Grampian Caledonides—introduction

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Stephenson, D, and Gould, D. 1995. British regional geology: the Grampian Highlands. Fourth edition. Reprint 2007. Keyworth, Nottingham: British Geological Survey.
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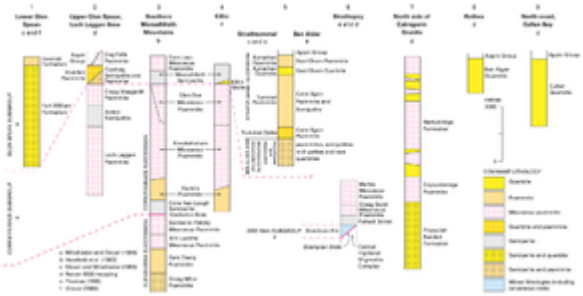
Contents

Introduction

The last two editions of this regional guide emphasised that, despite a long and distinguished history of research, aspects of the stratigraphy and structure of the Grampian sector of the Caledonides remained controversial. To a lesser extent that remains the position today. Continuous geological work since the publication in 1966 of the third edition of this guide has certainly led to an improved understanding of Grampian geology. The general outlines of the stratigraphy and structure are now well established. However, the precise status of a number of stratigraphical units, and the relationships between some of the major divisions still remain conjectural. Also there is no overall consensus about the detailed structural evolution of the Grampian Caledonides. We do now have a reasonably consistent correlation of local successions of metamorphic rocks throughout the Grampian Highlands, as shown in P915417 and (P915418). The distribution of the major lithostratigraphical units across the Grampian Highlands is illustrated in (P915411) and the generalised overall structure in P915427.



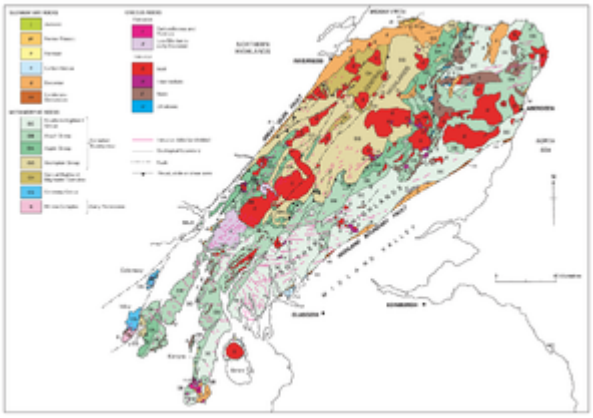
Lithostratigraphical units in the Grampian Group. P915417.

Composite lithostratigraphical sections (not

to scale) of the Appin, Argyll and Southern Highlands groups. P915418.

Stratigraphy

Much of the Grampian Highlands is underlain by a wide variety of metasedimentary and metavolcanic rocks which are now mostly assigned to the Dalradian Supergroup. However, the basal Grampian Group was previously considered to be part of an older succession which was equated with the Moine north-west of the Great Glen. Migmatites, which are spatially associated with the Grampian Group metasedimentary rocks in the northern part of the Grampian Highlands, were also correlated originally with the Moine (Hinxman and Anderson, 1915; Horne, 1923). Subsequent detailed studies of the migmatites, which referred to them as the Central Highland Division, retained their correlation with the Moine. However, this correlation has been questioned and their stratigraphical position is not fully resolved, as the following summary of the history of stratigraphical studies will show.



Solid geology of the Grampian Highlands. P915411.

Block diagram of major structures in the Grampian Highlands. P915427.

It was in 1891 that Sir Archibald Geikie first introduced the name ‘Dalradian’ for the varied group of metamorphic rocks which lies to the east of the Great Glen and which was thought to be younger than the Lewisian Gneiss of the North-west Highlands. The 1892 and 1910 editions of Bartholomew’s 10-miles-to-one-inch Geological Map of Scotland, compiled under Geikie’s direction, extended the name ‘Dalradian’ to include all the metamorphic strata east of the Moine Thrust. However, Geikie made it clear in his explanatory notes to the map that the ‘Moine Schists’ of the Northern Highlands were different in character from the ‘Dalradian’ rocks south-east of the Great Glen. As research proceeded, quartzofeldspathic rocks of ‘Moine Schist’ facies were mapped and described south-east of the Great Glen where they were variously referred to as, from north-east to south-west, ‘Granulitic Schists of the Central Highlands’ (Hinxman and Anderson, 1915), ‘Struan Flags’ (Barrow, 1904) and ‘Eilde Flags’ (Bailey, 1910). This left the Dalradian *sensu stricto* as an assemblage of

rocks lying mainly in the south-western and south-eastern parts of the Grampian Highlands, and characterised by the presence of black schists, quartzites and limestones with, in its upper part, metagreywackes.

