The Dalradian rocks of the north-east Grampian Highlands of Scotland

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Abstract

The North-east Grampian Highlands, as described here, are bounded to the north-west by the Grampian Group outcrop of the Northern Grampian Highlands and to the south by the Southern Highland Group outcrop in the Highland Border region. The Dalradian succession therefore encompasses the whole of the Appin and Argyll groups, but also includes an extensive outlier of Southern Highland Group strata in the north of the region. The succession includes shallow-marine sequences, glacigenic deposits at two stratigraphical levels, the earliest evidence for volcanism in the Dalradian, a later major development of basaltic and picritic sub-marine lavas, and thick turbiditic sequences.

In the south, the Grampian-Appin group boundary is a high-strain zone, with no obvious dislocation or stratigraphical excision, which was formerly termed the Boundary Slide. Shear-zones at higher structural levels are associated with pre-tectonic granites, such as the Ben Vuirich Granite, which have been dated at *c*. 600 Ma and hence place limits on the timing of sedimentation, deformation and metamorphism. The region is divided from north to south by a major zone of shearing and dislocation with associated igneous intrusions, termed the Portsoy Lineament. To the west of the lineament, the stratigraphy is more-or-less continuous along strike with that of the Central Grampian Highlands. D1, D2 and D3 structures extend from the Tummel Steep Belt north-eastwards throughout this area. The stratigraphical succession is broadly continuous across the Portsoy Lineament but to the east, in the Buchan Block, correlations are more tenuous and do not extend below subgroup level. High-grade migmatitic paragneisses were once interpreted as pre-Dalradian basement but they are now assigned to the Crinan Subgroup, within the Dalradian succession. Within the Buchan block the outcrop pattern is controlled by two broad, open, post-metamorphic folds, the Turriff Syncline and the Buchan Anticline.

The Buchan Block is the international type area for the high-temperature/low-pressure Buchan-type regional metamorphism. To the south and west, this passes into higher pressure Barrovian-type metamorphism. South of Deeside, metamorphic conditions reached 820°C and over 8 kbar, well into granulite facies and the highest recorded in the Grampian Terrane. The detailed relationship between the high heat-flow and the emplacement of large bodies of

basic and silicic magma is a matter of ongoing research. Plutons of the North-east Grampian Basic Suite, emplaced at *c*. 470 Ma, during or shortly after the peak of metamorphism and the D3 deformation, provide key evidence for the timing of the Grampian orogenic event.

1 Introduction

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The North-east Grampian Highlands are defined here largely by two geological boundaries (Figure 6.1). To the north-west, the boundary with the Northern Grampian Highlands is taken at the Grampian–Appin group junction, which to the south of the Cairngorm Pluton is marked by the Boundary Slide or the Loch Tay Fault; farther north, a rapid stratigraphical transition is present, albeit with some local shearing. To the south, the boundary with the Highland Border region is taken at the top of the Loch Tay Limestone Formation between Pitlochry and the Mount Battock Pluton, and then along the projected continuation of the Argyll–Southern Highland group junction on Deeside, east to Aberdeen. The short south-western boundary with the Central Grampian Highlands is the valley of the rivers Garry and Tummel, as followed by the railway and A9 road, between Pitlochry and Blair Atholl.

The region is divided into three distinct geological areas by two of the major lineaments of the Grampian Highlands (see Stephenson et al., 2013a). The east–west Deeside Lineament, to the north of the River Dee, is marked by a line of large granitic plutons with only narrow intervening outcrops of Dalradian strata. The Dalradian succession is generally coherent across this essentially late-Caledonian lineament, although some facies changes have been recognized and many of the formation names change. Hence it is a useful boundary for descriptive purposes, at least in upper Deeside. The north–south Portsoy–Duchray Hill Lineament is an older structure that was active during Dalradian sedimentation and was a locus for basic magmatism and major tectonic dislocation during the Caledonian Orogeny (Fettes *et al*., 1986; Goodman, 1994). It forms a fundamental stratigraphical and structural boundary stretching from the north coast at Portsoy to Glen Muick on south Deeside. To the south-west of the Lochnagar Pluton, it is less well defined but marks changes in stratigraphy that were recognized by Barrow (1912). It is coincident with the later, brittle Glen Doll Fault for some distance but turns towards the south-west, along strike, and peters out beyond Duchray Hill in Glen Shee.

To the west of the Portsoy–Duchray Hill Lineament, Dalradian successions and structures can be traced into those of the Northern and Central Grampian Highlands with little difficulty. A generally eastward-younging stratigraphical succession does seem to continue, albeit with some attenuation and disruption, across the lineament and elements of the structural history are common to both sides. However, to the east of the lineament only tentative stratigraphical and structural correlations can be made with higher parts of the Dalradian succession elsewhere and this area seems to have had, to some extent, a distinctly different sedimentological, structural and metamorphic history. It is commonly referred to as the ‘Buchan Block’ and has been regarded by several authors as a tectonically juxtaposed separate subterrane. Regional gravity and magnetic anomalies, which show steep gradients coincident with the Portsoy–Duchray Hill Lineament, suggest that there are fundamental differences in the sub-Dalradian basement (Trewin and Rollin, 2002). The southern margin of the Buchan Block is difficult to define either geologically or geophysically. It extends southwards at least to the Deeside Lineament, where the geophysical anomalies are subsumed by the plethora of large granitic plutons. To the south of Deeside the lithologies and structures gradually merge with those of the Highland Border region.

Early interpretations divided the succession in the Buchan Block into a ‘Banff division’, restricted to a ‘Banff Nappe’, separated by a slide from an underlying, more typical Dalradian sequence, termed the ‘Keith division’ (Read, 1923, 1955; Read and Farquhar, 1956). Although some authors have also suggested that parts of the area are allochthonous (Sturt *et al*., 1977; Ramsay and Sturt, 1979), most current interpretations have attempted to correlate the stratigraphical succession in broad terms (i.e. at subgroup level) with Argyll and Southern Highland group successions farther to the south-west (Harris and Pitcher, 1975; Ashworth, 1975; Harte, 1979; Treagus and Roberts, 1981; Ashcroft *et al*., 1984; Fettes *et al*., 1991; Harris *et al*., 1994; Stephenson and Gould, 1995).

Several other lineaments and dislocations in the North-east Grampian Highlands have been recognized as being of more than just local significance. Some have contributed significantly to debates over the timing of Caledonian and earlier deformation, and their associated intrusions have provided material for precise radiometric age determinations that now define magmatic events both at 600 Ma and 470 Ma.

1.1 Stratigraphy

1.1.1 Pitlochry–Blair Atholl area to Deeside

In this area, most of the Appin and Argyll group succession can be correlated precisely with that of the adjoining Central Grampian Highlands, certainly down to formation level and in many cases also down to member level (Figure 6.2). However, facies changes do occur, most notably the disappearance of the Schiehallion Quartzite between Glen Tilt and Glen Shee, partly resulting from structural excision but most probably due to non deposition or a local unconformity. The absence of this familiar marker, together with its basal tillite sequence, does cause problems in that it results in the juxtaposition of the Killiecrankie Schist (Easdale Subgroup) upon the lithologically similar upper part of the Blair Atholl Subgroup. As the Cairn Mairg Quartzite of the Central Grampian Highlands is also absent from this area, correlations of some key units between the lower part of the Blair Atholl Subgroup and the distinctive graphitic pelites and calcareous schists in the upper Easdale Subgroup are rather uncertain (Goodman *et al.*, 1997; Crane *et al.*, 2002). This in turn makes it difficult to estimate the magnitude and significance of ductile displacements on some high-strain zones. Local names for stratigraphical units are a particular problem owing to the large number of workers who have worked here at different times, with varying success in attempts to correlate with adjoining areas. Unfortunately, many of these names have been adopted on BGS maps, the publication of which which has spanned a significant time period. Only recently has an attempt been made to rationalize the nomenclature in the BGS Lexicon of named rock units and those names have been used in this special issue wherever possible.

