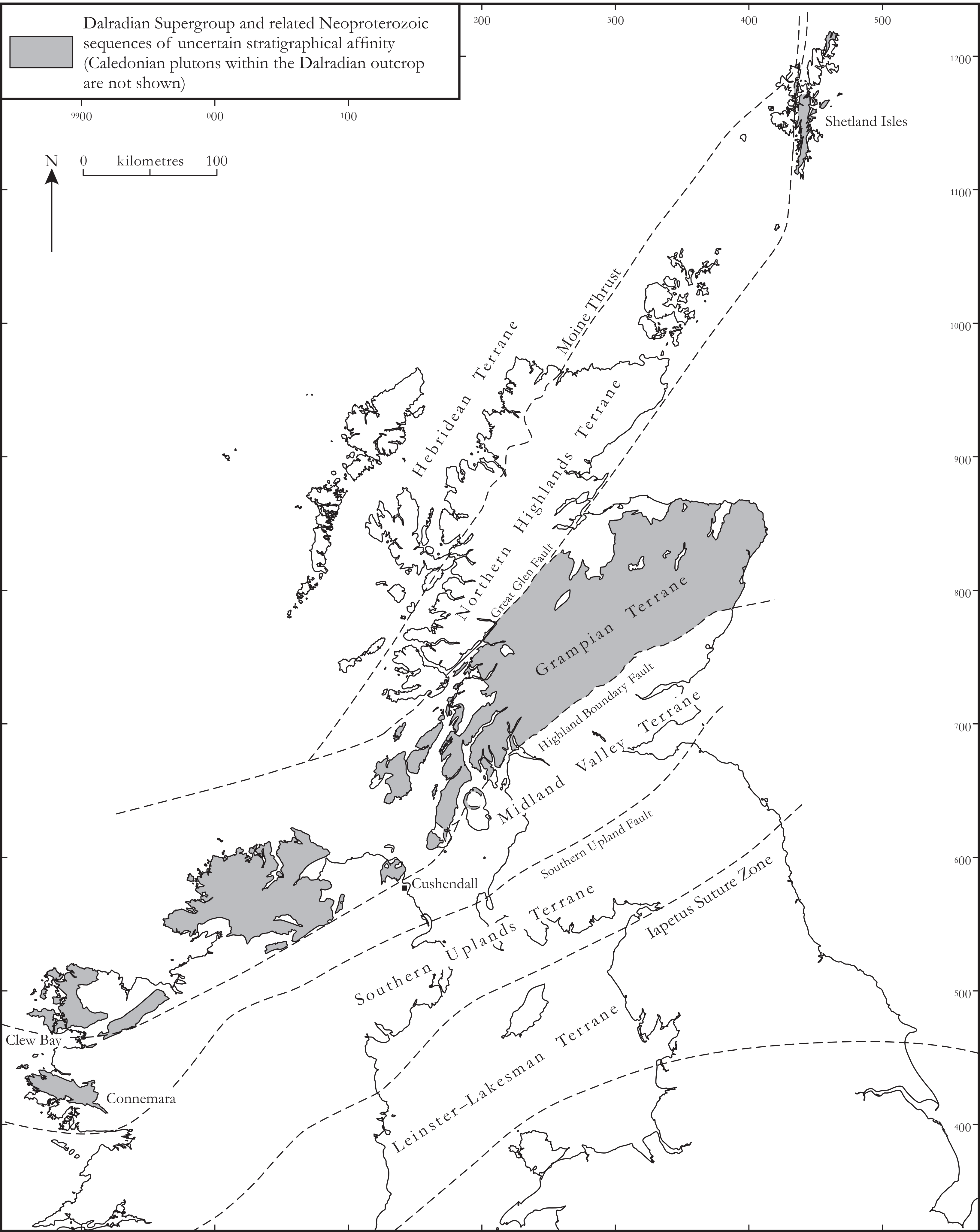
83 Scalloway	Representative of Colla Firth Permeation and Injection Belt, within Whiteness Group. Granite sheets and veins indicate minimum age of deformation and peak of metamorphism in Shetland Dalradian, which might be significantly earlier than in Scotland.
84 Hawks Ness	Representative section from top of Whiteness Group into lower part of Clift Hills Group, records deepening marine environment with volcanism. Exhibits short-wavelength isoclinal folding and mineral assemblages record two metamorphic events.
85 Cunningsburgh	Representative of Dunrossness Spilitic Formation, youngest Dalradian unit in Shetland. Submarine lavas and volcaniclastic rocks with minor deep-water sediments intruded by gabbro. Serpentinized and brecciated ultramafic rocks contain distinctive elongate pseudomorphs after olivine.

Figure 1.1



Inverness
GLF
Great Glen Fault
SF
MF
ELF
RF
Aberdeen
800
700
Mull
PBF
CF
BBF
LTF
GDF
Highland Boundary Fault
Colonsay
Gruinart Fault
Jura
Islay
Kintyre
Arran
N
0 kilometres 50
200
300
400
post-Dalradian sedimentary and volcanic rocks within the Grampian Terrane
Dalradian Supergroup
Southern Highland Group
Argyll Group
Appin Group
Grampian Group
Colonsay Group and Bowmore Sandstone Formation
pre-Dalradian basement - Badenoch Group and Rhinns Complex
intrusive igneous rock, undivided
faults and high-strain zones

Figure 1.2



Dalradian Supergroup and related Neoproterozoic sequences of uncertain stratigraphical affinity (Caledonian plutons within the Dalradian outcrop are not shown)
N
0 kilometres 100
Shetland Isles
Moine Thrust
Hebridean Terrane
Northern Highlands Terrane
Great Glen Fault
Grampian Terrane
Highland Boundary Fault
Midland Valley Terrane
Southern Upland Fault
Southern Uplands Terrane
Iapetus Suture Zone
Leinster–Lakesman Terrane
Cushendall
Clew Bay
Connemara

Figure 1.3

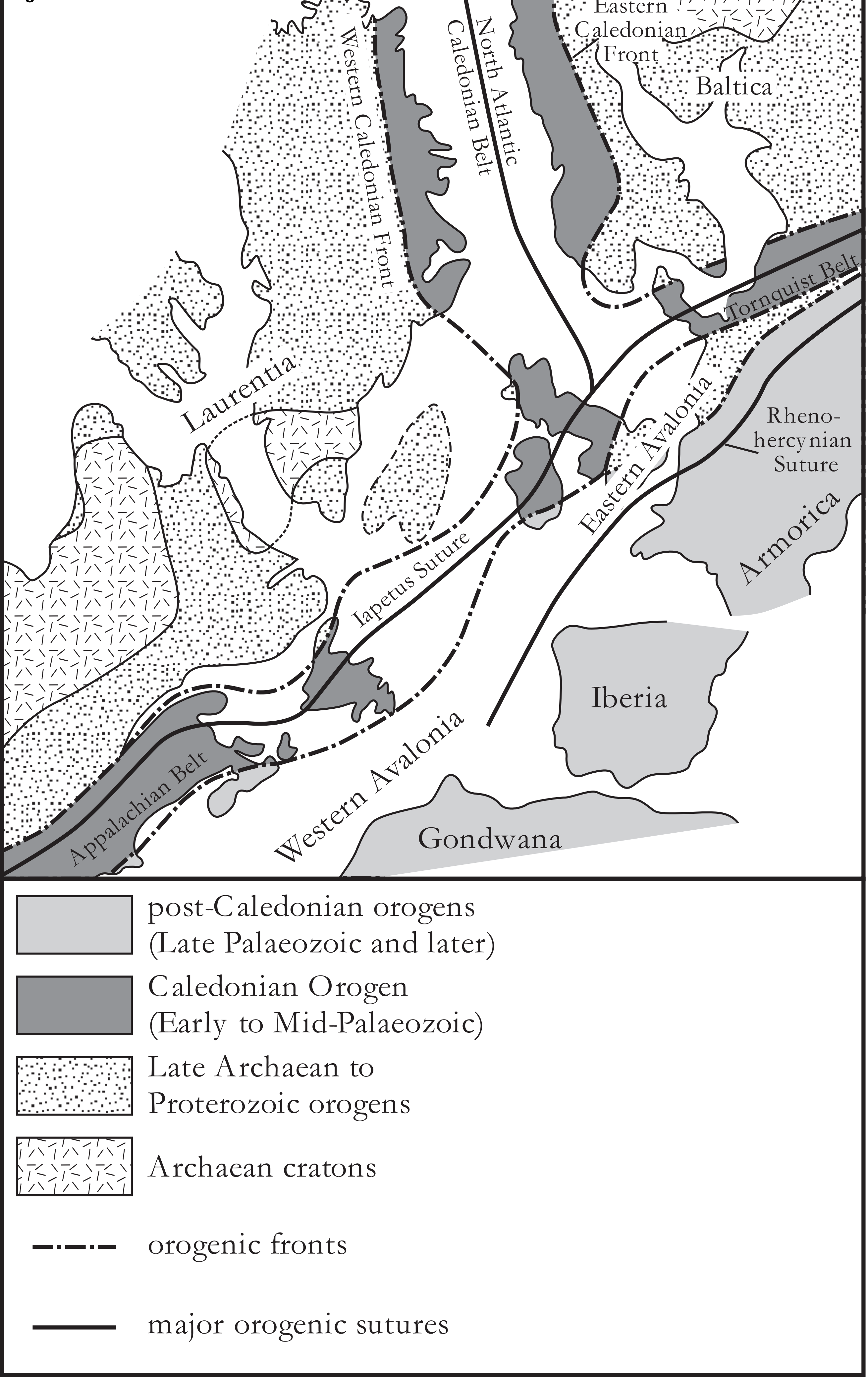
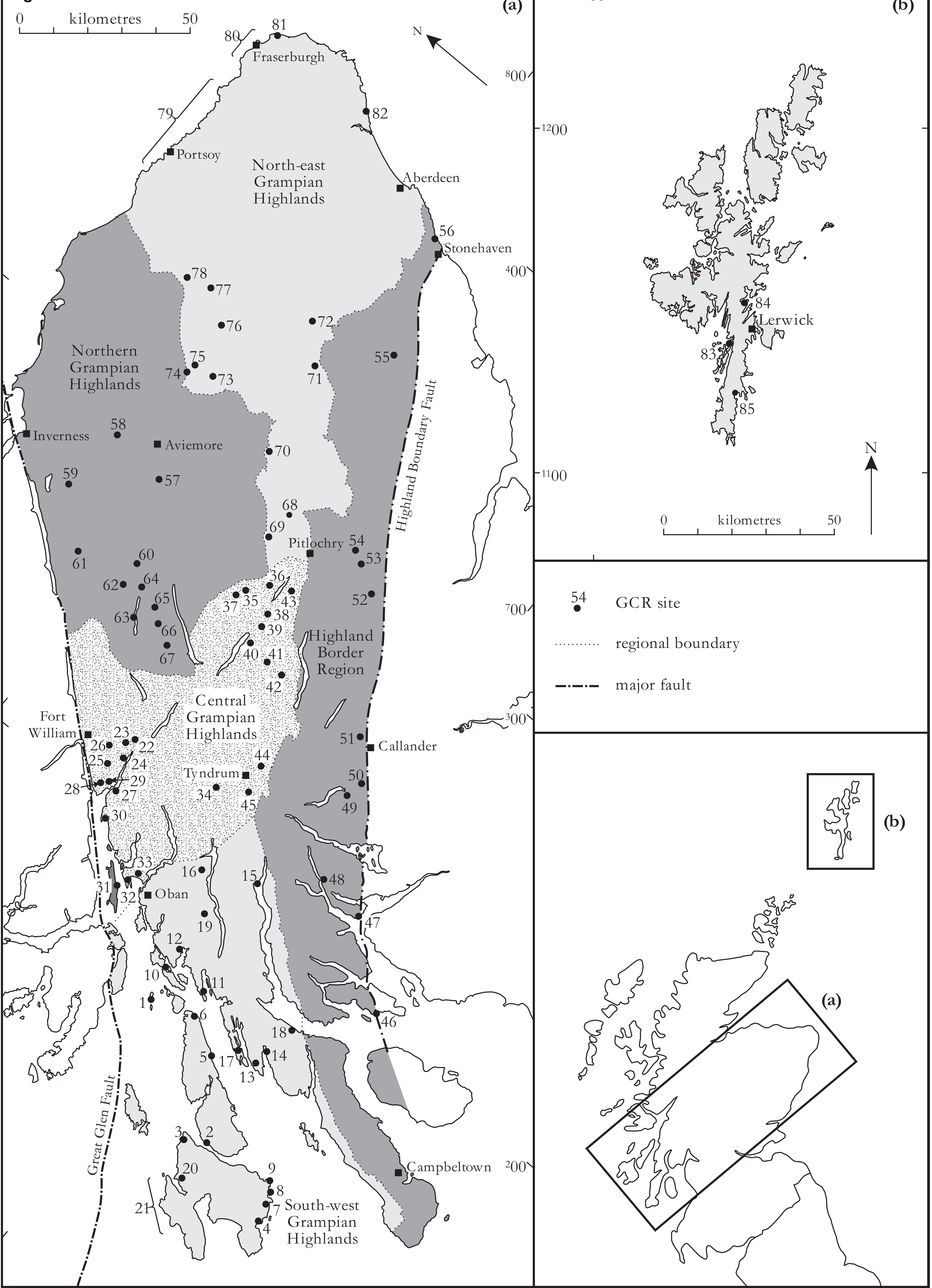

