13 Cullen to Troup Head

[NJ 511 673]–[NJ 828 669]

D. Stephenson, J.R. Mendum and D. Gould

Published in: The Dalradian rocks of the north-east Grampian Highlands of Scotland. PGA 124 (1–2) 2013 https://doi.org/10.1016/j.pgeola.2012.07.011. Also on NORA

13.1 Introduction

This very large GCR site extends for 32 km along the north coast of the North-east Grampian Highlands from Cullen Harbour in the west to Troup Head in the east. Apart from a 1 km-wide outcrop of Caledonian igneous rocks at Portsoy and a 2 km-wide outcrop of Devonian sedimentary rocks at Gardenstown, the bedrock is entirely Dalradian (Figure 6.25). It comprises a near-complete succession from the Cullen Quartzite Formation at the top of the Grampian Group to the highest parts of the Macduff Formation of the Southern Highland Group, although the Portsoy–Duchray Hill Lineament forms a major stratigraphical, structural and metamorphic break in the middle of the section (see 1.2.1 in *Introduction*). Exposure is generally excellent, notably in the intertidal zone, in marked contrast to the drift-covered inland areas where it is largely confined to generally poor stream sections. The coast therefore provides an invaluable and unique type section for the Dalradian succession that can be compared and contrasted with that of the Central Grampian Highlands. To the west of the Portsoy–Duchray Hill Lineament, many elements of the stratigraphy are common to both successions, and correlations are possible to subgroup and in some cases to formation level. However, east of the lineament correlations, even at subgroup level, are more tenuous.

The strata young overall from west to east, with only minor local reversals. To the west of the Portsoy–Duchray Hill Lineament, structures are comparable to those of the Central Grampian Highlands and are dominated by tight NW-verging folds. Here, there is no high-strain zone comparable to the Boundary Slide at the Grampian–Appin group boundary, but shear-zones do occur at higher stratigraphical levels. The lowest, stratigraphically and structurally, is the Keith Shear-zone, which encloses pods of 600 Ma granite and whose trace intersects the coast just west of Portsoy. Deformation increases dramatically eastwards towards the Portsoy–Duchray Hill Lineament, with most structures becoming largely coplanar and colinear. The wide shear-zone that here marks the lineament contains variably deformed mafic and ultramafic intrusive igneous rocks of the 470 Ma North-east Grampian Basic Suite. East of the lineament, in the so-called ‘Buchan Block’, the rocks show small- and medium-scale folding, in parts with interference patterns, but the regional outcrop pattern is dominated by the broad, open Turriff Syncline, whose axis plunges gently to the north-north-east.

The coast section also provides a continuous section across the low-pressure regional metamorphic Buchan zones that characterize this part of the North-east Grampian Highlands (Stephenson et al., 2013a, fig. 12). The overall grade of metamorphism increases from low greenschist facies (biotite zone) in the centre of the Turriff Syncline in the east, to upper amphibolite facies (sillimanite-K feldspar zone) adjacent to the Portsoy Lineament farther west. Immediately to the west of the lineament the Buchan mineral assemblages have been overprinted by higher pressure metamorphism of Barrovian type (lower amphibolite facies; kyanite zone), and there is evidence that pressures increased to the west.

The area was first mapped for the Geological Survey by J. Horne, and one-inch Sheet 96 (Banff) was published in 1895. The area was subsequently remapped in greater detail by H.H. Read who published the first full account of the district (Read, 1923) together with a revised one-inch map (also published in 1923). Read’s work established the lithostratigraphy of the coast section and led to numerous important publications on the magmatism, structure and metamorphism of the region (Read, 1919, 1936, 1955; Read and Farquhar, 1956). These in turn prompted and inspired other investigations, such that this coast section became one of the most intensively studied parts of the whole Dalradian outcrop. It has certainly been studied by the greatest number and variety of workers. The sedimentation was studied by Sutton and Watson (1955) and Loudon (1963), but most of the subsequent investigations concentrated upon the structure and metamorphism (Sutton and Watson, 1956; Johnson and Stewart, 1960; Johnson, 1962; Loudon, 1963; Fettes, 1970, 1971; Treagus and Roberts, 1981; Moig, 1986). Several papers have concentrated upon the position and nature of the western margin of the Buchan Block and its relationship to the 'main' part of the Grampian Terrane (Elles, 1931; Sturt *et al*., 1977; Ramsay and Sturt, 1979) leading to speculation on the nature and significance of the Portsoy–Duchray Hill Lineament (Ashcroft *et al*., 1984; Fettes *et al*., 1986, 1991). More-detailed studies of the metamorphism have been undertaken by a number of workers (Chinner, 1966; Ashworth, 1975, 1976; Hudson, 1980, 1985; Hudson and Harte, 1985; Baker, 1985, 1987; Beddoe-Stephens, 1990; Dempster *et al*., 1995). The presence of glacigenic boulder beds at two separate stratigraphical levels has generated much interest and discussion on the age of the succession (Sutton and Watson, 1954; Spencer and Pitcher, 1968; Hambrey and Waddams, 1981; Stoker *et al*., 1999) but the palaeontological studies of the higher parts of the succession are now viewed as inconclusive (Skevington, 1971; Downie *et al*., 1971; Bliss, 1977; Downie, 1984; Molyneux, 1998). The area has been remapped by the British Geological Survey, resulting in the publication of two 1:50 000 sheets, 96W (Portsoy, 2002) and 96E (Banff, 2002). As part of this remapping programme, samples from the coast section contributed to a regional geochemical study of metacarbonate rocks that proved to be of value in stratigraphical correlation (Thomas, 1989).