Throughout much of this area the junction of the Appin Group with the underlying Grampian Group is coincident with a zone of high strain that is a continuation of the Boundary Slide-zone from the Central Grampian Highlands. However, at the *Gilbert's Bridge* GCR site in Glen Tilt there does appear to be a continuous stratigraphical transition from the Struan Flags of the Grampian Group into calcareous semipelite lithologies of the Glen Banvie Formation that have been assigned to the Lochaber Subgroup. A similar situation occurs south-west of Braemar at the *Glen Ey Gorge* GCR site, where flaggy psammites of the Grampian Group are overlain by highly strained pelites and semipelites of the Tom Anthon Mica Schist Formation (Upton, 1986).

All the constituent formations of the Ballachulish Subgroup can be traced from the Blair Atholl area (Smith and Harris, 1976) north-eastwards to Braemar (Upton, 1986), where they can still be matched almost bed for bed with those in the type areas of Lochaber and Appin. The distinctive basal dolomitic metalimestone, the graphitic pelites passing via a striped transition into the An Socach Quartzite, and the topmost limestone and phyllite formation with its crystalline white limestone and striped 'tiger rock', can all be found throughout this area (Figure 6.2).

The base of the Blair Atholl Subgroup is well marked throughout the area by a change from a background lithology dominated by semipelites and psammites to one in which dark schistose pelites predominate. Thick units of dark bluish-grey graphitic metalimestone in the lower part of the subgroup are a distinctive feature and several have been quarried extensively. Higher parts of the subgroup tend to be paler and more semipelitic. Although some of the metalimestones are laterally persistent, some units have been recognized only locally, and it is the broad characteristics of the subgroup that enable it to be traced from Blair Atholl through the Glen Shee area almost to Braemar (Bailey, 1925; Pantin, 1961; Smith and Harris, 1976; Upton, 1986; Goodman *et al*., 1997; Crane *et al*., 2002).

The Schiehallion Quartzite is the only unit of the Islay Subgroup represented in the Blair Atholl area. In the lower part, locally developed conglomeratic beds contain scattered clasts of granite and quartzite and are considered to be equivalent to the tillites of the Schiehallion Boulder Bed; dolomitic beds are also present locally. The quartzite thins considerably north-eastwards and is eventually excised by a slide in Glen Tilt. It re-appears, with basal boulder beds, farther north-east in the Glen Shee area, where it is termed the Creag Leacach Quartzite. This passes up through a transition formation of interbedded quartzite and black graphitic pelite into the graphitic Glas Maol Schist Formation, followed by calcareous semipelite and schistose calcsilicate rocks (the Glen Girnock Calcareous Formation), a sequence typical of the upper part of the Easdale Subgroup in the Central Grampian Highlands (i.e. Ben Eagach Schist and Ben Lawers Schist equivalents). At Coire Loch Kander, stratabound syn-sedimentary barium deposits, similar to those at the

Craig an Chanaich to Frenich Burn GCR site in the Central Grampian Highlands and at the same stratigraphical level, occur in the Glas Maol Schist Formation. A 15 m-thick band of barian quartzite contains sphalerite, galena and iron sulphides, and bedded baryte-quartz rock, 4.5 m thick, has been proved by drilling over a strike length of 700 m (Fortey *et al*., 1993). The upper part of the Easdale Subgroup is dominated in places by basic meta-igneous rocks. On Ben Vrackie, near Pitlochry, these have been interpreted as intrusions, but in the Ballater area a sequence of banded amphibolites at the top of the Easdale Subgroup represents basic lavas in an equivalent position to the tuffaceous Farragon Beds (Goodman and Winchester, 1993; Fettes *et al*., 2011) (Figure 6.2).

In the Pitlochry area, the Crinan Subgroup is represented by the dominantly semipelitic Ben Lui Schist Formation, as is the case throughout the Central Grampian Highlands. However, north-eastwards from Ben Vrackie, the metamorphic grade of the Ben Lui Schist increases. The unit becomes migmatitic with abundant concordant quartzofeldspathic segregations and thick pegmatite veins and pods. In the Glen Shee area and through to the headwaters of Glen Isla and Glen Clova, the Ben Lui Schist Formation (known locally as the Caenlochan Schist) grades into lit-par-lit migmatites that constitute the Duchray Hill Gneiss Member (Williamson, 1935). The equivalent Queen's Hill Formation can be traced north-eastwards into Glen Muick and to the eponymous Queen's Hill, near Aboyne (Read, 1927, 1928). The dominant migmatitic semipelites and pelites, well seen at the *Balnacraig, Dinnet* GCR site, are interbedded with psammites, rare quartzites and thin bands of calcsilicate rock. The formation also includes numerous bands of gneissose amphibolite, implying that it was a preferred horizon for the intrusion of basic sheets, which dominate the *Cairn Leuchan to Pannanich Hill* GCR site. Similar migmatitic and gneissose lithologies occur in lower Deeside between the Hill of Fare and Mount Battock granites.

The Tayvallich Subgroup is represented by the Loch Tay Limestone Formation, which can be traced from Pitlochry to Glen Doll. Farther to the north-north-east, calcareous semipelites around the head of Glen Mark pass into ribbed calcsilicate rocks and metalimestones of the Water of Tanar Limestone Formation. In middle Deeside, this becomes the Deeside Limestone Formation (Read 1927, 1928), which consists mainly of calcsilicate rocks with calcareous psammite, amphbolite and thin layers of impure metalimestone. These calcareous rocks are overlain by a diverse but dominantly psammitic unit, the Tarfside Psammite Formation, consisting of quartzites, psammites, semipelites and pelites but with locally abundant calcsilicate and amphibolite bands (Harte, 1979). Parts of this unit are gneissose.

1.1.2 Deeside to the north coast, west of the Portsoy–Duchray Hill Lineament

To the north of the Cairngorm, Glen Gairn, Ballater and Mount Battock granitic plutons that mark the enigmatic 'Deeside Lineament', many elements of the Appin Group and lower Argyll Group stratigraphy of the Central Grampian Highlands can still be recognized. This is particularly true of the Lochaber and Ballachulish subgroups, in which correlations are possible at formation level. The Blair Atholl, Islay and Easdale subgroups can also be defined with confidence from their overall lithological characteristics. The succession is terminated to the east by the shear-zone that marks the Portsoy Lineament (Fettes *et al.*, 1991). The continuous section along the north coast that forms the western part of the *Cullen to Troup Head* GCR site has been well known since the work of H.H. Read (1923, 1936), but its connection with the established succession of Perthshire was not known until the detailed resurvey of the North-east Grampian Highlands by the British Geological Survey in the 1980s and 1990s.

A poorly defined association of micaceous psammites with thin lenticular quartzite units overlies Grampian Group psammites conformably south of Tomintoul. However, farther north, psammites grade upwards into slaty and calcareous semipelites, which represent a thin development of the Lochaber Subgroup, well seen at the *Bridge of Brown* GCR site. Close to the contact the psammites and semipelites are commonly flaggy and highly strained, recalling the features seen along the Boundary Slide-zone farther to the south-west.

Still farther north, the Lochaber Subgroup thickens markedly between Dufftown and the north coast (Read, 1923, 1936; Peacock *et al*., 1968). Here a thick sequence of flaggy, micaceous psammites and semipelites, the Findlater Flag Formation, forms the lower part of the subgroup, whereas the upper part contains calcareous lithologies, recalling the division in the Lochaber type area. The calcareous rocks are lithologically variable but are characterized locally by abundant tremolitic amphibole (Stephenson, 1993). They are dominated by thinly banded grey, cream and pale-green calcareous psammites and semipelites termed the Pitlurg Calcareous Flag Formation, which grades laterally into the

Cairnfield Calcareous Flag Formation towards the coast. Beds and lenses of metalimestone occur locally in the upper parts of this formation, presaging the limestone development in the Ballachulish Subgroup.