Eastern
Caledonian
Front
Baltica
Western Caledonian Front
North Atlantic
Caledonian Belt
Laurentia
Tornquist Belt
Eastern Avalonia
Rheno-
hercynian
Suture
Armorica
Iapetus Suture
Iberia
Appalachian Belt
Western Avalonia
Gondwana
post-Caledonian orogens
(Late Palaeozoic and later)
Caledonian Orogen
(Early to Mid-Palaeozoic)
Late Archaean to
Proterozoic orogens
Archaean cratons
orogenic fronts
major orogenic sutures

Figure 1.4

Click here to download high resolution image

Figure 1.5



(a)
(b)
kilometres
0
50
N
Fraserburgh
Portsoy
Aberdeen
Stonehaven
North-east Grampian Highlands
Northern Grampian Highlands
Inverness
Aviemore
Pitlochry
Highland Boundary Fault
Highland Border Region
Central Grampian Highlands
Fort William
Tyndrum
Callander
Oban
Great Glen Fault
Campbeltown
South-west Grampian Highlands
Lerwick
400
800
1200
1100
700
300
200
GCR site
regional boundary
major fault
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85

Figure 1.6

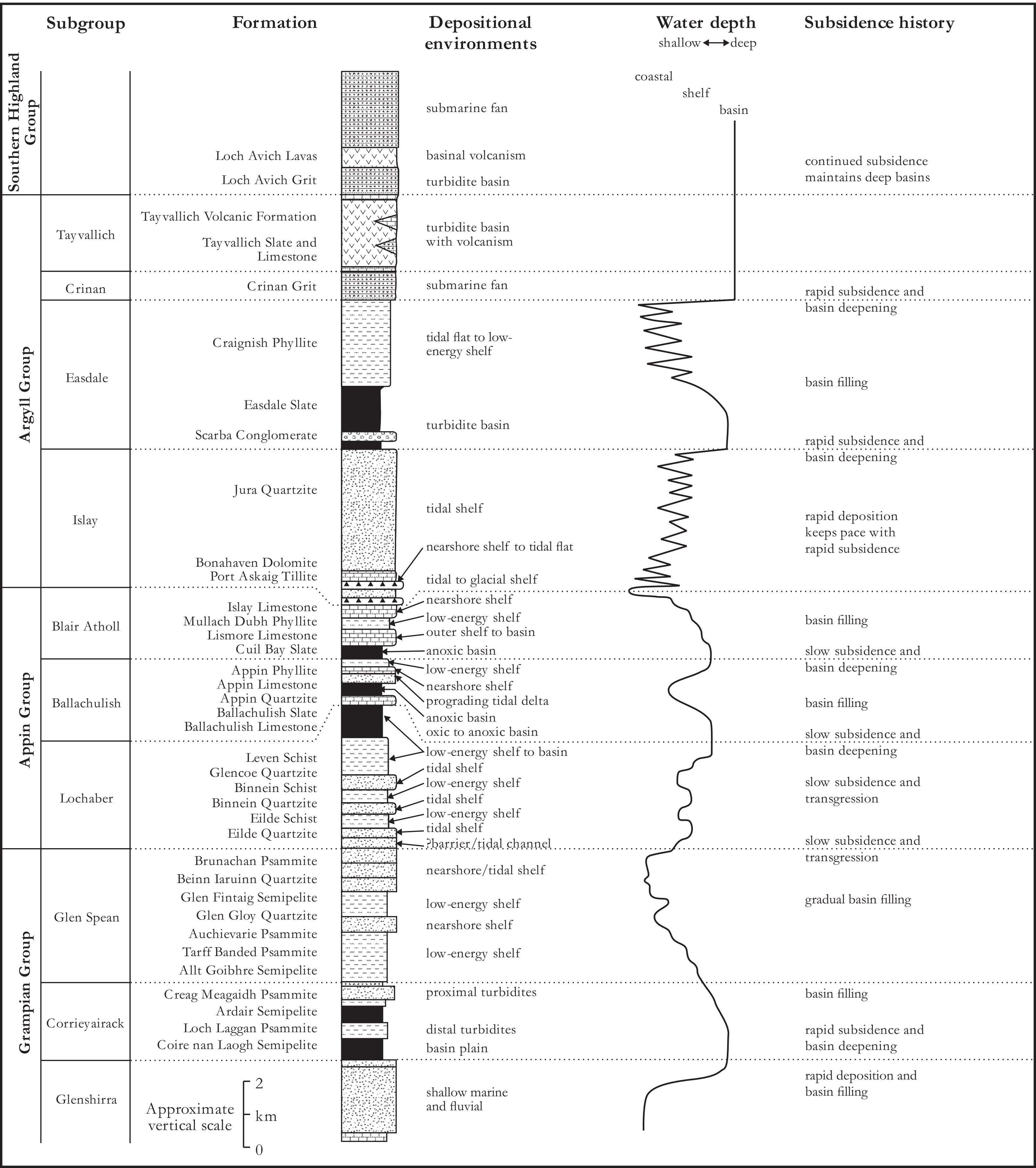
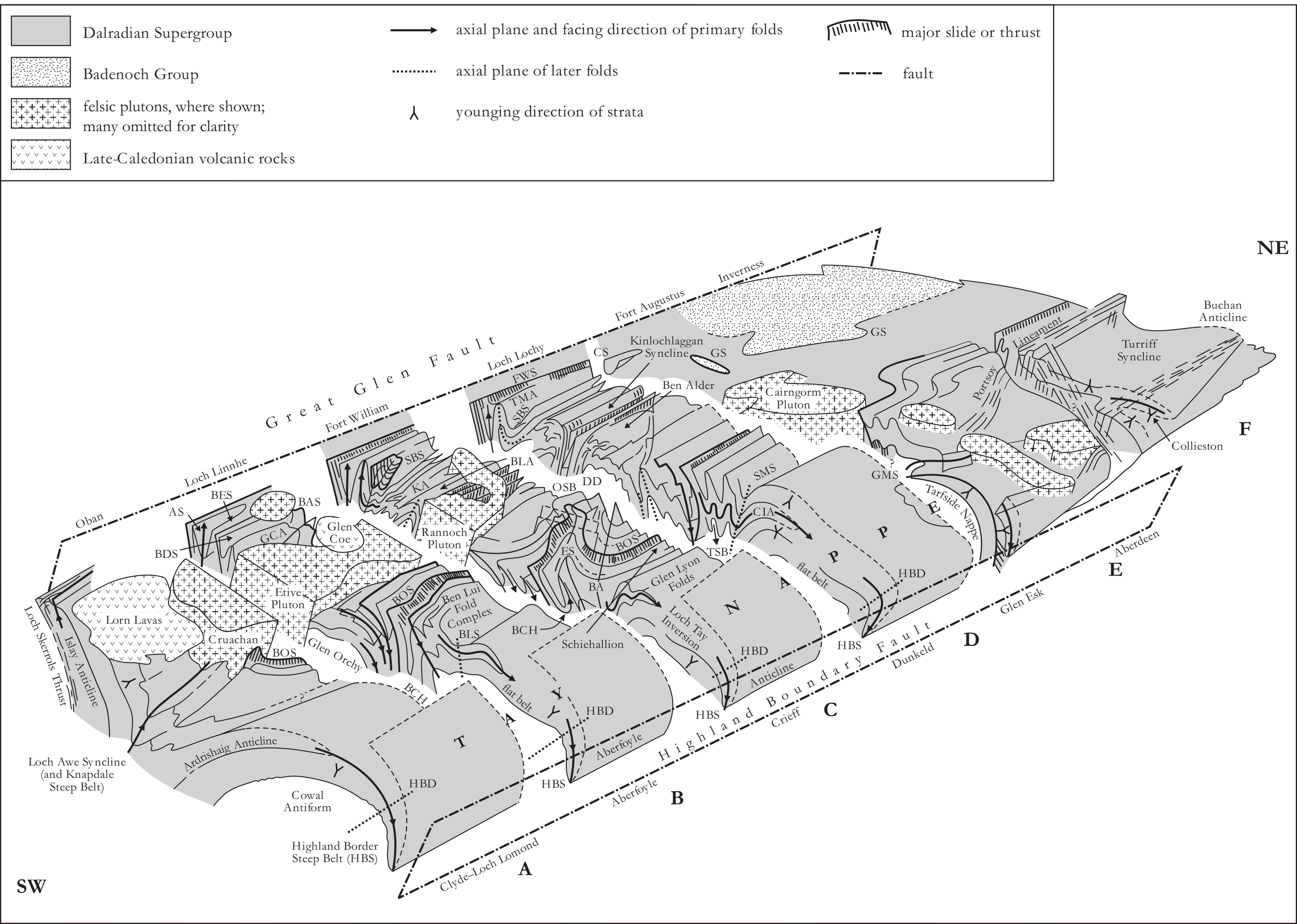
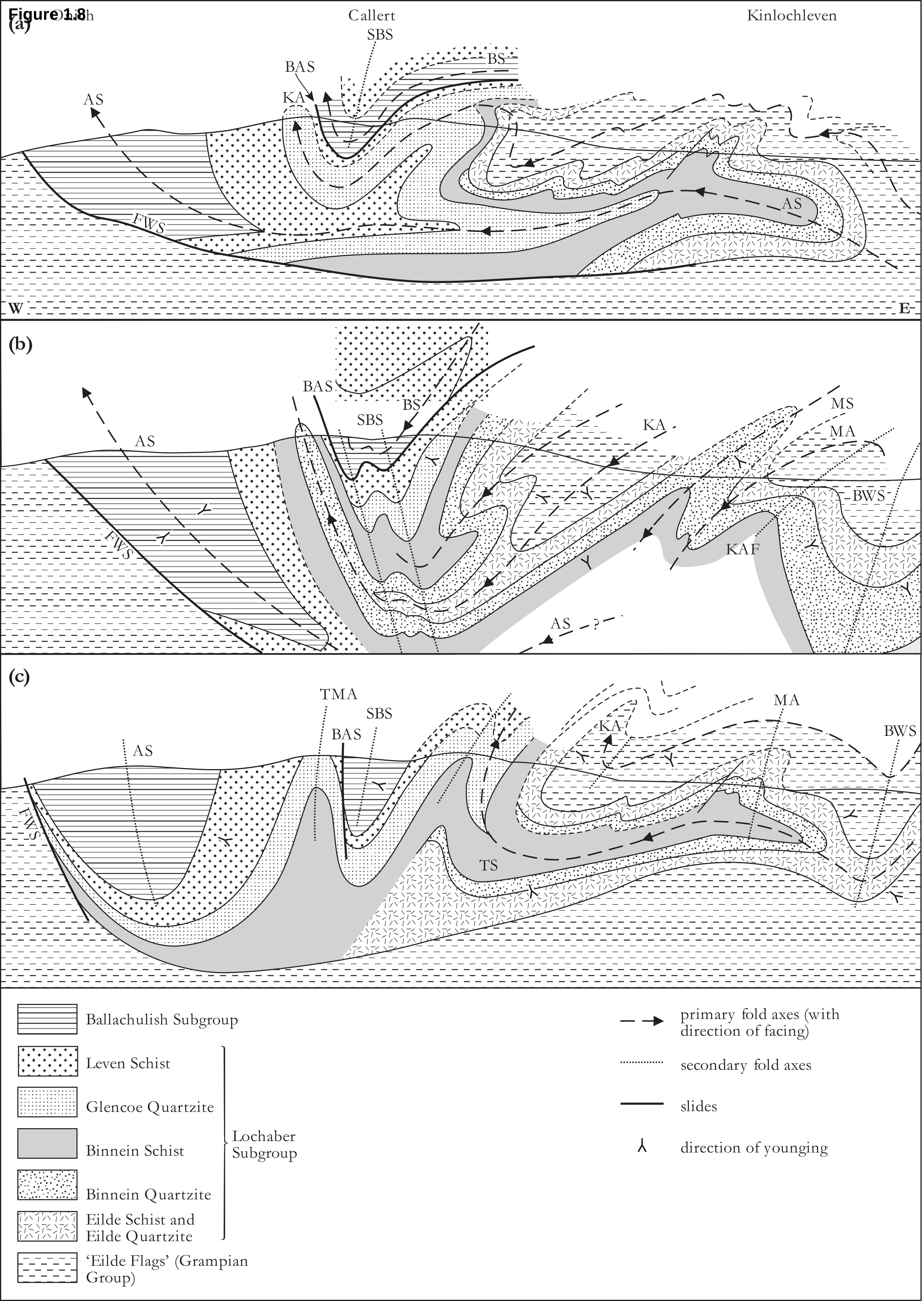