Local successions were established in the Dalradian by detailed mapping throughout the first part of this century. This work was reviewed by Anderson (1948) who noted that the base of the 'Dalradian Assemblage' had been placed at different stratigraphical levels in different parts of the Grampian Highlands. He proposed that all rocks stratigraphically above, and including, a lowermost limestone should be regarded as Dalradian. All underlying strata should be included in a 'Moinian Metamorphic Assemblage'. This comprised a 'Central Highland Psammitic Group' made up of the quartzofeldspathic flags and gneisses regarded unanimously in the various local stratigraphical successions as Moinian, and an overlying 'Pelitic and Quartzitic Transition Group'. The latter included various quartzite/pelitic schist sequences recognised across the Grampian Highlands from Islay to the Banffshire coast and regarded by many of Anderson's contemporaries as Dalradian. In fact, the third edition of this guide referred to the 'Pelitic and Quartzitic Transition Group' as the lowest unit in the 'Dalradian Assemblage', which was subdivided into nine 'groups', the lower six groups forming the Lower Dalradian, the remaining three groups the Upper Dalradian. The various local stratigraphies established by detailed mapping during the first half of this century were all incorporated within this internal stratigraphical framework.

Major revisions, since 1966, of the internal stratigraphy of the Dalradian *sensu stricto*, have amended the internal correlations of the different local stratigraphical sequences. The Dalradian was accorded Supergroup status and subdivided into three groups (Harris and Pitcher, 1975). The correlation of the underlying quartzofeldspathic rocks of the Central Highland Psammitic Group with the Moine was retained, although it was realised that newly acquired isotopic ages of about 740 Ma from the Moine north-west of the Great Glen (van Breemen et al., 1974; Brook et al., 1976) brought this correlation into question. The isotopic ages, mostly from pegmatites, provided a minimum age for the original sedimentation and early deformation. In contrast, the quartzofeldspathic rocks south-east of the Great Glen were regarded as younger. This was based on the fact that they were known to grade locally upwards into the Dalradian sequence and to share, apparently, a common tectonothermal history, which of necessity was younger than the youngest Dalradian rocks, regarded as of uppermost Precambrian or lower Palaeozoic age. To overcome this age problem it was proposed that the Moine could be divided into an 'Older Moine' and a 'Younger Moine' with the possibility of an undetected unconformity separating the two lithologically similar divisions (Johnstone, 1975). The 'Older Moine' referred to rocks north-west of the Great Glen and cut by the pegmatites dated at about 740 Ma, the 'Younger Moine' referring to the quartzofeldspathic rocks which immediately underlie the Dalradian south-east of the Great Glen.

Detailed mapping south of Inverness over the last 20 years initially resulted in a subdivision of the Moine of the Grampian Highlands into an older migmatitic basement referred to as the Central Highland Division and an overlying sequence dominated by unmigmatised quartzofeldspathic flags termed the Grampian Group or Grampian Division (Piasecki and Van Breemen, 1979a; 1979b; Piasecki, 1980). Deformed pegmatites from shears which locally define the contact of the Grampian Division with the migmatitic rocks were dated at about 750 Ma by numerous Rb-Sr isotopic analyses of muscovite, leading to the proposal that the Central Highland Division is a crystalline basement, equivalent to the 'Older Moine' exposed north-west of the Great Glen. Such an interpretation has been challenged (see Chapter 5; Lindsay et al., 1989). Instead it has been proposed that the Central Highland Division comprises the migmatitised lower part of the Grampian Group, which essentially reverts to the conclusion of the original geological surveys (Hinxman and Anderson, 1915; Horne, 1923). To emphasise that the migmatites are a lithodemic unit the informal lithostratigraphical term 'Division' is abandoned and the migmatites in this guide are referred to as the 'Central Highland

Migmatite Complex'.