The Ballachulish Subgroup is well developed and can be traced northwards as far as the Keith area. The Mortlach Graphitic Schist Formation is several hundred metres thick in Glen Livet but thins locally to 5 or 6 m. A dark metalimestone, the Dufftown Limestone Member, is commonly present at or near the base of the formation, and other metalimestones occur in the lower part, notably in Glen Rinnes. The formation appears to thicken markedly on the north-east side of the NW-trending Rothes Fault and, although much of this thickening is probably due to fold repetition, the fault could coincide with an earlier synsedimentary structure or lineament (Fettes *et al*., 1986). At the base of the Corryhabbie Quartzite Formation there is a transitional unit of interlaminated pelite and psammite, which is thick in the south but is reduced to a few metres farther north, where the formation is made up of a lower thick-bedded psammite unit, a clean, cross-bedded quartzite, and an upper psammite unit. The succeeding Ailnack Phyllite and Limestone Formation consists of phyllitic semipelite, with several distinctive thin white metalimestones, calcsilicate beds and one more-persistent banded metalimestone member. The Dufftown Limestone and Mortlach Graphitic Schist are particularly well seen at the *Auchindoun Castle* GCR site and most of the succeeding units are exposed at the *Bridge of Avon* GCR site.

Farther to the north-east, marked facies changes, probably associated with NW-trending growth faults, and increased structural complexity, make individual units difficult to trace so that formations become ill defined. The graphitic character of the lower part of the subgroup is locally much reduced and thick, persistent metalimestones are absent. A condensed sequence of metalimestone and graphite-schist is seen around Deskford, but in boreholes on the coast at Sandend Bay over 300 m of kyanite-rich schistose graphitic pelite has been proved. The pelite is overlain directly by phyllitic semipelite and metalimestone with no intervening quartzite.

The Blair Atholl Subgroup consists mainly of schistose semipelites, which are locally pelitic, graphitic and calcareous. A thick bluish grey metalimestone formation, the Inchrory Limestone, occurs in its central part (see the *Bridge of Avon* GCR site report) and minor metalimestones occur locally in the lower part. Maximum development of the subgroup occurs in the upper Donside–Braes of Glenlivet area. Farther north, around Edingight, black graphitic pelites with staurolite are interbedded with thin beds of blue-grey metalimestone. From there the metalimestones thicken considerably northwards and become dominant in the Fordyce Limestone Formation that constitutes the only part of the subgroup exposed on the coast in the *Cullen to Troup Head* GCR site.

The lowest units of the Argyll Group can be traced intermittently to the coast. The lower part of the Islay Subgroup consists of two interdigitating and diachronous formations, both of which are represented in the *Kymah Burn* GCR site. On Donside, semipelites and pelites with thin metalimestones and metadolomites comprise the Nochty Semipelite and Limestone Formation. These lithologies pass laterally northwards and westwards into thinly interbedded, locally graded, psammites, semipelites and minor pelites, which comprise the Ladder Hills Formation. This formation is several kilometres thick in its type area, but is absent or only thinly developed elsewhere. Boulder beds, typically associated with thin metadolomite beds, occur locally towards the top of the Ladder Hills Formation. The best section of these boulder beds is found in the *Muckle Fergie Burn* GCR site, south of Tomintoul, where a metadolostone unit is succeeded by a 10 m-thick boulder bed containing clasts of dolostone in its lower, calcareous part and of granite above. Minor beds of basic metatuff also occur locally and in the Muckle Fergie Burn basaltic pillow lavas have been recognized a short distance below the boulder beds. In some areas, for example in upper Donside near Corgarff, boulder beds occur within the lower units of the overlying Kymah Quartzite Formation and in the *Kymah Burn* GCR site thin basic lavas and tuff lenses are found near the base of the quartzite. The quartzite varies considerably in thickness, from only 10 m over fault-controlled structural highs (e.g. Lecht–Cockbridge) to a more-typical development of 300 to 500 m in adjacent basins. To the west of Huntly the Islay Subgroup is cut out structurally by the Portsoy Shear-zone. However, north of the River Isla, the Durn Hill Quartzite is confidently assigned to this subgroup on account of loose blocks of metadiamictite (boulder bed) that have been found within the outcrop of the underlying Arnbath Psammite Formation in several locations around Fordyce and Edingight (Spencer and Pitcher, 1968).

A typical Easdale Subgroup sequence crops out from east of the Glen Gairn Pluton to north of Glenbuchat. There, the Kymah Quartzite is overlain by the Culchavie Striped Formation, a thick sequence of striped semipelites and psammites with a distinctive pebbly quartzite. These are succeeded in turn by the Glenbuchat Graphitic Schist Formation, followed by calcareous semipelites and minor psammites with metalimestone and calcsilicate beds that constitute the Badenyon Schist and Limestone Formation. Graphitic pelites and semipelites are also present around the headwaters of the River Don and in the eastern part of the *Muckle Fergie Burn* GCR site, where they include the Delnadamph Volcanic Member, consisting of basic pillow lavas and volcaniclastic beds.

To the north of these outcrops, the Easdale Subgroup is cut out completely by the Portsoy Shear-zone. However, on the coast, in the *Cullen to Troup Head* GCR site, a thin development of the Durn Hill Quartzite is succeeded eastwards by a sequence of graphitic pelites and semipelites with metalimestone and quartzite in its upper part, which are intruded by gabbroic and ultramafic rocks within the Portsoy Shear-zone. This Easdale Subgroup sequence, consisting of the Castle Point Pelite and Portsoy Limestone formations, is highly strained and very much attenuated as it effectively lies within the shear-zone.

1.1.3 The Buchan Block

Within and immediately to the east of the Portsoy Shear-zone are a number of formations, which are commonly bounded by ductile shears and are interspersed with mafic and ultramafic intrusive rocks of the 470 Ma North-east Grampians Basic Suite. They are difficult to correlate with any established successions, but their overall lithological character, consisting largely of semipelites and graphitic pelites with gritty psammites and a few minor metalimestones, is typical of the Argyll Group (Fettes *et al.*, 1991). On published maps they are mostly designated as 'Argyll Group, subgroup unassigned', and they probably belong in the Easdale, Crinan and Tayvallich subgroups.

Most notably, in the Cabrach area, a turbiditic sequence of black pelites, semipelites, psammites, pebbly psammites and metavolcanic rocks is termed the Blackwater Formation. The metavolcanic rocks dominate the lower part of the formation, which is well exposed in the *Black Water* GCR site. They are composed of aphyric, pyroxene-phyric and pillowed tholeiitic metabasalts and both massive and autobrecciated metapicrite lavas (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 tentatively correlated with the 600 Ma Tayvallich Volcanic Formation of the South-west Grampian Highlands, with which they share some geochemical characteristics such as unusually strong Fe and Ti enrichment and some evidence for crustal contamination (Fettes *et al*. 2011).

The higher parts of the Argyll Group form a broad horseshoe outcrop of generally gneissose semipelitic rocks around the Turriff Syncline, from mid-Donside to Fraserburgh and in a narrower zone from Huntly to Portsoy. Within these poorly exposed areas, thick, mixed sequences of semipelite, psammite and pelite show little mappable variation and no consistent detailed stratigraphy has been established. The metamorphic grade is generally high and most of the rocks are gneissose with local migmatization. The gneissose and migmatitic textures clearly transgress primary lithological boundaries but, by analogy with the development of the Queen's Hill and Duchray Hill gneisses to the south, they have been assigned to the Crinan Subgroup (Read, 1955; Harris and Pitcher, 1975; Harris *et al*., 1994; Stephenson and Gould, 1995). However, some probably belong to the Tayvallich Subgroup and it is possible that minor units of the Easdale Subgroup are included in some areas (e.g. near Portsoy). Hornfelsing and partial melting have further complicated relationships close to the major basic intrusions.