Much of the coastline is relatively easily accessible and it is very popular with field parties. Excursions have been described by Read (1960) and by C. Gillen, N.H. Trewin and N.F.C. Hudson (in Trewin *et al*., 1987).

13.2 Description

The coastal section is described here from west to east, moving up the stratigraphical succession to originally higher structural levels and correspondingly lower metamorphic grades (Figure 6.25), (Figure 6.26).

13.2.1 Grampian Group: Cullen Quartzite Formation

The GCR site includes only the upper three members of the Cullen Quartzite Formation, the lowest, the Findochty Quartzite Member is exposed between Buckie and the western side of Cullen Bay.

The section from Cullen Harbour [NJ 5110 6733] to Logie Head [NJ 5310 6810] exposes the upper 1000 m of the *Logie Head Quartzite Member*, some 70% of its total thickness. The strata are overturned, and dip at between 55° and 90° to the north-west; apparently shallower dips are mostly due to landslips. They are largely psammites with thin pelitic and semipelitic interbeds. Planar-laminated beds with flat bases, generally less than 0.5 m thick, together with tabular cross-bedded units, are characteristic. Some psammite units show aligned mud clasts and a poorly defined wispy lamination. Fold axes of prominent slump folds imply an original palaeoslope towards the north-north-west. At the western side of Portlong Hythe [NJ 5215 6765], some 70 m of pale-brown thicker bedded quartzites are present, but along its eastern side psammites are interbedded with semipelite beds ranging from a few centimetres up to 7 m thick. Pale-green garnet-clinozoisite-bearing calcsilicate pods and lenses are developed locally (e.g. at [NJ 5254 6770]). Thick lenticular quartzite and psammite beds form the western and eastern promontories of Logie Head, separated by thinly bedded micaceous and feldspathic psammites and semipelites with calcsilicate lenticles.

The *Dicky Hare Semipelite Member*, *c.* 200 m thick, is exposed on the foreshore east of Logie Head from [NJ 5310 6810] to [NJ 5325 6755]. It consists of thinly bedded, flaggy micaceous and feldpathic psammites, and garnetiferous semipelites and pelites with scattered calcsilicate lenses and rare centimetre-thick garnet-rich bands. In the upper part of the member, sedimentary structures include fine-scale and ripple-drift cross-bedding, flame structures and slump structures. Minor and medium-scale, close to tight and rarely isoclinal tectonic folds are also abundant in the mixed lithologies. The folds are generally asymmetrical with a Z-profile, and their axes mainly plunge gently to the south-west. In parts a folded lineation (L1) is seen and in the more-pelitic units a penetrative crenulation cleavage (S3) is developed. Read (1923) considered this unit to be a faulted repetition of the lowest part of the West Sands Member of the succeeding Findlater Flag Formation. The contact with the overlying Sunnyside Psammite Member is defined by a strike-fault, marked by several metres of shattered rock, but this does not result in any significant repetition of the near-vertical strata.

The *Sunnyside Psammite Member*, some 500 m-thick, consists of typically grey to fawn, planar bedded quartzite and psammite, with tabular cross-bedding seen in parts. Individual beds are normally less than 1 m thick and semipelitic interbeds are present near the top of the member. Open to tight folding (F3 and F1) is present, particularly in its lower part.

13.2.2 Appin Group: Lochaber Subgroup: Findlater Flag Formation

The Findlater Flag Formation consists of grey to brown, planar, thin-bedded to laminated, micaceous and feldspathic psammites with some thin, schistose, locally garnetiferous semipelite units. Flaggy partings rarely exceed 15 cm in thickness. They strike north-east, generally dip steeply south-east and show few outward signs of early large-scale fold structures. However, in parts minor folds with axial planes roughly parallel to bedding and gently NNE- or SSW-plunging axes are developed. The psammitic beds are not conspicuously deformed, but the more-pelitic lithologies have a well-developed schistosity commonly at a low angle to bedding.

Two members are recognized within the formation, which is otherwise undivided. The basal *West Sands Mica Schist Member* is about 125 m thick and consists of dark-grey to green-grey schistose garnetiferous semipelites, with psammitic ribs up to 1 cm thick. The bedding and well-developed schistosity are both subvertical, but centimetre-scale minor folds have axes that plunge gently to the south. The *c.* 7.5 m-thick *Findlater Castle Quartzite Member* forms the spine of a conspicuous promontory, topped by the ruins of Findlater Castle at [NJ 5418 6720]. The white to fawn quartzite is thickly bedded and steep bedding surfaces show conspicuous large-scale ripple marking (Figure 6.27). Cross-bedding is visible on clean-washed exposures at the base of the promontory. At low water the quartzite can be traced into the bay to the east where it is tightly folded.

