18 Stonehaven to Findon: Dalradian structure and metamorphism

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Purpose

To examine the structure and metamorphism of the Dalradian rocks of the Kincardine coast from the Highland Boundary Fault near Stonehaven northwards to the environs of the village of Findon, about 13 km south of Aberdeen.

Access

The excursion is divided into three coastal itineraries. Low tide is an advantage, but by no means essential for all the localities described (see details in individual itineraries). Many of the localities described are along the shore line, which is normally backed inland by cliffs (often 50 to 60 metres high). Descending the cliff line to reach the shore sometimes involves walking steep and narrow paths, which can also be slippy in wet weather. Walking across raised boulder beaches is also arduous in places.

(Figure 1) shows the locations of each of the three itinerary areas in relation to one another. The area is largely covered by Geological Survey 1:50,000 sheet 67 (Stonehaven). Detailed topography, roads etc are given on the Ordnance Survey sheets: 1:50,000, sheet 45; and 1:25,000 sheets 406 (Aberdeen) and 396 (Stonehaven).

Introduction

This guide covers the major part of the coast section between Stonehaven and Aberdeen, and is concerned with rocks belonging to the Southern Highland Group of the Dalradian Supergroup. The Dalradian rocks show a considerable range in metamorphic grade from biotite zone to sillimanite zone. Barrow (1912) showed the zones in this region largely as an extension of the zones he had first mapped (Barrow 1893) further west in Glens Clova and Glen Esk, with the exception that he did not recognize the kyanite zone near the coast section. Chinner (1966) further noted the absence of kyanite near Stonehaven and suggested that the pressures of metamorphism increased to the west. Harte and Hudson (1979) presented further evidence for lower pressure near Stonehaven on the basis of the occurrence of mineral assemblages with chloritoid+biotite in the coast section. For a general map of the distribution of metamorphic zones in the Barrovian and Buchan regions of the Eastern Highlands, and a brief outline of historical developments see the guide to Barrow's Zones in Glen Esk (Harte 2015) — see the Aberdeen Geological Society website for Field Guides).

The Kincardine coast section also illustrates well the progressive incoming of different phases of deformation in the Dalradian rocks as one proceeds north from the Highland Boundary Fault. Five phases of deformation have been recognised in the section (Booth 1984) but since the fourth phase has no regional correlative it is treated as a subphase of D3 and not discussed separately here. All other phases are similar to those found in Glen Esk and elsewhere to the southwest in the southern and central Highlands (Tanner et al. 2013; Stephenson et al. 2013). Therefore, D1 relates to the formation of the major Dalradian nappes, whilst D4 relates to the formation of the major Highland Border Downbend structure, which runs NE–SW in the Dalradian close to the Highland Boundary Fault (Harte et al. 1984). The south to north traverse of the Stonehaven section passes into progressively deeper and more complex structural regimes. The initial section south of the Limpet Burn is characterized by D1 folds and associated cleavage (S1). North of this point the D1 structures are strongly modified by subsequent deformations. D2 structures which are absent south of Limpet Burn increase in intensity northwards such that bedding (S0), S1 and S2 commonly form a composite fabric. S3 fabrics are present intermittently along the section but significant D3 folds only appear north of Portlethen Bay. D4 folds are present throughout the section verging towards the Highland Border Downbend whose axis lies in the Tilly Tenant – Castle Rock o' Muchalls area (Figure 7).

The three itineraries in this guide are summarized below and subsequently described in detail with designated localities in each itinerary. To complete all three itineraries in a single day is not possible if the rocks are to be examined carefully. Visitors may also wish to combine the first itinerary in this guide with final section of excursion 23 (see below).

Outline of itineraries

Features to be examined in each of the itineraries are summarized below.

Itinerary 1. Skatie Shore to Limpet Burn (Localities 1–7, (Figure 2))

To see the succession of metamorphic mineral assemblages from biotite to staurolite zones (including the occurrence of chloritoid). To examine the D1 fold system and see that the S1 cleavage is continuously downward facing; although the position of the F1 fold axes can be constrained by bedding-cleavage relationships, only in rare cases can an actual fold closure be seen. Examples of possible D3, D4 and post-D4 folds and cleavages may be found.

This itinerary may be easily combined with visiting localities 10 to 15 in the excursion guide by Gillen and Trewin (2015) available on the Aberdeen Geological Society website. Locality 10 of Gillen and Trewin is the unconformity of Old Red Sandstone sediments on the Highland Border Complex (HBC); localities 11 to 14 cover the Highland Border Fault (HBF) and the (HBC) including pillow lavas and chert units; locality 15 is on Skatie Shore which is also the place of the 1st locality in this guide.

Itinerary 2. Muchalls Area (Localities 8–11, (Figure 7))

This itinerary is largely concerned with structural features. Several phases of minor folding are observed. D2 structures, which were scarce in the areas of itinerary 1, are now found; and there is particular emphasis on the D4 folds and the major D4 structure of the Highland Border Downbend.

Itinerary 3. Portlethen to Clashrodney (Localities 12 to 15, (Figure 10))

Stops are suggested at three main points (Portlethen village, Findon and Findon Ness, Blowup Nose and Clashrodney) to see aspects of minor structures and observe the transition from high grade staurolite zone to sillimanite zone (without staurolite). Notes are also given on granitic injection sheets in pelites-psammites and amphibolites at Blowup Nose/Clashrodney on the south side of the Cove granite.

Itinerary 1. Skatie Shore to Limpet Burn (Figure 2)

The whole of this itinerary may be done from a single parking place (P on (Figure 2)) and takes around 3 to 4 hours for the principal localities (1 to 7 of (Figure 2)). If the end part of excursion 23 (localities 10 to 14) are also to be done, an extra 2 to 3 hours should be allowed. Locality 1 requires low-medium tide; locality 3 requires low tide; other localites may be done with moderately high tide.

Park in the layby [NO 883 878] about 300 m north of the railway bridge near the entrance to Stonehaven Golf Club (Figure 2). If you are driving from Stonehaven take the road leading towards Stonehaven Golf Club, and go under the railway bridge just beyond the entrance to the Golf Club. If you are driving from Aberdeen on the dual carriageway (A90) be aware that a minor slip road leading directly to the layby at [NO 883 878] has now been partially closed, and you should carry on past it to leave the dual carriageway at the next major road junction following signs for Stonehaven. From Stonehaven follow signs for Stonehaven Golf Club as noted above.

If you are planning to do the end part of the Excursion covering the Highland Border Complex and Highland Boundary (Gillen and Trewin 2015), in addition to the present itinerary, walk down the road from the parking area, pass under the railway bridge and take the path leading down to the old kirk (St Mary's Church) and graveyard on the clifftops overlooking the sea. From here you may do the localities 10 to 15 from Ruthery Head to Skatie Shore described by Gillen and Trewin (2015).

To proceed directly to the first locality described in this itinerary, walk about 80 m up (north) along the road from the parking area, and then take the path to the right – a small sign says the path goes to Skatie Shore and the Highland Boundary Fault. The path leads down through the trees into a gully (glacial overflow channel) heading towards a major viaduct for the railway. At [NO 8890 8815] you have to ascend over a mound, which runs across the gully. On climbing this mound you will see that it carries a track crossing the gully. This track is for the golf-players; do not follow it, but cross it and descend some steps leading back to the floor of the gully. Follow the path down the gully, under the railway viaduct and eventually down to the beach. You meet the shore just to the south of locality 2 [NO 8911 8807] on (Figure 2). Turn right heading southwest parallel to the shore until you come to locality 1.

