Barrow's Zones in Glen Esk, Angus, Scotland

Ben Harte

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Purpose

To examine the sequence of regional metamorphic zones developed in Dalradian rocks within the type area of Barrow (1893, 1912); and to note some of the lithological and structural features seen in the Dalradian Supergroup and the immediately adjacent Highland Border Complex (HBC).

Access

The field itineraries are in Glen Esk and commence at the foot of the Glen where the B966 crosses the North Esk at Gannochy (Figure 1) and (Figure 2), near the village of Edzell. To reach Edzell from the north (Aberdeen and Stonehaven) leave the A90 about 12 km south of Stonehaven, and take the B966 to Fettercairn and Edzell. To reach Edzell from the south (Perth and Dundee) leave the A90 just north of Brechin, and take the B966. Detailed directions from Gannochy are given within the itinerary sections.

In this itinerary various options are indicated according to the means of transportation and time available. The Glen roads are not well suited to large buses or motor coaches, but it is possible to use a small bus for 20 to 25 persons. Bus parties should walk (about 5 km) all the way from the Highland Border Complex to the staurolite zone (localities 1 to 4), and thereafter proceed by bus to the roadside nearest to localities 5, 6 and 7. With a car it is generally possible to approach within 1 km of each locality before it is necessary to walk. Further notes are given in the guide for each locality. Two options (localities 6 and 7) are given for examining sillimanite zone rocks.

The time required for examination of the rocks from the Highland Border Complex to the first sillimanite zone locality (Localities 1 to 6, (Figure 2), (Figure 3) is about five hours. Note that the main river (river North Esk) cannot usually be crossed except by a bridge. The second sillimanite zone option (locality 7, (Figure 2)) shows better mineral assemblages and more lithologies than locality 6, but involves an extra drive of about 14 km further up Glen Esk, and a steep uphill walk; it requires an extra 2 hours at least.

The area is covered by Ordnance Survey 1:50,000 sheet 44, and 1:25,000 sheets 389 and 395; it is within British Geological Survey sheet 66W.

There are public conveniences beside the recreation area on the northern margin of Edzell. There are also hotels and cafes in Edzell; and there is also a cafe in Glen Esk at the Retreat museum near Tarfside (Figure 2).

Introduction

This excursion to Glen Esk provides localities for seeing each of Barrow's zones: chlorite, biotite, garnet, staurolite, kyanite, sillimanite (Barrow 1893, 1912; Tilley 1925). Barrow's Zones lie in the southern part of the region of complex metamorphism found in the Dalradian rocks of the Eastern Highlands of Scotland (Figure 1).

Studies in this region of the Eastern Highlands played a critical role in the development of the concepts of regional metamorphism (Horne, 1884), and the recognition of metamorphic zones (Barrow, op. cit.). For an overview of 'regional' metamorphism in the whole of the region of (Figure 1), see Harte & Hudson (1979). In addition to this guide there are itineraries for other parts of the region by: Hudson & Johnson (2014) for the Buchan metamorphic zones near Banff; Johnson & Kneller (2014) for the area near Fraserburgh; Johnson & Fischer (2014) for the area to the E and SE of Fraserburgh; Harte, Booth & Fettes (2015) for the coastal section from Stonehaven to Aberdeen. In Glen Esk increasing metamorphic grade from chlorite to sillimanite zones is seen in a NW direction from the Highland Boundary (Figure 2). Diagrams summarizing the changes in the mineral assemblages across the garnet to kyanite zones are given in (Figure 13), and may be compared with the mineral assemblage diagrams for the metamorphic zones on the Stonehaven coast section (Harte, Booth & Fettes 2015).

The localities described in this guide for the chlorite, biotite and garnet zones lie within an extensive set of exposures on the banks of the river North Esk, extending from the Lower Old Red Sandstone in the south, across the Highland Border Complex, to the Dalradian in the north (Figure 2). These first three localities are on the west bank of the river to allow easy access to a garnet zone locality. After the third locality, the itinerary continues on the east side of the river North Esk (further notes in details on localities).

With the exception of the Highland Border Complex and locality 7 (Figure 11) all the rocks visited in this excursion guide belong to Southern Highland Group of the Dalradian Supergroup (Harris & Pitcher 1975). At locality 7, rocks belonging to the Argyll Group (locally called the Tarfside Limestone and Quartzite Group), as well as Southern Highland Group, may be seen. Furthermore, the latter may be seen to overlie the former in normal stratigraphic succession (Harte 1979), rather than in the inverted succession seen in the Southern Highlands of Scotland in Perthshire and further SW. Most of the Dalradian sedimentary succession is of Late Proterozoic age, and summaries of the major geological relationships, geochronology and metamorphism are given by Stephenson & Gould (1995), Stephenson et al. (2013a, 2013b) and Tanner et al. (2013).

Notes on major rock relationships

(1) Barrow's Zones

Barrow's original delineation of his zones was centred on Glen Clova and Glen Esk (Barrow, 1893) and was subsequently extended to the coast at Stonehaven (Barrow 1898, 1912). Barrow's mapping of the metamorphic zones has only been marginally changed by later workers (e.g. Harte 1966; Chinner and Heseltine 1979). He referred to the region as one of *"regional crystalline metamorphism"* (1912, p.3) but given the presence of mineral zones and increasing mineral grain sizes he drew an analogy with “aureoles of thermo-metamorphism” around granite bodies. Barrow clearly recognized that his zones preceded the intrusion of large coherent "Newer Granites" in the Scottish Highlands and instead related them to the presence of "Older Granites"[1] ([1] Barrow had no radiometric data to provide estimates of absolute age, and thus made relative estimates by comparison with other geological events in the Scottish Highlands. The Newer Granites he referred to in the Highlands have now yielded radiometric dates of 420 to 395 Ma (e.g. Table 2, Stephenson & Gould, 1995).. Barrow (1893) particularly mapped such "Older Granites" in Glen Clova (location on (Figure 1)), and distinguished a range from lit-par-lit intrusive bodies in a western gneissose “permeation area” to more discrete foliated granites and pegmatites to the east and south-east in Glen Clova. To the east of Glen Clova, Barrow considered his "Older Granite" intrusions to largely continue underground, with evidence of this being given particularly by the occurrence of pegmatite bodies in the sillimanite zone in Glen Esk (Figure1). The roughly parallel orientation of the southern boundary of these pegmatite bodies and the boundaries between his sillimanite, kyanite and staurolite zones particularly convinced him that it was:

"…..reasonable to attribute both the minerals and the crystallization to the thermometamorphism of the intrusion." (Barrow 1893, page 337).

Tilley (1925) extended Barrow's mineral zone mapping to the west across the Dalradian of the central and south-western Scottish Highlands. In this he introduced the term 'chlorite zone' for the combined zones of 'clastic mica' and 'digested clastic mica' previously recognised by Barrow. The area mapped by Tilley (1925, Plate IX) was formed by the newly-defined chlorite zone together with the biotite and garnet zones; though he was aware (Tilley, 1925, in 'Discussion', p. 112) of an area of staurolite and kyanite-bearing rocks to the north of the area covered by his Plate IX. Throughout the whole of the central and south-west Highlands, Tilley noted the rarity of 'Older Granites' and thought it more likely that they were a product rather than a cause of metamorphism. Tilley thought it reasonable to suggest:

"…..that the metamorphism of this region was essentially acquired at a stage in Dalradian history when the disposition of the zones was in approximate accord with the depth of burial of the sediments…." (Tilley 1925, p. 109).

Barrow's and Tilley's opinions largely rested on the spatial distribution of the metamorphic zones, and other essential field relationships, and these matters have continued to contribute to debates on the origin of the metamorphic zones. In addition, knowledge relevant to the origin of the zones has grown extensively in the following fields:

1. the detailed history of deformation and structure development, accompanied by petrographic evidence of phases of mineral growth in relation to detailed structural history;
2. detailed knowledge of mineral compositions and phase equilibria;
3. the development of models of heating and heat transfer in the lithosphere;
4. the use of radiometric dating to provide evidence of the ages of igneous intrusions, migmatites and metamorphic mineral growth.

With respect to structural history and the petrographic textures of mineral growth, four major phases of deformation (D1, D2, D3, D4) have been widely recognized; with D1-D2 associated with nappe development (especially the Tay Nappe), and D4 associated with major folding particularly represented by the Highland Border Downbend structure (Shackleton, 1958; Harte et al. 1984; Stephenson et al., 2013a; Tanner et al., 2013). The growth of metamorphic index minerals (garnet, staurolite, kyanite, sillimanite) has been found to be predominantly associated with the period between D2 and D3 and overlapping D3, but with some relatively late growth of sillimanite probably following D3 (Chinner, 1961; Harte & Johnson, 1969; Harte & Hudson, 1979; McLellan, 1985; Robertson, 1991, 1994). With regard to the matrix minerals (largely quartz, muscovite and biotite), Harte & Johnson (1969) believed they had undergone major recrystallization and grain coarsening in association with the D3 phase of deformation.

Chinner (1966) led the way with a new approach to questions considering temperature distribution, depth and structural evolution, by using the variable P-T constraints of mineral reactions at the boundaries of metamorphic zones, to map relative temperatures and pressures and their pattern of variation with respect to one another. Chinner suggested that synmetamorphic folding had given rise to a thermal anticline near centre of the combined Barrovian and Buchan metamorphic zones. Harte & Hudson (1979) followed Chinner's approach of attempting to delineate isotherms and isobars across the Eastern Highlands, and determined the actual temperatures and pressures involved by using a petrogenetic grid in which the isograd reactions were defined. They concluded that the major pattern of temperature and pressure distribution favoured the formation of the metamorphic zones, the migmatites and the 'older granite' bodies as a result of extensive regional magma intrusion in the deep crust. Overall, Harte and Hudson (1979) estimated that the garnet to sillimanite zones had formed at temperatures of ca 520 to 680 °C, and pressures of near 6 kbar (but lower pressures on the Stonehaven coast section than in Glens Clova and Esk). More recent detailed estimates on specific zones and mineral assemblages have confirmed a similar range of temperatures and pressures (e.g. Dempster 1985; McLellan 1985; Baxter et al. 2002; Viete et al. 2011a; Vorhies & Ague 2011).

In considering the general pattern of arrangement of the metamorphic zones in (Figure 1), Harte & Hudson (1979), and subsequently Harte & Dempster (1985), also drew attention to the possible influence of tectonic effects on the southern margin of the region in Barrow's type area covered by this excursion guide. In Glen Esk and adjacent areas extending to the coast at Stonehaven the chlorite, biotite and garnet zones are very narrow and imply high gradients in temperature adjacent to the line of the Highland Boundary. Given that this tectonic lineament was long-standing (Harte et al. 1984) and potentially separated the Barrovian terrain from one with a much cooler geothermal profile, the above authors suggested the possibility that the high thermal gradients between Barrow's high-grade zones and the Highland Boundary lineament reflected not only the magmatic thermal input in Barrow's high-grade zones, but also a lateral cooling effect from the rocks south of the lineament. This apparent high thermal gradient may also have been a product of tectonic thinning Phillips and Autun (1997).

Tilley's alternative model of the metamorphic zones as basically reflecting the increase of temperature with depth within the metamorphic pile was re-examined for the garnet zone in the western central Highlands by Richardson and Powell (1976). They concluded that garnet- zone temperatures of ca. 535 °C could be supported by radioactive heat production within a thick Dalradian metasedimentary pile plus an underlying thickness of Moinian metasediments, and that there was no need to invoke the presence of underlying magmatic intrusions. Richardson & Powell (1976) also noted the transient nature of their thermal model, because the thickened Dalradian pile would take time to heat itself up and after thickening would be thinned by erosion. A wide range of dynamic models of this type were further developed by England & Richardson (1977) and England & Thomson (1984) showing that a thickened sedimentary pile might undergo thickening, heating and erosion and reach temperatures appropriate for the highest grade Barrovian metamorphic rocks. However, the timescales for development of high grade rocks in this manner was typically shown to take tens of millions of years, and the time at which peak metamorphic temperatures were reached in each metamorphic zone might also differ by tens of millions of years.

