Metamorphism, Grampian Highlands

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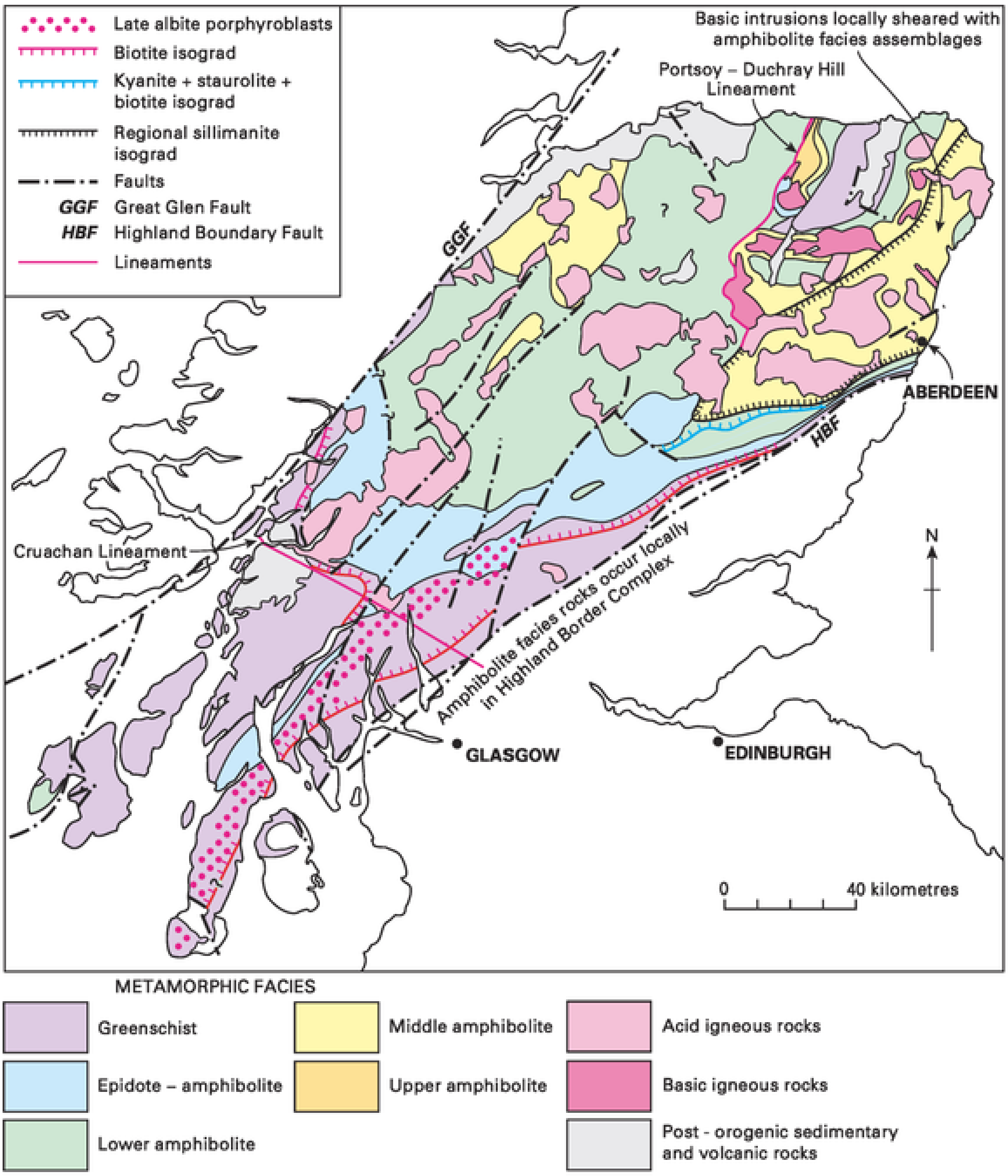
Metamorphism