Subgroup
Formation
Depositional environments
Water depth
shallow ↔ deep
Subsidence history
Southern Highland Group
Loch Avich Lavas
Loch Avich Grit
submarine fan
basinal volcanism
turbidite basin
coastal
shelf
basin
continued subsidence maintains deep basins
Argyll Group
Tayvallich
Tayvallich Volcanic Formation
Tayvallich Slate and Limestone
turbidite basin with volcanism
Crinan
Crinan Grit
submarine fan
rapid subsidence and basin deepening
Easdale
Craignish Phyllite
Easdale Slate
Scarba Conglomerate
tidal flat to low-energy shelf
turbidite basin
basin filling
rapid subsidence and basin deepening
Islay
Jura Quartzite
Bonahaven Dolomite
Port Askaig Tillite
tidal shelf
nearshore shelf to tidal flat
tidal to glacial shelf
rapid deposition keeps pace with rapid subsidence
Appin Group
Blair Atholl
Islay Limestone
Mullach Dubh Phyllite
Lismore Limestone
Cuil Bay Slate
nearshore shelf
low-energy shelf
outer shelf to basin
anoxic basin
basin filling
slow subsidence and basin deepening
Ballachulish
Appin Phyllite
Appin Limestone
Appin Quartzite
Ballachulish Slate
Ballachulish Limestone
low-energy shelf
nearshore shelf
prograding tidal delta
anoxic basin
oxic to anoxic basin
basin filling
slow subsidence and basin deepening
Lochaber
Leven Schist
Glencoe Quartzite
Binnein Schist
Binnein Quartzite
Eilde Schist
Eilde Quartzite
low-energy shelf to basin
tidal shelf
low-energy shelf
tidal shelf
low-energy shelf
tidal shelf
?barrier/tidal channel
slow subsidence and transgression
slow subsidence and transgression
Grampian Group
Glen Spean
Brunachan Psammite
Beinn Iaruinn Quartzite
Glen Fintaig Semipelite
Glen Gloy Quartzite
Auchievarie Psammite
Tarff Banded Psammite
Allt Goibhre Semipelite
nearshore/tidal shelf
low-energy shelf
nearshore shelf
low-energy shelf
gradual basin filling
Corrieyairack
Creag Meagaidh Psammite
Ardair Semipelite
Loch Laggan Psammite
Coire nan Laogh Semipelite
proximal turbidites
distal turbidites
basin plain
basin filling
rapid subsidence and basin deepening
Glenshirra
shallow marine and fluvial
rapid deposition and basin filling
Approximate vertical scale
2
km
0

Figure 1.7



Dalradian Supergroup
Badenoch Group
felsic plutons, where shown; many omitted for clarity
Late-Caledonian volcanic rocks
axial plane and facing direction of primary folds
axial plane of later folds
younging direction of strata
major slide or thrust
fault
NE
SW
Great Glen Fault
Highland Boundary Fault
Inverness
Fort Augustus
Loch Lochy
Fort William
Loch Linnhe
Oban
Kinlochlaggan Syncline
GS
CS
FWS
TMA
SBS
Ben Alder
Cairngorm Pluton
Buchan Anticline
Turriff Syncline
Portsoy Lineament
Collieston
F
BLA
KA
OSB
DD
Rannoch Pluton
BES
BAS
AS
BDS
GCA
Glen Coe
Etive Pluton
Lorn Lavas
Cruachan
BOS
Glen Orchy
Ben Lui Fold Complex
BLS
BCH
ES
BA
Glen Lyon Folds
Loch Tay Inversion
Schiehallion
SMS
CIA
TSB
GMS
Tarfside Nappe
TAY NAPPE
flat belt
HBD
HBS
Anticline
Aberfoyle
Crieff
Dunkeld
Glen Esk
Aberdeen
A
B
C
D
E
Loch Skerrols Thrust
Islay Anticline
Loch Awe Syncline (and Knapdale Steep Belt)
Ardrishaig Anticline
Cowal Antiform
Highland Border Steep Belt (HBS)
Clyde–Loch Lomond

Figure 1.8



(a)
Onich
Callert
Kinlochleven
SBS
BS
BAS
KA
AS
FWS
AS
W
E
(b)
BAS
BS
SBS
AS
FWS
KA
MS
MA
BWS
KAF
AS
?
(c)
TMA
SBS
BAS
AS
FWS
KA
MA
BWS
TS
Ballachulish Subgroup
Leven Schist
Glencoe Quartzite
Binnein Schist
Binnein Quartzite
Eilde Schist and Eilde Quartzite
Lochaber Subgroup
'Eilde Flags' (Grampian Group)
primary fold axes (with direction of facing)
secondary fold axes
slides
direction of younging