The gradational contact seen locally between the Grampian Group metasedimentary rocks and the basal rocks of the Dalradian Supergroup (as defined by Harris and Pitcher, 1975), together with their common tectonothermal history formed the basis for the subsequent incorporation of the Grampian Division as a formal group in an extended Dalradian Supergroup (Harris et al., 1978). Such a proposal is not accepted unanimously and the separation of the Grampian Group from the Dalradian Supergroup, largely on the basis of perceived lithological contrasts, does attract significant support (Thomas, 1980; Anderton, 1985). The similarities between the Grampian Group, the Central Highland Migmatite Complex and the Moine north-west of the Great Glen remain, although no detailed correlations have been offered and the Grampian Group rocks are no longer referred to as 'Younger Moine'.

The formal hierarchical lithostratigraphy of the Dalradian Supergroup is shown in P915417 and P915418. Early impetus for a unified Dalradian lithostratigraphy was provided by the recognition of similar sedimentary associations extending right across the Grampian Highlands (Sutton and Watson, 1955; Knill, 1959; Roberts, 1966; Rast and Litherland, 1970). A remarkable agreement of stratigraphical detail is, in fact, preserved in parts of the succession along the whole strike length of over 700 km of the British Caledonides from Western Ireland to the Banffshire coast. Application of modern sedimentological concepts has shown that the initial, predominantly sedimentary pile comprised a complex three-dimensional juxtaposing of different lithofacies and lacked a simple 'layer-cake' structure (Litherland, 1980; Anderton, 1985; Glover and Winchester, 1989). Syndepositional (possibly listric) faulting as well as later polyphase folding and ductile shearing contribute to the overall complexities (Anderton, 1988).

The original gross lenticular nature of the sequence is attributed to the continually changing internal morphology of the depositional sedimentary basins. The polyphase deformation has also both thinned and thickened the original sedimentary-volcanic pile (Borradaile and Johnson, 1973), which now youngs overall from the north-west to the south-east and south-west.

There is also a general temporal change from stable estuarine, coastal or intertidal environments during Grampian and Appin group times to unstable turbidite environments with accompanying volcanicity at the time of deposition of the Argyll and Southern Highland groups (Fettes and Harris, 1986). After early sedimentation on a single shelf, increasing instability, attributed to progressive lithospheric stretching, produced a series of fault-bounded basins. Submarine fan deposits recognised in the Southern Highland Group draped over the faults controlling basin development on a subsiding continental shelf (Anderton, 1985).

Episodes of igneous activity generally took place at the time of the later periods of basin deepening; there was little contemporaneous igneous activity associated with the early sedimentation. The thickest volcanic sequences overlie areas of supposed greatest crustal attenuation (Anderton, 1985). As the chemical composition of the extruded lavas is similar to those formed at extensional plate margins it has been suggested that the attenuation led to actual crustal rupturing with small basins possibly floored by oceanic crust (Graham and Bradbury, 1981).

Several occurrences of syngenetic mineralisation in the Argyll Group have been discovered as a result of detailed geochemical, geophysical and geological mapping and increased mineral exploration activity in the past 20 years. The most important of these are the Aberfeldy baryte deposits, situated near the top of the Ben Eagach Schist in the Argyll Group. The synsedimentation concentration of metals, which extends intermittently over a strike length of at least 90 km, from Loch Lyon to Loch Kander, is thought to have occurred in brine pools at the edge of small fault-bounded basins (Coats et al., 1984).

Structure and metamorphism

Current structural interpretations of the Grampian Caledonides are still based upon those proposed by E B Bailey, which drew on 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 Southern Highlands are disposed in large recumbent folds. The lower limbs of many of these folds are partly replaced by low-angled, extensional faults, termed ‘slides’, with postulated movements of several kilometres. In 1922 Bailey produced a comprehensive synthesis in which major slides were perceived as fundamental tectonic dislocations separating nappe complexes, each complex having its own stratigraphical succession and structural style. Initially three such nappe complexes were recognised and named, in ascending structural order, the *Ballappel Foundation* (from the type areas of Ballachulish, Appin and Loch Eilde), the *Iltay Nappe* (from Islay 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.