In mid-Donside, between the eastern margin of the Morven–Cabrach Intrusion and the Tillyfourie area, lies the Craigievar Formation, which consists mainly of finely interlayered, schistose and gneissose psammites and pelites. Major developments of pelitic gneiss, concordant amphibolite and thin developments of metalimestone and calcsilicate-bearing rock occur locally. East and north-east of the Bennachie Granite Pluton, equivalent Crinan/Tayvallich subgroup rocks are known as the Aberdeen Formation (Munro, 1986). The dominant lithologies are less pelitic than those to the west, consisting mainly of psammites and semipelites and characterized by small-scale compositional banding.

The gneisses of the Ellon Formation crop out around the lower Ythan valley (Read, 1952; Munro, 1986). They are derived mainly from semipelitic and psammitic metasedimentary rocks, although amphibolites are abundant locally. Calcsilicate rocks are rare. The gneisses are distinguished from those of the Aberdeen Formation by their lack of regular lithological banding, their poor fissility and a foliated, streaky appearance. Bodies of migmatitic 'granite' are widespread.

The boundary with the Aberdeen Formation is transitional in places but elsewhere it is marked by shear-zones. To the north and east of Ellon, the Ellon gneisses grade into the structurally overlying Stuartfield ‘division’ of semipelites, pelites, psammites and metagreywackes. The upper part of this ‘division’ has a more coherent stratigraphy and is termed the Strichen Formation. To the north this may be further divided into a lower part containing massive channel quartzites up to 500 m thick (e.g. the Mormond Hill Quartzite Member) and an upper part containing calcareous beds; the latter have been taken to indicate that the Strichen Formation spans the boundary between the Crinan and Tayvallich subgroups (Kneller, 1988).

To the north of Peterhead is the Inzie Head Gneiss Formation(see Read and Farquhar, 1956). This mixed assemblage of rocks, exposed in the *Cairnbulg to St Combs* GCR site, has a general migmatitic appearance due to more-homogeneous granitic gneisses alternating with schollen and schlieren gneisses. The schollen show a wide range of metasedimentary lithologies, including calcsilicate rock and psammite, and can be discerned locally in trails resembling dismembered sedimentary units. More-coherent bands of amphibolite, psammite and calcareous schist with impure metacarbonate rock have been mapped in places. On the west side of the Turriff Syncline, the Cowhythe Psammite Formation crops out along the coast east of Portsoy (see the *Cullen to Troup Head* GCR site report), and extends southwards to near Huntly (Read, 1923). It is composed essentially of schistose psammite and semipelite with rare metalimestone and pelite beds. Streaky lit-par-lit migmatites and feldspathized rocks occur, particularly in the semipelitic units, but for the most part the original compositional banding can still be discerned.

Most of the dominantly gneissose units described above probably include some Tayvallich Subgroup rocks, as indicated by the presence of calcsilicate and metalimestone beds. Notable examples are the calcareous parts of the Strichen Formationand its lateral equivalent, the Kinnairds Head Formation, which is well exposed on the north coast in the *Fraserburgh to Rosehearty* GCR site. Although metalimestone beds up to 20 m thick do occur in the Strichen Formation, calcareous units are restricted in general to thin-banded calcsilicate beds in an overall sequence of pelite, semipelite and psammite.

On the west side of the Turriff Syncline, the Tayvallich Subgroup comprises a 1200 m-thick sequence of semipelite, calcsilicate rock and metalimestone, termed the Boyne Limestone Formation (Read, 1923; Sutton and Watson, 1955). It includes the Boyne Castle Limestone Member, a thickly bedded but finely banded metalimestone, some 200 m thick (Figure 6.2) (see the *Cullen to Troup Head* GCR site report). The metalimestones can only be traced inland for some 2.5 km through poorly exposed ground.

The Southern Highland Group occupies the broad core of the Turriff Syncline, represented by the *Fraserburgh to Roseharty* GCR site and the eastern part of the *Cullen to Troup Head* GCR site, and a small outlier on the east coast around the *Collieston to Whinnyfold* GCR site.

In the Turriff Syncline a sedimentological transition from the Argyll Group into the Southern Highland Group is well seen. On its western limb, the base of the Southern Highland Group is drawn in the coast section at the base of the first gritty psammite that marks the change from lagoonal deposition of calcareous silts and muds to turbiditic sedimentation. The overlying succession consists of some 2000 m of psammite, with subordinate semipelite and pelite, referred to as the Whitehills Grit Formation. On the eastern limb a similiar transition is observed from the calcareous successions of the Kinnairds Head Formation and the Strichen Formation into the non-calcareous psammites and pelitic lithologies of the Rosehearty Formationand Methlick Formation(Read and Farquhar, 1956). In the core of the syncline the Southern Highland Group is represented by the Macduff Formation (1700 m), a finer grained, more-distal turbidite facies with slump deposits, clean channel sandstones and subsidiary greywackes (Sutton and Watson, 1955). A more-persistent semipelitic facies to the south-west has been termed the Clashindarroch Formation, and this unit has been quarried extensively in the past for roofing slate in an E–W-trending belt to the north of the Insch and Bogancloch intrusions.

The closure of the Turriff Syncline can be traced to the south of the Insch Intrusion, in the Correen Hills. There, the Southern Highland Group is represented entirely by the Suie Hill Formation, which consists dominantly of semipelite and gritty psammite with prominent pelite units. The base is taken at a magnetite-bearing schistose pelite, which forms a regional magnetic anomaly. Similar magnetic units occur on the western limb of the syncline and elsewhere in the basal part of the group; the influx of detrital magnetite could indicate a change in provenance caused by the unroofing of a new source or a mafic volcanic input.

On the east coast, low-grade turbiditic rocks occur in an eastward-younging sequence, represented almost in its entirety by the *Collieston to Whinnyfold* GCR site but traceable for only a few kilometres inland (Read and Farquhar, 1956; Munro, 1986). These rocks, termed the Collieston Formation, are assigned to the Southern Highland Group and form a predominantly psammitic graded sequence with characteristic 'knotted' pelites containing andalusite and cordierite. Contacts with adjoining units are not exposed but south of Collieston lenses and beds of calcsilicate rock are common and thin impure metalimestones also occur, possibly indicating a transition downwards into the Argyll Group.

Boulders and pebbles of igneous and metamorphic rocks, some of extrabasinal origin, occur in the higher exposed part of the Macduff Formation in the coastal section at Macduff (see the *Cullen to Troup Head* GCR site report). These deposits have been interpreted as the products of ice-rafting or as debris flows linked to marine tills (Sutton and Watson, 1954; Hambrey and Waddams, 1981; Stoker *et al*., 1999). Some poorly preserved microfossils have also been found in the adjacent rocks and correlations with various glacial periods, some as young as Ordovician, have been suggested (see Stephenson et al., 2013a).

1.2 Structure

1.2.1 Major dislocations

The development of the concept of a 'Boundary Slide' separating the Grampian Group from higher stratigraphical units of the Dalradian throughout much of the Grampian Highlands has been fully discussed by Stephenson et al. (2013a). The Boundary Slide can be traced north-eastwards from Glen Tilt, where it is well exposed in a continuous section at the historic *Gilbert's Bridge* GCR site, through the *Glen Ey Gorge* GCR site in upper Deeside to the eastern end of the Cairngorm Granite Pluton (Upton, 1986). However, there its overall effect might be much reduced. Farther north, zones of high strain, accompanied locally by slides, are common at or below the Grampian– Appin group transition, e.g. around Strath Avon, at the *Bridge of Brown* GCR site, and in the upper part of Glen Rinnes. Between Glen Rinnes and the north coast, at the western end of the *Cullen to Troup Head* GCR site, the Grampian–Appin group boundary appears to represent a relatively undisturbed, rapid stratigraphical passage.