Traditionally the metamorphic grade or facies in the Grampian Highlands is referred to zones defined by a set of index minerals developed in pelitic rocks. These zones in the south-east Highlands were first described by Barrow (1893; 1912). Slightly modified by Tilley (1925) the *Barrovian zones* (chlorite–> biotite–> garnet–> staurolite–> kyanite–> sillimanite) were subsequently extended across the Southern, South-west and Central Highlands, mainly by Elles and Tilley (1930) and Kennedy (1948). At the same time Read (1923; 1952) identified a different style of metamorphism in the North-east Highlands which formed the basis of the *Buchan zones* (biotite – > cordierite–> andalusite–> sillimanite). Subsequently Winchester (1974), working mainly from assemblages in calc-silicate rocks, which he was able to correlate on an empirical basis with the pelitic zones, extended the Barrovian zones across the remaining areas of the Grampians region.

The two zonal sequences define different styles of metamorphism or facies series. Read (1952) regarded the Buchan and Barrovian styles of metamor-phism as the products of separate events. However, Fettes et al. (1976) showed that the two zonal sequences reflected a regional variation from an intermediate/high-pressure facies series in the South-west Highlands through to a low-pressure facies series in the North-east Highlands. This transition between the Barrovian and Buchan series was formalised by Harte and Hudson (1979) who defined four zonal sequences, namely, in order of decreasing pressure: *Barrovian* (biotite–> garnet–> staurolite–> kyanite); *Stonehavian* (biotite–> garnet–> chloritoid + biotite–> staurolite–> silliman-ite); *West Buchan* (biotite–> cordierite–> andalusite–> staurolite–> kyanite); and *East Buchan* (biotite–> cordierite–> andalusite–> sillimanite).



Metamorphic zones of the Grampian Highlands (modified after Fettes et al., 1985). P915433.

Distribution of facies

Fettes et al. (1985) and Harte (1988) devised metamorphic facies maps of the Grampian region based on the wealth of published data on the distribution of pelitic and calc-silicate index minerals allied to data from assemblages in basic rocks (Wiseman, 1934).

The facies map (P915433) shows the South-west Highlands as lying almost wholly in the greenschist facies. The grade rises to the amphibolite facies in the north (at lower stratigraphical levels) and east (at similar stratigraphical levels) with the greenschist facies wedging out northwards against the Great Glen and narrowing markedly eastwards against the Highland Boundary Fault, so that on the Stonehaven coast section the metamorphic grade rises rapidly northwards from the fault. Greenschist facies assemblages reappear northwards in the Turriff Syncline of Buchan.

The greater part of the higher-grade area lies in the lower amphibolite facies, characterised by kyanite + staurolite- and andalusite + cordierite-bearing assem-blages. In the North-east Highlands and in the northern Central Highlands, middle and upper amphibolite facies rocks are found. These are defined, respectively, by sillimanite + muscovite- and sillimanite + K-feldspar-bearing assemblages. The sillimanite-bearing rocks are commonly characterised by the presence of quartzofeldspathic lenses and augen. They have been referred to as migmatites (e.g. Johnstone, 1966), although they have evolved through a wide variety of processes including partial melting, metamorphic segregation and metasomatism; they are therefore better termed sillimanite-gneisses.

The facies boundaries or isograd surfaces are broadly flat lying in the Central Highlands, steepening markedly against the Highland Boundary Fault. This general disposition of facies and facies boundaries gave rise to the concept of a 'thermal anticline', the high-grade rocks of the Central Highlands forming the core and the 'axis' plunging to the south-west along the spine of epidote-amphibolite facies rocks in Knapdale and Cowal (Kennedy, 1948).

The regional facies pattern is taken to reflect the peak conditions of meta-morphism. Most of the early workers regarded this metamorphic imprint as resulting from a single metamorphic event, albeit *polyphasal* with progressive phases broadly related to burial and retrogressive phases broadly related to uplift. However, the possibility exists that in the northern Central Highlands the rocks were subjected to more that one metamorphic event and are *poly-metamorphic*. In these cases the facies pattern is likely to be composite, reflect-ing the effects of the various metamorphisms.