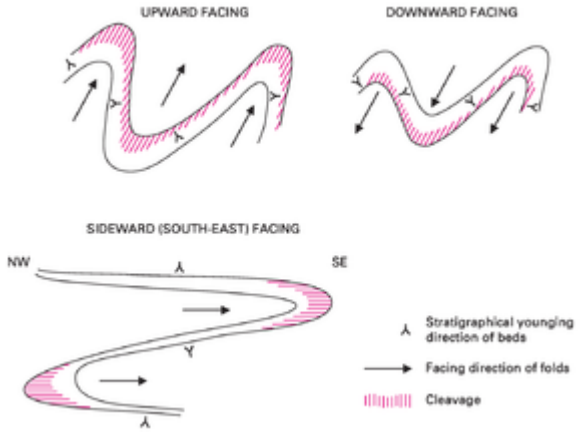


Diagram to illustrate the concept of facing direction of folds as defined by Shackleton (1958). P915415. P915415.

A better understanding of the stratigraphy, following the recognition of sedimentary structures in quartzitic rocks as way-up indicators, led to modifications of the early structural models. Bailey himself used such observations in the Loch Leven area to completely reverse the order of superposition used in his 1922 paper and revised his structural interpretation in a further major review paper (Bailey, 1934). Further developments and modifications resulted from the recognition of graded units and other internal structures in turbiditic rocks, first applied by Shackleton (1958) to the structure of the Southern Highlands and the Highland Border. The concept of ‘facing’ was introduced as a means to describe the structural ‘way-up’ of strata (P915415). Shackleton (1958) 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 is commonly used to infer the direction of tectonic transport. H H Read, who had commenced work in the north-east Grampians as a member of the Geological Survey, initiated research which resulted in several detailed studies of the Banff Nappe and related structures.

Bailey’s model remained the basis of structural descriptions of the Grampian Highlands until the 1960s and was used in the last edition of this regional guide, in which descriptions of the Ballappel Foundation and Iltay Nappe were extended north-eastwards as the ‘Northern Grampians Nappe Complex’ and ‘Southern Grampians Nappe Complex’ respectively (Johnstone, 1966).

Continuing detailed stratigraphical and structural studies have resulted in further refinements to the Bailey model. Several alternative structural models have emerged, although many of the major fold structures originally named by Bailey are still recognised. However, detailed interpretations of the relative ages and original geometry of differing sets of folds and their overall tectonic significance remain problematical. Many of Bailey's slides are still recognised as important and complex zones of low-angled tectonic dislocation and stratigraphical attenuation. However, it has been shown that, on a regional scale, both the structure and the stratigraphy of the Grampian Highlands are more integrated and continuous than inferred by Bailey, with elements of the succession being traced vertically through the nappe pile as well as laterally along the full strike length. Hence most of the Dalradian must be regarded as autochthonous or parautochthonous and the slides may have lost much of their original significance as major tectonic and stratigraphical boundaries. In most current models, where tectonostratigraphical boundaries are recognised they are commonly defined by cross-strike lineaments. Such lineaments are taken to represent fundamental, deep-seated crustal fractures which have influenced sedimentation, igneous activity and structural development over a long period of time. They can have a marked influence on the outcrop pattern and are recognised by various combinations of features such as abrupt lateral facies changes in the metasedimentary sequence, sites of igneous activity, geochemical and geophysical changes and zones of structural discontinuity.

The structure of the Grampian Caledonides is discussed in detail in Chapter 6. However, in order to describe the stratigraphy of the area in Chapter 5 it is necessary to have some knowledge of the major fold structures and tectonic dislocations that influence the disposition of the lithostratigraphical units. Most were established by E B Bailey and are shown on (P915427). They are described below without recourse to complex and controversial discussions of deformation phases, relationships with adjacent or other structures, metamorphic textures or related fabrics.