Returning to consideration of the high-grade metamorphic zones of Barrow's type area and the Eastern Highlands in general, the thermal models of England and co-workers provide a framework for comparison with the results of radiometric dating. In the Buchan region, Fettes (1970) demonstrated that there was a continuity in the development of minerals found in the Buchan regional andalusite zone and in the aureole of major gabbro bodies; thus the dating of these bodies at close to 470 Ma (Lower/Middle Ordovician) simultaneously became a time marker and a potentially important control on the distribution of the metamorphic zones in the Eastern Highlands (Dempster et al. 1995, 2002). During the last 30 years a wide variety of radiometric dates have pointed to the overwhelming importance of the relatively short time period from ca 470 to ca 460 Ma. Ages have been obtained from U/Pb determinations on zircons from intrusive granitic and gabroic rocks and from migmatites. In addition ages have been obtained on metamorphic minerals (radiometric Nd/Sm on garnets; K/Ar on micas), and by using time constraints from diffusion profiles. All determinations show a close approach to synchroneity of magmatic intrusions and ages of metamorphic mineral growth in a variety of metamorphic zones around the 470 to 460 Ma time period. Presentation and discussion of these radiometric data may be found in Oliver et al. (2000), Baxter et al. (2002), Ague & Baxter (2007), Vorhies & Ague (2011), Viete et al. (2011a, 2011b, 2013) and references therein. Overall, the data are interpreted to show the importance of the advection of heat dominantly by magmatic intrusions. This is in broad harmony with Barrow's original 1893 concept. However, considerable emphasis is now placed on the extensive gabbroic intrusions to the north of the area, and on repeated episodes of granitic intrusions; rather than on a single contact aureole model. In broad terms the relatively narrow radiometric time frames for metamorphism confirm the textural-structural evidence of limited time periods for mineral growth and granitic intrusion (Harte & Johnson, 1969; Fettes, 1970; Robertson, 1991; Philips & Autun, 1997).

Although there now appears to be a broad consensus in favour of regional magmatic intrusions as the cause of heating in the Barrovian type area, some differences of opinion remain. Viete et al. (2013) believe all the heat input came from episodic intrusions (perhaps accompanied by episodes of fluid flow). Vorhies & Ague (2011) believe magmatic heat was instrumental in getting the higher grade rocks to high temperatures in a short time; but in contrast to Viete et al., they suggest the magmatic heat transport operated in addition to thermal input from a thickened pile of radiogenic metasediments as in the models of England & Thompson (1984). Vorhies & Ague (2011) emphasise the magmatic input of heat for the Eastern Highlands, but not for the lower grade central and south-western Highlands. This contrast has features reminiscent of the original differences of opinion of Barrow (1893, 1912) and Tilley (1925) for the respective areas that they mapped.

(2) Highland Border Complex

The rocks found adjacent to the southern margin of the Dalradian metamorphic rocks, at the Highland Boundary, have also prompted much debate. In Glen Esk (Figure 2) and (Figure 3) the Highland Border Complex (HBC) consists of two main lithological units:

1. *The Jasper and Greenstone Series* — formed largely of altered fine grained basic igneous rocks (greenstones), cherts and some shales in a low grade of metamorphism. Pillow structures occur in some metabasic rocks. These rocks are widely believed to be related to metabasalts and serpentinites occurring at several places along the Highland Border (including nearby at Garron Point, Stonehaven). Many workers have accepted the suggestion that at least some of these rocks are of ophiolitic origin; but there have been different opinions about the extent of their tectonic separation in time and place from the Dalradian.

2. *The Margie Series* — this consists of weakly metamorphosed pebbly sandstones ('grits'), shales and limestones. A Lower Ordovician age has recently been demonstrated from conodont evidence in the limestone (Ethington 2008), and this is consistent with the fossil evidence from other low-grade metasediments in the Highland Border Complex near Aberfoyle (Tanner and Sutherland 2007).

Dips of bedding and cleavage are commonly steep (Figure 4), and the Margie Series has two areas of outcrop, one on either side of a central zone of Jasper and Greenstone Series (Figure 3). The more northern one is succeeded across the North Esk Fault by the Dalradian pelites and psammites of the Southern Highland Group.

A continuity in structural history between the Margie Series and the Dalradian rocks to the north was emphasised by Johnson and Harris (1967). However, Henderson and Robertson (1982) and Harte et al. (1984) felt that this evidence was distinctly tenuous because some obviously different geological terrains can show similar structural histories. Henderson and Robertson (1982) suggested that the whole Highland Border Complex represented part of an ocean-floored marginal basin located to the north of Highland Boundary line.

The debate has continued more recently. Tanner, Stephenson and others (e.g. Tanner and Sutherland 2007; Tanner et al. 2013; Stephenson et al. 2013b) have argued that the whole HBC in the River North Esk belongs to the Dalradian Supergroup; they have placed it within a widespread Trossachs Group, which they believe forms the uppermost unit of the Dalradian and occurs in several regions along the Highland Border. Other workers (e.g. Bluck 2010, cf Tanner and Bluck 2011) have questioned this continuity between the HBC and the Dalradian, and doubted whether the timescales for subsequent polyphase deformation and 470 Ma regional metamorphism are compatible with an early Ordovician age for parts of the Highland Border Complex (e.g. Ethington 2008).

In the River North Esk, the southern margin of the Highland Border Complex (HBC) against the Lower Old Red Sandstone (LORS) is often portrayed as the Highland Boundary Fault (HBF), but Henderson and Robertson (1982) suggested that it is actually an upturned unconformity. A similar unconformity at the base of the LORS, but on HBC metabasalts, is seen at Stonehaven (Gillen and Trewin, 2015).

Traverse from the Chlorite Zone to the Staurolite Zone

This section of the excursion, covering the chlorite to staurolite zones (localities 1 to 4), is described in a single section because it is possible to walk through the whole of this sequence without using a vehicle; the river is crossed by a footbridge between localities 3 and 4. This walking itinerary is particularly useful for coach parties, since some roads/tracks are very unsuitable for motor coaches (see below). However, notes are given on parking places for small vehicles so that people driving themselves may easily do localities 1 to 3 on the west side of the Glen, before driving to the east side of the Glen to locality 4.

Proceed along the (B966) to near Gannochy where the B966 bridges the River North Esk about 1.6 km north of Edzell (Figure 2). Near the southern end of the Gannochy houses [NO 599 707], about 300 m SW of the Gannochy Bridge, take the minor unsignposted road heading NW. This minor and narrow road leads to Dalbog and other farms on the western side of Glen Esk. The main road heading up Glen Esk is on the eastern side of the river and Gannochy Bridge, and is signposted to Glen Esk, Tarfside and Invermark. We will follow this 'main' road later after completing the first three localities on the west side of the river.

After leaving the B966 follow the narrow road north-west for 2 km until reaching the road and track junction at [NO 5864 7190], just beyond the main Dalbog farm buildings and before reaching a very large cattle shed. *This location by Dalbog farm is marked with a 'P' on (Figure 3), and is the farthest point along this road that coaches should proceed,* though cars and minibuses can proceed further and usually stop at the other parking places marked 'P' on (Figure 3) (but check with the farmers at Dalbog if in doubt). *Coaches should turn at the junction by Dalbog* and return to the B966 and take the main Glen Esk road east of the river (see above) to await the party at a layby at [NO 5757 7512] marked 'P' on the map near locality 4a. This layby is approximately 5 km from the B966. About 1 km before layby the road crosses a fairly narrow bridge adjacent to quite sharp bends in the road (near Auchmull farm — see (Figure 3)). From this bridge the road heads gently uphill, and shortly after passing a signpost to Haughend on the left, the road bends right and starts heading downhill. The layby for parking is on the right (east) side of the road just around the bend — *beware it is easy to drive past the layby*.

From the road junction by Dalbog pedestrians and small vehicles head on north passing the large cattle shed on the left until reaching the point [NO 587 728] where a pylon line crosses the track (Figure 3) and (Figure 4). If the ground is firm cars and minibuses should park beside the track about 100 to 150 metres beyond the pylon line; the party can walk down from here to geological locality 1. Alternatively, the best parking point for all of localities 1 to 3 is at a small disused quarry at [NO 5820 7355] on the west side of the road 100 m beyond the bridge across the Burn of Mooran (Figure 4).

Locality 1. Highland Border Complex and Dalradian chlorite zone

Looking from the track near the pylon line [NO 587 728] the River North Esk is seen to lie within a wooded gorge which provides extensive exposures extending from the Lower Old Red Sandstone (LORS) through the Highland Border Complex (HBC) to Dalradian Southern Highland Group (SHG) — (Figure 3) and (Figure 4). The contact between the HBC and the SHG is about 300m upstream from where the pylon line crosses the river. The SHG is in the chlorite zone here, but the grade increases rapidly northwards. Looking north from by the pylon line to the hills on the opposite side of the river, the nearest hill is heavily forested whilst the second hill has a major spur facing the observer. This spur forms the Craig of Weston where the staurolite zone localities occur; their nearness (ca 3 km) gives a good impression of the narrowness of Barrow's zones in Glen Esk.

Leaving the parking area beside the track and pylon line [NO 587 728], you may spend some time around locality 1A. If your time is limited proceed directly to locality 1B (Figure 4), by heading NNE to a point on the edge of the river gorge about 120m south-east of where a small burn enters the river from the west. From here you will be able to easily descend to the river's edge at locality 1B.

Locality 1A [NO 587 731]

Visitors may spend a little time around here, on the south side of the pylon line (Figure 4), where limited exposures of greenstones and cherts occur sparsely before reaching the trees lining the river gorge. The greenstones are fine-grained chlorite-rich schists, and the cherts are largely pale- to dark-grey. Streaks of red chert (jasper) also occur, and cobbles of jasper may also be seen lying loose along the edge of the trees lining the river gorge. These rocks belong to the Jasper and Greenstone Series; they are extensively exposed in the main river gorge, but access and proceeding along the river's edge is difficult.

Locality 1B [NO 5870 7324]

This locality (Figure 4) is at the junction of the Margie Series rocks with the Jasper and Greenstone Series rocks. Exposures are seen amongst the trees at the river's edge, and immediately south-east of here there are extensive craggy exposures on both banks of the river.

At the northern end of the prominent crags a conglomerate occurs (the 'Green conglomerate') consisting of greenstone pebbles and cobbles in a fine-grained schistose green matrix which largely resembles the greenstones mineralogically, but is occasionally more pelitic. Although most of the clasts in the conglomerate are of fine-grained rocks, some occur which may be derived from dolerite or gabbro. There are also rare jasper pebbles. A few metres to the SE the more usual massive greenstones are encountered.

When the river water is low, almost continuous exposures show that, to the NW, the conglomerate changes over a few metres from conglomerate with few relict clasts in the schistose matrix, through green schist without clasts, to paler highly schistose rocks and eventually to brown-weathering cleaved dominantly psammitic rocks with small pebbles ('grits' in local terminology). The last of these is definitely a Margie Series lithology.