Locality 1. Skatie Shore [NO 8906 8782]

At this locality a prominent but dissected ridge runs from the cliffs into the sea. The rocks here are typical of the Southern Highland Group of the Dalradian Supergroup and consist of pelites and psammites with many of the psammites being meta-conglomerates — they show relict clasts of 2 to 6 mm grain size. These rocks are commonly called 'grits' in traditional Scottish highland terminology. The small pebbles are grey-white-pink in colour and are of feldspar and quartz, lying within a fine-grained pelitic matrix. In the more pelitic units, small porphyroblasts (1 to 2mm) of biotite are visible. Relict bedding on scales of centimetres to metres is well seen, and sometimes graded bedding is visible. A strong cleavage, of pressure solution type is present and is often more conspicuous than bedding. The cleavage often appears sub-parallel to bedding, but small angular relationships to bedding may be seen on careful inspection. Both bedding and cleavage dip steeply to the north-west (NW) (Figure 3).

Cleavage, bedding and graded bedding are particularly well seen on WSW-facing vertical rock faces between high and low tide. Here bedding typically dips at 70° to the NW whilst the S1 pressure solution cleavage in grit units dips at 55° to the NW. Grading in pebble beds indicates that the beds young to the north, hence the S1 cleavage is downward facing (Shackleton 1957).

A few metres to the south, across a small sandy patch in exposures near to the high tide mark, there are beds younging south (i.e. the opposite direction), but here, although the angle between cleavage and bedding is much smaller, cleavage dips more steeply NW than bedding. Thus S1 is still downward facing, but between these two localities there lies an F1 synformal closure — it is thus a synformal anticline as the beds young away from the core of the fold (Figure 3b). Although several folds can be identified in the section these are generally evidenced by younging reversals and related changes in the cleavage/bedding angle; actual fold closures are difficult to see.

Locality 2. [NO 8911 8807]

Localities 2, 3, 4 are in the southern part of Perthumie Bay, just north of where the path from the parking area meets the beach (see above). In this area there are extensive rock exposures in the tidal zone, and those close to the high tide mark are often quite clean. At locality 2, two D1 fold hinges may be found with patient searching. The first is close to the western (high tide) margin of the intertidal exposures, and is only a few cm across; the more seaward of the two is more easily found and is a much larger example, having a wavelength of 2 m. The folds here close to the east and west with very steep axial plunges and S1 can be seen to fan around the fold axes. These are rare exposures, actually showing D1 fold hinges — **please do not hammer them.**

By examining the S1/S0 intersection lineation you can see that it is parallel to the plunge of the folds. By analyzing such intersections it is possible to show that the fold plunges vary from near horizontal to vertical.

Locality 3. [NO 8914 8817]

This locality is a gully through an upstanding rock mass on the wave cut platform. The rocks form a sea stack at high tide and are only accessible at below half tide. Whereas many of the rocks in the intertidal zone are difficult to observe because of seaweed, etc, the rocks in the gully are quite clean and it is possible to see three ages of cleavage.

Although all three cleavages may be seen at several places along Skatie Shore and Perthumie Bay, the main S1 cleavage is generally the most preponderant one by far. This locality is particularly good for distinguishing various cleavages — the basic relations of cleavages are seen on the ENE side of the gully. The S1 cleavage is essentially subparallel to bedding and dips steeply to the north. S3 is developed in semi-pelites and takes the form of a quartz ribbed segregation cleavage, which is sub-vertical at this locality. S4 is found weakly developed in semi-pelites but is better seen in pelites; it is a mica schistosity or grain alignment cleavage, dipping moderately NW. Along the southern side of the ridge, seaward of the gully, there are many fine examples of graded pebbly beds which show that these beds young to the north.

Locality 4. [NO 8905 8823]

This locality is marked by the seaward protrusion of the grassy platform (raised beach) at the base of the cliffs. There are several thick pelitic beds developed immediately around here. In them one can find porphyroblastic biotite, clearly visible to the naked eye. Roughly parallel to bedding is a fine S1 schistosity which is crenulated by S4 which dips moderately steeply NW.

Near the high tide line to the north and south of the grassy feature there are many fine examples of graded bedding and some of the largest angles between S1 and bedding.

In the region from a little north of locality 4 to locality 2, it is possible to find several reversals of the younging direction, and changes in the relative inclination of bedding and cleavage. However, it usually takes a little time to get used to distinguishing bedding and cleavage and picking out the graded bedding. With time, several fold axes may be tied down to a few metres but fold closures are not easily seen.

Locality 5. Red Man [NO 8925 8872]

From locality 4 proceed northwards along the shore following rough paths close to the boundary between the shingle beach and the grassy area of the raised beach. As you approach the northern end of Perthumie Bay (Figure 2), the lower parts of the cliffs jut out towards the sea, to form craggy exposures into the tidal zone. At this point it is best to ascend 5 to 10 metres to a grassy platform and follow it northwards to reach the Red Man exposures of locality 5. In the course of travelling to here from locality 4, you will cross the garnet and chloritoid isograds[1] where these minerals first appear in the rocks as you head upgrade (Figure 2). At these isograds the occurrence of both garnet and chloritoid is limited, and it takes considerable time to locate the place of their first occurrence precisely. You are advised to proceed directly to Red Man to find good examples of both garnet- and chloritoid-bearing assemblages.

Mineral assemblages at the Red Man.

The Red Man–Limpet Burn area is notable for showing a significant number of pelitic and semi-pelitic beds in contrast to the grits and psammites which dominate the succession along Skatie Shore and Perthumie Bay.

On the Red Man promontory there are reasonably accessible exposures just above a grassy bank near the base of the ESE facing cliffs (Figure 4). These pelitic schists include beds carrying substantial numbers of grey-green chloritoid porphyroblasts (1 to 3 mm) which are readily visible to the naked eye. Some layers (particularly those accessible a little way up the cliff) also contain garnet.

The mineral assemblages on the promontory here and a little distance to the south are:

Chloritoid-bearing assemblages	**Biotite-bearing assemblages**
Chloritoid-Chlorite (commonest)	Biotite-Garnet-Chlorite
Chloritoid-Garnet-Chlorite	Biotite-Chlorite
Chloritoid-Garnet	

In addition some schists contain garnet and chlorite without chloritoid or biotite (see (Figure 5)a. All these assemblages include quartz, white mica and sodic plagioclase as major phases. The occurrence of chloritoid with garnet and chlorite

indicates that some of the rock bulk compositions in this area are unusually rich in Al_2O_3 — Dalradian bulk compositions usually plot below the garnet-chlorite tie-lines in (Figure 5)a (Atherton and Brotherton, 1972; see also the field guide for Barrow's Zones in Glen Esk (Harte 2015).

Folds and cleavages at Red Man.

On a ledge one third of the way up the promontory and accessible from the grassy slope on the south side, one can see a similar cleavage relationship as at locality 3 with S1, S3 and S4 cleavages. S1 and S3 have been folded by a large D4 fold, (wavelength 3 to 4 metres) which verges towards an antiform to the north, and to which the S4 cleavage is clearly axial planar. The relatively large scale of these D4 structures (related to the major Highland Border Downbend structure) at Red Man has produced a significant area of gently dipping beds in contrast to the steep dips generally encountered along Skatie Shore and Perthumie Bay.

About 40 m ENE from the promontory and a little below the high water mark, one can see open D4 folds with a moderately well-developed S4, and another cleavage which dips moderately to the SE. This latter cleavage maintains a constant dip and is not obviously folded by D4 — it belongs to a sporadically and generally weakly developed post-D4 deformation that is responsible for much of the gentle warping of bedding that can be seen along the section traversed so far.

1 The term 'isograd' is used here simply to refer to a line of first occurrence of a metamorphic index mineral as one heads upgrade.

Locality 6. [NO 8920 8880]

The bay between Red Man and Limpet Burn (Figure 2) contains many intertidal rock exposures, but they are generally dirty and covered with seaweed. The cleanest exposures occur near where these rock exposures meet the shingle beach, but they are variably exposed in that they are periodically covered with shingle.