The overall structure of the Grampian Highlands is most easily described and understood with reference to structures in the South-west Highlands (Roberts and Treagus, 1977). Here the major folds are seen to diverge on either side of a central *Loch Awe Syncline* which is interpreted as an early primary structure. Apparently geometrically similar structures farther to the north-east include the *Ben Lawers Synform* and *Sron Mhor Syncline* but these are actually due to later refolding events. To the south-east of the Loch Awe Syncline, the *Ardrishaig Anticline* is interpreted as the core of a large SE-facing nappe, the *Tay Nappe*, which dominates the overall structure of the Southern Highlands. The Tay Nappe is flat-lying, although in the south-west it is folded across a broad arch known as the *Cowal Antiform*. The erosion level is such that most of the outcrop constitutes part of the inverted limb of the nappe, 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 Zone, the Tay Nappe is bent downwards to form the *Highland Border Steep Belt*. The hinge zone of the nappe thus becomes downward facing as a synformal anticline, recognised in the Southern Highlands as the *Aberfoyle Anticline* (Shackleton, 1958).

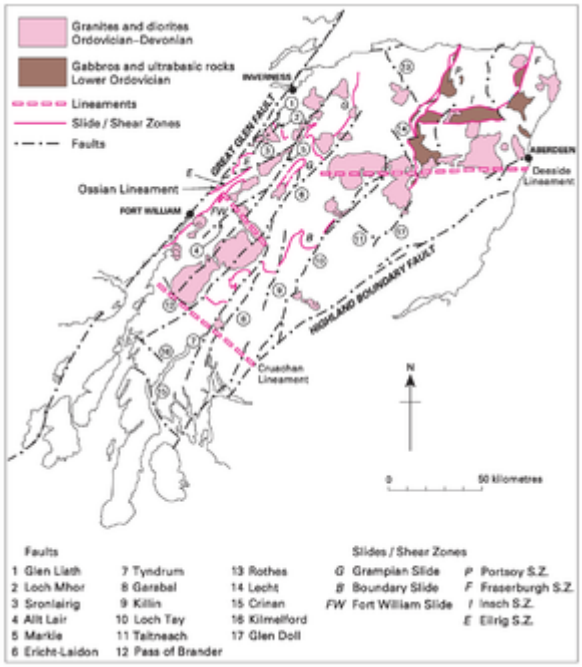
To the north-west of the line of the Loch Awe Syncline is a pile of apparently NW-facing folds, including the *Islay Anticline* and the folds of the original 'Ballappel Foundation' such as the *Beinn Donn Syncline, Ballachulish Syncline* and *Appin Syncline* (Treagus, 1974; Roberts, 1976). Several major slides are recognised within this nappe pile. The *Boundary Slide* transgresses several fold limbs in the upper part of the overall pile resulting in the attenuation or removal of large parts of the Dalradian succession. For most of its length it is coincident with the boundary between the Grampian Group and Appin Group. Towards the base of the pile in Lochaber, the *Fort William Slide* locally forms the boundary between the Grampian Group and lower parts of the Appin Group. These two slides were the major tectonostratigraphical boundaries in the early stratigraphical

interpretations of Bailey.

Because of the mushroom-like structure resulting from the divergent facing directions of the major folds, many of the early models suggested that a fundamental 'root zone' lay beneath the Loch Awe Syncline (Rast, 1963). This zone was then projected north-eastwards beneath the Sron Mhor Syncline and the associated *Tummel Steep Belt* (Sturt, 1961; Harris, 1963). However, it has subsequently been shown that these folds, and the steep belt, are later structures which postdate, and therefore fold, the early major recumbent nappes (Roberts and Treagus, 1979; Bradbury et al., 1979). Folds immediately to the north-west of the Loch Awe Syncline are now known to face downwards and hence south-eastwards, including those of the Glen Orchy area (Thomas and Treagus, 1968) and the *Atholl Nappe* (Thomas, 1979; 1980). Thus, if a root zone does exist, it must lie farther to the north-west, possibly in the region of a 4 km-wide zone of upright, isoclinal folds known as the *Ossian-Geal Charn Steep Belt* (Thomas, 1979; 1980). Other workers, whilst recognising the existence of the steep belts, reject the idea entirely of any connection with a root zone.