13.2.3 Cairnfield Calcareous Flag Formation

This formation consists mainly of micaceous psammite and semipelite but is characterized by the presence of calcsilicate- and carbonate-bearing units. Most lithologies contain amphibole in the compositional range tremolite–magnesio-hornblende but its mode of occurrence varies (Stephenson, 1993). The dominant flaggy, finely bedded calcareous psammites and semipelites, range in colour from striped dark-grey and cream to pale-green and bluish grey. Amphibole in these beds is mainly fine grained and disseminated but some of the more-schistose lithologies contain radiating coarse-grained aggregates (c.f. 'garbenschiefer'). The beds strike north-north-east and dip very steeply to the east-south-east. Small-scale tight folding is common locally and fold interference patterns are seen in places. Fold axes typically plunge gently to the north-north-east or south-south-west.

In the coast section, two distinctive members can be recognized. The lower, *Crathie Point Calcsilicate Member* consists of about 300 m of predominantly pale-fawn and grey calcsilicate-bearing rocks with beds of impure cream metacarbonate rock, possibly dolomitic; the latter weather typically with a pale brownish and honeycombed surface. Some 250 m south of Crathie Point (around [NJ 5490 6716]), thin bands of gneissose muscovite-biotite semipelite contain kyanite and staurolite, indicative of lower amphibolite-facies metamorphism. This lithology can be correlated southwards as far as Glenlivet and the Cairngorm Pluton (see the *Bridge of Brown* GCR site report). The upper, *Garron Point Tremolitic Flag Member* consists of about 350 m of generally dark-grey, thin-bedded, flaggy muscovitic psammite and semipelite with abundant disseminated amphibole. Thin beds of dark green amphibole-rich rock (para-amphibolite) are characteristic and thin beds or lenses of impure metacarbonate rock occur rarely.

13.2.4 Ballachulish Subgroup: Mortlach Graphitic Schist Formation

About 250 m east of Garron Point (at [NJ 5565 6685]), rocks of the Garron Point Member are stratigraphically overlain by black, pyritic, highly graphitic pelite interbedded with metalimestone. These lithologies pass upwards at Sandend Harbour into grey calcareous psammite and semipelite with subsidiary graphitic pelite and metalimestone units. These lithologies constitute the *Sandend Harbour Limestone Member*, the basal unit of the Mortlach Graphitic Schist Formation. The beds of white to pale-grey coarsely crystalline metalimestone are up to several metres thick. They are prominent among the intertidal exposures on account of their creamy yellow weathering and well-developed banding, with many pelitic partings. Some are finely laminated and it has been suggested that they might be stromatolitic. Thin beds rich in amphibole, similar to those in the Garron Point Member, are also present in places. Abundant tight to isoclinal minor folds plunge at low angles to the north-north-east.

The main part of the Mortlach Graphitic Schist Formation lies beneath the beach and dune sands of Sandend Bay. It has been proved by a series of BGS boreholes (1992) to be *c.* 325 m thick and to be composed of dark-grey, graphitic, schistose to slaty pelite, with pale-grey kyanite porphyroblasts abundant in places. The boreholes found no trace of an overlying quartzite, the Corriehabbie Quartzite, one of the most persistent markers in the Appin Group of the Central and North-east Grampian Highlands. However, the quartzite does crop out inland, some 10 km to the south-west of Sandend Bay.

13.2.5 Tarnash Phyllite and Limestone Formation

A disused and flooded quarry behind the dunes of Sandend Bay at [NJ 5578 6595] exposes centimetre-scale, banded, flaggy, pale-grey metalimestone with phyllitic semipelite partings and some thin beds of micaceous psammite. This is the *Linkbrae Limestone Member* that occurs at the base of the Tarnash Phyllite and Limestone Formation. Its lower contact was penetrated in a BGS borehole, in which the Mortlach Graphitic Schists pass upwards into banded greenish grey psammites and semipelites, which are calcareous in parts. The remainder of the formation (the major part) that consists of grey schistose to phyllitic semipelite, is very poorly exposed ephemerally on the beach at Sandend.

13.2.6 Blair Atholl Subgroup: Fordyce Limestone Formation

Exposures on the east side of Sandend Bay are of blocky to massive, thin- to thick-banded, generally blueish grey crystalline metalimestones with subsidiary interbedded phyllitic to schistose pelites and semipelites. Cherty lenses and calcite veining are common. In contrast to the exposures on the west side of the bay, the axes of the numerous tight minor folds here plunge steeply (45–60°) to the east-north-east. Fold interference patterns are seen in parts. The metalimestones are overlain unconformably by Old Red Sandstone breccia and sandstone.

13.2.7 Argyll Group: Islay Subgroup: Arnbath Psammite Formation

The upper part of the Fordyce Limestone Formation is cut out by a NW-trending fault that passes through Red Haven [NJ 5640 6630]. To the north-east of this fault, and beyond a complex zone of shearing, most of the headland that terminates in Redhythe Point [NJ 5760 6715] is composed of quartzites, micaceous and feldspathic psammites and minor semipelites that constitute the Arnbath Psammite Formation. Calcsilicate pods are locally abundant. Small shear-zones are developed and the quartzite beds are commonly boudinaged giving a complex structurally disharmonic appearance to the rocks. Close upright F3 folds that plunge southwards at 30 to 45° are prominent in the cliff exposures, which are composed dominantly of thinly banded and laminated grey quartzites of the basal *Redhythe Quartzite Member*. The upper parts of the formation crop out inland and are very poorly exposed. However, on the north-west flank of Durn Hill (at [NJ 567 642]), some 2 km from the coast, numerous blocks of metadiamictite in field walls, almost certainly derived from the upper parts of this formation, have been interpreted as tillites (Spencer and Pitcher, 1968).