About 30m north of the northern edge of the Red Man promontory at the normal high tide level some low exposures include a darkish grey-green pelitic unit (Figure 6)), which contains 1 to 3mm porphyroblasts of staurolite. The porphyroblasts are not easily distinguished; they are typically yellow-brown in colour and most obvious when the rocks are wet. The mineral assemblage is staurolite-chloritoid-chlorite (plus quartz, white mica, sodic plagioclase and accessories). This is the lowest grade occurrence of staurolite reported in this section, and it is notable that the mineral assemblage is not so much suggestive of normal staurolite grade metamorphism as of an unusual aluminous bulk composition (Figure 5)b. This assemblage is only recorded from this one locality on the Stonehaven coast section.

Also occurring in this region near Red Man and the staurolite-chlorite rich rock, are mineral assemblages containing the critical association of chloritoid+biotite together with either chlorite or garnet (see Figure 5b). Identifying such rocks in the field is difficult, because grain sizes are quite small and the rocks are rather altered (Chinner 1967) and the exposures rather dirty. The chloritoid+biotite assemblage has not been found on the Red Man promontory itself (locality 5). Comparing the chloritoid-biotite assemblages with the assemblages listed above for the promontory it is evident that garnet-chlorite tie-lines of the Red Man assemblages are replaced by chloritoid-biotite tie-lines to give the assemblages of (Figure 5)b. See Droop and Harte (1995) for further details, and consideration of the importance of manganese (Mn) in promoting the occurrence of garnet.

About 100m north of Red Man there are some small ridges that stick up through the shingle beach at the high tide mark. About 15 m north of these ridges just on the high tide mark there is a large antiformal, isoclinal fold of possible D3 age with a wavelength of 5 metres. It can be traced along the wave-cut platform since its axial trace is close to the strike of bedding. Associated with this fold, and others developed between here and Red Man, is an axial planar grain alignment cleavage with the same orientation and structural relationships as the S3 segregation cleavage seen at localities 3 and 5.

Locality 7. [NO 8930 8902]

On the north side of the bay and starting about 100 m south of the Limpet Burn there are abundant craggy exposures at high tide mark and above. The more pelitic units here are remarkable for their abundance of staurolite and biotite in small porphyroblasts (1 to 3 mm). The staurolite, which is exceptionally abundant, forms small stumpy prisms sometimes showing a yellow to brown colour; but often of a very pale colour due to replacement of staurolite by fine- grained white mica (Barrow's 'shimmer aggregate'). In the more southerly of these exposures garnet is hard to find, but it becomes more abundant as you approach Limpet Burn.

Rocks containing chloritoid may also be found around Limpet Bum, but are difficult to spot in the field. Some rocks showing layering on a scale of a few millimetres show interlayered staurolite- and chloritoid-bearing assemblages.

The assemblages seen around locality 7 are summarized in (Figure 5)c. The major change from locality 6 is the replacement of chloritoid-chlorite tie-lines by staurolite-biotite tie-lines. With further increasing grade, chloritoid becomes unstable; thus, a little to the north of Limpet Burn chloritoid becomes exceedingly scarce and is preserved only as small relicts largely pseudomorphed by white mica (as seen in thin section). From Limpet northwards, the characteristic mineral assemblage in pelitic rocks is staurolite-biottite-garnet, until the sillimanite isograd is crossed between Porthlethan and Findon (see (Figure 10)). Further notes on the mineral assemblages from Red Man to Limpet Burn are presented in Droop and Harte (1994).

Access to the A90 from the shore at Limpet Burn is difficult, and it is necessary to retrace your steps southwards to locality 2 and then ascend the path passing under the railway line and return to the layby from which you started out (Figure 2). Itineraries 2 and 3 occur to the north of here, but from the lay-by, it is necessary to drive southwards towards Stonehaven to gain access to the A90 dual carriageway. At the road junction on the outskirts of Stonehaven, follow signs to Aberdeen.

Itinerary 2. Muchalls area (fig. 7)

A quick tour of localities 8 and 9 may be done in 1.5 to 2.0 hours, but much more time should be allowed if you wish to examine the structures in any detail and do localities 10 and 11. Note that the path leading down to the shore at Muchalls is steep and slippery and not well maintained – proceed with caution! For locality 11 you need to drive from Muchalls village to the Mill of Muchalls (Figure 7).

To reach locality 8, leave the Stonehaven-Aberdeen dual carriageway (A90) at [NO 899 925], follow the signs for Muchalls, and head into the centre of the village. Follow the road (MarineTerrace) round to the right at the telephone box and proceed to where the road ends in a small parking area at [NO 9017 9192] (beside the railway line). From here walk south parallel to the railway line for about 150 metres before turning sharp left through a tunnel under the railway line. From the tunnel walk straight ahead down the path heading directly away from the railway line. After about 200m (at [NO 9022 9166]) and shortly before a metal bench seat looking out to sea, a small path leads down to the right – this path may be overgrown and is easily missed. Take the path — it descends a very steep grassy bank and leads to the shore for locality 8 by Ship Hole (Figure 7), which is a sea arch whose shape is controlled by faulting and jointing. The path is steep, often slippery, and may be in a poor state of repair.

Locality 8. Ship Hole [NO 9028 9158]

On the southern face of the sea arch (Ship Hole) there are many D4 folds ranging in scale from a centimetre to several metres, with an overall vergence to the major Downbend antiformal axis (D4) in the south-east. Separated from the rocks of Ship Hole by a narrow gully a few metres wide is an elevated slab whose top surface is a bedding plane folded by a D4 fold pair verging on an antiform to the SE. The lithology is a psammite with a very strong NNW- trending D2 stretching lineation that lies on the bedding surface. This is a good place to see how folding affects the orientation of a lineation. Note also how the spacing of the S1 pressure solution cleavage, which parallels bedding to form the basic composite fabric of these rocks, is much more closely spaced than the same cleavage at Skatie Shore (Figure 3).

Locality 9. [NO 9019 9144]

Near this locality there is a large stack detached from the cliff by about 15m. Along the high tide line four large blocks protrude from the shingle and are separated by three gullies (about 3 to 5m deep). The middle gully of the three provides probably the best exposure in which to see the complex range of D2 structures developed in the area. There are D2 folds with wavelengths from 1 cm to 1 m. The small folds form a variety of styles from stacked shear folds to buckle folds. There are no folds of other ages in the middle gully though the whole block is folded by a large somewhat open D4 fold.

Locality 10. (If time permits) [NO 9022 9126]

Southwards from locality 9 across a large pink felsite dyke, locality 10 lies in a small bay in which a stream pours forth from the mouth of a cave (the felsite has been extensively quarried above the cliff here, diverting the stream into the cave). Low tide is necessary before this locality can be reached. On the northern side of the bay just above the shingle it is possible to see examples of S3 folded by D4. In places here the lithology is of alternating bands of pelite and psammite about 10 cm thick. In several instances S4 is not only a good axial planar mica- schistosity but is complemented by thin (2 to 4 mm) spaced white mica seams — a spaced segregation cleavage. Locally an earlier muscovite segregation cleavage is folded by the D4 folds. This cleavage has the same geometrical relationships to bedding and S1 as the S3 cleavages seen at localities 1–6 and is thus correlated with them.

Locality 11. (If time permits) [NO 9012 9091]

Although the distance from locality 10 to Locality 11 is short, it is difficult get around Doonie Point, and it is best to drive from Muchalls to the Mill of Muchalls. Proceed from Muchalls back to the A90 dual carriageway and turn left. After a short distance take the small road to the left from the dual carriageway at [NO 897 914], heading down towards a major bridge on the railway line. Park under the railway bridge, just before reaching the houses of Mill of Muchalls. Walk southwards past the houses and gardens until you reach an open field and then proceed SE up to the line of the cliff tops. At this point there is a break in the cliffs and a steep grassy bank drops down to the shore. Descend to the shore by a rough old track that runs obliquely down the steep grassy bank.