In this northern part of the region, ductile dislocations occur at both higher and lower stratigraphical levels than the Grampian–Appin group boundary, although it is unclear whether any of these relate specifically to the Boundary Slide. The zones of shearing in Glen Rinnes can be projected north-eastwards towards a major NE- to NNE-trending shear-zone that passes through Keith and can be traced for some 30 km to reach the coast between Sandend and Portsoy in the *Cullen to Troup Head* GCR site. The effect of this Keith Shear-zone upon the succession is difficult to determine owing to poor exposure and uncertainties about the stratigraphical affinities of some of the units involved but it appears to have excised parts of the Ballachulish Subgroup in places. The shear-zone consists of multiple branches, each dipping at a low to moderate angle towards the south-east quadrant and commonly showing a very strong down-dip stretching lineation. Shear-sense indicators suggest a thrust (top to north-west) sense of movement. Between the branches are several pods and lenses of deformed muscovite-biotite granite, and zircons from two separate lenses of this Keith–Portsoy Granite have yielded a precise U-Pb intrusion age of *c.* 600 Ma (Barreiro, 1998). Although the granite pods and adjacent metasomatic country rocks were deformed and metamorphosed during the Grampian Event, which was undoubtedly a time of major movement on the shear-zone, the sites of the individual shears were clearly a locus for the intrusion of granite sheets. Hence they must follow earlier lineaments that were in existence at around 600 Ma, possibly soon after sedimentation as the youngest rocks affected are lower Islay Subgroup.

The best known and most extensively studied of the pre-Caledonian *c.* 600 Ma intrusions is the Ben Vuirich Granite, between Pitlochry and Glen Shee, which has yielded much vital information about the timing of Caledonian deformation and metamorphism. Determinations of the age of the intrusion and interpretations of its structural setting have changed considerably since its significance was first recognized by Bradbury *et al.* (1976) and these make the *Ben Vuirich* GCR site one of the most significant in this special issue. The granite was intruded into Blair Atholl Subgroup strata at around 590 Ma and hence provides a minimum age for Appin Group deposition (Rogers *et al*., 1989; Pidgeon and Compston, 1992). It is now considered to have been deformed by the D2 phase of deformation of the Grampian Event (Tanner, 1996). The age and significance of an earlier, D1 fabric affecting the granite is still a matter of debate (e.g. Dempster *et al*., 2002; Tanner, 1996; Tanner *et al*., 2006). The intrusion does crop out between major slides to the north-west and south-east, but there is no evidence that these are earlier structures that might have controlled granite emplacement. However, smaller nearby bodies of foliated granite, at Glach Ghlas in Glen Tilt, and near Fealar Lodge, are either located between major slides or within ductile shear-zones.

A number of major zones of shearing and dislocation occur on the western margin of the Buchan Block and each of these has been used at some time to define its limit. Thrust-related fabrics at the western margin of the Cowhythe Psammite Formation were attributed by Elles (1931) to a Portsoy Thrust, which is now regarded as the eastern limit of the 1 km-wide Portsoy Shear-zone, described in detail in the *Cullen to Troup Head* GCR site report. Earlier fold axes and lineaments have been rotated so that they plunge down-dip adjacent to and within the zone and a down-dip stretching lineation is present locally. Highly sheared mafic and ultramafic igneous rocks occupy the centre of the zone and cross-cutting, but lineated, sheet-like granite bodies are present near the margins. This zone can be traced inland to the south-south-west as a narrower zone of dislocation that forms the western boundaries of the Huntly-Knock and Morven-Cabrach mafic-ultramafic intrusions (Munro and Gallagher, 1984; Ashcroft *et al*., 1984) and defines the northern part of the Portsoy–Duchray Hill Lineament (Fettes *et al*., 1986, Goodman 1994). Major stratigraphical and structural discontinuities occur across the shear-zone and marked differences in metamorphic history on opposite sides indicate major westward overthrusting during the regional D3 event (Baker, 1987; Beddoe-Stephens, 1990). The margins of major syn-D3 mafic–ultramafic intrusions of the North-east Grampian Basic Suite are severely affected by this and by other related shear-zones, and their aureoles have been displaced by several kilometres in places, suggesting significant lateral movement (Ashcroft *et al*., 1984). Kneller and Leslie (1984) demonstrated that the shearing occurred whilst the adjacent rocks were at or close to their peak metamorphic conditions. Farther south, the Coyles of Muick Shear-zone, to the west of the *Cairn Leuchan to Pannanich Hill* GCR site, lies on the same lineament, although there the discontinuities are less marked (Goodman, 1994).

On the eastern edge of the Cowhythe Psammite Formation outcrop is another zone of highly deformed rocks with some thin mylonites. This zone marks the position of the Boyne Line of Read (1955), which was interpreted as a major slide underlying his proposed allochthonous Banff Nappe. In Read’s model, movement on the Boyne Line was held responsible for the excision of Tayvallich Subgroup calcareous lithologies, which are absent over much of the North-east Grampian Highlands, apart from the Boyne Limestone Formation, which is seen only in the coast section.

Some structural and Rb-Sr geochronological evidence has been interpreted to infer that the Cowhythe Psammite Formation, along with all the other gneissose units of the North-east Grampian Highlands, represents a pre-Caledonian Neoproterozoic basement gneiss complex (Sturt *et al*., 1977). Ramsay and Sturt (1979) suggested that all the rocks above the Portsoy Thrust constitute an allochthonous block, and that this consists of a gneissose basement separated from a Dalradian metasedimentary cover by a décollement along Read’s Boyne Line. However, subsequent detailed mapping and advances in the reliability of radiometric dating techniques now suggest that the gneissose parts of the succession can be explained as part of the Dalradian stratigraphy, albeit heavily deformed, thrust and metamorphosed during the mid Ordovician Grampian Event (see Ashcroft *et al*., 1984; Stephenson and Gould, 1995).

1.2.2 Folding

Between the Tay Nappe and the Boundary Slide there is a progressive change in dips from the flat-lying strata and pervasive S2 cleavage of the Flat Belt, north-westwards into a 10 km-wide zone of steep to vertical folded strata known as the Tummel Steep Belt (Bradbury *et al.*, 1979) (Stephenson et al., 2013a, fig. 7). The tight, upright folds characteristic of the steep belt have been documented in the Central Grampian Highlands east of the Loch Tay Fault by Treagus (1999, 2000) and a similar structural pattern can be traced north-eastwards into the Kirkmichael–Glen Shee area (Crane *et al.*, 2002) and on towards Braemar, where it is known as the Cairnwell Steep Belt (Upton, 1986). Throughout these areas, the steepening has been interpreted as at least partly the result of late, D3 to D4, ENE-trending flexuring and corrugation of pre-existing flat-lying, recumbent, SE-facing D1 and D2 structures linked to the Tay Nappe and its complementary underlying syncline, formerly referred to in this area as the Kirkmichael Fold (Bailey, 1925; Read, 1935, 1955). Tight F3 folds are commonly co-axial with the earlier folds and hence the F1, F2 and F3 fold closures can be difficult to distinguish. In some areas, large-scale F2 and F3 folds trend north-west, most notably in the complex 5 km-wide NW-trending Carn Dallaig Transfer Zone that effectively links the Tummel Steep Belt and the offset Cairnwell Steep Belt (Crane *et al.*, 2002, fig. 19). This transfer zone has a marked effect upon the outcrop pattern in the Gleann Fearnach area, but as the F2 fold axes are not re-orientated within it, Crane *et al.* interpreted it as a steep transpressive D2 structure, analogous to a lateral ramp in thrust terrains.

To the north of the Deeside Lineament and west of the Portsoy–Duchray Hill Lineament, Appin and Argyll group rocks are disposed in a series of large-scale NW- to SW-facing early tight folds, which can be traced downwards into the underlying Grampian Group. A related fine-scale penetrative cleavage (S2) is also developed. Later folds, which fold the S2 fabric and post-date the primary metamorphic assemblages, are commonly co-axial with the early folds. The related S3 penetrative cleavage, typically a finely spaced or a tight crenulation, is best developed in the more-pelitic lithologies (well seen in the *Auchindoun Castle* GCR site). These F3 folds are typically close to tight and upright to NW-facing. Their axes trend north or north-east and they exert a strong control on the outcrop pattern both locally and regionally, as is well demonstrated by the Ardonald Fold in the Dufftown area. Post-D3 minor chevron folds and kink bands are widely developed but usually only local in extent. In part they are related to late uplift, faulting and basement block movement.