From about 300 m south-east of Redhythe Point, at [NJ 5765 6695], the strata dip steeply and consistently to the south-east and display a strong bedding-parallel fabric; fold axes plunge more steeply (45 to 70°) to the south-east and east-south-east. At the inlet of Foul Hole [NJ 5775 6675] there is a sharp contact of quartzites with gneissose and locally migmatitic psammites and semipelites, which is interpreted as the position of the Keith Shear-zone. About 1500 m south of here, at Boggierow Quarry [NJ 5747 6516], a highly foliated and xenolithic pale- to mid-grey muscovite-biotite granite, the Portsoy Granite, is inferred to mark the position of the shear-zone. U-Pb dating of zircons from the granite has given an emplacement age of 599.9 ± 2.5 Ma (Barreiro, 1998). Farther east, at [NJ 5780 6679], folded migmatitic and gneissose psammites, semipelites and quartzites are cross-cut by a 12 m-thick amphibolite body with foliated margins, which is cross-cut in turn by a *c.* 60 cm-wide irregular sheet of foliated muscovite-biotite granite.

13.2.8 Durn Hill Quartzite Formation

East of Foul Hole, in a rocky semicircular bay at [NJ 5790 6659], a fault divides amphibolite to the west from micaceous psammites overlain by c. 13 m of finely banded cream and grey metalimestones and metadolostones. Amphibolite lenses and pods are common and a 2.2 m-wide talc-magnesite pod occurs at the base. The metacarbonate rocks are succeeded by thick-bedded quartzites that contain a few quartz and granite pebbles, and pass up into poorly bedded, blocky to massive quartzites with subsidiary siliceous and micaceous psammites. The 'beds' dip steeply eastwards but are characterized by a strong foliation and steep down-dip lineation. Although traces of tight to isoclinal folds with steeply plunging axes can be distinguished in parts, in other areas the quartzites are rodded to form mullions. Deformation features dominate here and the lithologies are not typical of the Durn Hill Quartzite as seen inland.

13.2.9 Easdale Subgroup: Castle Point Pelite Formation

At St John's Well, the rapid transition from the Durn Hill Quartzite into the Castle Point Pelite Formation is well exposed on the foreshore. Graphitic pelite and semipelite are dominant at the base but pass eastwards into mid- to dark-grey, schistose, partly graphitic semipelite and pelite with minor thin beds of micaceous psammite. Calcsilicate pods and metacarbonate beds are present but only become abundant near the top of the formation at the outdoor swimming pool west of Portsoy. The formation typically shows abundant small-scale chevron-style folding and crenulation cleavages, but in its upper part close to tight, small- to medium-scale folding is well seen. Fold axis orientations are variable with refold patterns present. The rocks contain kyanite locally, both as blades and as pseudomorphs of chiastolite (andalusite); notable examples can be seen in the uppermost part of the formation at [NJ 5846 6638]. Staurolite is also present in parts and sillimanite has been recorded from muscovite-bearing pelites at Sandy Pots [NJ 5844 6654].

13.2.10 Portsoy Limestone Formation

The Portsoy Limestone Formation encompasses all of the metasedimentary rocks within the Portsoy Shear-zone on the coast section. It cannot be traced inland where thick superficial deposits mantle the bedrock, but many of its elements are certainly lenticular and its lateral continuity southwards is questionable. The variable lithologies are tightly folded and generally very strongly deformed, in parts having almost mylonitic fabrics.

The basal part of the formation, well exposed at Legg Moon [NJ 5851 6645], consists of tight to isoclinally folded pale to dark and bluish grey metalimestones with thin pelitic laminae. These thick metalimestones mark the transitional change up into more-varied lithologies. Semipelites and quartzites succeeding the metalimestones are intruded by gabbros and a large serpentinized lherzolite or harzburgite body, known locally as the 'Portsoy Marble'. This is succeeded eastwards by graphitic pelite, quartzite, semipelite and micaceous psammite. Pebbly and gritty quartzites show strong rodding and folding about steep, commonly near-vertical axes on a distinctive promontory at [NJ 5864 6632] (Figure 6.28); they are succeeded by tightly folded and refolded metadolostones, graphitic pelite and psammite, and white to pale-grey, tight folded metalimestone. The metalimestone also contains small veins of sphalerite, pyrite and chalcopyrite.

13.2.11 Intrusive igneous rocks of Portsoy

The metasedimentary rock outcrop is terminated against a vertical pod of anorthosite and to the east, beneath the town of Portsoy, variably deformed and amphibolitized ultrabmafic and mafic intrusive rocks, cut by sheets and pegmatitic veins of granite, dominate an across-strike section of 750 m. However, substantial screens and rafts of metasedimentary rocks are present in the Old Harbour area. The mafic and ultramafic rocks are interpreted as being truncated against a major fault on the eastern side of Links Bay, which probably coincides with a steep shear-zone on the eastern edge of the Portsoy Lineament. Almost all of the intrusive rocks have been shown by U-Pb zircon dating to have been emplaced at c. 470 Ma. Their complex field relationships and wider age constraints imply that emplacement was coeval with thrusting and penetrative deformation.