Structures in the northern part of the Grampian Highlands are still being elucidated, but it has been suggested that the Grampian Group and the Central Highland Migmatite Complex contain comparable structures and share a common history of structural development with those of the overlying Atholl Nappe (Lindsay et al., 1989). The status of the *Grampian Slide* which separates the migmatitic from the non-migmatitic units is a matter of current debate and is discussed in Chapters 5 and 6. Major folds which influence the outcrop pattern considerably are recognised in the west of this area, above the Fort William Slide. They include the *Stob Ban Synform* and the *Appin Synform* which are responsible for large infolds of Appin Group rocks within the Grampian Group.

In the north-east Grampians, recumbent folds which may be correlated with those of the Tay Nappe have been identified in sections around Collieston on the east coast. However, the area is dominated by broad NNE-trending late folds, principally the *Turriff Syncline* and *Buchan Anticline*. Within these structures the upper parts of the Dalradian succession occur in right-way-up sequences. Early interpretations classed this succession as a separate 'Banff division' in an allochthonous 'Banff Nappe', which was separated by a slide from an underlying Dalradian sequence continuous with that of the Central Highlands (Read, 1955; Read and Farquhar, 1956). Although other authors have also suggested that this area is allochthonous (Sturt et al., 1977; Ramsay and Sturt, 1979), current interpretations suggest that the succession is essentially autochthonous, passing downwards from the Southern Highland Group into an Argyll Group succession which correlates with that farther to the south-west (Harris and Pitcher, 1975; Ashworth, 1975; Harte, 1979; Treagus and Roberts, 1981; Ashcroft et al., 1984). If this is so, then it is not necessary to invoke the presence of a Banff Nappe and underlying slide. However, the area is bounded to the west and south by major shear belts 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 which can be traced from the north coast to the Glen Shee area (Fettes et al., 1986). To the west of this 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.



Distribution of lineaments, shear zones and major brittle faults in the Grampian Highlands. P915450.

The main outcrop pattern of the Dalradian as depicted in P915411 is largely governed by the major folds described above. During the later stages of orogenesis, many of these structures were further modified by block uplift and faulting, which occurred at different rates and at different times throughout the Dalradian outcrop (Harte et al., 1984; Dempster, 1985). The differential uplift resulted in an outcrop pattern that reveals wide variations in levels of exposure. Later, post-orogenic, brittle fault movements have displaced boundaries, by several kilometres in some cases (Chapter 16). Between the major boundary faults of the Great Glen and the Highland Boundary lie a whole series of parallel, NE-trending faults showing sinistral displacement. Of these, the *Glen Markie, Ericht–Laidon, Tyndrum, Bridge of Balgie* and *Loch Tay faults* have particularly significant displacements (P915450). In some areas, appreciable displacements, largely of a vertical nature, also occur on NW-trending faults such as the *Rothes* and *Pass of Brander faults*, some of which may reflect fundamental deep level tectonostratigraphical lineaments (Chapter 6).

The Dalradian rocks occur at the surface in a variety of metamorphic states, illustrated best by the pelitic rocks which range from slate and phyllite, especially in the south and east, to coarse-grained schists, gneisses and migmatites in the north. In detail, as outlined in Chapter 7, the metamorphic development in space and time was complex, but the overall pattern exposed can be described in terms of two main components:

- an overall thermal anticline plunging towards the south-west (Kennedy, 1948), resulting in greenschist and epidote-amphibolite facies rocks in the South-west Highlands, along the Highland Border and in Buchan; the rocks there are generally at the higher structural and stratigraphical levels. Amphibolite facies rocks in the north are mainly of the lower stratigraphical units, the Grampian Group and the Central Highland Migmatite Complex.
- a superimposed area of high-grade rocks in the eastern Grampian Highlands, where there are also numerous layered basic/ultrabasic intrusive complexes.

This overall rather simple pattern obscures the fact that the pressure conditions under which the metamorphism occurred varied from relatively high pressure in the south-west, south-east and north

(Barrovian metamorphism) to intermediate/low pressure in the north-east (Buchan metamorphism). It has also been shown, from mineral transformations, that in some places there were pressure increases during the metamorphism, possibly as a result of tectonic thickening.

Over most of the Grampian Highlands the peak metamorphic mineral assemblages and textures, developed during the nappe folding, are largely preserved; there is, however, widespread, but mostly minor, retrogression of the rocks associated with the final phases of deformation and uplift.

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