The Green conglomerate was considered by Barrow (1912) to be separated from the main Jasper and Greenstone Series outcrop to the south by a minor thrust. Other workers (Pringle 1941; Henderson and Robertson 1982) have also placed a fault or thrust in this position, though Pringle emphasised the lithological similarities of the conglomerate and the greenstones. With respect to the Margie Series, Barrow (1912) considered the Green conglomerate as forming its base with a passage upwards into the main Margie rocks. However, Pringle (1941) noted that, at exceptionally low water, exposures (on the opposite side of the river) suggested that a fault or shear zone separated the greenish shaly/schistose rocks from the paler (brown-weathering) shaly/schistose rocks and grits.

Localities 1B to 1C [NO 587 733] to [NO 586 734]

The Margie Series outcrops in the interval between localities 1B and 1C; but in this interval rock exposures are infrequent by contrast to the craggy exposure which border the river both upstream and downstream. There is usually patchy exposure along the water's edge and if the water is particularly low, much rock may be seen within the river.

For about 50 m upstream of the Green conglomerate, the exposures are mainly of the pale grit. Locally, these grits show brecciation and at one point a very dark brecciated band is seen. For the next 50 metres after the pale gritty psammites, black and then purple shales/slates dominate the exposure at the water's edge on the west bank (Figure 4); but the area is much overgrown with small trees. Near the end of this zone a small burn enters the river from the west, and on the northern side of this a small but prominent exposure of purple slate occurs in the riverbank. The exposure shows a cleavage dipping at almost 90° to the SE and a linear structure defined by small fold hinges plunging 70° to the SW. Along the water's edge immediately to the NW of here a mixture of Margie Series exposures of grey phyllite and dark grey limestone may be seen – but only at low water. On the opposite (eastern) bank of the river, in a small worked out quarry, limestones have yielded conodonts indicative of a Tremadocian- Arenigian age (Ethington 2008).

The whole exposure of the Margie Series is very complex. Although similar rock types are seen on both banks their proportions on the two banks are very different (Figure 4). Examination of the exposures when the river is very low (Booth 1984) reveals breccia zones and faulted lithological contacts as well as folding. The Margie Series exposures end on their north-western side against the poorly exposed North Esk Fault, and are succeeded to the north- west by extensive typical exposures of Dalradian Southern Highland Group metasediments at locality 1C.

Locality 1c [NO 586 734]

At this point an upstanding craggy exposure occurs at the water's edge and, immediately behind it, crags around 4 m high commence and form the western margin of the river upstream.

The exposures consist of compositionally layered, grey-green, pelitic and more psammitic, chlorite-muscovite schists or phyllites (Figure 5). They are fine-grained but not generally sufficiently pelitic or mica-rich to be termed slates. Overall the composition of the rocks is probably semi-pelitic rather than pelitic, but the rocks here are free of thick beds of psammite or coarse grit (conglomerate) and have therefore been mapped as pelites rather than grits (Figure 3). Small dark porphyroblasts (up to 2 mm) occur sparingly (forming small pimples on the schistosity surfaces) and are most commonly of magnetite but are sometimes pyrite with an altered (limonitic) coating.

The layering within the rocks at locality 1C is bedding and this may be demonstrated where occasional grit beds containing clasts of quartz and feldspar occur. Such evidence is more easily seen at locality 2. A cleavage (schistosity) occurs sub-parallel to the bedding, which dips upstream at moderate angles. This dip is much shallower than that generally seen in the section. Also dipping upstream, but at a shallower angle than the bedding, a second cleavage may be seen, particularly in pelitic beds.

These two cleavages belong to the two dominant deformation episodes to have affected the Dalradian rocks adjacent to the Highland Boundary. The first (close to bedding) cleavage is associated with D1, the early nappe-forming episode. The second cleavage is associated with D4, the major Highland Border Downbend structure. D2 and D3 structures of easily identifiable style are not seen in the Dalradian here, and only become common further away from the Highland Boundary, as elsewhere in the Dalradian (e.g. Harte et al. 1984; Harris et al. 1976; Tanner et al. 2013).

Locality 2. Biotite zone [NO 5838 7348]

From locality 1C retreat a short distance back towards the Margie exposures and scramble up the bank forming the western side of the river gorge. Proceed NW, keeping a little above the river gorge until you are within a few metres of reaching the vehicle track (Figure 4). Scramble down the side of the gorge and examine the fairly flat rock surfaces immediately adjacent to but 4–5 m above the river.

The rocks here generally dip steeply NW (Figure 4) and (Figure 6), though there is some variation which is probably largely associated with D4 folds of several metres amplitude. Evidence of these folds is seen in the varying orientation of bedding on the opposite side of the river, though there is insufficient depth of exposure to make clear the overall shape of the folds. A prominent ribbed rock surface is seen on the opposite bank and these ribs represent a series of shallow D4 minor folds. On both sides of the river two major cleavages may be seen as at locality 1C. The first is largely subparallel to steeply dipping bedding and represents the regional D1, the second dips upstream at shallow to moderate angles and is associated with D4.

The lithology here is similar to that at locality 1C but includes distinct beds of pebbly meta-sandstones ('grits') up to about 1 m thick (Figure 7). Quartz and feldspar clasts up to 1 cm across occur in some of these 'grits' and include pebbles of blue quartz. In the more pelitic beds, dark biotite porphyroblasts, commonly around 1 mm across, are abundant. The biotite porphyroblasts are more easily distinguished on broken rock surfaces where previous visitors have hammered the rocks. PLEASE DO NOT hammer the rocks needlessly.

Locality 3. Garnet zone. [NO 578 744]

From locality 2 climb back up the bank to the road/track and follow it NW across the Burn of Mooran and past the small quarry [NO 5820 7355] where cars may have been parked (Figure 3), (Figure 4). About 250m further on the road swings left to Cornescorn (Figure 3), but keep straight on along a track through birch woods. After another ca 250m a track goes off to the east to connect with a bridge across the river[2];([2]There are good exposures beneath this bridge, but they are very dominantly psammitic with much fine conglomerate ('pebby grit'). Graded bedding may be seen against rare pelitic units. I have not seen garnet at this locality). but again ignore this track and keep heading NNW for another ca 250m where there is a small hut on the right of the track – this point is ca 800m beyond the Burn of Mooran. By the hut, you should leave the track and head NE to gain the top of the bank overlooking the river at the point where the extensive birch woods give way northwards to more open ground and fields. A fence forms the northern edge to the birch woods and may be crossed by a stile at the top of the river bank. The exposures of locality 3 occur near to this fence, by a bend in the river, and at the water's edge.

The lithology is of the bedded pelitic and more psammitic units similar to those seen downstream. The grain-size is a little coarser with a schistosity defined by chlorite and muscovite. Biotite forms small porphyroblasts, generally up to about 3 mm. Garnet is sporadically abundant in porphyroblasts of 2–5 mm; it is particularly well seen on the SE side of low exposures which protrude into the river. Similar rocks may be seen under overhanging trees along the river's edge for a short distance to the SE, but further away the lithology includes much coarse 'grit', and garnet is hard to find.

Locality 4. Staurolite zone

Looking north obliquely across the river from locality 3, the major spur of the Craig of Weston faces the observer and the staurolite zone rocks of locality 4 ('A' and 'B') lie on and adjacent to this spur. The route to these localities from locality 3 depends on the transport arrangements of the field party, but in all cases the ascent of the Craig of Weston may be conveniently made from a layby at [NO 5757 7512] on the main road up Glen Esk on the east side of the river (marked P on (Figure 3)). It is to this layby that motor coaches should have been directed from near Dalbog Farm at the start of the itinerary.

Field Parties on foot from Dalbog should return to the track (150 m west of locality 3), and follow it NW for about 0.7 km. At this point a track forks to the right and leads down into a field containing barrack-like huts. Behind the huts the river is crossed by a footbridge from which a path leads to the main Glen Esk road; and the layby at [NO 5757 7512] is 400 m south along the road.

Field parties driving themselves should return to their vehicles and drive back to Gannochy and the B966, and then take the road signposted to Tarfside and Invermark up the east side of the valley to reach the layby at [NO 5757 7512] – see instructions given above for motor coaches.

Locality 4A [NO 578 753]

From the layby at [NO 5757 7512] walk SE along the road for about 0.5 km to a large gate through the deer fence on the uphill side of the road. Proceed through the gate and along the track, which bends round to the NW and locality 4a (Figure 3). The track has been widened in this area and there are some rock exposures as well as big boulders beside the track of staurolite-bearing schists. However, you will need to search carefully for the staurolite because many of the rocks are psammites and semi-pelites without staurolite. The general grain size of the rocks is much greater than that seen at the lower grade localities. Usually the staurolite and garnet are most readily seen as upstanding crystals on clean weathered rock surfaces.

The staurolite usually forms upstanding stumpy prisms 2–3 mm long (Figure 8)a,b. Unfortunately, the staurolite is often partly altered to fine-grained white mica (Barrow called it 'shimmer-aggregate'), with the result that it appears pale grey in colour, rather than the characteristic brown colour seen in Figure 8. Occasionally, the staurolite shows interpenetrant twins; with the (231) twin law, giving intersections of approximately 60°; these are more common than that of (031) twin law which gives 90° cruciform twins. Where it occurs, staurolite is frequently far more abundant than garnet. Biotite often forms 2–3 mm porphyroblasts though it may also form part of the matrix schistosity. Chlorite is not conspicuous; though it is usually seen in thin section, typically as an alteration product of biotite and garnet.

At this point the field party may return to their vehicles at the [NO 5757 7512] layby. If it is desired to see more staurolite zone rocks and in particular minor folds and cleavages, the party may leave the track and head straight uphill to a knoll bearing a few isolated trees. There is much loose rock on the hillside here and some probable material in situ. Much psammitic material occurs, but there are staurolite schists similar to those already described. To see rocks more obviously in situ (or almost so!) head for locality 4B.

Locality 4B [NO 583 756]

This location is about 400 m NE of the knoll with isolated trees described above, and on the south-eastern side of the ridge heading upwards to the top of Maolearn hill (Figure 3). Staurolite-bearing pelitic schists here show similar features to the rocks described at locality

4A. Again, they are not abundant because much of the rock is semi-pelitic to psammitic and they should be searched for at the SE margin of the area of exposure. Please do not hammer the in situ rocks. Loose material showing the typical assemblage (garnet-staurolite-biotite-muscovite schist) may be found just beyond the SE margin of the exposure adjacent to a shallow gully (probably a small glacial overflow channel).

The rocks at 4B show a composite foliation dipping moderately steeply to the ESE. This foliation includes cleavage structures and compositional layering; the latter is indicated to be bedding by the occurrence of psammitic layers which appear to be the higher grade equivalents of some of the finer-grained grits seen at the lower grade. The cleavages forming part of the composite foliation include schistosity in pelitic layers, which passes into a spaced cleavage in semi-pelitic to psammitic layers. In places the spaced cleavage reveals small shear zones typical of Dalradian D2 deformation structures (Harris et al.1976; Harte et al. 1984). Relicts of D1 cleavage may be seen traversing some of the lithons (commonly 0.5–2.0 cm thick) between the attenuated D2 shear zones, thus proving the composite nature of the dominant foliation structure. A ribbing or rodding lineation largely lying in the foliation plane may be seen on some quartz veins and psammitic surfaces. This is probably also of D2 age and in Glen Esk is generally much easier to find than separate evidence of both D1 and D2 structures in the composite foliation.

Obvious tight minor folds of amplitudes from a few centimetres to a few metres also occur at locality 4B. At the hinges of these folds pelitic layers often show an axial planar cleavage which passes into parallelism with the composite foliation in fold limbs. These folds also fold the probable D2 lineation and are thus considered to be D3 in age. It is however extremely difficult to find a clear example of obviously composite D1 + D2 fabric being folded around the hinges of these folds (such evidence is generally much harder to find in Glen Esk than on the Stonehaven coast section - see the excursion guide to the Stonehaven coast section (Harte et al. 2015). Cleavage associated with D4 is not so well developed here as in the river (localities 1C and 2), but crenulations of schistosity with axial planes dipping northwest are almost certainly of D4 age. Some other crenulations may be seen. Altogether, there is evidence at locality 4B of the four main deformation events seen in much of Glen Esk; these are the D1 to D4 of Harte and Johnson (1969), which are in fact common to much of the Dalradian of the Southern Highlands (Harris et al. 1976; Harte et al. 1984).