The nature of the chemical reactions governing the development of the various index zone assemblages and isogradic surfaces has been extensively studied. A full discussion of these is not possible here but excellent summaries are given, amongst others, by Atherton (1977), Harte and Hudson (1979), and Chinner and Heseltine (1979).

Metamorphic provinces

Harte (1988) divided the Grampian metamorphic rocks into six provinces or domains on the basis of their metamorphic characteristics. The provinces are as follows:

South-west province

Covers the area south-west of the Cruachan Lineament. The province is defined by greenschist-facies assemblages and high pressures. The area also includes thick accumulations of basic lavas and associated sills (Graham, 1976).

South-east province

Lies east of the Portsoy – Duchray Hill Lineament and between the Highland Boundary Fault and the sillimanite zone. This area, which encompasses the type area of Barrow's zones, is characterised by intermediate/high pressure and high thermal gradients (narrow meta-orphic zones) adjacent to the Highland Boundary Fault and has a distinctive uplift history.

Southern province

Comprises the area bounded to the west by the Cruachan Lineament, to the east by the Portsoy–Duchray Hill Lineament, to the north by the Tummel Steep Belt and to the south by the Highland Boundary Fault. Its metamorphic characteristics are transitional between provinces 1 and 2. A zone of albite porphyroblasts of regional extent occurs between Balquidder, Cowal and Kintyre. The zone straddles the junction of the greenschist and epidote-amphibolite facies and the boundary between the Southern and South-west provinces; the porphyro-blasts are believed to have developed relatively late in the metamorphic history.

Buchan province

Comprises north-east Scotland east of the Portsoy–Duchray Hill Lineament and is characterised by low-pressure metamorphism. The highest- grade rocks are granulite-facies hornfelses found in the aureoles of the basic complexes in the Buchan area. These hornfelses are characterised by garnet-orthopyroxene-cordierite and related assemblages (Droop and Charnley, 1985).

Central province

The area north of the Tummel Steep Belt and west of the Portsoy–Duchray Hill Lineament. The area is characterised by marked increases in pressure during the peak metamorphism.

North-west province

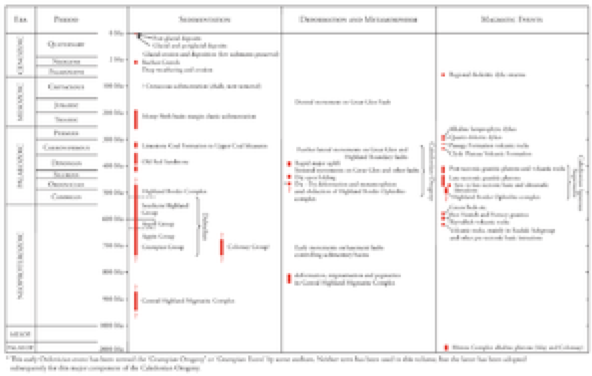
The remaining part of the Grampian Highlands. Part of this area may be polymetamorphic.

To these six provinces a small seventh one near the Great Glen south of Fort Augustus may now be added. Here Phillips et al. (1993) have proved greenschist facies rocks at low structural levels beneath the Eilrig Shear Zone, which separates them from amphibolite-facies rocks above (P915433).

Metamorphic history

Early workers regarded deformation and metamorphism as single events, although there was considerable debate on the relative ages of the two. For example, Bailey (1923) regarded the two as contemporaneous, Read (1952) suggested that the metamorphism was later and Elles and Tilley (1930) believed that the deformation was later. Much of this debate was based on the spatial attitude of the isogradic surfaces and how far, if at all, this reflected deformation. However, detailed textural studies by, amongst others, Rast (1958), Sturt and Harris (1961), Johnson (1962; 1963), Harte and Johnson (1969) and Upton (1986) showed that the development of the metamorphic assemblages could be referred to stages marked by deforma-tional phases. The results of these and similar studies have shown that pro-gressive metamorphism occurred during the main nappe-forming movements (D_1 and D_2) and reached a peak around the time of the nappe-folding events (D_3). Retrogressive metamorphism took place during uplift and associated movements (D_4). The isograd surfaces were folded by these late structures, for example, the Boyndie and Ben Lawers synclines and the Highland Border Downbend.