Near the end of this track exposures of rock commence at [NO 8989 9087]. Good examples of D4 folds (on scales to up to a metre) folding an earlier composite schistosity may be seen. Further good examples of D4 folds are seen at [NO 9003 9092] on the southside of the rocky headland of Doonie Point. S4 is locally well developed (Figure 8). D2 folds may also be found around here.

Highland Border Downbend and haematite-cordierite schists.

To the south of Doonie Point, between Castle Rock of Muchalls ([NO 8992 9031]) and the headlands at Tilly Tennant ([NO 8993 9015]) and Tilly Daff ([NO 8985 8995]) there are views of the hinge region of the major Highland Border Downbend (D4) structure, and interesting exposures of haematite-cordierite schists. These are exceptional localities and were described in first edition of this guide (1987), and are again mentioned here because of their unique nature**.** *However, at the present time access to these areas is very difficult and we cannot recommend a convenient safe route to the exposures from the landward side.*

Hinge of Highland Border Downbend between Castle Rock of Muchalls and Tilly Tennant.

The hinge is not a single large hinge but a whole series of small-moderate folds on scales up to several metres The folds are 'M' folds (with neutral vergence), with well-developed axial plane cleavage dipping about 45° NW. The position of the major axis is well constrained: north of the axis along the coast the dominant orientations of bedding and D1–D3 cleavage have a gentle southerly dip, whilst to the south the rocks have mainly steep dips, with minor D4 folds showing appropriate vergence.

Haematite-cordierite schists at Tilly Tennant and Tilly Daff.

Similar, distinctly unusual, rocks are exposed at both these localities, for the most part a little above H.W.M.. At first glance the rocks have something of the appearance of conglomerates in which matrix- supported pebbles and cobbles (hereafter referred to as 'cobbles') are embedded in a pelitic matrix. The 'cobbles' also appear to be pelitic in composition

though with smoother weathered surfaces than the pelitic matrix. Examination of the matrix reveals essentially mica schists carrying abundant opaque grains (hematite and magnetite). Examination of the 'cobbles' shows that they carry an internal fabric which appears to be very similar to the composite bedding- cleavage structure of the matrix but rotated in the 'cobbles'. In some cases the bedding- cleavage structure, despite rotation, appears to pass continuously from the matrix through the 'cobbles' (Figure 9).

Clearly these 'cobbles' are not what they superficially appear to be — they cannot be clasts of sedimentary origin, but are large crystals that have grown within the rock and appear to be porphyroblasts of metamorphic origin. The textural features are those frequently seen in fabric relationships of porphyroblasts and matrix, it is just that the scale is greater. It is suggested that the 'cobbles' are in fact altered porphyroblasts of cordierite. Cordierites of this size are not exceptional (Eskola 1914). Unfortunately, when examined in thin section the rocks are found to have undergone retrogression, and the porphyroblasts now consist of typical cordierite alteration products of fine-grained white mica and chlorite along with haematite. The unusual occurrence of cordierite here is attributed to two factors: (i) the hematite-mica schists provide unusual bulk rock compositions because their Fe is largely in the Fe^{3+} form and as a consequence they have a high $Mg/(Mg + Fe^{2+})$ ratios (Chinner 1960; Harte 1975); (ii) the lower pressure of the Stonehaven section by comparison with the original type area of Barrow's Zones further west (Harte and Hudson 1979) would favour the occurrence of cordierite in rocks of high $Mg/(Mg + Fe^{2+})$.

Itinerary 3. Portlethen to Clashrodney (Figure 10)

The first locality concerns the coast section by Portlethen village and requires about 1 hour. The objective is to examine D3 and D4 minor structures. In this region D3 minor structures are abundantly and widely developed, unlike in the areas further south. This is also an excellent locality for seeing high grade staurolite zone (staurolite-garnet-biotite) mineral assemblages and Southern Highland Group rocks which contain much less coarse clastic material (grit) than those at low grade (Skatie Shore, Perthumie Bay).

From the dual carriageway take the road through the modern parts of Portlethen following the signs for Old Portlethen or Portlethen Village. Old Portlethen is perched close to the cliff tops, and as you enter the village, the road turns sharp left at the local public house – the Neuk. Immediately on the left, opposite the Neuk is a moderately large parking area (Figure 10), and if your vehicle is larger than a private car then you must park here. From this parking area take the road which proceeds half-left — Broadhaven Road. At the bottom of this road turn left, and then take the rough track on the right heading towards the sea – the rocks to be examined are straight ahead of the start of this track and form extensive exposures of bare rocks with a general shallow-moderate dip to the the north. Follow the track swinging round the small natural harbour with small boats and proceed past the fishing station onto the rocks. It is possible to park a car at a couple of places (e.g. [NO 9341 9625]) near the start of this track, but the lower part near the harbour is restricted.

Locality 12. Portlethen [NO 9360 9625]

The extensive exposures here include some pelitic layers as well as abundant psammitic and semi-peltic rocks. Staurolite, typically in small yellow-brown prisms 2–3 mm long, is very abundant in some of these pelitic layers. The common assemblage is muscovite-bitotite-staurolite-garnet, though garnet is far less abundant than staurolite. The mineral assemblage is in fact very similar to that well seen in the highest grade rocks of locality 7 at Limpet Burn.

The rocks around this area also exhibit many fine examples of D3 minor folds, particularly on north facing joint surfaces (Figure 11). The wavelengths are of the order of 10cm to a few metres and the folds are tight to nearly isoclinal. The bedding and cleavage fabric folded by these folds is a composite SO/S1/S2 fabric. Locally an S3 fabric is well developed and is commonly seen as a spaced axial plane cleavage (Figure 9b). On fold limbs the S3 becomes part of the composite fabric. At this locality, D4 folds are easily distinguished from D3 by their more open nature and their axial planes which dip at 40° to the N and at an appreciable angle to the average gentle southerly dip of the composite SO/Sl/S2 fabric.

As seen at Muchalls (Locality 11), bedding surfaces in this area show a strong D2 stretching lineation in psammites trending NNW–SSE. There is also a second stretching lineation in psammites that trends about WNW–ESE, which overprints the D2 lineation and is folded by D4. Good examples of D3 folds and their relations to the other fold episodes

and their foliations may also be seen on the south side of Portlethen Bay.

Locality 13 And 13a. Findon and Findon Ness [NO 942 978]

Allow 1 to 1.5 hours for this locality if you only wish to examine the minor structures, but two hours if you wish to see good exposures of sillimanite-bearing schists.

Park vehicles by the road junction [NO 938 976] and proceed NE down the track heading obliquely towards the coast (Figure 10). Where the track bifurcates, follow the track around to the right heading directly towards the sea. After 200m the track turns southwards to run roughly parallel to the coast. Numerous low-lying exposures occur in this area with the track bordering them on their northern and eastern sides (Figure 10). Numerous examples of D3 minor folds with gently dipping axial planes are seen. As at Portlethen, D3 are folds of a composite bedding and cleavage structure and show an axial plane cleavage (S3) which becomes subparallel to the folded bedding-cleavage structure on the fold limbs. However, with careful searching here it is easier than at Portlethen to find evidence that the folded cleavage structure includes both D1 and D2 elements, because occasional D2 microlithons are seen to preserve within themselves a rotated S1 fabric.