Between the garnet-zone exposure (Locality 3) and the staurolite-zone (Locality 4) the rocks have changed quite significantly in other characters besides the increase of grade marked by the staurolite-garnet-biotite assemblage. The effects of D2 and D3 deformation have become manifest, whilst the essential pelitic to psammitic characteristics of the rocks have remained much the same. It is a great pity that the garnet-staurolite zone transition is generally so badly exposed in Barrow's zones. Higher up Glen Esk and in adjacent Glen Lethnot, it has been shown that the main growth of garnet, staurolite and kyanite porphyroblasts is prior to and partly synchronous with D3 (Harte and Johnson 1969; Dempster 1985); whilst much of the coarsening of the rock matrix seems to be associated with the D3 deformation, whose axial plane cleavage becomes part of the composite foliation on the limbs of D3 folds.

After examining the 4B exposures, parties may descend Craig of Weston to recover their vehicles at the [NO 5757 7512] layby. Walking enthusiasts could proceed to locality 5 (by Craigoshina, Figure 3) on foot. The walk is largely across open heather-covered hillsides — however, walking is not recommended during the grouse shooting season.

Locality 5. Kyanite–bearing rocks [NO 575 766]

Locality 5 is directly uphill from Craigoshina cottage which is on the roadside at [NO 572 764] – (Figure 3). Small vehicles may park tight into the side of the road immediately beyond the end of the Craihoshina buildings. For minibuses and small coaches there is a small grassed- over quarry or pit on the east side of the road about 400m north of Craigoshina. Also near here on the east side of the road are some wide entrances to tracks through gates in the deer fence; be wary of blocking these entrances especially during the shooting seasons.

To gain access to the area with good exposures of kyanite-bearing rocks go to the fence immediately across the road from the northern end of the Craigoshina buildings. Immediately to the left of a stout corner fence post, examination of the fence shows that the wires two to three feet above ground level are arranged so that they may be flapped upwards, making a space where you may bend and get through without damaging the fence. Please take care, and remember to lower the wires back in place after passing through.

Proceed directly up the hillside away from the fence, passing through a wooded zone before reaching an area with rock exposures and much loose rock, 300–400 m up the hillside from Craigoshina (Figure 3). The rocks here are pelites with subordinate more psammitic rocks, but they are generally both greyer and more silvery than those seen at locality 4. They are a variety of pelitic-psammitic schist in which much of the iron in the rocks occurs in the ferric rather than the ferrous oxidation state – high $Fe_2O_3/(Fe_2O_3+FeO)$. As a consequence there is a lower modal proportion of ferromagnesian silicates (biotite, garnet, staurolite) and a higher proportion of muscovite and Fe^{3+} oxides than in the normal pelites (Chinner 1960; Harte 1966, 1975a). In addition, these schists are often rich in kyanite. In effect the decreased stability of the ferrous-bearing silicates means that some Al_2O_3 which might otherwise contribute to biotite, garnet or staurolite is available to form muscovite and kyanite.

In the kyanite-haematite schists, the kyanite prisms may be 0.5 to 3.0 cm long. Unfortunately these prisms do not have the usual attractive streaky blue-white colouring, because they are often rather altered and full of small haematite inclusions; thus on weathered surfaces the kyanites form upstanding prisms with a dark silvery-grey appearance similar to that of the body of the schists. Barrow (1893) referred to such kyanite as “black-leaded”. Sometimes, due to alteration to fine-grained mica, the kyanite acquires a waxy appearance. Occasional dark seams and patches may be seen within the schists and these represent concentrations of haematite. Some haematite-bearing schists with lower ferric:ferrous ratios show staurolite in stumpy prisms 2–4 mm long.

Kyanite-rich rocks are particularly well seen in the uppermost part of the extensive exposures. In addition spectacular quartz veins with abundant kyanite may be found (Figure 9). In these veins, the kyanite often shows its characteristic blue-white colouring and prisms several cms long are common. Again the kyanite may show some retrograde alteration to fine- grained mica, and rarely it develops a scaly appearance due to the development of margarite.

Please do not hammer attractive exposures of the kyanite-quartz veins; it is possible to obtain some specimens from loose-lying material.

In Glen Lethnot, which is the next glen to the SW of Glen Esk (Figure 2), it is possible to show that the development of kyanite in hematite schists may occur at substantially lower grade than in ordinary (ilmenite-bearing) pelitic schists (Harte 1966, 1975a), and Barrow himself recorded kyanite occurrences within his normal staurolite zone (Irvine and Barrow 1897). Because of this, Chinner and Heseltine (1979) used the occurrence of kyanite in typical ilmenite-bearing schists, containing biotite with M/FM (MgO/(MgO+FeO) compositions of 0.51, as the basis for defining the normal low-grade boundary of the kyanite zone. This isograd has been placed close to the Craigoshina locality (Chinner and Heseltine, 1979; and (Figure 2) and (Figure 3) of this guide). However, there is a lack of normal (haematite-free) pelitic schists near Craigoshina, and so it is difficult to say whether the locality strictly lies within or just outside the normally-defined kyanite zone. Exposures of more normal (haematite free) kyanite–bearing rocks may be found in the hills between Glen Esk and Glen Lethnot (Harte 1966), but they are not easily accessible in a short excursion.

Sillimanite Zone localities

Two options are described below for viewing sillimanite zone rocks. The first option (locality 6) is a short drive up the Glen of about 3km from Craigoshina (Figure 3), and a short walk uphill. The second option (locality 7) shows more lithologies and more spectacular mineral assemblages than locality 6, but involves an extra drive of about 14 km further up Glen Esk (Figure 2), (Figure 11) and a steep uphill walk; it requires at least 2 hours.

Locality 6. Sillimanite zone by Hillock [NO 559 784]

From the vicinity of Craigoshina, drive north up Glen Esk for approximately 3 km to a road bend at [NO 560 782]. A track forks off the NE side of the road and obliquely ascends a steep bank from the top of which the farm buildings of Hillock overlook the road. Small vehicles may drive up the track and park adjacent to the farm buildings (check with people at the farm if necessary). Coach parties should leave the bus on the road and walk up the track, as there are no convenient parking places for larger vehicles on or near the roadside. After depositing their passengers, coaches will have to drive further up the Glen to turn round (e.g. by Millden, [NO 541 789], (Figure2), and then return (perhaps after 1 hour) to await the party on a straight stretch of road near Hillock.

To reach the exposures on the nearby hillside, walk along the western side of the most westerly farm building and then across a field and a belt of ferns with the remains of sheep pens on the right. In the group of rock exposures facing you there are again many psammitic and pelitic rocks. Sillimanite-bearing pelites are most easily seen on the north-western margin of the extensive exposures.

In these exposures a composite foliation of bedding and cleavage (probably of more than one generation - see notes on locality 4B) generally dips steeply (50–90°) to the SE. A linear structure of probable D2 age lies within the foliation plane. Shallower dips of the composite foliation, some of them to the NW, occur locally, and are seen to be associated with fairly open folds or kinks with flat-lying axes striking NE–SW. Some of these folds have axial planes dipping NW with congruent crenulations of the mica schistosity; they are probably D4 structures. However, other folds with similar orientations of fold axes have axial planes dipping SE and appear to belong to a fold set which is not as widely developed.

The lithology is dominantly semi-pelitic in composition and formed of grey-green mica schists. Garnet is present, but staurolite and kyanite are exceedingly rare. Sillimanite may be found on careful searching, and would probably be found to be widespread with extensive thin- sectioning. The sillimanite is of the fibrolitic variety, as elsewhere in Glen Esk, and is easily seen in the field in two situations.

1. As welts and knots of tiny fibres which dominantly show a fairly smooth silky or waxy appearance on clean weathered surfaces. Such welts may be a centimetre long and are usually greyish-white, sometimes with a greenish tinge.

   As upstanding 'blobs' of fibrolite, 0.5 to 2.0 cm across on weathered surfaces and typically surrounding garnets (Figure 10).

Locality 7. Sillimanite zone by Glen Effock [NO 456 780]

This locality has a greater variety of sillimanite-bearing rocks than those at locality 6, and includes schists/gneisses containing garnet, staurolite and kyanite. The best exposures with these index minerals occur in the Southern Highland Group (SHG) of the Dalradian (as with localities 1 to 6). However, the area around locality 7 also shows exposures of the Argyll Group (Tarfside Limestone and Quartzite Group) and these include meta-limestones. Visiting this area involves a drive of approximately 14 km from near Craigoshina (locality 5) and then an ascent of Auld Craig-Hare Cairn (Figure 11), immediately south of Glen Effock Farm. You should allow about two hours for starting from and returning to the roadside by Craigoshina. If the party is interested, other exposures of Argyll Group rocks may also be easily examined in the river North Esk near Glen Effock (Figure 11).

From Craigoshina drive NW up the road, past the Retreat to the village of Tarfside. The Retreat has a museum, craft shop and tea room. From Tarfside follow the signs for Invermark, taking a sharp left turn just over the bridge in Tarfside. The road/track for Glen Effock farm leaves the Invermark road 4 km from Tarfside, and there is sufficient space for a motor coach to turn in the farmyard. Ask permission for parking and access at the farmhouse.

From the farmyard walk south to cross the Water of Effock by a footbridge, and then commence the ascent of Auld Craig (Figure 11). Head for the relatively low and isolated crag (location A on (Figure 11)) to the SSW of the footbridge and NW of the main crags of Auld Craig.

Throughout the Auld Craig exposures the composite foliation (bedding and cleavages) dips generally E or SE at about 20°, but there are abundant minor folds and the structural sequence of Harte and Johnson (1969) is developed. D3 structures form a particularly extensive group of close to tight folds, with axial planes dipping gently in an easterly or southerly direction. In mica schists there is usually an axial plane cleavage (often a schistosity) to the D3 minor folds, which passes into sub-parallelism with the composite foliation on the fold limbs. In psammites, a grain alignment fabric (D1 or composite D1/D2) may usually be seen folded around the D3 hinges. A D2 ribbing lineation may be seen on the surfaces of psammitic beds or thin quartz veins (subparallel to the composite foliation); it typically plunges gently to the SE and may occasionally be seen to be folded around D3 folds. D4 structures are largely limited to crenulations of the mica-schistosity with axes sub-horizontal and striking NE–SW, whilst axial planes dip NW.

Locality 7A (Figure 11)

The lithology is dominantly of psammitic rocks, and these are much nearer to quartzites than the rather micaceous and feldspathic psammites seen at earlier localities lower down the Glen.

This change of character is a typical difference between the Argyll and Southern Highland Groups in Glen Esk. A less conspicuous, but nonetheless distinctive, feature of the Argyll Group seen here is the presence of mica schists in which the biotite forms clots on generally muscovite-rich schistosity surfaces (Harte 1979, Table 2).

Locality 7B

Lies about 150 m SE of 7A and is formed of low-lying weathered exposures of quartzose marble and calc-silicate rock. These exposures at 7A and 7B are characteristic of the quartzitic psammites and meta-limestones which form an essential part of the local 'Tarfside Limestone and Quartzite Group' (Harte 1979). On the basis of lithology this 'Group' is correlated with the upper part (Loch Tay Limestone and Ben Lui Schists) of the Argyll Group of the Dalradian Supergroup further SW in Scotland (Harte 1979; Harris and Pitcher 1975). Those who wish to see further exposures of 'Tarfside Limestone and Quartzite Group' rocks should examine those seen in the river North Esk as shown on (Figure 11); see also description and National Grid locations given in Harte (1979).