Within the main part of the Buchan Block, along the north coast that forms the eastern part of the *Cullen to Troup Head* GCR site and the *Fraserburgh to Rosehearty* GCR site, the rocks of the Macduff Formation exhibit locally complex open to tight upright F1 folding. A related S1 spaced cleavage, formed by pressure solution, is well developed in the psammites and a slaty cleavage occurs in the intervening pelites. The folding, is responsible for the generally steep bedding dips over much of the section, although regionally the dip of the overall stratigraphy is relatively shallow (Figure 6.3)a. In fact, the outcrop pattern is controlled by two late (D3 or D4), open, broad, upright folds, the Turriff Syncline and the Buchan Anticline, whose axes plunge gently to the north-north-east. Read (1955) considered that the Dalradian succession, which is generally the right way up across the section, constitutes the upper limb of a major early SE-facing recumbent anticline which he termed the Banff Nappe (Figure 6.3)b. The overall 'nappe' has similarities to the Tay Nappe of the Highland Border region and some authors have linked the two structures (e.g. Treagus and Roberts, 1981; Ashcroft *et al*., 1984). In Read's model, the high-grade migmatitic gneisses seen in the *Cairnbulg to St Combs* GCR site form the core of the nappe and are exposed in the hinge-zone of the later Buchan Anticline (Read and Farquhar, 1956). To the west of Banff the beds are subvertical and form the steep limb of a monoform, regarded as a major early (F1) fold closure by Sutton and Watson (1956) who named it the Boyndie Syncline. Subsequent workers have regarded this structure as a later (F3) structure, devaluing its regional importance (Johnson and Stewart, 1960; Johnson, 1962; Fettes, 1970), although Treagus and Roberts (1981) also assigned it to D1.

Recumbent, tight to isoclinal, east-facing F1 folds occur on the east coast and are well exposed at the *Collieston to Whinnyfold* GCR site. The fold geometry is in marked contrast to the north coast section, where bedding is generally steep within the shallow Turriff Syncline; here the generally flat-lying beds collectively define steeply dipping overall stratigraphical boundaries (Figure 6.40), a point that was highlighted by Read and Farquhar (1956). The beds are regionally inverted and the folds and cleavages face to the east. A major early fold closure must occur between this section and the coast sections around Fraserburgh, where the succession is the right way up. The axial surface of this fold cannot readily be traced; it lies in a poorly exposed complex sheared zone between Ellon and Inverallochy that is characterized by the presence of several mafic intrusions and high-grade metamorphism. It was regarded as the hinge-zone of the Banff Nappe by Read (1955) and Read and Farquhar (1956) and some later workers have regarded it as equivalent, at least in part, to the Tay Nappe (Stephenson et al., 2013a, fig. 7). Such a correlation must however remain highly speculative given the considerable distance between the traces of the structures and the intervention of the Deeside Lineament.

1.3 Metamorphism

The North-east Grampian Highlands include an area of Buchan metamorphism, characterized by low P/T, an area of typical Barrovian intermediate-P/T metamorphism and a transitional zone between the two focussed on the Portsoy–Duchray Hill Lineament. This pattern can be attributed to high heat flow in the Buchan area, falling off to the west and south. In general, the metamorphic grade increases with structural and lithostratigraphical depth, the lowest grade rocks occurring in the core of the Turriff Syncline (Stephenson et al., 2013a, fig. 12). The highest grade rocks are associated with late-metamorphic intrusions (see below). The porphyroblast growth was broadly synchronous across the region and occurred from syn-D2 to syn- to post-D3 (Johnson, 1962, 1963; Crane *et al*., 2002; Strachan *et al*., 2002).

In the area west of the Portsoy–Duchray Hill Lineament, metamorphic mineral assemblages are characteristic of the epidote-amphibolite facies in the south but mostly fall within the lower amphibolite facies. Mineral assemblages in pelitic lithologies are typical of Barrovian zones (biotite → garnet → staurolite → kyanite → sillimanite). In general, progressive increases in pressure are assumed to have taken place during the main phases of deformation, along a simple curve on a pressure-temperature plot, to reach a metamorphic peak in D3. However, in the Tummel Steep Belt the Barrovian zones are poorly developed and Dempster and Harte (1986) documented a significant post-D3 increase in pressure, with the replacement of chloritoid + biotite by garnet + chlorite, as well as the localized growth of kyanite- and staurolite-bearing assemblages. They ascribed the pressure increase, of *c.* 2–3 kbar, to rotation and burial of originally flat-lying strata (i.e. in the Flat Belt) associated with the development of the D3 steep belt.

In the north, there is good evidence that the line defining the inversion of regional andalusite to kyanite lay to the west of the Portsoy–Duchray Hill Lineament. In a well-defined zone up to 10 km wide, immediately to the west of the lineament, original andalusite is overprinted by later kyanite as a result of an increase in pressure due to westward overthrusting during D3 (Chinner and Heseltine, 1979; Baker, 1985; Beddoe-Stephens, 1990). Pseudomorphs of kyanite after andalusite are well seen in the *Auchindoun Castle* GCR site and immediately west of Portsoy in the *Cullen to Troup Head* GCR site.

To the east of the Portsoy–Duchray Hill Lineament, the metamorphic conditions were characterized by low pressures (2–4 kbar) and by a high temperature gradient. This is the type area for the Buchan zones (biotite → cordierite → andalusite → sillimanite → sillimanite+K-feldspar). The lowest grade rocks (greenschist facies) occur at the highest structural levels, in the core of the Turriff Syncline, and the metamorphic grade increases structurally downwards. The regional high geothermal gradients were closely associated with the emplacement of large volumes of basic and silicic magma, during or shortly after the peak of metamorphism at *c.* 470 Ma (Fettes, 1970; Pankhurst, 1970; Ashworth, 1975, 1976). Consequently the highest grade rocks are found in close contact with these igneous bodies, with local pressures and temperatures of over 8 kbar and *c.* 820°C, characteristic of granulite-facies conditions (Baker and Droop, 1983; Baker, 1985). Granulite-facies hornfelses and migmatites, characterized by garnet-orthopyroxene-cordierite assemblages, are found in the roof-zones, inner aureoles and in screens within the mafic and ultramafic intrusions, notably the Huntly–Knock Pluton (Fletcher and Rice, 1989). The assemblages imply that anatectic melting occurred at temperatures of 800–900°C under pressures of 4.5–5 kbar (Droop and Charnley, 1985; Johnson *et al*., 2001a; Droop *et al*., 2003). The link to the large early-Ordovician granite intrusions is not clear. However, Johnson *et al.* (2003) showed that granulite-facies metamorphism and emplacement of mafic rocks into the host Dalradian metasedimentary rocks is a feasible mechanism to have derived granitic melts, which might have coalesced to form larger bodies such as the Strichen and Aberdeen plutons (c.f. Oliver *et al*., 2008). The higher grade rocks have been subjected to widespread migmatization, as is well seen in the *Cairn Leuchan to Pannanich Hill*, the *Balnacraig, Dinnet* and the *Cairnbulg to St Combs* GCR sites.

The background cause of metamorphism across the Grampian Highlands was thermal relaxation of an overthickened crust. In addition, in the North-east Grampian Highlands there was a very significant advective heat input, leading to the low-P/T style of metamorphism (e.g. Vorhies and Ague, 2011). How far the various syn- to late-metamorphic igneous intrusions are the underlying cause of this advective heat and how far they are an expression of it is uncertain.