In general, progressive metamorphism is assumed to have taken place along a simple curve on a pressure–temperature plot. However, in central Perthshire, Dempster and Harte (1986) document a significant increase in pressure close to the peak of metamorphism, with the replacement of chlori-toid + biotite by garnet + chlorite as well as the localised growth of kyanite-and staurolite-bearing assemblages. They ascribe the pressure increase, of about 2 to 3 kb, to tectonic movements associated with the development of the D_3 Tummel Steep Belt. In the North-east Highlands, Baker (1985) and Beddoe-Stephens (1990) detailed a similar increase in pressure which they suggested is due to westward overthrusting during D_3; this resulted, locally, in the inversion of andalusite to kyanite over a restricted area lying immediately west of the Portsoy–Duchray Hill Lineament.



Geological sequence and events in the Grampian Highlands. P915452.

It has been suggested that the growth of sillimanite in the Buchan area may also depart from the simple progressive model. Chinner (1966) believed the sillimanite formed in response to a thermal overprint on a depth-controlled metamorphism. Ashworth (1976) suggested that, at least in the Huntly–Portsoy area, the sillimanite developed as a result of the thermal effects of the basic complexes, a suggestion supported by the work of Fettes (1970) and Pankhurst (1970) who believed that the basic masses were intruded close to the peak of metamorphism. Harte and Hudson (1979) recognised two phases of sillimanite growth, one regional and the other related to the basic masses, although they considered that the two phases were closely linked in time. They delineated a 'regional' sillimanite isograd within the mapped sillimanite zone (P915433), and regarded this isograd as the limit of the sillimanite zone prior to the intrusion of the basic complexes.

In the northern Central Highlands migmatisation and the development of metamorphic porphyroblasts may have begun before 750 Ma, that is prior to movement on the Grampian Slide. In the Southern and North-east Highlands the peak of metamorphism occurred at around 520 to 490 Ma (the Grampian Event of some authors; (P915452)). The question then arises whether the meta-morphism was polymetamorphic or a single event and, if the latter, whether metamorphic crystallisation was effectively suspended or interrupted for a period of over 200 Ma or whether there is marked diachroneity or differences in the tectonothermal evolution across the region. At present the geochrono-logical and geological evidence cannot be satisfactorily reconciled and the metamorphic evolution remains equivocal.

In the Southern and North-east Highlands retrogressive metamorphism took place from 490 to 390 Ma although considerable regional variation occurred in the rate and timing of uplift phases (Dempster, 1985). Watkins (1983) has argued that the growth of the albite porphyroblasts in the South-west Highlands occurred during the retrogressive phase. He suggests that this growth of albite was facilitated by dehydration fluids trapped in D_3 structures. Dymoke (1989), however, has suggested that the growth of albite was a late prograde reaction initiated by, and spatially related to, zones of D_3 movements, the rocks being close to the temperature conditions which they achieved during the pre-D_3 peak of regional metamorphism.

Presssure–temperature estimates

A considerable body of data has been produced on the pressure and tempera-ture (PT) conditions of metamorphism. These highlight the variation in pressure within various facies and index mineral zones. For example, peak temperatures in the kyanite + staurolite zone were between 500°C and 550°C across the region but pressures varied from 9–10 kb (c. 30km depth) in the Central Highlands (Moles, 1985; Baker, 1985), through 5–6 kb (c. 18 km) in Angus (Dempster, 1983; 1985; McLellan, 1985) to 3–4 kb (c. 11 km) in Banff-shire (Hudson, 1985; Beddoe-Stephens, 1990). Also, Graham

(1983) recorded pressures of 8–10 kb (c. 30 km) for epidote-amphibolite facies rocks in the South-west Highlands compared with 2–3 kb (c. 8 km) for similar grade rocks in Banffshire (Hudson, 1985). The highest temperatures occurred in the sillimanite + K-feldspar zones associated with the inner aureoles of the North-east Highlands basic complexes, with measurements of 800–850°C (Droop and Charnley, 1985). These extreme conditions are believed to have occurred in the roof zones of the basic masses (Fletcher and Rice, 1989).