Locality 7C

From locality 7B, the party should head uphill southwards, examining the western corner of the main crags of Auld Craig, and then head eastwards above the main face of the crags to a partially broken fence (Figure 11). In contrast to the exposures at localities 7A and 7B, the main crags of Auld Craig consist of pelitic and semi-pelitic quartz-feldspar-mica schists/gneisses usually of greenish colour. Garnet and sillimanite (fibrolite occurring as described under locality 6) may be seen in the field, and locally the schists appear to be moderately rich in opaques (magnetite and haematite). A gneissose banding is conspicuous in places and a migmatitic character is occasionally developed.

The fairly monotonous green quartz-feldspar- mica schists/gneisses of Auld Craig are representative of the 'Craig Dullet lithology', which forms the lowermost unit of the 'Effock-Lethnot Group' in Glen Esk (Harte 1979). This unit overlies the 'Tarfside Limestone and Quartzite Group' (TLQG) rocks, representatives of which were seen at localities 7A and 7B. Correlation of the Effock-Lethnot Group with the Dalradian Southern Highland Group (SHG), and the TLQG with the Dalradian Argyll Group, means the Argyll Group is structurally below the SHG in Glen Esk, with the Argyll Group rocks forming the core of a dome-like structure — the 'Tarfside Culmination' (Bailey *in* Read 1928; Harte 1979). This implies a 'right-way-up' stratigraphic succession in Glen Esk, in contrast to the inverted succession of Dalradian rocks seen in the lower limb of the Tay Nappe exposed further SW in the southern Scottish Highlands (Harte 1979).

Above the main face of the Auld Craig crags, follow the fence (Figure 11) southwards examining the low-lying exposures on the eastern side of the fence. These show more varieties of mica schists than the main face of the crags and include types containing garnet, staurolite, kyanite and sillimanite, which may all be identified in the field (Figure 12). The sillimanite is mostlv conspicuous as bundles of fibrolite surrounding garnet, whilst staurolite and kyanite are seen as small prisms (mostly 1 to 3 mm long), brown and grey-blue respectively. The rocks are generally quite fresh though some alteration of biotite and garnet to chlorite, and of aluminosilicates to shimmer aggregate, is usually seen in thin section. Although the chlorite in these rocks is obviously secondary, it is fitting to end an examination of Barrow's zones with rocks containing chlorite, biotite, garnet, staurolite, kyanite and sillimanite!

Summary of mineral assemblages across Barrow's Zones

The changes in the mineral assemblages across the Glens Clova-Lethnot-Esk region of Barrow's Zones are summarized in (Figure 13), using Al_2O_3-FeO-MgO projections of the KFMASH system (after Thompson, 1957). The incoming of garnet results from the movement of the three- phase field (garnet-biotite-chlorite) into bulk compositions of higher M/FM (MgO/(MgO+FeO) with increasing grade (Figure 13)a. The blue cross in (Figure 13) represents average Dalradian pelite compositions (Atherton and Brotherton 1982), and at lower grades these are represented by chlorite-biotite assemblages. At higher grades the garnet-biotite-chlorite triangle (in red) has moved to include average pelite compositions, and so the rocks come to contain garnet.

In the staurolite zone (Figure 13)b, the garnet zone tie-line between garnet and chlorite has broken down, and the stabilization of the staurolite-biotite tie-line brings staurolite into the fields of common rock bulk compositions (the blue cross). With increasing grade staurolite+chlorite ceases to be a stable assemblage, and kyanite becomes stable with biotite (Figure 13)c. The kyanite-staurolite-biotite triangle moves into rocks of lower M/FM (MgO/(MgO+FeO) with increasing grade and moves to include common rock compositions (Chinner 1965).

Thus, in abbreviated net reaction terms in AFM space (Figure 13), the reactions representing the isograds are:

GARNET ZONE: chlorite $\rightarrow$ garnet + biotite

STAUROLITE ZONE: garnet + chlorite $\rightarrow$ staurolite + biotite

KYANITE ZONE: staurolite $\rightarrow$ kyanite + biotite

In both the kyanite and the sillimanite zones the Al_2O_3 rich pelitic rocks quite often contain both garnet and staurolite as well as biotite and kyanite and/or sillimanite. In the pure KFMASH system this implies extra phases beyond those predicted by the phase rule. This is usually explained by suggesting that extra chemical components (in particular MnO in garnet, and ZnO in staurolites) lead to the stabilization of extra phases. When we reach the sillimanite zone we can find kyanite and sillimanite co-existing, which is commonly attributed to very sluggish kinetics of the polymorphic kyanite to sillimanite transition. It is in fact more common to find sillimanite forming haloes around garnet than directly replacing kyanite (Figure 10) and (Figure 11)b, and it seems possible that some sillimanite has formed by the net AFM reaction: garnet → sillimanite + biotite.

Considering the abundant occurrence of kyanite in haematite-rich schists, as described under locality 5; it is evident that the effectively high M/FM, (MgO/(MgO+FeO), of these schists places them within the bulk composition field of kyanite+biotite assemblages in (Figure 13)c, and thus ready to develop kyanite at lower grade than rocks of more usual composition (blue triangle).

The sequences of mineral assemblages and reactions described above, might be compared with those seen on the Stonehaven coast section (Harte et al. 2015, Aberdeen Geological Society website). Two striking differences may be noted:

1. Kyanite does not occur in the Stonehaven section and one passes directly from staurolite zone assemblages to the same assemblages containing sillimanite (Chinner 1966; Booth 1984).
2. The transition from garnet to staurolite zone assemblages at Stonehaven involves an additional zone where chloritoid+biotite assemblages occur (Harte and Hudson 1979). Thus the garnet-chlorite tie-line on the Stonehaven coast section is first broken by the development of a chloritoid-biotite tie-line. The critical chloritoid+biotite assemblage has not been found in the main part of Glen Esk; nor in Glen Lethnot and Glen Clova.

Both of these differences may be explained by pressures being lower near Stonehaven compared with further west. In calibrated pelite petrogenetic grids, chloritoid+biotite assemblages have a distinct upper pressure limit (Harte, 1975b, Harte and Hudson 1979; Powell and Holland 1990; Droop and Harte 1995; White et al. 2014). Using calculated pressures and temperatures based on specific mineral reactions and compositions, Vorhies and Ague (2011) also find lower pressures on the Stonehaven coast section compared to the region of Glen Clova and Glen Esk.

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Figures

(Figure 1) Outline map of regional metamorphic zones in the Dalradian Supergroup of the Eastern Scottish Highlands (after Chinner, 1966; Harte & Hudson 1979; Chinner & Heseltine 1979). The dashed line marking the Highland Boundary is the locus of occurrence of Highland Border Complex (HBC) rocks and the Highland Boundary Fault (HBF). Note that many granitic and gabbroic intrusions and their contact aureoles have been omitted. Sillimanite- bearing rocks in the Portsoy and Huntly areas have been omitted likewise, because they occur at the margins of gabbroic intrusions and represent an enhancement of the regional temperature distribution (Ashworth 1972). Chloritoid occurrences are omitted (see Chinner 1967; Harte & Hudson 1979). For summary information on zonal mineral assemblages and isograd reactions, see Harte & Hudson (1979).

(Figure 2) Barrow's Zones in Glen Esk and Glen Lethnot, with the seven localities of the excursion guide shown. The metamorphic zones are in colour, and all lie within the Southern Highland Group of the Dalradian Supergroup, apart from the hatched area within the sillimanite zone, which belongs to the Argyll Group (locally known as the Tarfside Limestone and Quartzite Group – see Harte 1979).The Highland Boundary line may be either a fault or an unconformity. Other faults (F) are largely based on displacement of the lithostratigraphic boundaries. The boundaries ('isograds') of the metamorphic zones are mapped as 'lines of first appearance' of the zonal minerals as one proceeds upgrade.; with the exception of kyanite 'isograd', which is based on the estimated position of the line of quartz-muscovite-biotite-staurolite-kyanite schists containing biotite with %MgO/(MgO+FeO) of 51 (Chinner and Heseltine, 1979). In haematite-bearing schists, which typically have biotite of higher %MgO/(MgO+FeO), kyanite occurs in the staurolite zone (Harte 1966, 1975a). Note that chloritoid has not been found in the main part of Glen Esk or Glen Lethnot, but is recorded near the western margin of the map (Barrow, 1898; Chinner, 1967).

(Figure 3) Detailed map of field locations 1 to 6. The 'Margie Series' and 'Jasper & Greenstone Series' are the two major components of The Highland Border Complex shown on (Figure 2).

(Figure 4) Dalradian and Highland Border Complex rocks exposed along the River North Esk; for localities 1 and 2. Largely after Johnson and Harris (1967) and Booth (1984).

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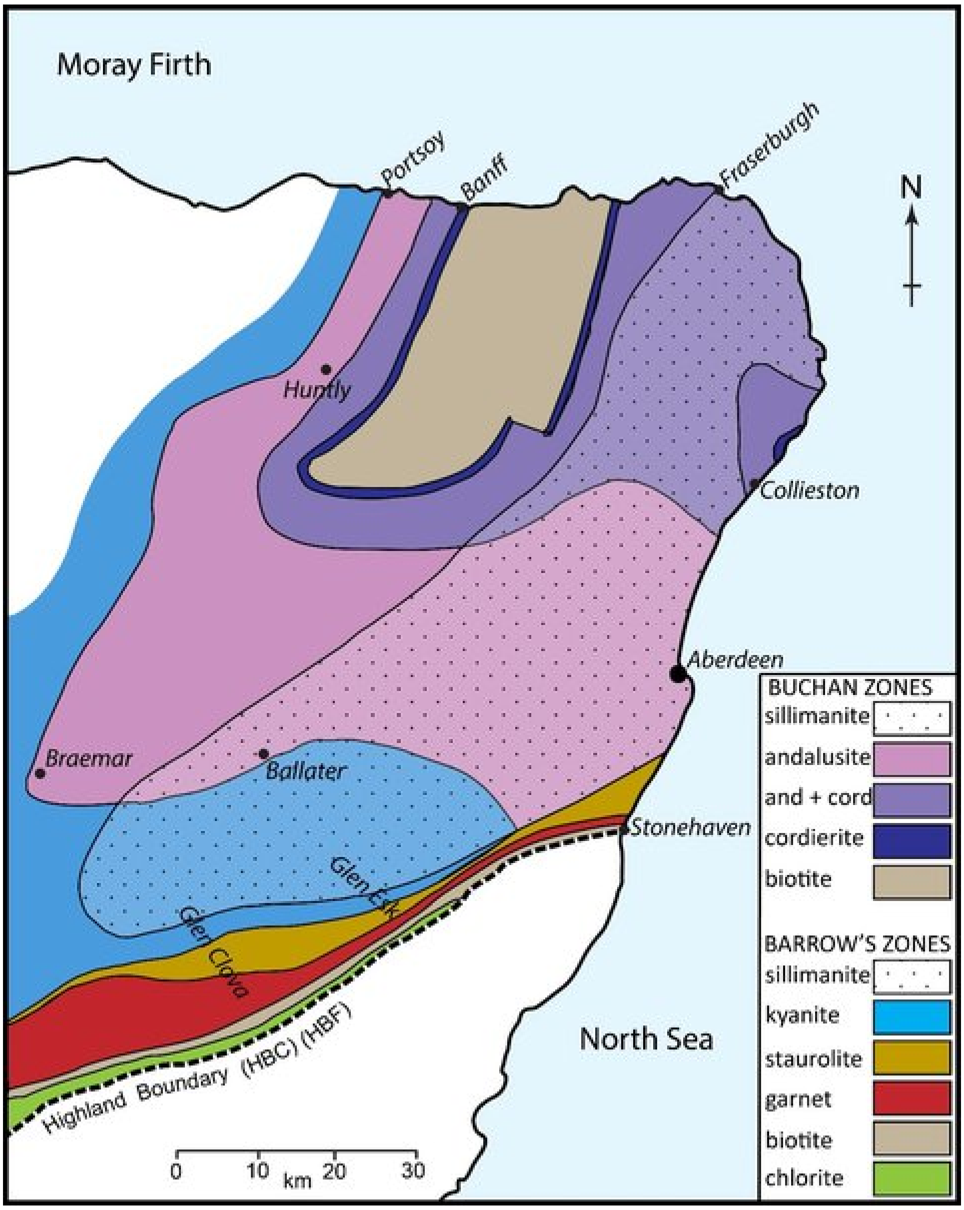
(Figure 13) Illustrations of mineral assemblages in the garnet, staurolite and kyanite zones in Glen Esk. The diagrams are Thompson (1957) AFM projections for pelitic assemblages containing quartz and muscovite. Mineral compositions are shown in colour. The blue cross shows the average composition of Dalradian Pelites after Atherton and Brotherton (1982). The 'A' axis is calculated as $(Al_2O_3–3K_2O)/[(Al_2O_3–3K_2O) + FeO + MgO]$.