Figure 1.9

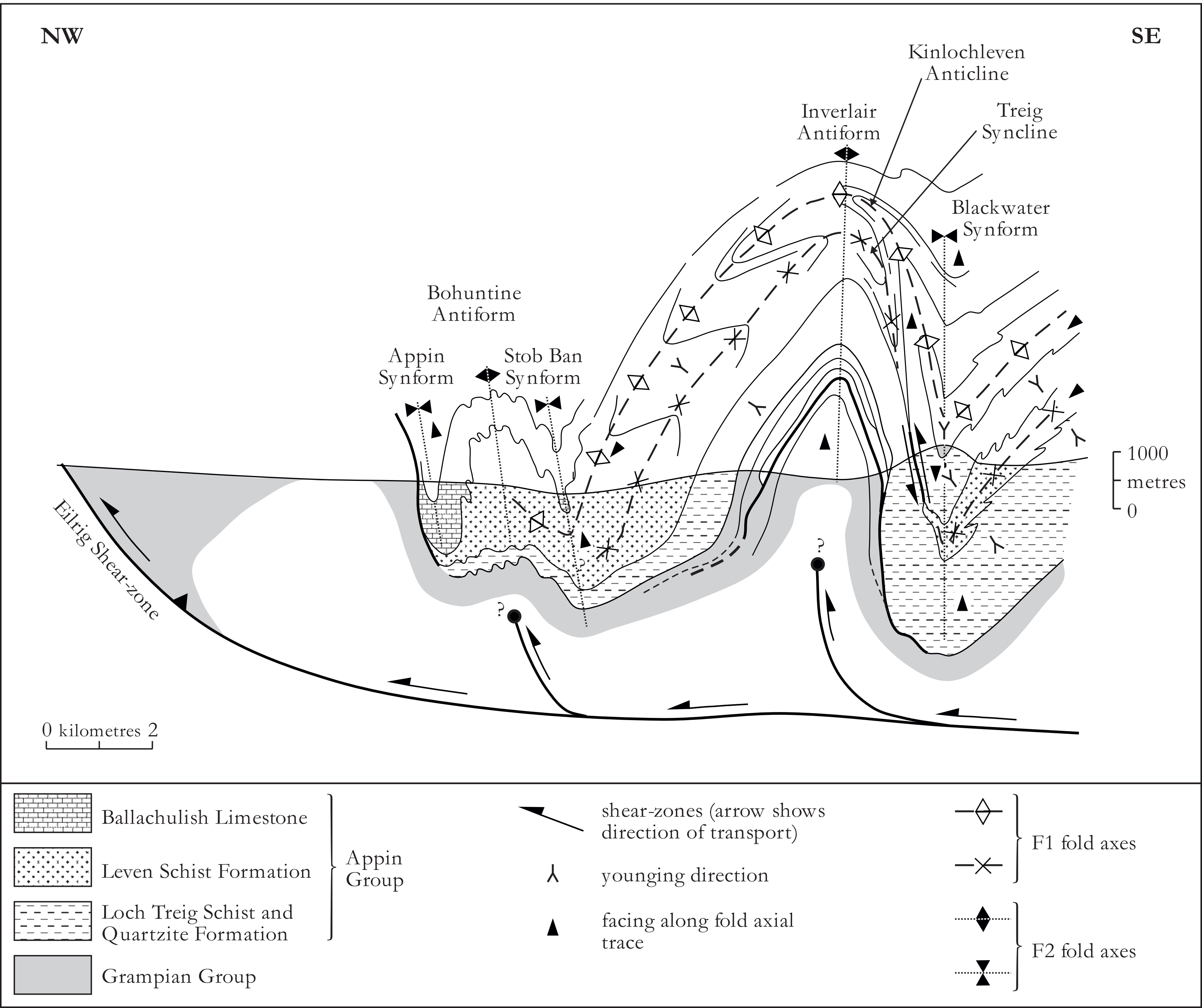
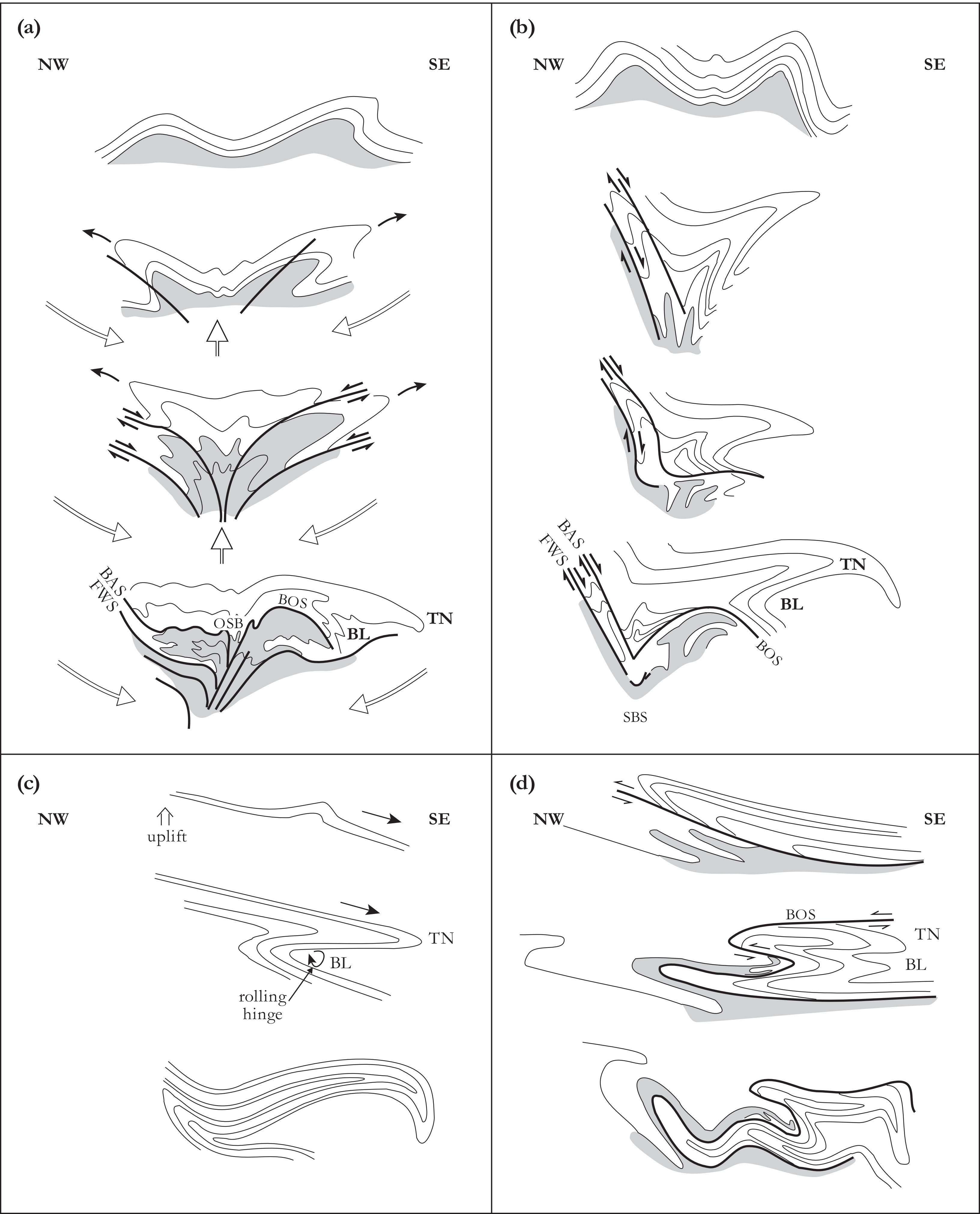

NW
SE
Kinlochleven Anticline
Inverlair Antiform
Treig Syncline
Blackwater Synform
Bohuntine Antiform
Appin Synform
Stob Ban Synform
Eilrig Shear-zone
1000 metres
0
0 kilometres 2
Ballachulish Limestone
Leven Schist Formation
Loch Treig Schist and Quartzite Formation
Appin Group
Grampian Group
shear-zones (arrow shows direction of transport)
younging direction
facing along fold axial trace
F1 fold axes
F2 fold axes

Figure 1.10



(a)
NW
SE
BAS
FWS
OSB
BOS
BL
TN
(b)
NW
SE
BAS
FWS
TN
BL
BOS
SBS
(c)
NW
SE
uplift
TN
BL
rolling
hinge
(d)
NW
SE
BOS
TN
BL

Figure 1.11

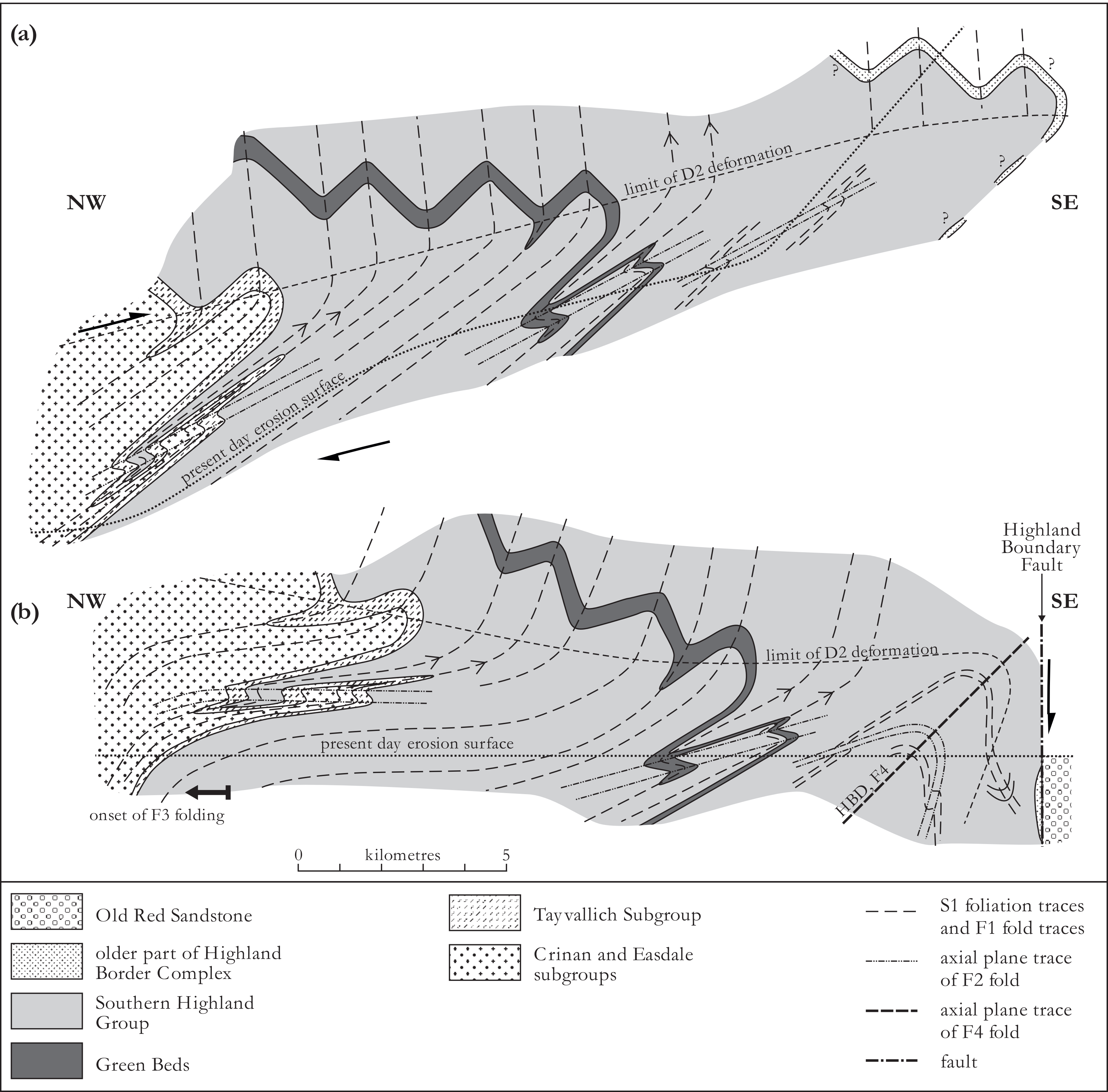

(a)
NW
SE
limit of D2 deformation
present day erosion surface
(b)
NW
SE
Highland Boundary Fault
limit of D2 deformation
present day erosion surface
HBD F4
onset of F3 folding
0
kilometres
5
Old Red Sandstone
older part of Highland Border Complex
Southern Highland Group
Green Beds
Tayvallich Subgroup
Crinan and Easdale subgroups
S1 foliation traces and F1 fold traces
axial plane trace of F2 fold
axial plane trace of F4 fold
fault