Many of the rocks here are psammitic and some are grits but there are occasional pelitic layers and these show the assemblage staurolite-biotite-garnet-sillimanite. Good examples of rocks with this assemblage are hard to find at locality 13, but particularly good exposures are seen at locality 13a ([NO 9440 9745]); to reach this locality you should keep along the path to the south from locality 13 until you see the bench at the viewpoint at [NO 9433 9742]. From the bench there is a small path heading towards Findon Ness headland. Good low-lying rock exposures commence along this path where you begin descent towards the shoreline. The weathered rock surfaces show innumerable small upstanding grey lumps or 'knots' , about 2 to 4 mm across and with a somewhat scaly appearance. These are essentially made of sillimanite of the fibrous variety (fibrolite). In the centre of the sillimanite knots dark red garnets, ca 2mm across, may sometimes be seen (Figure 12). Staurolite in yellow-brown crystals around 2mm long is also locally abundant.

In this region, sillimanite (fibrolite) first occurs proceeding upgrade near Arnot Boo and Pow Kebbuck about 0.7 km to the south of this locality (Figure 10). The reactions giving rise to fibrolite involve the replacement of staurolite (staurolite = garnet + sillimanite + biotite) and the restriction of garnet stability (garnet = sillimanite + biotite). The replacement of staurolite continues upgrade (see locality 14). Staurolite replacement does not proceed directly but via a reaction loop (Carmichael 1969) so that in thin section staurolite is most commonly replaced by muscovite (Booth 1984, Foster 1977).

Locality 14. Blowup Nose [NO 9464 9867] and [NO 9473 9904]

Allow 1.0 to 1.5 hours for the Blowup Nose locality, and another hour if also wish to visit locality 15 (Clashrodney).

From Findon drive northwards towards the North Mains of Findon buildings (Figure 10), where the road turns sharply to the left. Just around this bend a gate leads northwards into a field on the northwest side of the house and garden. It is possible to park a small car beside the roadside near the gate, but if you are in a larger vehicle it is probably best to leave it about 300m further south near where a road leads to the quarry. After entering the gate beside North Mains of Findon, walk round the house and garden, and then head north-east across the field to where another gate provides an exit from the field. From here continue north-east to the Diney Burn. The valley of this stream is very shallow and has reed beds and bogs. Keep on the southwestern side of the stream valley and follow it towards the cliffs. At the cliff tops the Diney Burn makes a spectular waterfall descending the vertical cliffs. You should follow the clifftops in a southeasterly direction to reach a point on the southern side of Blowup Nose (see Figure 10). At this point the main top of the cliff line is about 50–60m above sea level, but at ca 20m height there is a small plateau breaking the descent to the sea.

The plateau is easy to access and is covered in low-lying exposures of psammitic-pelitic schists and gneisses. The weathered surfaces of the more pelitic exposures show abundant sillimanite (fibrolite) in small (3–4 mm) upstanding knots or tufts. Garnet is rarely seen, usually embedded in fibrolite, but there is no staurolite, which has reacted out completely by this grade. Muscovite in 1 to 2mm bumps (+ fibrolite) may be seen on some surfaces and with the 'eye of faith' one may imagine some of them to represent replaced stumpy prisms of staurolite.

The pelites and psammites are locally intruded by sheets of granite (sensu lato) up to around 8m thick (Figure 13). As you return to the Diney Burn, you will see sheets of 'granite' in the vertical cliffs to the north of the Diney Burn waterfall.

Locality 15. Clashrodney [NO 9473 9904]

From the Diney Burn (above the waterfall!) you may proceed northeastwards behind the cliff line until you reach (after about 400m) another small stream running northeastwards towards the shoreline. Follow this stream to the top of the cliffs near Clashrodney (Figure 10). The cliffs to the north of here show extensive exposures of the Cove granite. Immediatedly to the south, near the top of the cliffs, the country rocks are pelites and psammites with some amphibolitic bodies; these are intruded by granitic sheets. The amphibolitic bodies are dominantly layered mafic hornblende-biotite-schists, and they also form a number of contorted and disrupted layers (0.2 to 2.0 m thick) within the 'granite'.

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Figures

(Figure 1) Map showing the areas covered in the three itineraries for the Stonehaven to Findon excursion guide.

(Figure 2) Map for itinerary 1.

(Figure 3) a Bedding and cleavage in Dalradian grits, Skatie shore , locality 1. Yellow lines are parallel to bedding (dipping ca. 70°NW), with a more pelitic unit between psammitic ('grit') units. In the right hand 'grit' unit, cleavage is well seen (parallel to the blue line and dipping ca 50°). Within the pelitic unit the cleavage (in red) is refracted to a steeper inclination. Within the grit units, pebbles are more abundant and larger at the right hand side. Hence the beds young to the left (N) and the cleavage is downward facing. 3b Stylised illustration of bedding/cleavage relationships associated with D1 folds. The fanning of the cleavage about the axial planes is exaggerated for clarity. The middle limb of the diagram corresponds to the rock picture above.

(Figure 4) The Red Man locality (No. 5) rock face with rocks showing abundant chloritoid and also garnet in the region of the arms of the person and above him.

(Figure 5) AFM projections (after Thompson, 1957) showing mineral assemblages occurring with increasing grade in the region from Red Man to Limpet Burn. The 'A' axis is $[(Al_2O_3–3K_2O)/(Al_2O_3–3K_2O) + FeO + MgO]$.

(Figure 6) A darkish grey-green pelitic layer (centre of photo) exposed on the edge of the shingle beach (locality 6) just north of Red Man. This seam of rock contains abundant porphyroblasts (1 to 3mm) of staurolite in a chlorite rich matrix.

(Figure 7) Map for itinerary 2 – the Muchalls area.

(Figure 8) a. Typical step-like D4 folds verging to SE towards the HBD axis. Bedding and the spaced S1/S2 composite cleavage are seen to be folded by D4. Doonie Point [NO 8989 9095]. b. D4 folds with spaced axial fabric (cleavage) visible in beds towards centre right and dipping at ca 40 degrees to the left (SW). Doonie Point [NO 9016 9095].

(Figure 9) Polished surface of haematite-cordierite schist showing dark porphyroblasts of probable retrogressed cordierite. In the porphyroblast near the bottom-right, fine laminae of the original bedding may be seen to be preserved within the cordierite.

(Figure 10) Map for itinerary 3 – the Porthlethen to Findon area.

(Figure 11) a. Typical D3 folds looking south. Porthlethan fishing station (locality 12) b. Typical D3 folds looking south with a poorly developed spaced cleavage in beds to the right. Porthlethan fishing station [NO 9360 9630].

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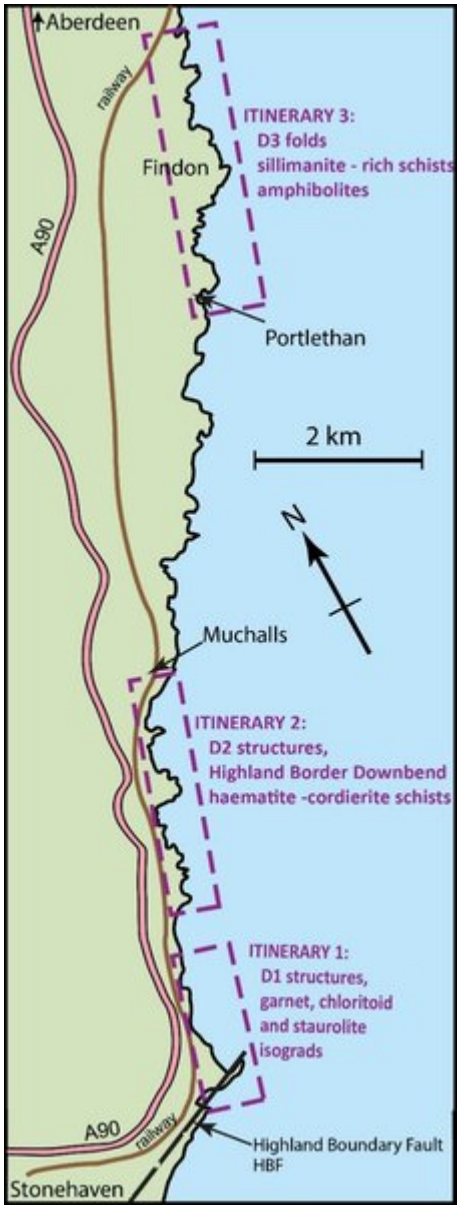
(Figure 13) Granitic sheet intruded in country rocks in cliffs north of Blow-up Nose and looking towards Clashrodney. [NO 9473 9904].