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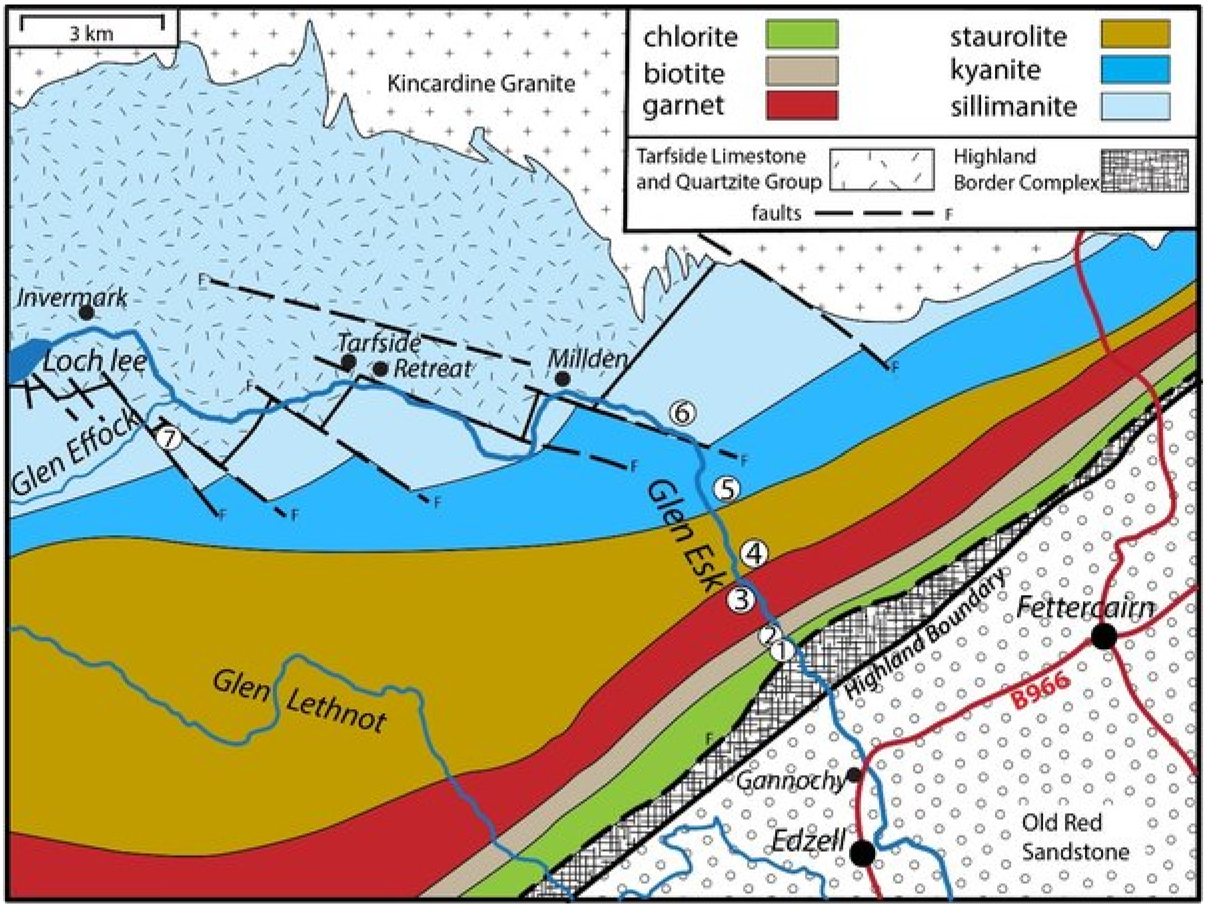

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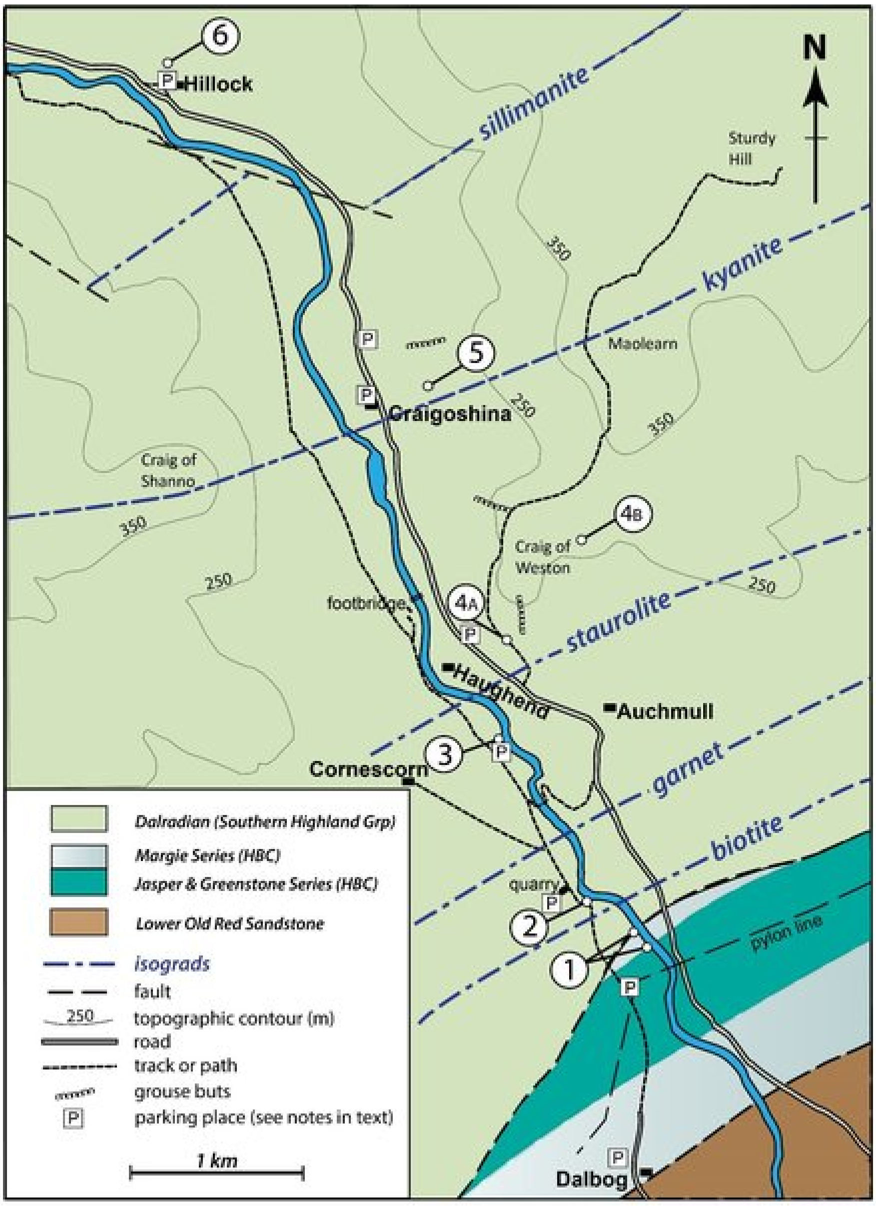

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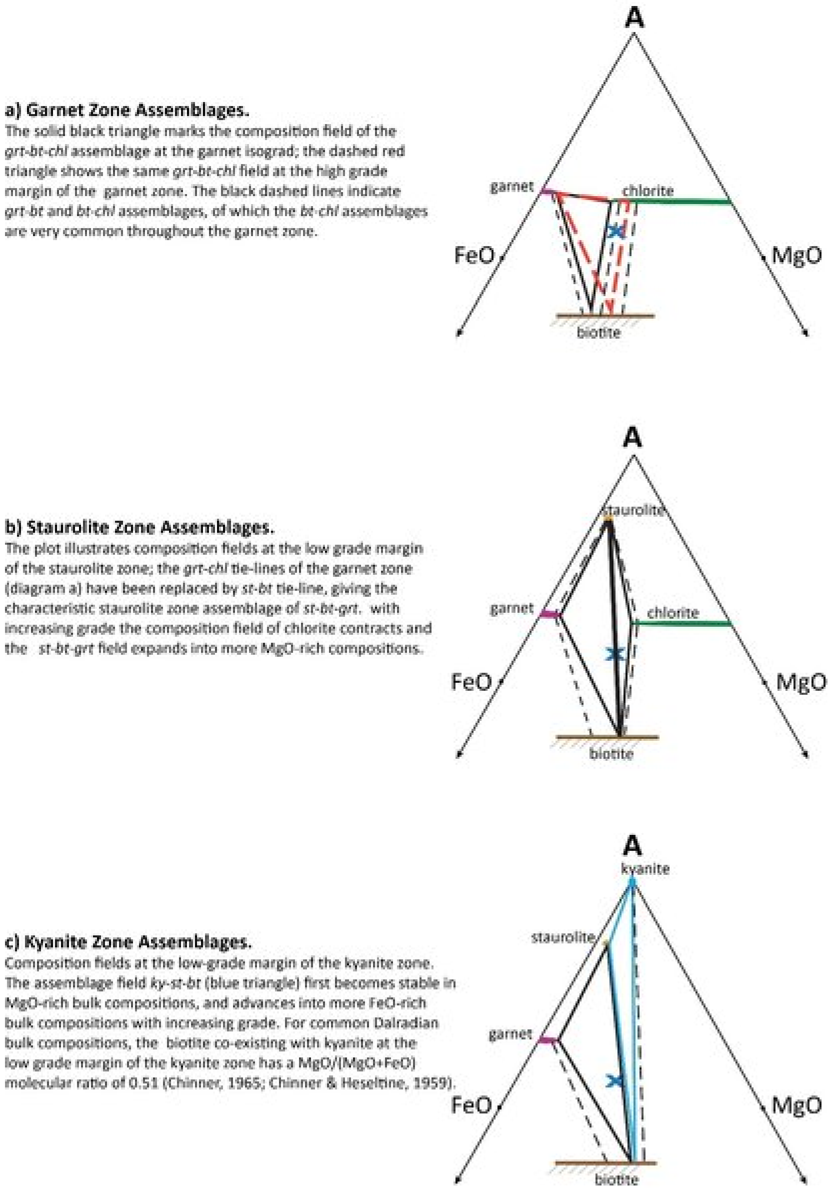