Figure 1.12

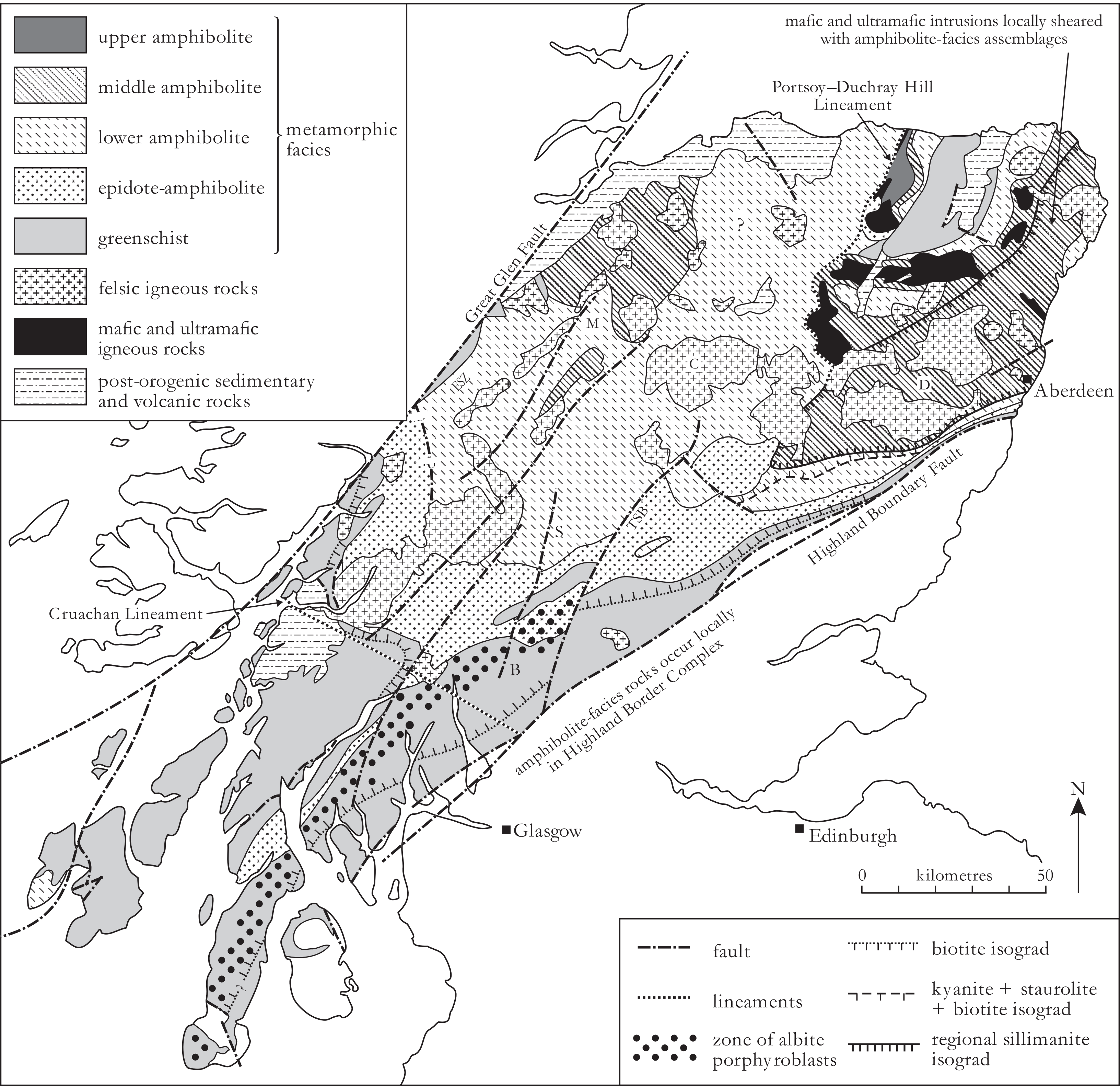

upper amphibolite
middle amphibolite
lower amphibolite
epidote-amphibolite
greenschist
metamorphic facies
felsic igneous rocks
mafic and ultramafic igneous rocks
post-orogenic sedimentary and volcanic rocks
mafic and ultramafic intrusions locally sheared with amphibolite-facies assemblages
Portsoy–Duchray Hill Lineament
Great Glen Fault
M
C
D
Aberdeen
S
TSB
B
Cruachan Lineament
Highland Boundary Fault
amphibolite-facies rocks occur locally in Highland Border Complex
Glasgow
Edinburgh
N
0
kilometres
50
fault
lineaments
zone of albite porphyroblasts
biotite isograd
kyanite + staurolite + biotite isograd
regional sillimanite isograd