13.2.12 Crinan Subgroup: Cowhythe Psammite Formation

The majority of this formation consists of micaceous and feldspathic psammite with subsidiary biotitic semipelite and some minor calcareous units, notably the distinctive Rosehall Croft Limestone and calcareous semipelites on Cowhythe Head. At the western edge of the outcrop, on the east side of Links Bay, are tightly folded calcsilicate rocks, metalimestones and semipelites with lenticular quartzite and psammites bodies. Although those beds are shown as part of the Cowhythe Psammite Formation on the BGS 1:50 000 Sheet 96W (Portsoy, 2002), some authors have attributed them to the Portsoy Limestone Formation.

The rocks have been metamorphosed to sillimanite grade and migmatization is variably developed, with the more-migmatitic units found in the western part of the outcrop. The first coherent unit of sheared and migmatitic semipelite that marks the eastern extent of the mixed calcareous rocks at Links Bay has been interpreted as marking the Portsoy Thrust (Elles, 1931; Ramsay and Sturt, 1979; see Interpretation below). Although deformation is high and small-scale dislocations are present, no major dislocation is now recognized in the sequence. Indeed, as Ramsay and Sturt (1979) showed, there are 'enclaves' of unmigmatized rocks within the migmatitic semipelitic units. Tight folding on very steeply dipping axes, large-scale cuspate structures and shear-zones can readily account for the complex detailed distribution of lithologies.

Anastomosing shear-zones are found near the south-eastern margin of the Cowhythe Psammite Formation, which is marked on the north-western side the bay of Old Hythe by a steep narrow zone of mylonitic biotite-rich semipelite and tightly folded recrystallized white metalimestones. This structure, termed the Boyne Line by Read (1923), was thought to represent a fundamental regional dislocation in the Dalradian succession, but later work has shown that it does not correspond to a major stratigraphical, structural or metamorphic break (see Interpretation). The structure is further complicated due to the presence of variably orientated, commonly steeply plunging F2 and F3 folds, a later monoform, and faulting (see Read, 1923, figure 5).

Although there are steep dips in parts, the overall bedding and structural profile of the Cowhythe Psammite Formation are only gently inclined. In some areas the bedding is notably lenticular and chaotic zones are present; this seems to be a primary depositional feature. Some idea of the structural complexity is given by the outcrop of the Rosehall Croft Limestone on the foreshore and cliffs around [NJ 5978 6640], which shows a refolded fold pattern that can be traced over a few hundred metres.

Two main fold generations can be distinguished, an earlier tight folding (F2) with a penetrative cleavage (S2), and a dominant late open to tight folding (F3) with a variably developed crenulation or penetrative cleavage (S3). Fold axes show a wide range of plunge orientations. A moderately plunging rodding lineation (L2) that appears to define the maximum finite extension direction during the D2 deformation episode, traces an arc between south-south-west at Links Bay and west at Kings's Head. Late-stage crenulation cleavages are developed locally in the more-semipelitic lithologies and monoformal structures also deform the earlier D2 and D3 fabrics and folds.

On the foreshore some 250–500 m south-west of East Head, around [NJ 667 600], are several small circular to ovoid bodies of ultramafic rock, which hornfels the adjacent metasedimentary rocks. By East Head, the gneises are cut by 3–4 m-thick NNE-trending veins of pink to orange muscovite and tourmaline-bearing pegmatitic granite.

13.2.13 Tayvallich Subgroup: Boyne Limestone Formation

The lowest unit of the formation, the *Old Hythe Semipelite Member* consists of purple-grey semipelites interbedded with white to grey metalimestones and calcsilicate-rock bands and lenses. Immediately east of the 'Boyne Line' ductile dislocation, the beds are tightly folded, contain small-scale shears, and show widespread development of a later fracture cleavage. Quartz pods are common. Semipelite outcrops in the central part of Old Hythe bay show more-typical structural patterns and sillimanite (fibrolite) has been recorded from these beds.

On the south-eastern side of Old Hythe, spectacularly refolded interbedded metalimestones and calcsilicate rocks of the succeeding *Boyne Castle Limestone Member* are exposed in the cliffs. F1 and F3 folding is abundant in these white, cream, pale-purple and greenish grey, laminated and thinly banded metalimestones and subsidiary calcsilicate rocks, which are very well exposed on the Craig of Boyne [NJ 6163 6612]. The distinctive fine-scale lamination, thin cherty layers and pelitic laminae of this unit might relate to an algal, partly stromatolitic origin. The unit has been extensively quarried immediately inland at Boyne Bay Quarry.

On the south-east side of Boyne Bay are thinly bedded, pale-grey to pink-purple, greenish grey and cream, calcsilicate rocks, impure metalimestones and calcareous semipelites. These candy-striped rocks mark the base of the *Whyntie Brae Calcsilicate Member* and show excellent F3 and earlier F1 folding with interference patterns common. F1 folds are tight and their axes typically plunge moderately to the north-east or south-west. The superimposed F3 folds vary from open to tight and verge to the north-west, with their axes mainly plunging gently to moderately to the south-west and south-south-west. Overall the beds dip gently to the south-east, but the folding gives rise to steeper dips locally.