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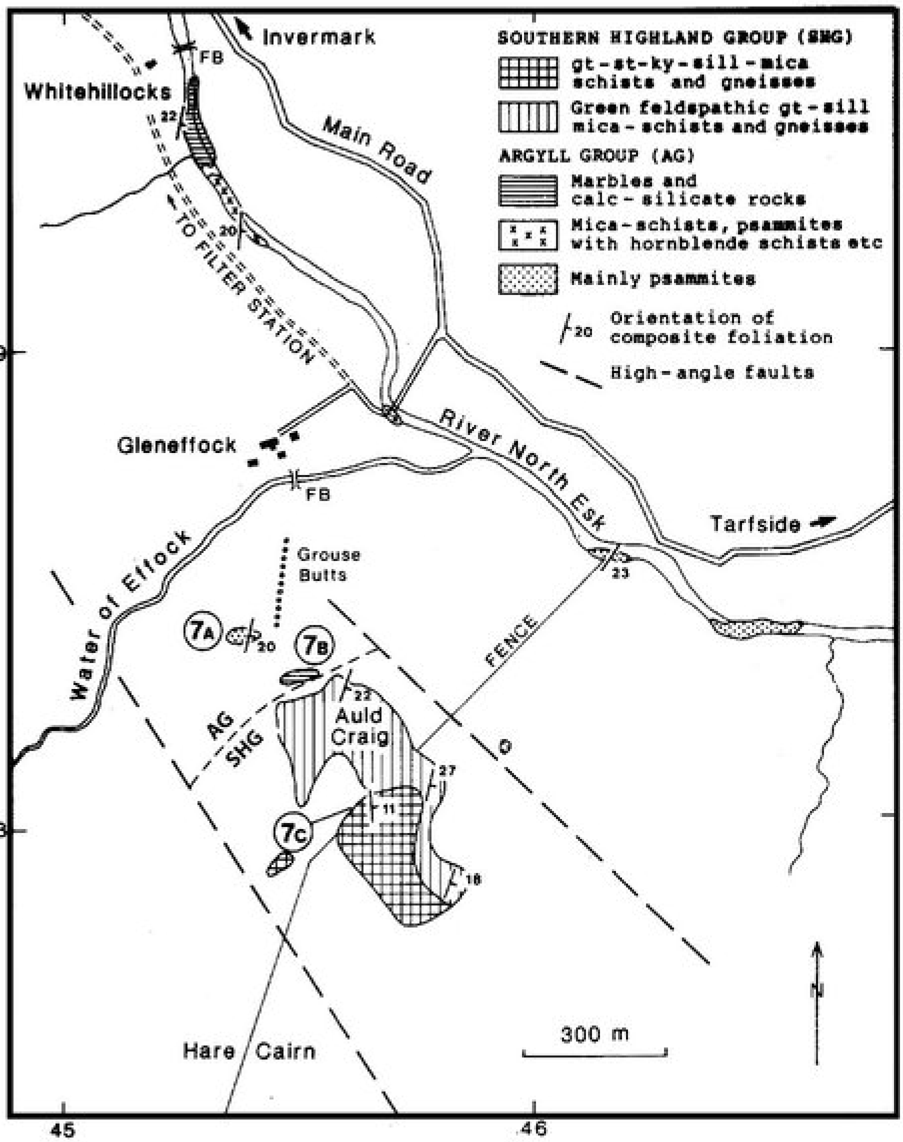

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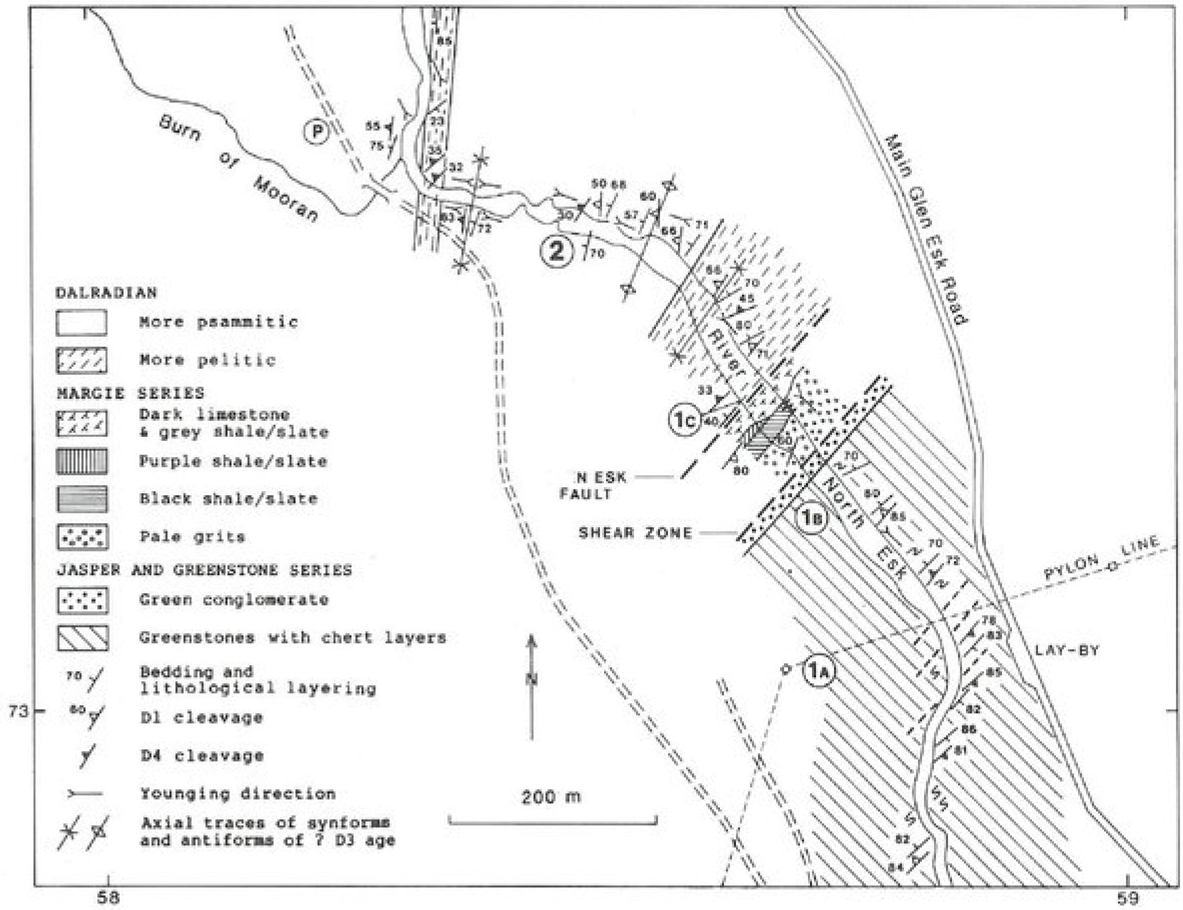

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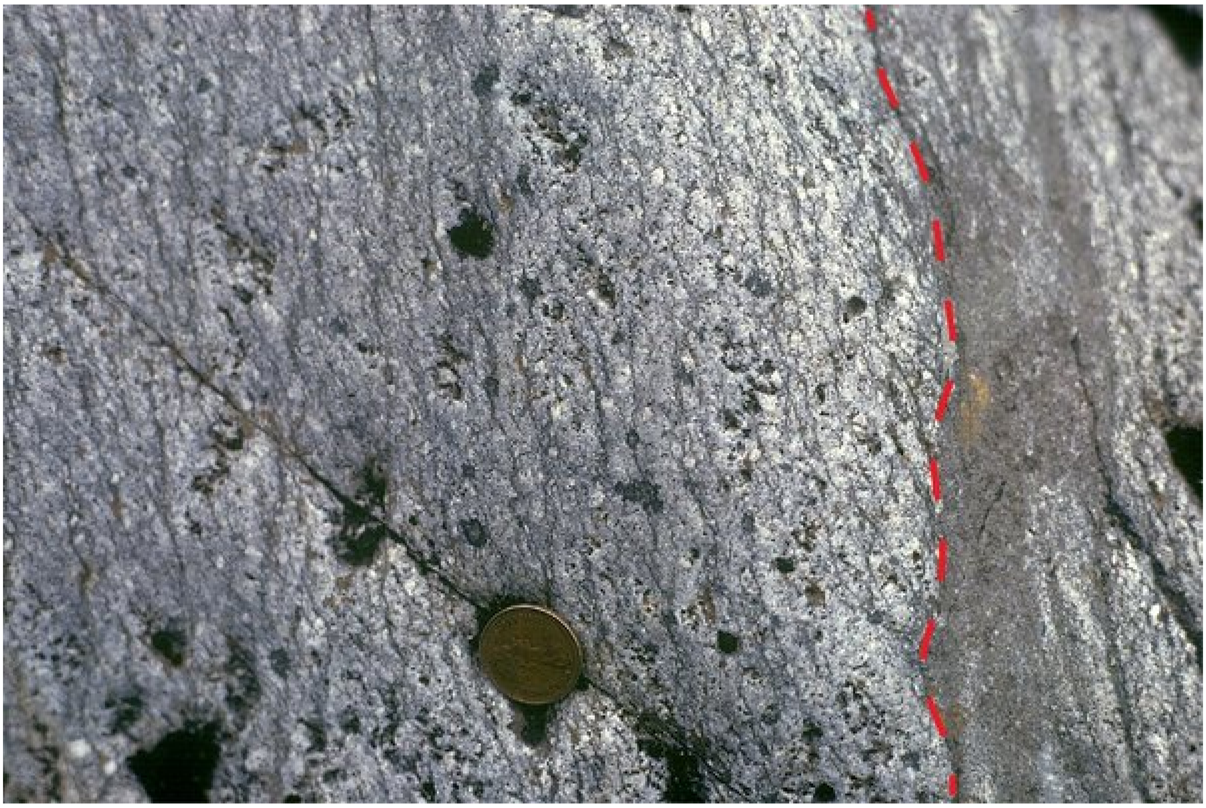

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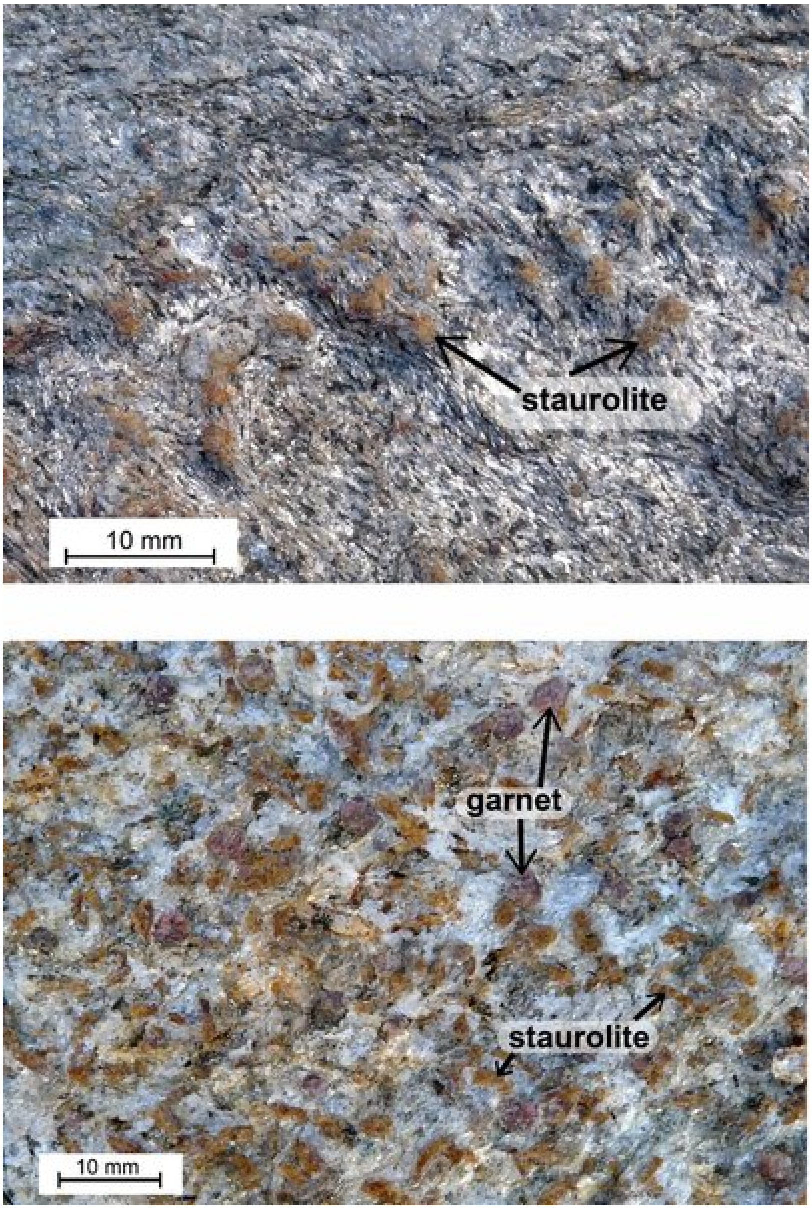