Figure 1.13

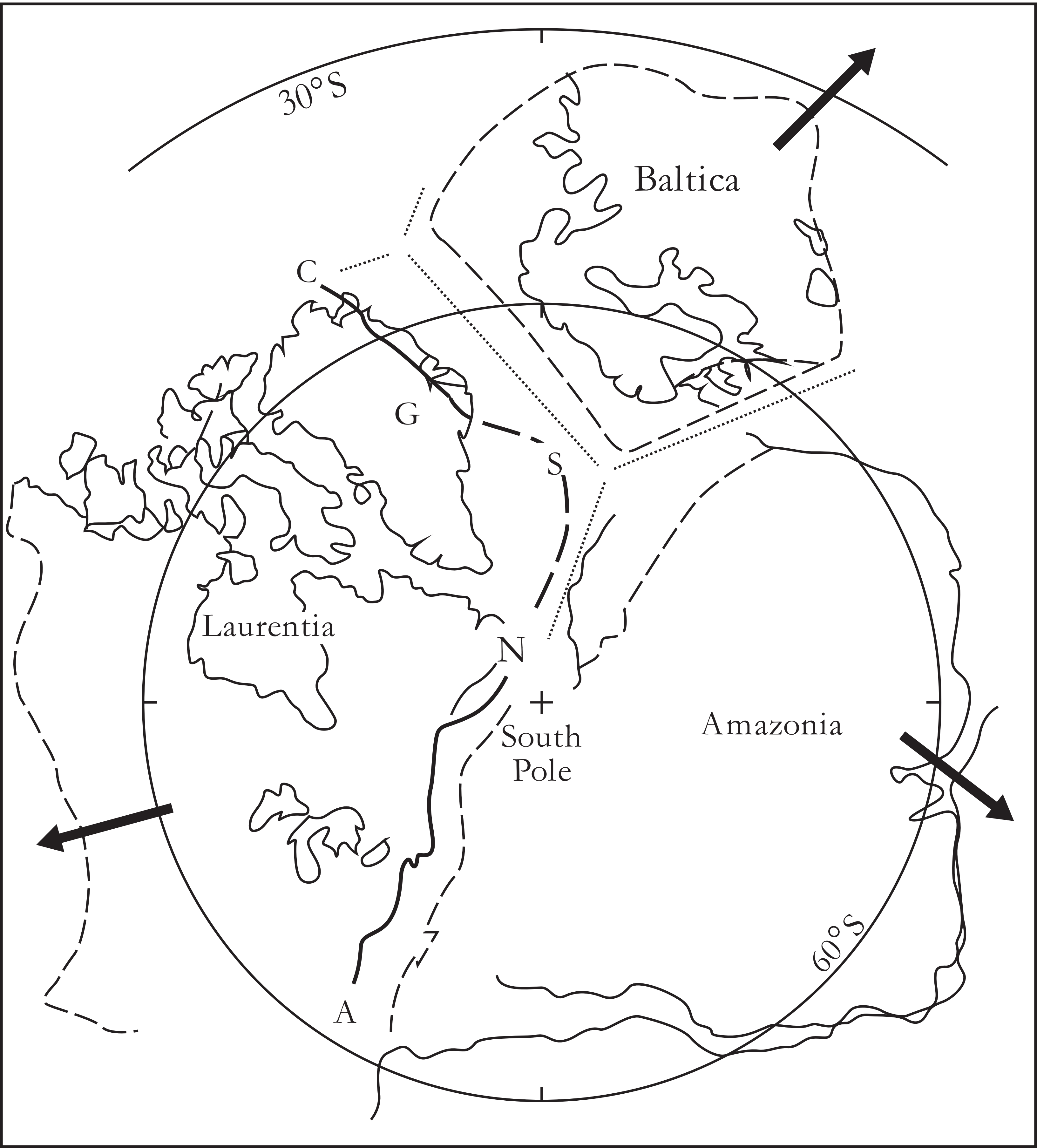


Figure 1.14

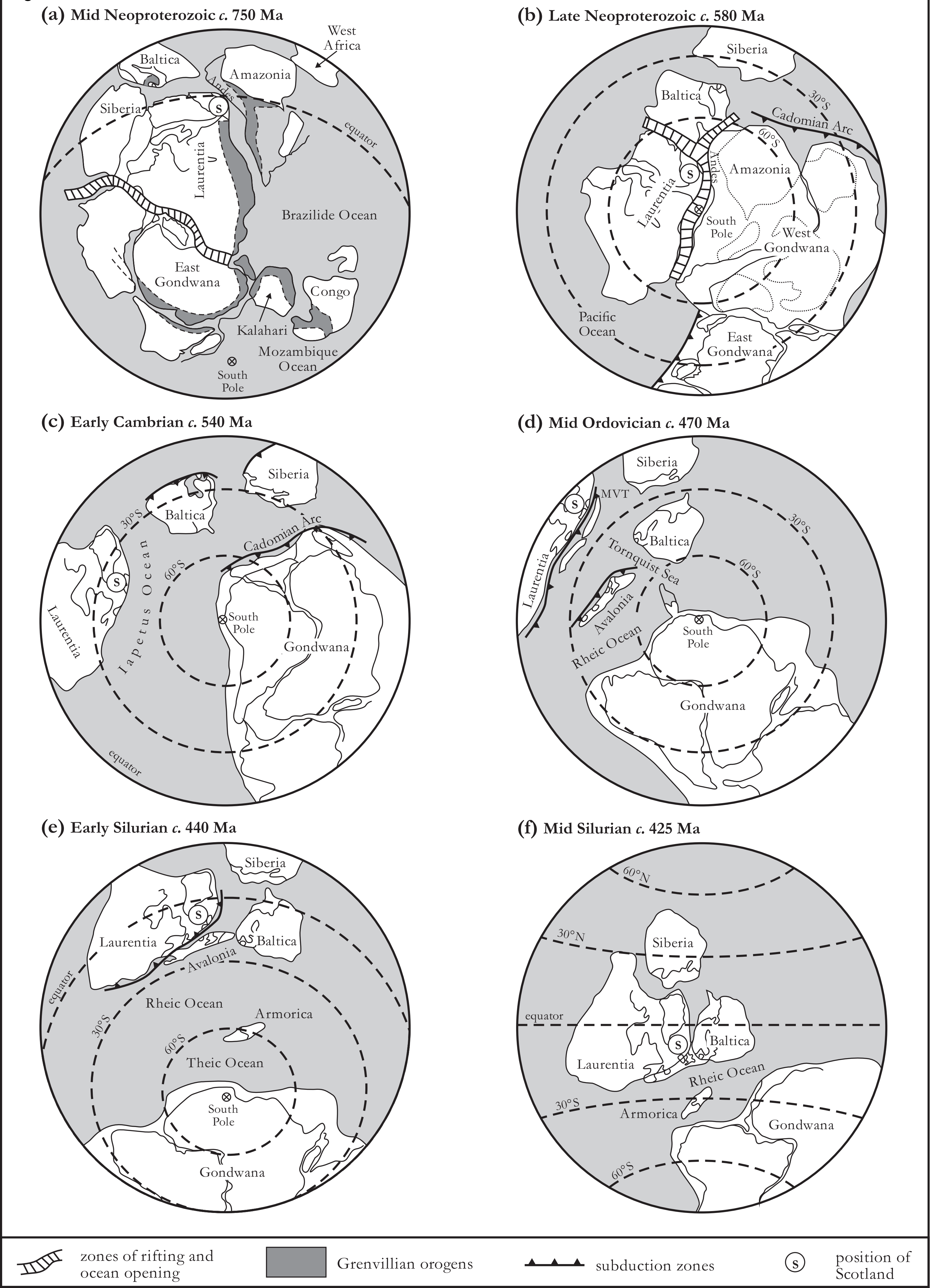

(a) Mid Neoproterozoic c. 750 Ma
West Africa
Baltica
Amazonia
Andes
Siberia
S
equator
Laurentia
Brazilide Ocean
East Gondwana
Congo
Kalahari
Mozambique Ocean
South Pole
(b) Late Neoproterozoic c. 580 Ma
Siberia
Baltica
30°S
Cadomian Arc
60°S
Andes
S
Amazonia
Laurentia
South Pole
West Gondwana
Pacific Ocean
East Gondwana
(c) Early Cambrian c. 540 Ma
Siberia
Baltica
30°S
Cadomian Arc
60°S
S
Iapetus Ocean
Laurentia
South Pole
Gondwana
equator
(d) Mid Ordovician c. 470 Ma
Siberia
S
MVT
30°S
Baltica
Tornquist Sea
60°S
Laurentia
Avalonia
Rheic Ocean
South Pole
Gondwana
(e) Early Silurian c. 440 Ma
Siberia
S
Laurentia
Baltica
Avalonia
equator
Rheic Ocean
Armorica
30°S
60°S
Theic Ocean
South Pole
Gondwana
(f) Mid Silurian c. 425 Ma
60°N
30°N
Siberia
equator
S
Baltica
Laurentia
Rheic Ocean
30°S
Armorica
Gondwana
60°S
zones of rifting and ocean opening
Grenvillian orogens
subduction zones
S
position of Scotland

Figure 1.15

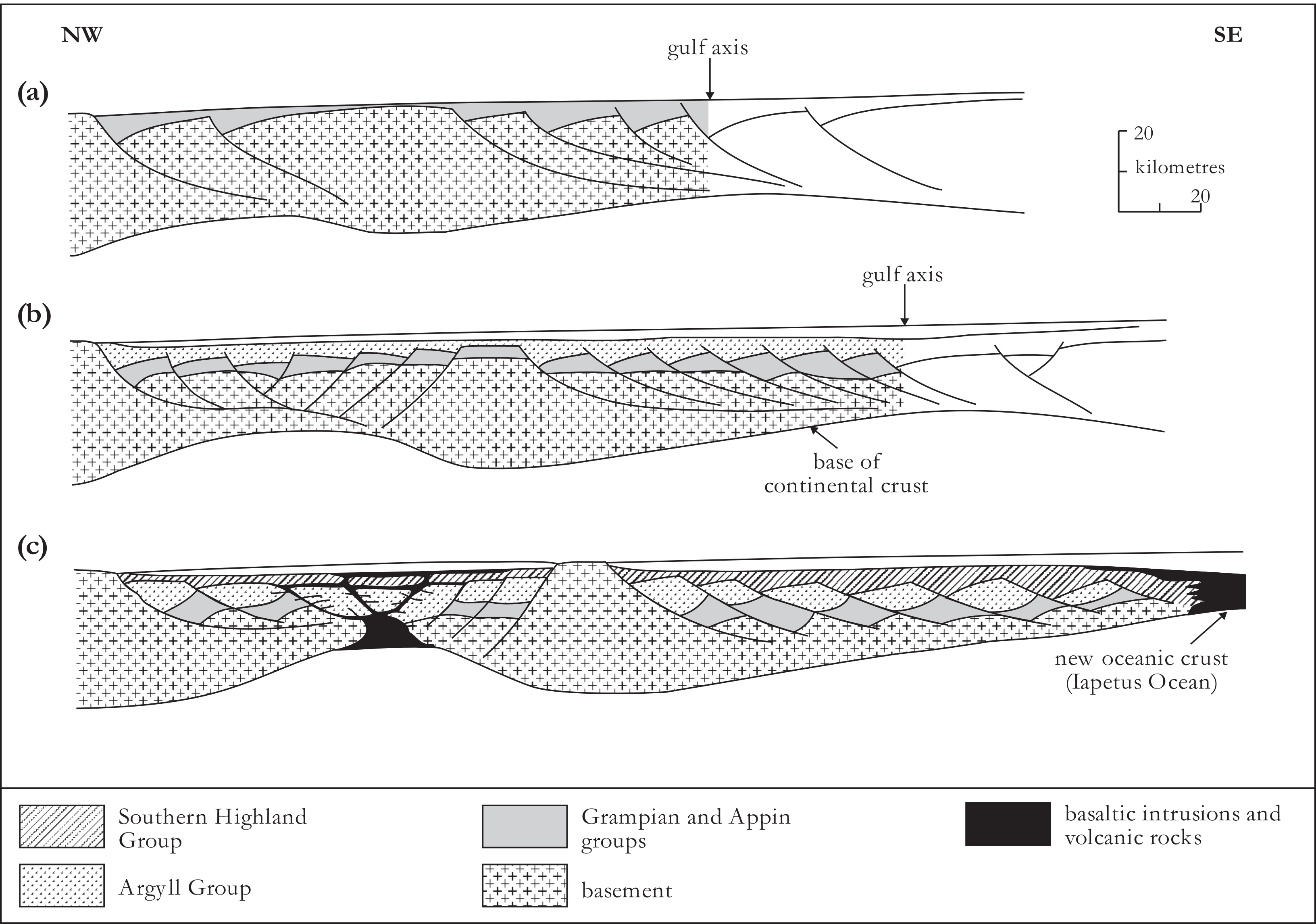
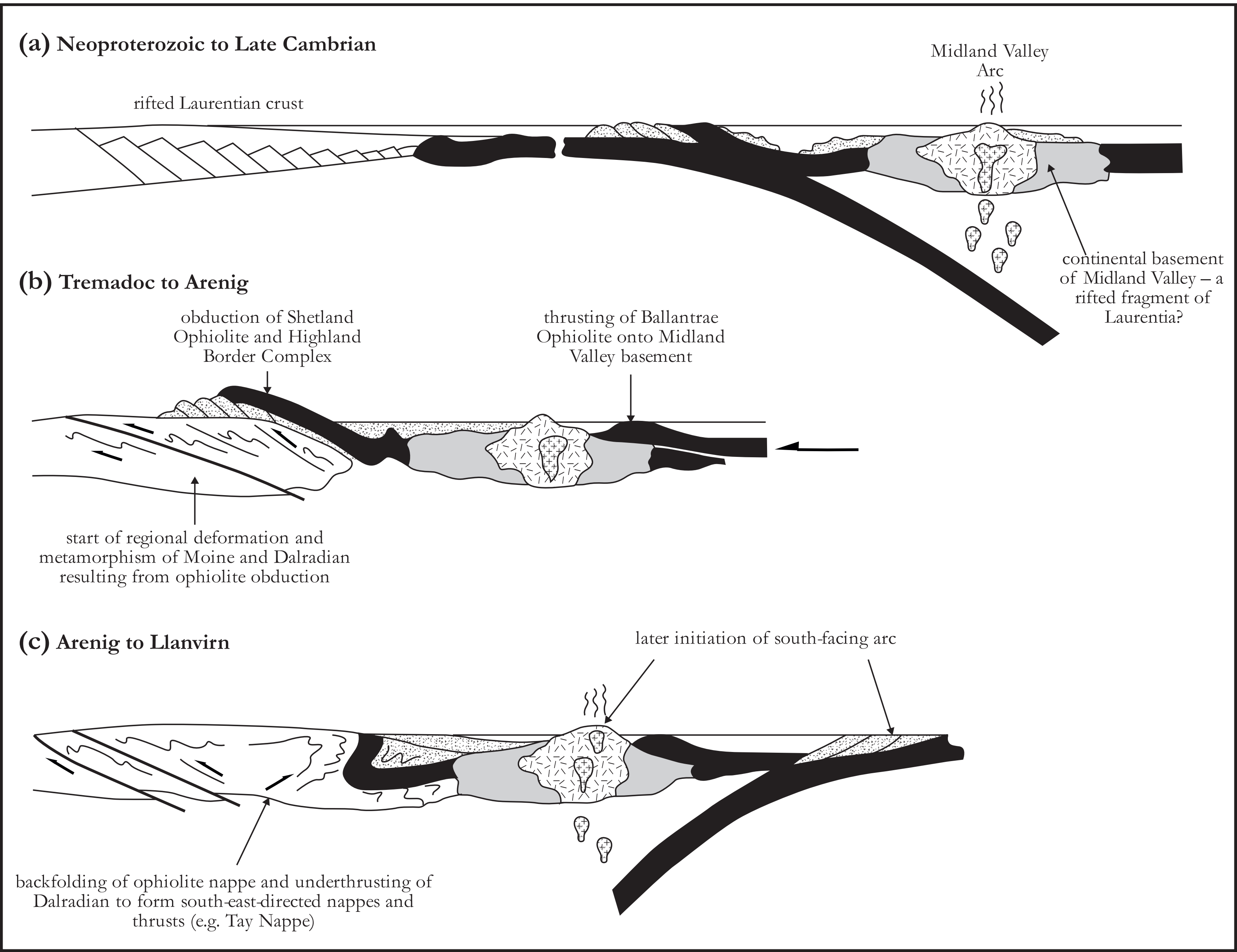
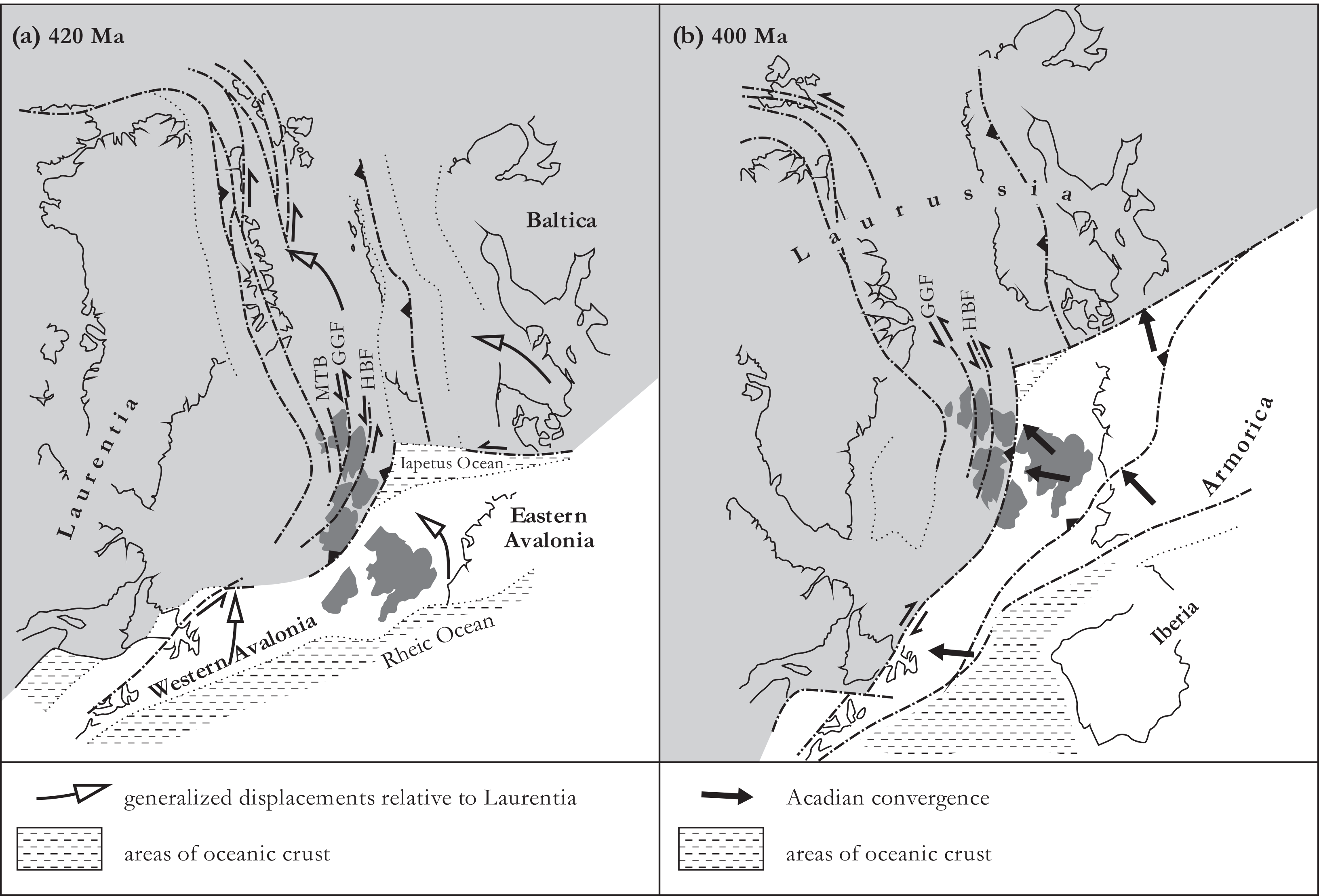