At [NJ 6215 6585] a *c.* 10 m-thick sheet of dark green-grey metadolerite intrudes the calcareous rocks. It is locally discordant to bedding, yet defines an upright, close, NW-verging fold-pair some 70 m across, interpreted as an F3 structure. At least four further metadolerite sills occur to the east, and an unfoliated hornblende metagabbro body, some 50–60 m thick, crops out around Whyntie Head (e.g. at [NJ 6284 6583]). These mafic bodies probably relate to the large poorly exposed Boyndie Intrusion that lies some 1.5 km to the south-south-east.

13.2.14 Southern Highland Group: Whitehills Grit Formation

The metagabbro sheet at Whyntie Head marks the base of the overlying Whitehills Grit Formation, which signals a change in the overall depositional facies of the Dalradian succession from shallow-marine shelf to deeper water turbiditic sedimentation. The Southern Highland Group rocks appear to overlie the underlying Argyll Group succession with slight unconformity. The basal lithology is a notably thick gritty psammite, locally calcareous in part. Farther east interbedded psammites, semipelites and pelites are more typical of the formation. A single metalimestone bed occurs near the base of this mixed succession but calcareous psammites and semipelites, and calcsilicate lenses are relatively abundant throughout. The thicker psammite beds are commonly gritty and show coarse to fine grading. A prominent thick, relatively planar bed of massive, cream to fawn calcareous gritty psammite is well exposed on the foreshore at Stake Ness [NJ 6442 598]. The bed has an erosional lower contact and shows internal, tight disharmonic folds, interpreted as slump folds. Similar intrafolial folds occur in some of the other thick psammite beds. The lower part of the formation is intruded by metadolerite sheets up to 4 m thick.

The formation has low overall regional dips but exhibits small- and medium-scale tight F1 folding, mainly along NE- and NNE-plunging axes. However, the outcrop pattern is dominated by the more-open, NW-verging F3 folds whose axes plunge gently to the north-east. Fold interference patterns are clearly seen in places. A penetrative S1 cleavage is normally present, but an S3 crenulation cleavage is only variably developed. Andalusite is seen in the pelitic units and the tops of graded psammite–pelite beds, and staurolite is present in some pelites (Hudson, 1980, 1985).

13.2.15 Macduff Formation

A thick gritty psammite unit forms the promontory and skerries of Craig Neen [NJ 6517 6571] at the western margin of Whitehills village; this effectively marks the end of the calcareous units and the base of the Macduff Formation. A kilometre-thick lower unit, the *Knock Head Grit Member* is dominated by pelite, semipelite and psammite units with minor calcsilicate lenses in the lower part but the frequency and thickness of intervening gritty psammites increases eastwards until, at Knock Head, pebbly psammites are dominant. From there, the pelitic element increases eastwards towards the west side of Boyndie Bay, where psammite is again subsidiary. The pelitic units commonly show concentrations of large (average c. 1 cm long) grey elongate ‘slugs’ of andalusite, and/or black rounded cordierite porphyroblasts, reflecting the respective iron-rich and less common magnesium-rich nature of the protolith muds (Figure 6.29). Porphyroblasts reflect the grading in the turbiditic units, becoming larger and more abundant in the pelitic tops. Small red manganiferous garnets and brown staurolites up to 2 mm long are also present. The bedding in the Knock Head Grit Member generally dips east at over 50°. Minor folding is only rarely seen, except near Whitehills where close to tight F1 folds with moderately north-plunging axes are present. D3 effects are mainly limited to development of a coarsely spaced crenulation cleavage in some pelitic units. S3 clearly overprints the porphyroblast growth, which overgrows the earlier S1 cleavage/schistosity (Johnson, 1962; Fettes, 1971; Hudson 1980). This steep zone forms the western limb of the so-called Boyndie Syncline, whose status is discussed below.

The Dalradian outcrops lie close to the Devonian land surface in this area, and small patches of breccioconglomerate are present. In parts the Dalradian rocks are heavily stained red-brown; in other areas the andalusite is stained red, with the pelitic matrix remaining mid to dark grey.

The higher parts of the Macduff Formation occupy the remainder of the coast section from the eastern side of Boyndie Bay to More Head and around Troup Head, which is north-east of the Devonian outlier at Gardenstown. The metamorphism is greenschist facies (biotite grade) and only a single deformation phase is present. Hence, the sedimentary features of the interbedded psammites, semipelites and pelites are clear. Bouma sequences are common, with flame structures, grading, cross-bedding, ripple lamination and mud-flake breccias, all indicative of a turbiditic, density current origin. The psammites, which vary from quartz-rich to micaceous, have gritty and even pebbly bases locally. Good examples can be seen in Tarlair Bay, around [NH 7188 6450]. The more-quartzose lithologies commonly form discrete lenticular units and probably represent reworked channel-fill material in an offshore fan.

At Macduff thin metadiamictite units, with pebbles, cobbles and rare boulders, are interspersed in a turbiditic succession that occurs on the broad hinge of a syncline between [NJ 7128 6491] and [NJ 7144 6488]. These beds were interpreted as glaciomarine deposits by Sutton and Watson (1954). Stoker *et al.* (1999) have documented the sequence in detail and confirmed that at least some of the larger boulders are probable dropstones from floating ice (Figure 6.30).