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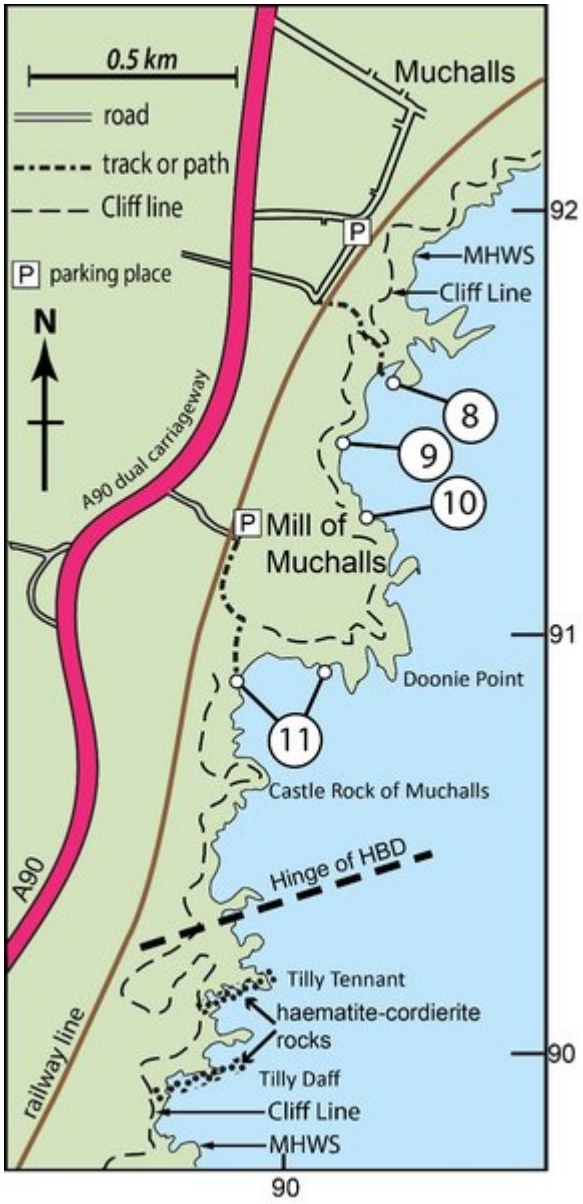

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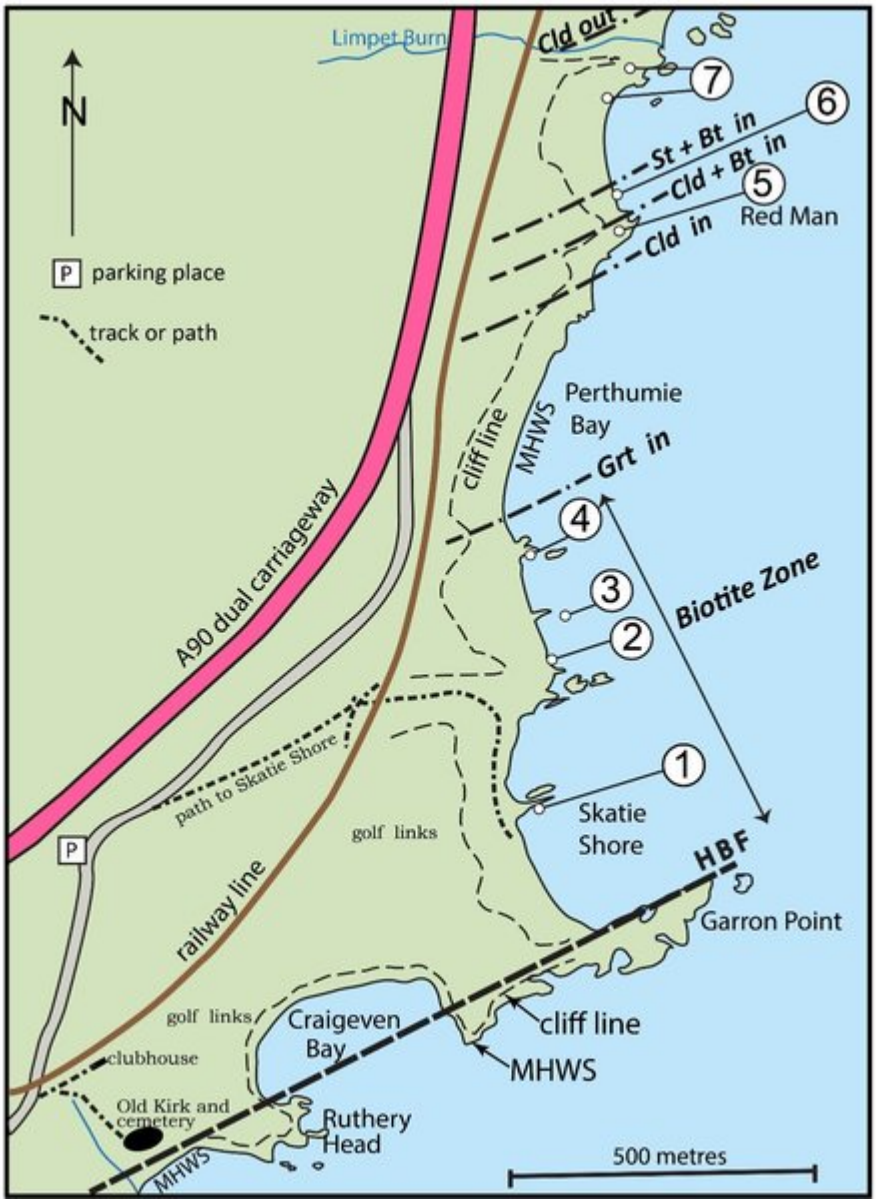