Initial workers believed that the thermal effects of the igneous bodies were imposed on a regional metamorphic pattern. For example, Chinner (1961, 1966) argued that sillimanite formed in response to a thermal overprint on an original depth-controlled metamorphism. However, Fettes (1970) demonstrated that the ‘regional’ porphyroblast growth was also directly related to the effects of the igneous bodies. Harte and Hudson (1979) recognized two phases of sillimanite growth, closely linked in time, one ‘regional’ and the other related to the basic intrusions. On this basis, they delineated a ‘regional’ sillimanite isograd within the overall sillimanite zone (Stephenson et al., 2013a, fig. 12), although they agreed that both phases might relate to a general high heat input. However, in the high-grade areas of the south the distinction is problematical and more-recent work, for example in the area around the *Cairn Leuchan to Pannanich Hill* GCR site, has regarded the sillimanite growth as the climax of a single prograde event (Smith *et al*., 2002).

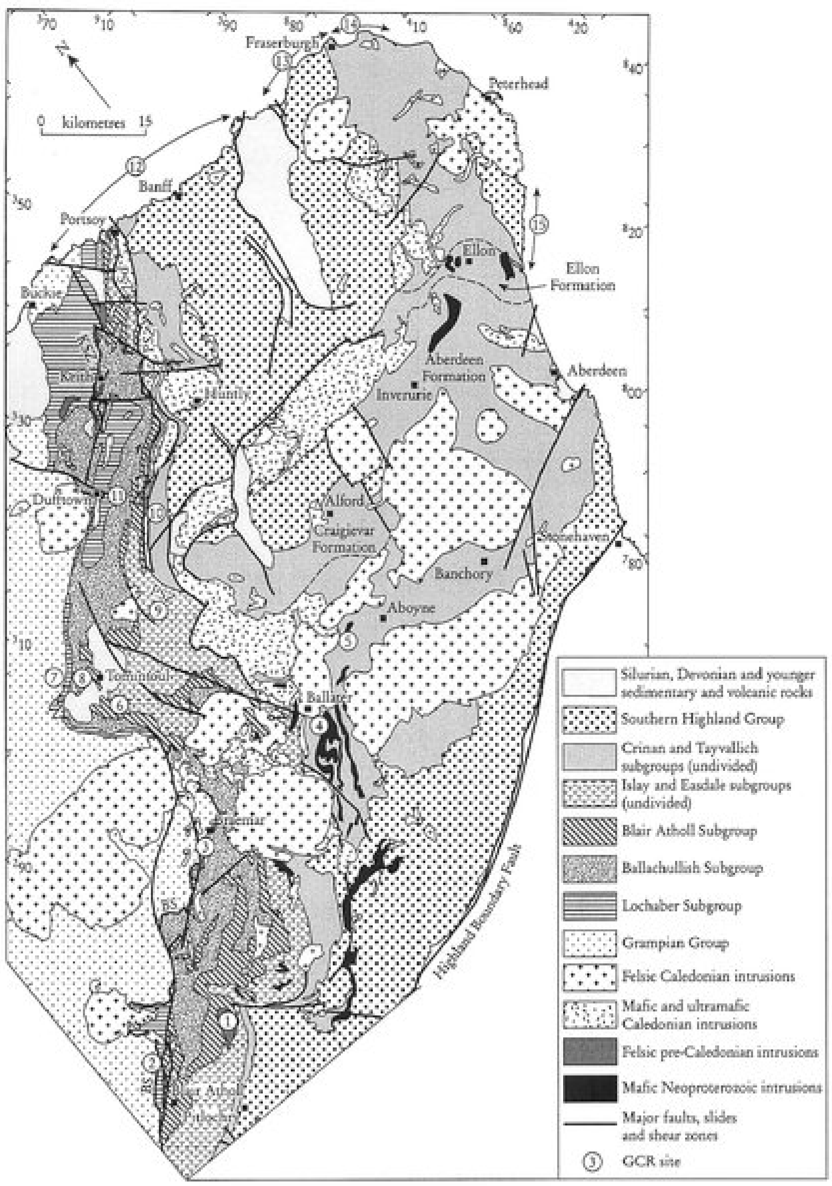
Current models for metamorphism clearly identify the advective heat input (including that from the igneous bodies) as the primary cause of the higher grades of metamorphism. Thus the growth of sillimanite must be seen as the culmanating phase of the progressive metamorphism in the areas of greatest heat input. As such, any separation of growth phases might relate to a pulsed heat input (Ague and Baxter, 2007; Vorhies and Ague, 2011).

The cause of the high heat input and associated magmatism in Buchan is uncertain; it might relate to lithospheric stretching and/or slab drop-off beneath the Buchan area immediately following the main arc–continent collision that resulted in the Grampian orogenic event (Kneller, 1985; Oliver, 2002).

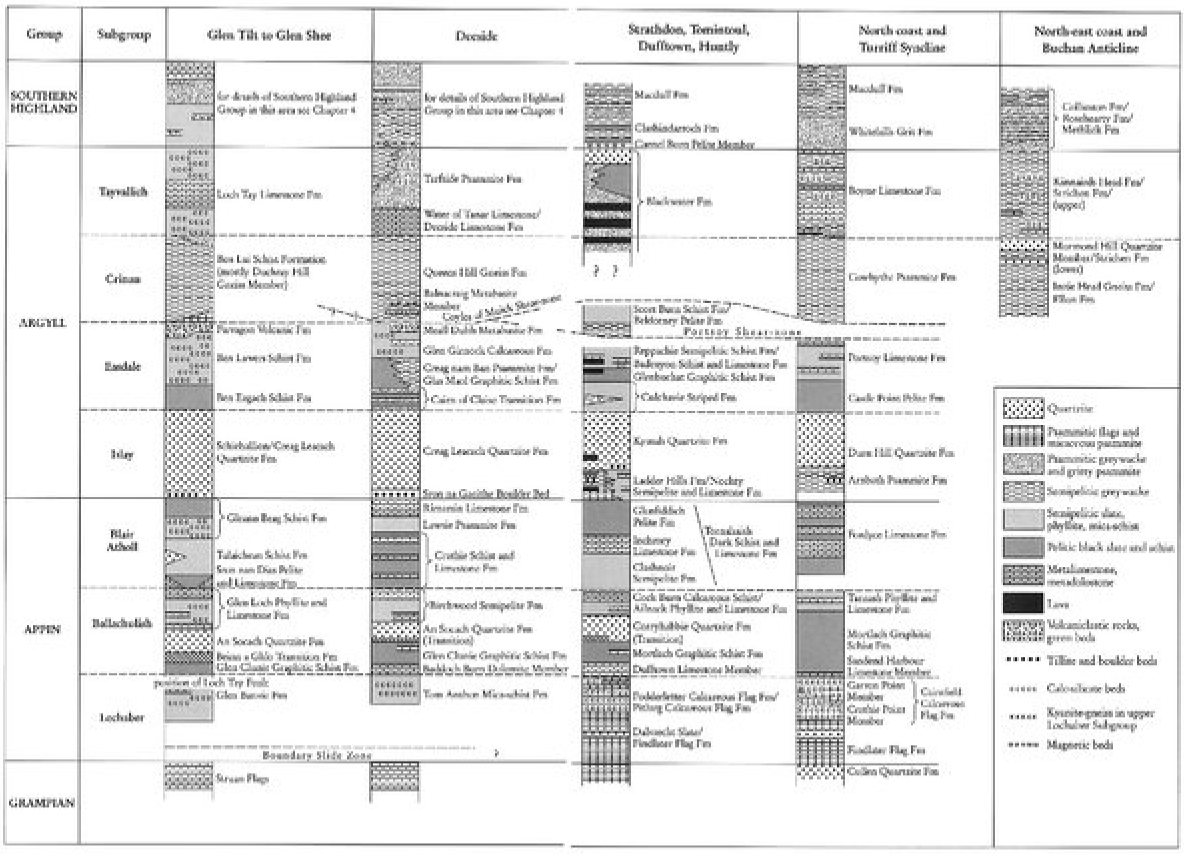
1.3.1 The North-east Grampian Basic Suite

The large intrusions of mafic and ultramafic rock are entirely confined to the Buchan Block and comprise the North-east Grampian Basic Suite. They are described in some detail in the *Caledonian Igneous Rocks of Great Britain* GCR volume (Stephenson *et al*., 1999) but the relationships between the intrusions, the Buchan metamorphism and the D3 deformation make the suite a vital time marker for the peak of the Grampian Event. A number of U-Pb mineral ages are now available from these intrusions, which imply that basic and silicic magmatism was focussed in a short time interval at around 470 Ma. It seems clear that the Grampian Event in the North-east Grampian Highlands was well under way by 480–475 Ma and was completed by *c.* 460 Ma (Oliver *et al*., 2000; Oliver 2001; Carty 2001; Dempster *et al*., 2002).