Metamorphic grade increases from east to west. Rounded dark-grey cordierite porphyroblasts, seen to be altered to pinite in thin section, are first seen in the pelitic units west of Banff Harbour. Farther west at Scotstown the cordierites are paler with only partial or marginal dark-grey alteration to pinite. Zoned calcsilicate pods are present locally (Hudson and Kearns, 2000). A little farther west, at [NJ 6817 6459], Hudson (1987) recorded the first andalusite porphyroblasts as small whitish grey laths or square-section crystals in cordierite-bearing pelitic units and staurolite appears on the west side of Boyndie Bay in the Knock Head Grit Member.

The rocks of the Macduff Formation are disposed in a series of open to tight F1 folds typified by steeply dipping bedding, well seen on the foreshore at Banff and Scotstown. However, somewhat perversely, the overall or sheet dip is shallow, with the succession defining a very open regional syncline, the Turriff Syncline (Figure 6.3)a, (Figure 6.26). Although it is difficult to correlate the detailed stratigraphy, the upper part of the formation exposed on this coast section could be only 2–3 km thick.

Farther east at the Howe of Tarlair [NJ 719 646], a thick gritty psammite unit defines an upright F1 anticline-syncline pair with an amplitude of some 130 m and a wavelength of *c.* 320 m. F1 axes plunge gently northwards. The related S1 cleavage is a variably developed pressure-solution cleavage in the psammites but a slaty cleavage in the pelitic units. Cleavage-bedding relationships are well seen and the abundant sedimentary features clearly show that the structures are upward facing. The fold structure is controlled by the thickness of psammite units and generally the folds have a neutral vergence. However, at Stocked Head, the F1 fold vergence changes from neutral to westerly and S-profile folds dominate farther east. Late kink folds are common locally and the F1 structures are refolded by open monoforms. All of these structures lie within the broad axial zone of the Turriff Syncline.

The Gardenstown outlier of Devonian sandstones, siltstones and conglomerates has faulted boundaries against Dalradian rocks, although an unconformity can be seen in a small exposure at Crovie. The Macduff Formation rocks to the north-east that form the peninsula of Troup Head are fault bounded to the south-east and form an isolated enclave. They consist of psammites and pelitic units and have gentle but variable dips. Their overall dip is easterly and they show west-verging close F1 folds.

13.3 Interpretation

13.3.1 Stratigraphy and sedimentation

The generally clean, mature nature and ubiquitous cross-bedding of the Cullen Quartzite Formation suggest that the sands were deposited under shallow marine conditions where tidal, wave and current action were important. Slumped units suggest that at times deposition was rapid and local instabilities resulted. The succeeding more-pelitic units probably represent quieter sedimentation conditions dominated by mud deposition under inshore intertidal, lagoonal or estuarine conditions. Similar conditions prevailed during deposition of the overlying Findlater Flag Formation. The clean quartzite units such as the ripple-marked and cross-bedded Findlater Castle Quartzite probably represent short-lived sandy channels (Figure 6.27). However, the upper parts of the Lochaber Subgroup, as elsewhere in the Grampian Highlands, show a progressive increase in calcareous material. Calcsilicate rocks are abundant and dolomitic metacarbonate rocks, calcareous semipelites, and minor kyanite-bearing rocks characterize parts of the succession. A study of the tremolitic amphiboles that are a major component of the Cairnfield Calcareous Flag Formation revealed that the protolith muds were very high in Mg relative to Ca, with high but variable Al (Stephenson, 1993). The aluminous, magnesian and potassic nature of these lithologies imply input of periodic weathered material, probably under very shallow water, locally evaporitic, partially emergent conditions, with only restricted circulation of seawater (Thomas, 1999). Detrital input of silica and clay minerals was variable and possibly seasonal, giving rise to the colour banding; marl beds with a low detrital component gave rise to the essentially monomineralic para-amphibolites.

The graphitic pelite and metalimestone succession of the Ballachulish Subgroup is indicative of a widespread marine transgression across the Dalradian basin, marked by deposition of anoxic or reduced mudstones and chemical or derived limestones. In this section, boreholes have revealed a continuous stratigraphical passage from the graphitic pelites up into overlying thinly bedded semipelites, metalimestones and calcsilicate rocks of the Tarnash Phyllite and Limestone Formation. A return to very shallow water conditions with possible local evaporates is indicated, though without any major influx of detrital siliciclastic material, as represented by the quartzite seen elsewhere at this stratigraphical level. The deposition of graphitic semipelites and pelites and metalimestones, typical lithologies of the Blair Atholl Subgroup, signals a further transgression phase.

The Islay Subgroup has a locally developed metadiamictite at the base that relates to a marine glacial event. This was accompanied and followed by local basin formation and deposition of largely siliciclastic sediments. Although the Arnbath Psammite Formation contains a greater proportion of semipelite than is normal at this stratigraphical level, it does contain much sandy material including a quartzite member. The overlying Durnhill Quartzite Formation is also reduced in thickness and purity by comparison with its manifestation inland.