The wealth of PT data allied to detached mineral cooling ages has allowed the erection of sophisticated PT evolution paths (at least for the later phases) for the South-east Highlands (Dempster, 1983; 1985); these illustrate regional variation as well as phases of rapid uplift and cooling in the periods 460 to 440 Ma and about 410 Ma.

Metamorphic models

A great variety of models has been produced to explain the metamorphic pattern. The models have included the thermal effects of older granites (Barrow, 1912), burial (Elles and Tilley, 1930), the tectogen or mountain root model of Kennedy (1948), uprising migmatite domes (Read, 1952; Read and Farquhar, 1956), the self generation of heat in a tectonically thickened crust (Richardson and Powell, 1976), and crustal overplating on a NW-directed thrust duplex analagous to the Alps (Bradbury, 1985).

The North-east Highlands were not only characterised by high geothermal gradients during metamorphism, but also by a suite of late- to post-kinematic granites and, uniquely in Scotland, basic and ultramafic complexes. However, although it is accepted that high heat flow is a factor in the metamorphic evolution, its exact cause is uncertain. It has been ascribed to the influence of deep-seated magmatic intrusions (Harte and Hudson, 1979) and lithospheric stretching (Kneller, 1985).

In the South-east Highlands the extremely steep lateral thermal gradients and possible inverted zoning have been related to some form of underthrust-ing by cold crust (Chinner, 1978), the junction of a Dalradian block heated and uplifted by deep-seated intrusions against a subsiding basin filled with cold sediment (Harte and Hudson, 1979), and the southward translation of a relatively hot Tay Nappe (Chinner, 1980).

The South-west Highlands contrast markedly with the Buchan region in having an intermediate- to high-pressure facies series, an absence of granite plutons and thick accumulations of basic lavas and related intrusions which may have produced a dense relatively thick crust which suppressed the geothermal gradient.

In the Balquidder area Watkins (1984) suggested that the inverted metamor-phic zoning noted by Tilley (1925) is related to the southward translation of relatively hot rocks, in the core of the Tay Nappe, over cooler strata during D_2 (cf. Dempster and Bluck, 1991). However, Dymoke (1989) and C M Graham (oral communication, 1992) have established that the position of the present garnet isograd in north Kintyre is a product of retrogression. The 'original' garnet isograd, related to the progressive metamorphism, lay to the south-east of the present position with a symmetrical arrangement to the Cowal Antiform; this negates the arguments for inversion, at least in the South-west Highlands.

The various models illustrate the complex variations imposed on the meta-morphic pattern during the progressive phases of metamorphism. Dempster (1985) has also shown that variable uplift and tectonism during the retrogres-sive phases, involving the juxtaposing of relatively warm and cold rocks, distorts and complicates the facies pattern.

These regional variations in the metamorphic history make it difficult to sustain any simple single model for the Grampian Highlands. The six provinces recognised by Harte (1988) may therefore represent domains with different metamorphic histories.

Harte (1988) regarded the boundaries to the domains or blocks as part metamorphic and part tectonic. This concept is built in part on the work of Ashcroft et al. (1984) and Fettes et al. (1986), who recognised the long-lived influence of major lineaments such as the Cruachan and Portsoy–Duchray Hill lineaments on the evolution of the Grampians. In particular the linea-ments delimit domains with different sedimentological and tectonothermal histories. Regionally, therefore, the metamorphic pattern was influenced by variations in the thickness and nature of the sedimentary pile, degrees of compression, tectonic thickening or lithospheric stretching, igneous events and rate and degree of uplift, all of which produced a complex series of pressure–temperature–time curves for the Grampian region.

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