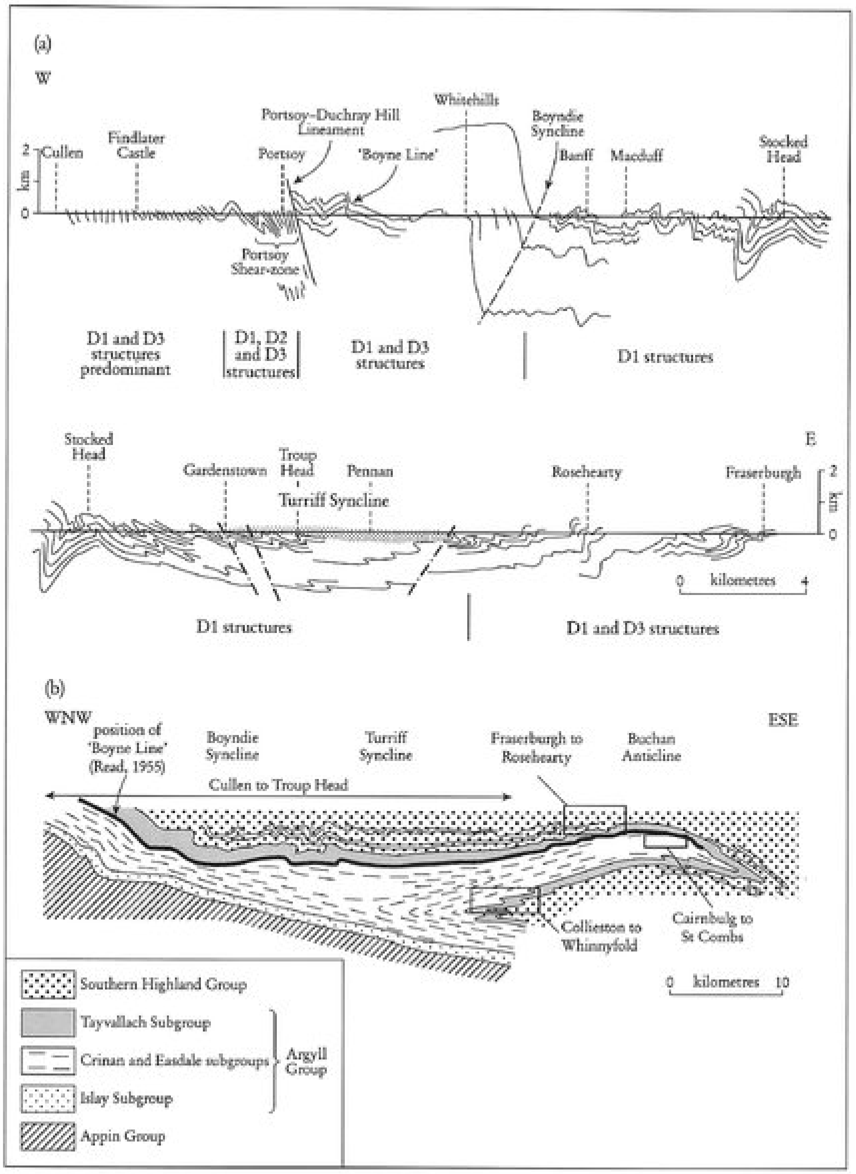
References



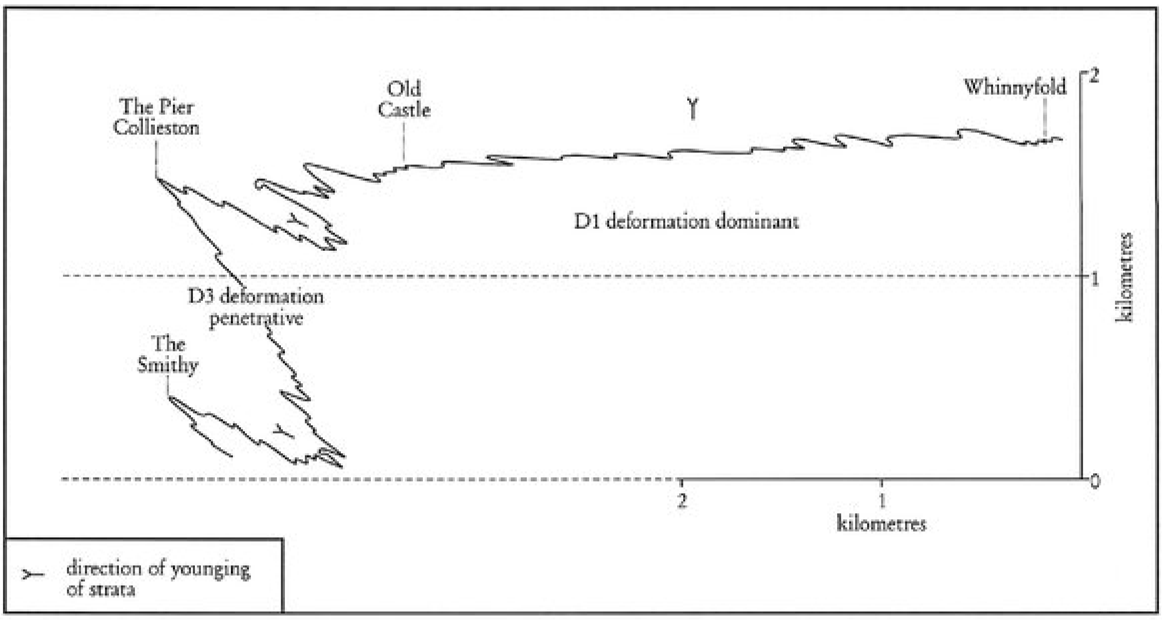
(Figure 6.1) Map of the North-east Grampian Highlands based upon BGS 1:50 000-scale maps and showing the location of Dalradian GCR sites. GCR sites: 1 Ben Vuirich, 2 Gilbert's Bridge, Glen Tilt, 3 Glen Ey gorge, 4 Cairn Leuchan, 5 Balnacraig, Dinnet, 6 Muckle Fergie Burn, 7 Bridge of Brown, 8 Bridge of Avon, 9 Kymah Burn, 10 Black Water, 11 Auchindoun Castle, 12 Cullen to Troup Head, 13 Fraserburgh to Rosehearty, 14 Cairnbulg to St Combs, 15 Collieston to Whinnyfold. BS Boundary Slide, KSZ Keith Shear-zone, PSZ Portsoy Shear-zone.



(Figure 6.2) Principal stratigraphical units in the Dalradian of the North-east Grampian Highlands, adapted from Stephenson and Gould (1995, figure 10). The columns are not to scale.



(Figure 6.3) (a) Generalized cross-section along the north coast of the North-east Grampian Highlands from Cullen to Fraserburgh showing the main structural features and dominant deformation/fold phases (Stephenson and Gould, 1995, figure 21, partly after Loudon, 1963). Stipple = the Old Red Sandstone outlier at Gardenstown. The entire section is included in the Cullen to Troup Head and Fraserburgh to Rosehearty GCR sites. (b) Highly generalized cross-section across the Buchan Block to illustrate the broad structure as envisaged by Read (1955) as modified by Kneller (1987). The approximate locations of GCR sites relative to the structure are shown.



(Figure 6.40) Composite cross-section of the coast section between Collieston and Whinnyfold, showing the overall fold pattern in a plane normal to the fold axes. From Mendum (1987).