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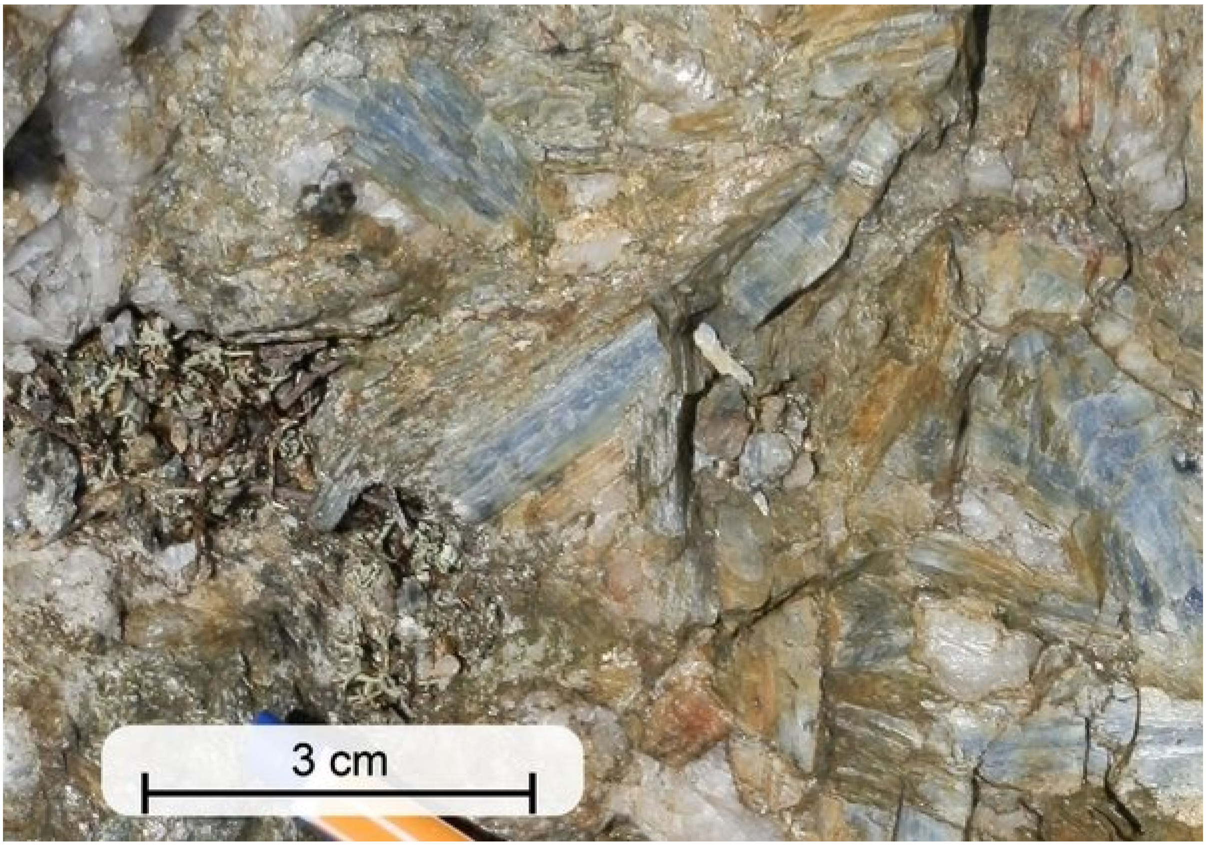

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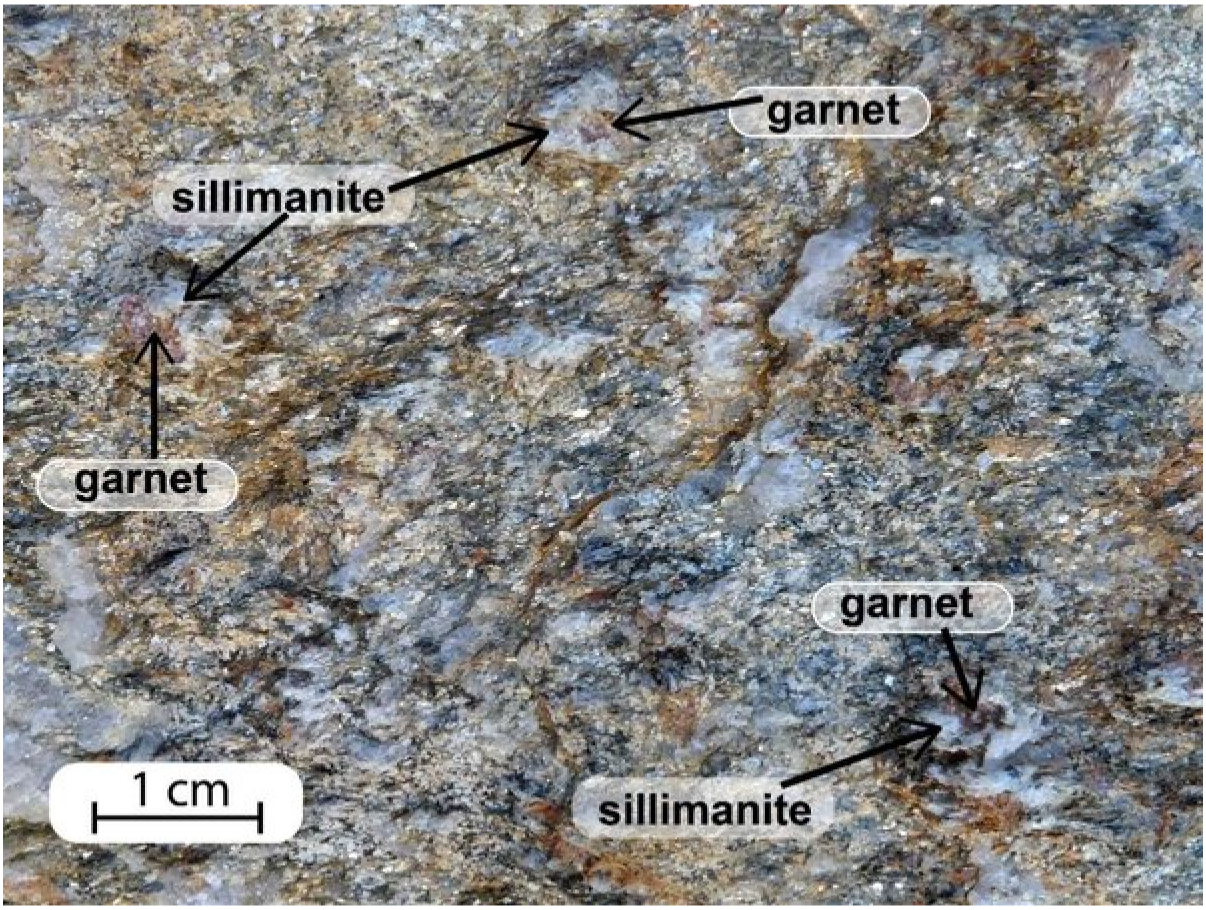

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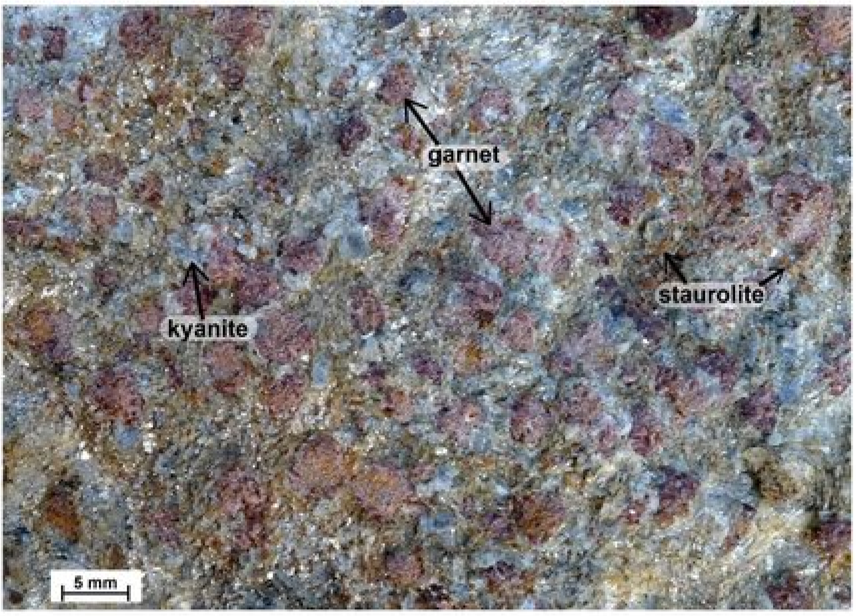

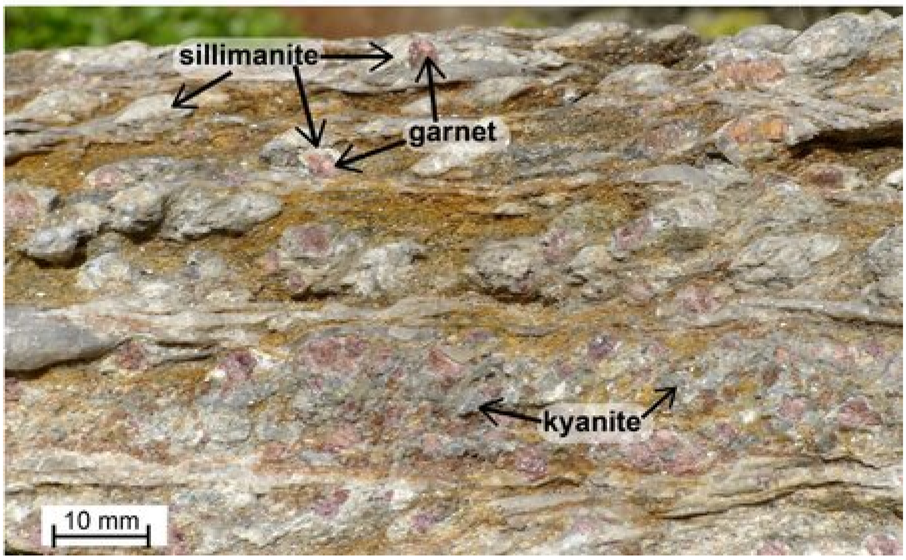

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