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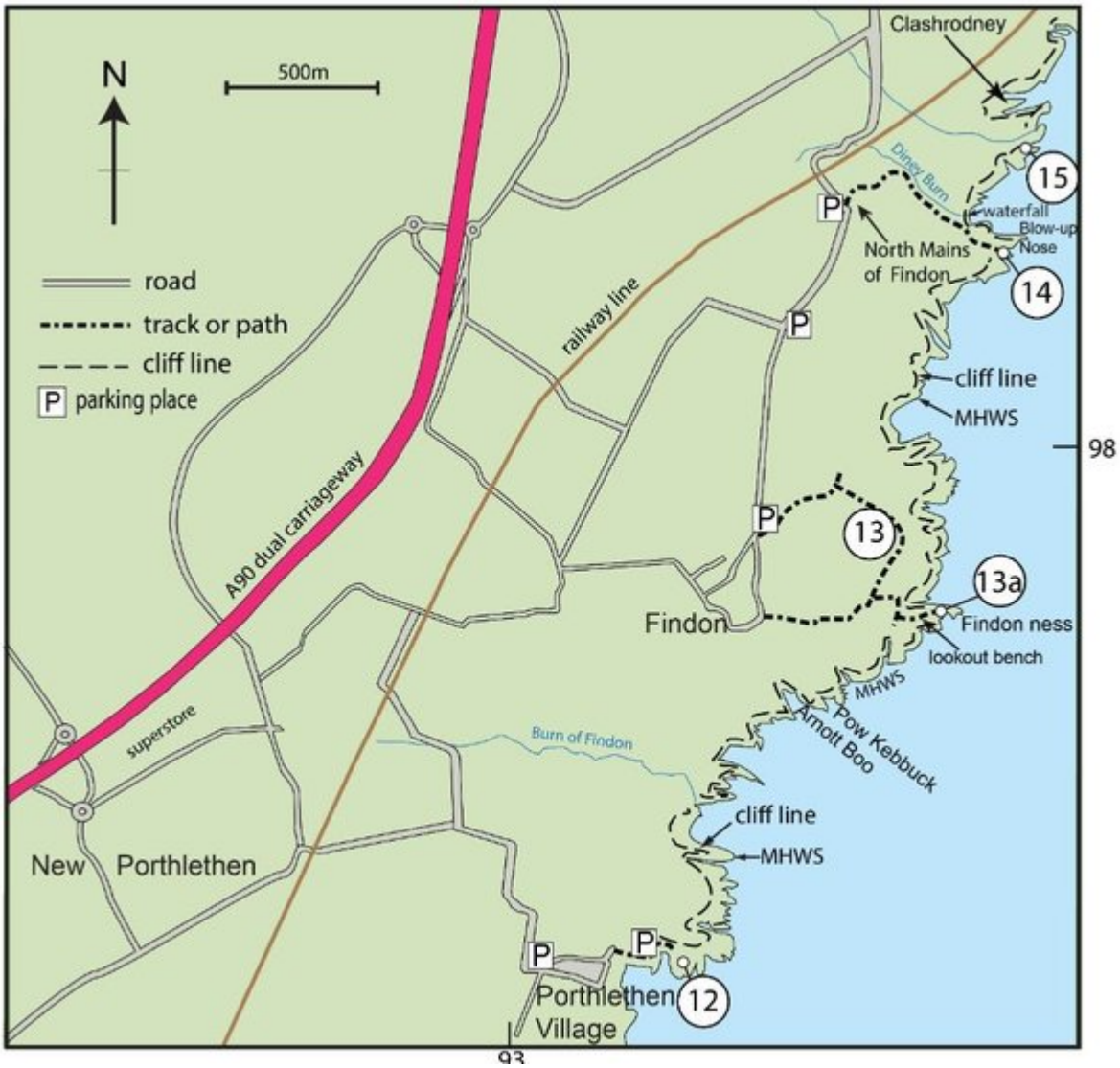

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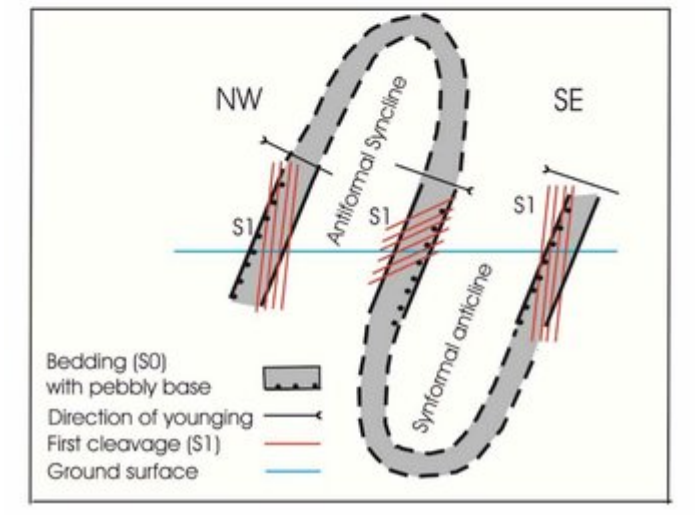

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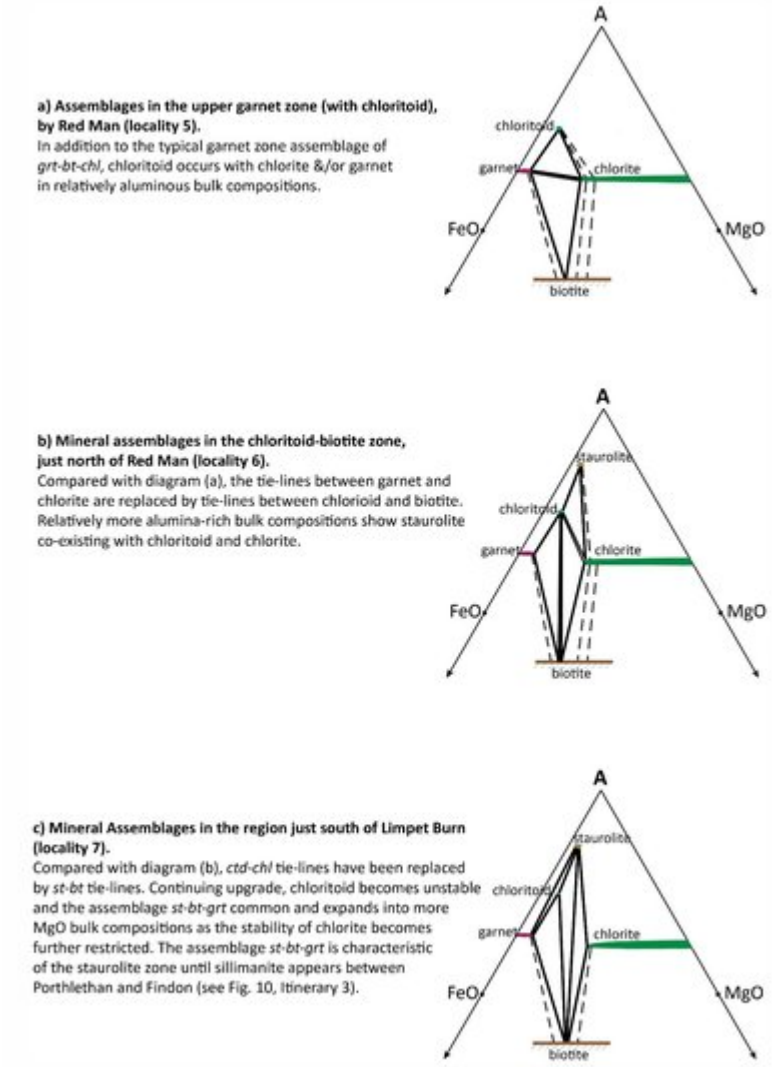