NW
SE
(a)
gulf axis
20
kilometres
20
(b)
gulf axis
base of
continental crust
(c)
new oceanic crust
(Iapetus Ocean)
Southern Highland Group
Grampian and Appin groups
basaltic intrusions and volcanic rocks
Argyll Group
basement

Figure 1.16



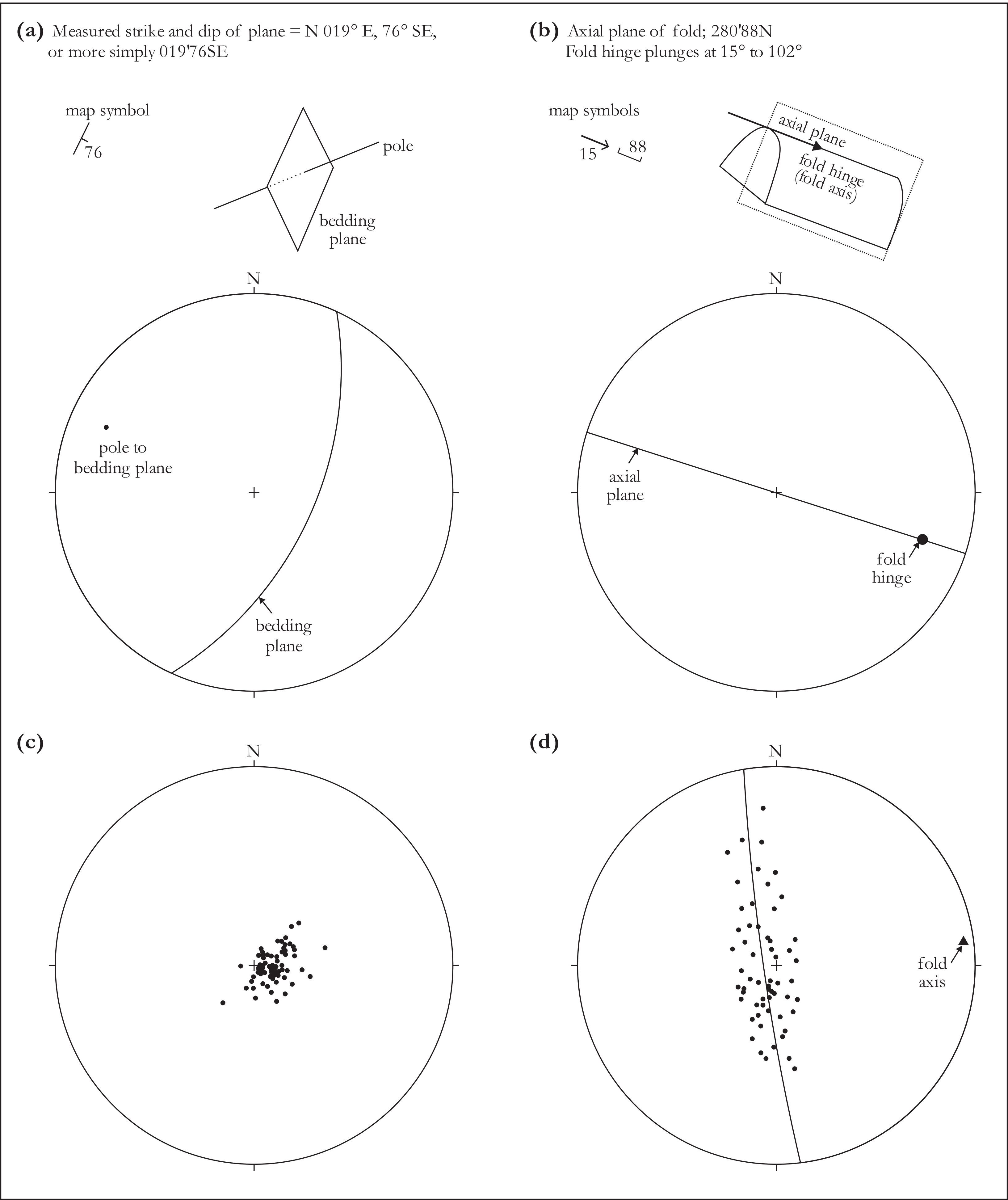
(a) Neoproterozoic to Late Cambrian
Midland Valley Arc
rifted Laurentian crust
continental basement of Midland Valley – a rifted fragment of Laurentia?
(b) Tremadoc to Arenig
obduction of Shetland Ophiolite and Highland Border Complex
thrusting of Ballantrae Ophiolite onto Midland Valley basement
start of regional deformation and metamorphism of Moine and Dalradian resulting from ophiolite obduction
(c) Arenig to Llanvirn
later initiation of south-facing arc
backfolding of ophiolite nappe and underthrusting of Dalradian to form south-east-directed nappes and thrusts (e.g. Tay Nappe)

Figure 1.17



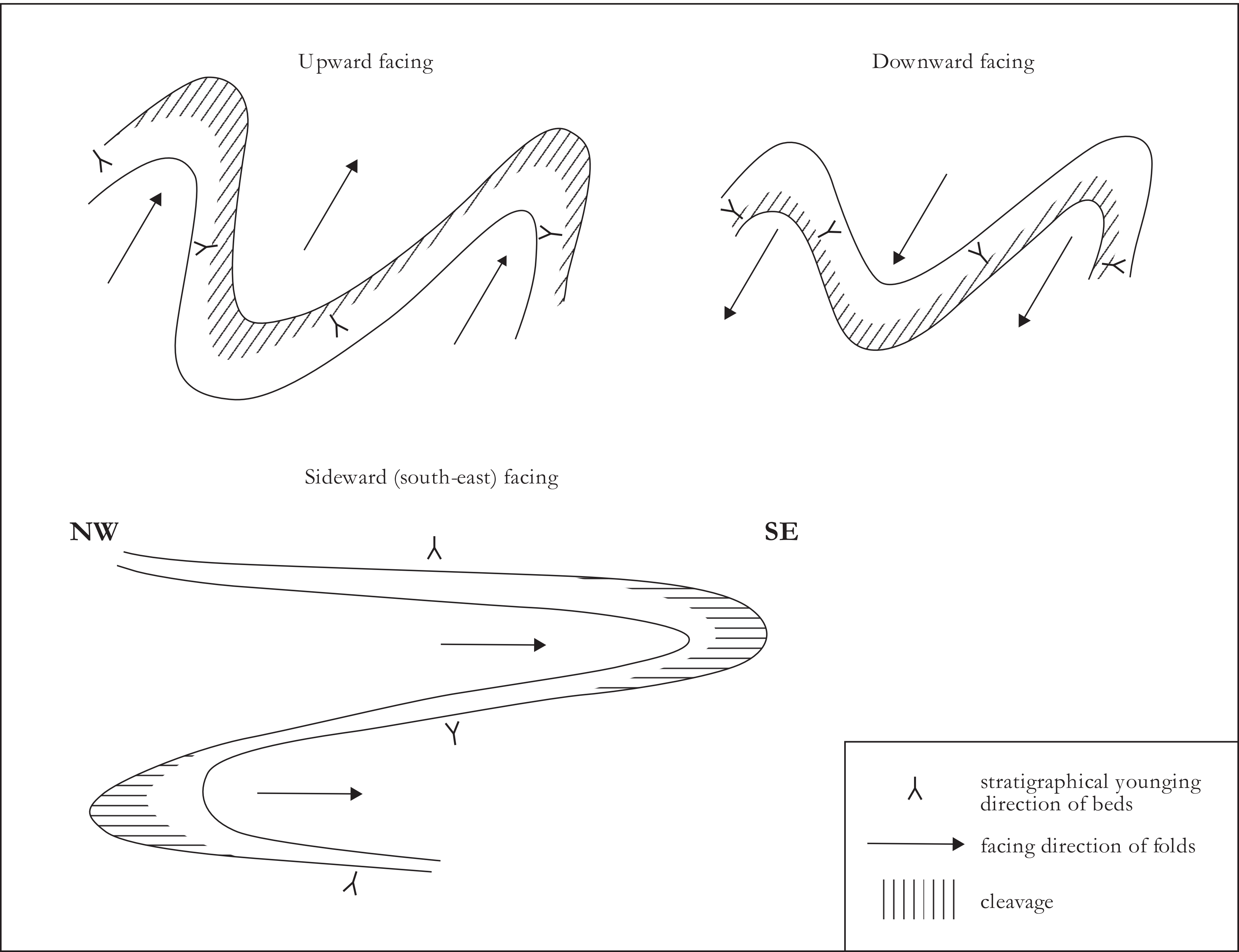
(a) 420 Ma
Laurentia
Baltica
MTB
GGF
HBF
Iapetus Ocean
Eastern Avalonia
Western Avalonia
Rheic Ocean
(b) 400 Ma
L a u r u s s i a
GGF
HBF
Armorica
Iberia
generalized displacements relative to Laurentia
areas of oceanic crust
Acadian convergence
areas of oceanic crust