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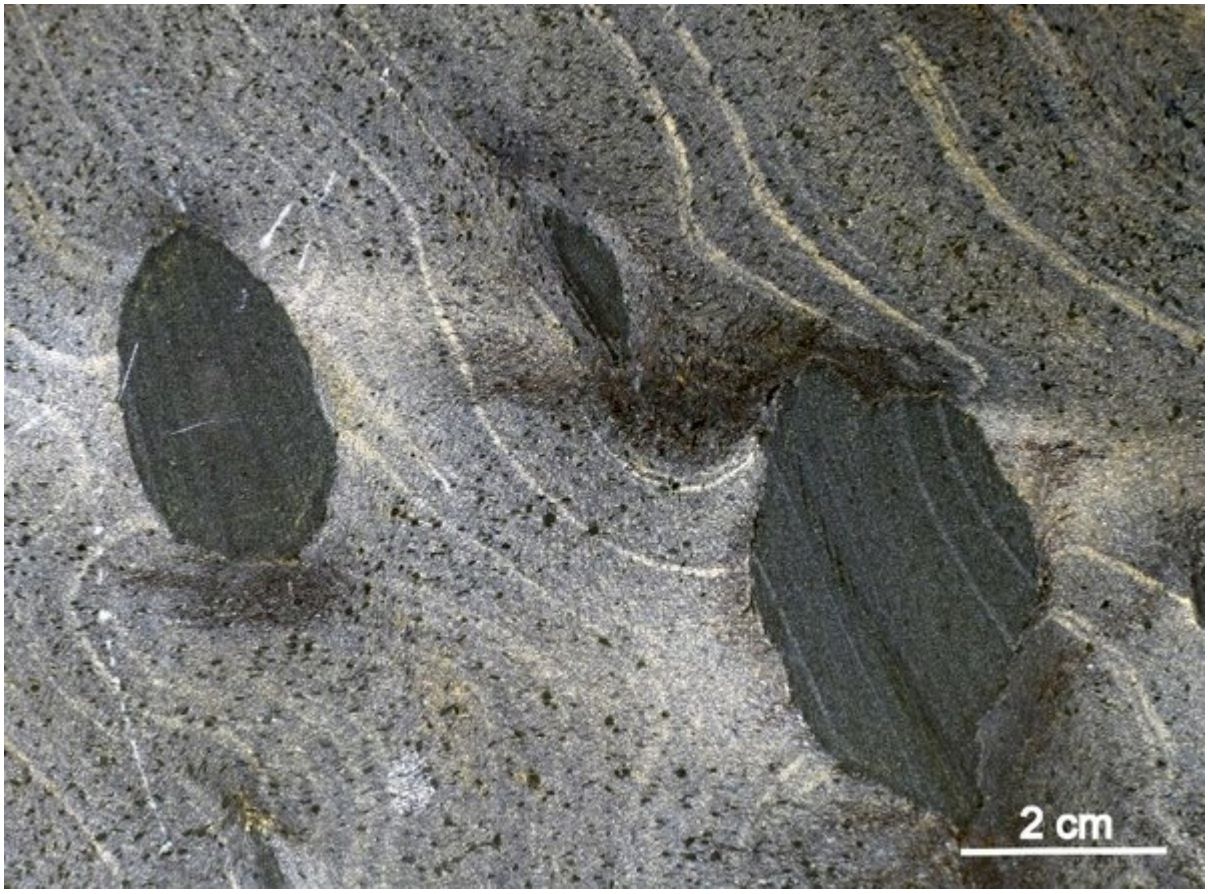

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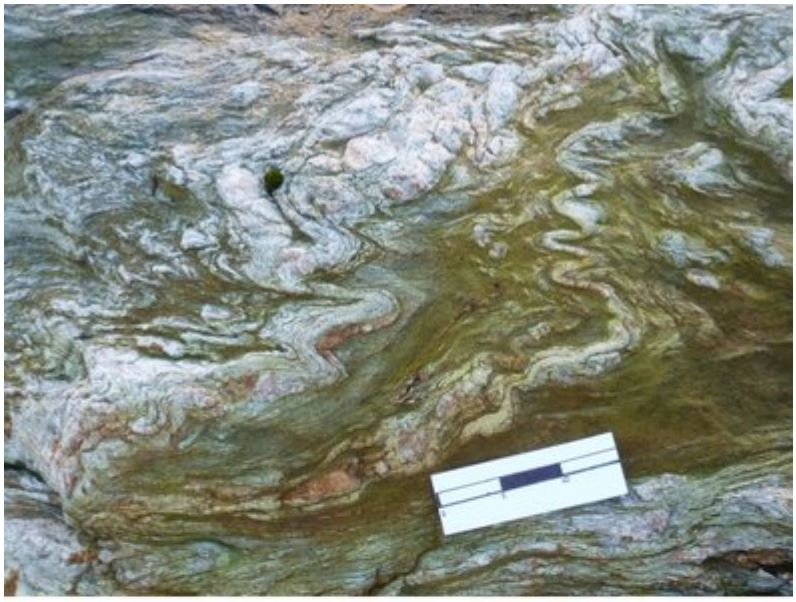

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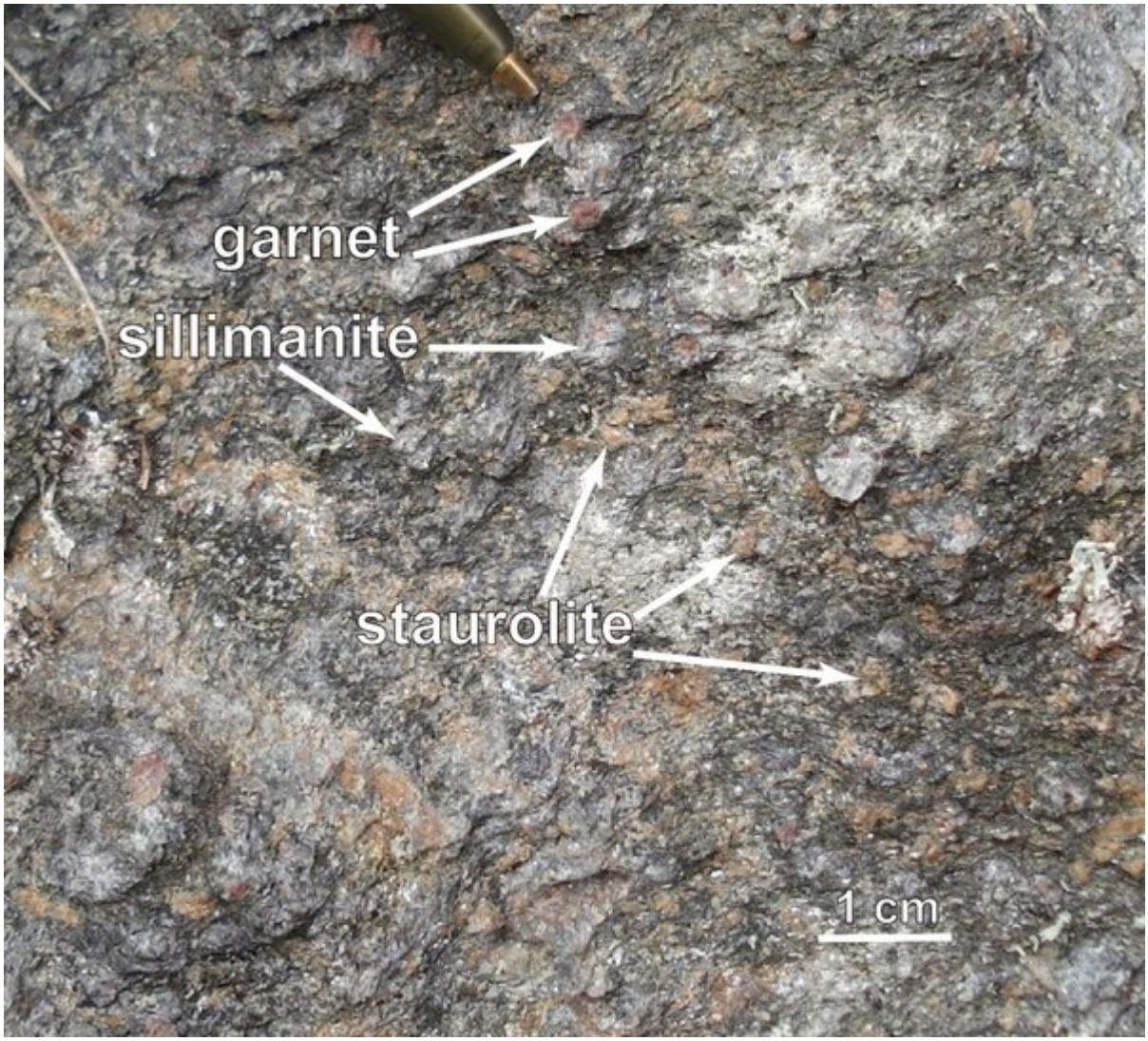

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