Figure G.1



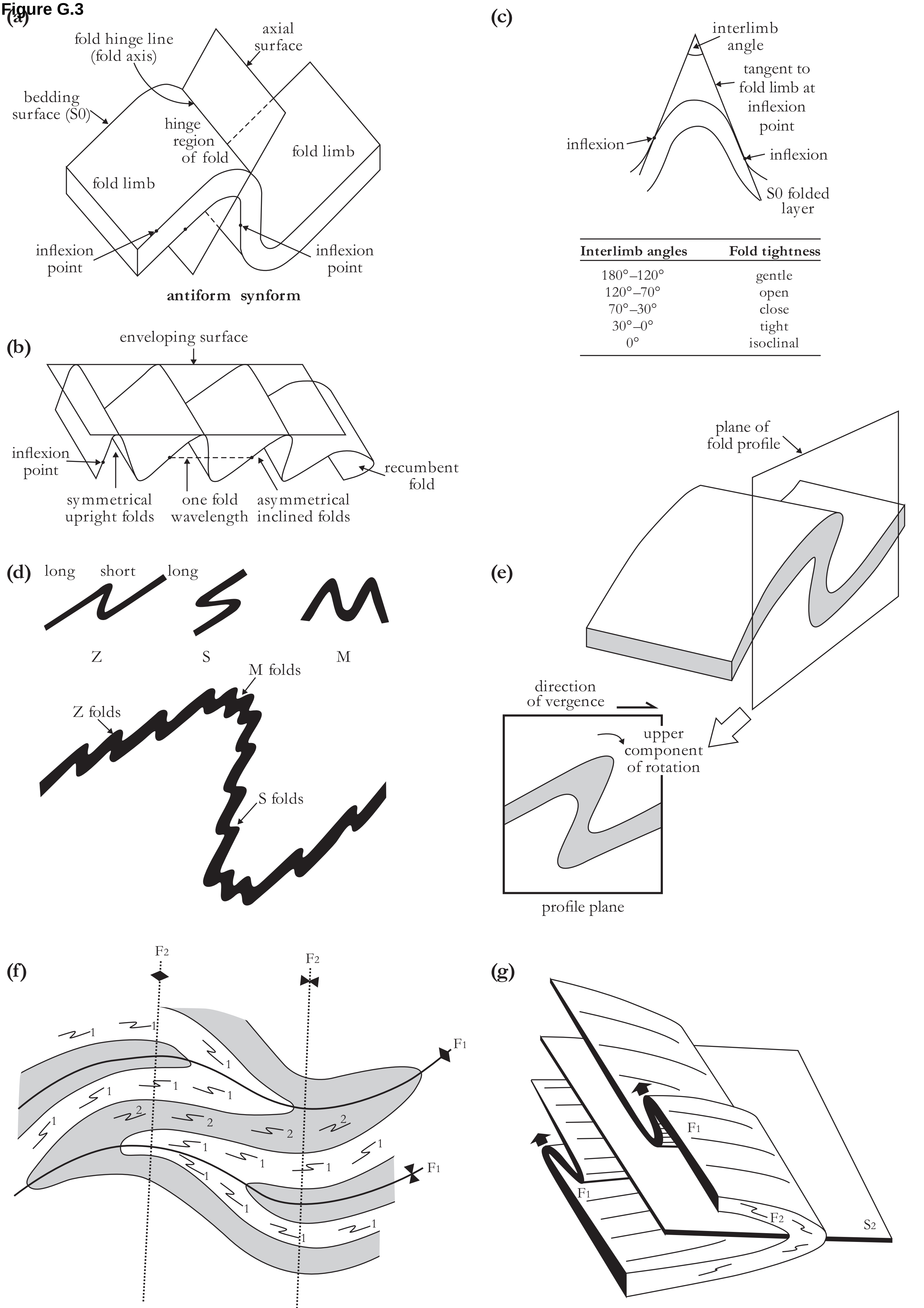
(a) Measured strike and dip of plane = N 019° E, 76° SE,
or more simply 019'76SE
map symbol
76
pole
bedding plane
N
pole to bedding plane
bedding plane
(b) Axial plane of fold; 280'88N
Fold hinge plunges at 15° to 102°
map symbols
15
88
axial plane
fold hinge (fold axis)
N
axial plane
fold hinge
(c)
N
(d)
N
fold axis

Figure G.2



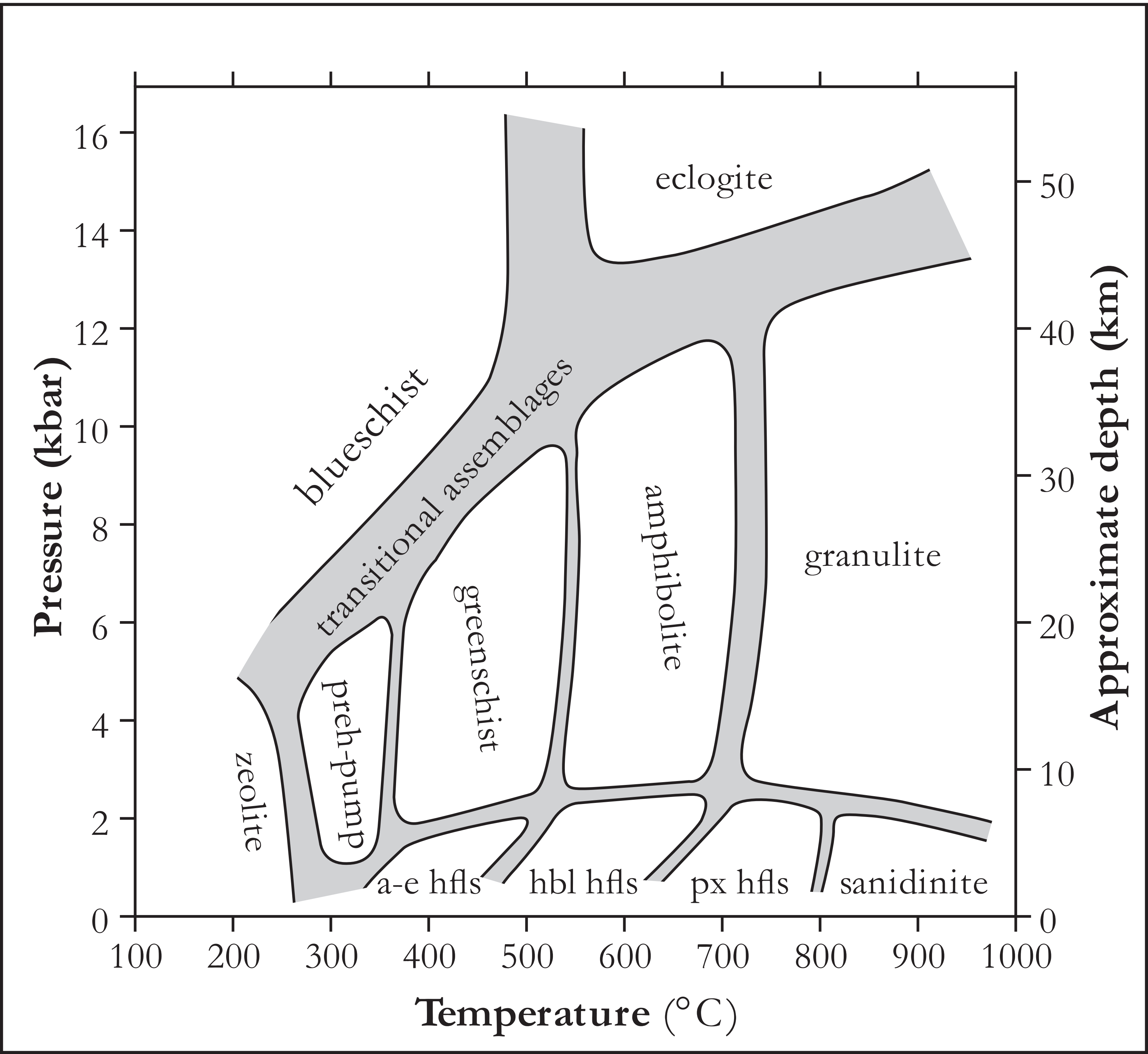
Upward facing
Downward facing
Sideward (south-east) facing
NW
SE
stratigraphical younging direction of beds
facing direction of folds
cleavage

Figure G.3



Interlimb angles	Fold tightness
180°–120°	gentle
120°–70°	open
70°–30°	close
30°–0°	tight
0°	isoclinal

Figure G.4


eclogite
blueschist
transitional assemblages
amphibolite
granulite
greenschist
preh-pump
zeolite
a-e hfls
hbl hfls
px hfls
sanidinite
Pressure (kbar)
Approximate depth (km)
Temperature (°C)
0
2
4
6
8
10
12
14
16
10
20
30
40
50
100
200
300
400
500
600
700
800
900
1000