The rapid change to more-graphitic and aluminous pelitic rocks of the Easdale Subgroup (Castle Point Pelite and Portsoy Limestone formations) appears to mark a transgression, although this could reflect formation of a local marine basin. The presence of isolated quartzite lenses, a pebbly quartzite unit, and mixed metalimestone–graphitic pelite–quartzite units suggests that the palaeoenvironment and sediment provenance were locally varied. The overlying Cowhythe Psammite Formation, assigned to the Crinan Subgroup, is highly metametamorphosed, structurally complex and partly migmatitic. However, in places in the psammite and semipelite unit there are suggestions of grading, disrupted bedding, and slumped or chaotic units. The beds might have been turbiditic and if that was the case they would represent the infill of a local deeper water basin. The rapid transition up into semipelites and metalimestones of the Boyne Limestone Formation (Tayvallich Subgroup) represents a shallowing, with marine shelf conditions becoming dominant. The thick metalimestones in this formation show laminae and small-scale structures suggestive of algal reef growth, implying that warm shallow conditions prevailed. The overlying calcareous semipelites and calcsilicate rocks were originally marls and possible evaporitic deposits, suggesting possible lagoonal conditions with some local emergence.

This quiet shallow marine-shelf deposition was interrupted by the incoming of the first turbiditic units of the Southern Highland Group and signalled the development of a deeper marine basin that developed subsequently into the Iapetus Ocean. The lowest psammite unit of the Whitehills Grit Formation appears to cross-cut the underlying Argyll Group succession regionally, suggesting that it might mark a slight angular unconformity. The sediments deposited ranged from coarse siliciclastic to muddy but contained a large component of derived carbonate material, probably from nearby reefs. The succeeding Macduff Formation consists of psammites and intervening pelitic units that show excellent features typical of turbiditic fans. The rocks have been interpreted as channel, overbank or outer-fan deposits, depending on the coarseness of the units, Bouma features and lithological associations (Kneller, 1987). Hence, the Knock Head Grit Member represents a channel environment, whereas the adjacent more-pelitic succession represents an interchannel or perhaps outer-fan environment.

The Macduff Boulder Bed, which lies near the top of the stratigraphical sequence in this GCR site, has been interpreted as a glaciomarine deposit with slumped units and dropstones (Figure 6.30) (Sutton and Watson, 1954; Hambrey and Waddams, 1981; Stoker *et al*., 1999). By analogy with Pleistocene deposits offshore to the north-west of the British Isles, such glacigenic deposits are characterized by debris-flow packages and the Macduff succession is compatible with distal deposition in a base-of-slope or basin-plain situation, with a water depth of over 1000 m. The deposit has been correlated with Ordovician glacial episodes on the basis of a single acritarch *Veryhachium lairdii* collected from adjacent pelitic units (Molyneux, 1998). However, failure to replicate this find and its atypical state of preservation despite metamorphism to biotite grade cast doubt upon the acritarch evidence, which should probably be discounted at the present time. Hence, the glacial deposits more likely correlate with dropstone localities near the base of the Southern Highland Group in Donegal (Condon and Prave, 2000), which would imply that only the lowermost parts of the group are exposed in the North-east Grampian Highlands, albeit in a relatively thick sequence.

13.3.2 Structure

(Figure 6.26) shows the composite cross-section along the coast, based upon recent British Geological Survey mapping and the overall structure is illustrated in (Figure 6.3)a. Note that on these sections, the areas of steeply dipping succession have been much reduced, compared with previously published sections (e.g. Sutton and Watson, 1956; Treagus and Roberts, 1981). This has several consequences: the stratigraphical succession is thinner than formerly estimated; the Boyndie Syncline is reduced to a smaller scale steep zone with more-gently dipping, locally subhorizontal beds on either side; the Cowhythe Head and Redhythe Point areas, that lie respectively east and west of the Portsoy Shear-zone, also show regionally shallow dips. In detail many parts of the coastal section show alternating steep and shallow dipping zones and it is unclear as to their age relative to main phases of folding and related cleavage formation. The following discussion progresses broadly from higher structural levels in the east of the section to deeper levels as seen in the west.

The linked concepts of the Boyne Line and the SE-facing Banff Nappe were introduced by Read (1955) to explain the major structure of the North-east Grampian Highlands (see 1.2.2 in *Introduction*; (Figure 6.3)b). Along much of the coast section east of Boyne Bay, the rocks exhibit locally complex F1 folding with steep dips, but regionally they are the right way up and are disposed in a broad, gentle syncline, the *Turriff Syncline*, which would constitute the upper limb of the nappe in Read's model. The overall structural and metamorphic sequences of this section are quite well understood due to detailed studies of the minor structures (Johnson, 1962; Loudon, 1963; Fettes, 1971; Treagus and Roberts, 1981). Early (F1) folds and related cleavages face consistently upwards and the style of the folds varies according to structural level, being generally upright and open to close at the highest levels in the centre of the Turriff Syncline and generally recumbent and tight on the limbs. Across the whole section F1 folds face to the north-west, apparently contrary to Read's (1955) model of a SE-facing Banff Nappe. However, Read attributed these folds to gravitational flow on the western limb of the Buchan Anticline, which he envisaged as having developed as an early structure accompanying nappe formation.

Post-D1 structures are restricted to the lower structural levels and hence are seen only on the western and eastern limbs of the Turriff Syncline. There is some confusion, particularly in the Portsoy area, as to the number of major fold phases that can be identified, and their relationship to regional D2 and D3 defined elsewhere in the Grampian Highlands. Both Johnson (1962) and Treagus and Roberts (1981) have identified separate D2 and D3 phases but differ as to their distribution and interpretation. Their conclusions are incorporated in the following summary, which is based largely on that of Kneller (1987). D2 folds and cleavages are recognized only to the west of the Boyne Limestone outcrop and to the east of Fraserburgh Bay. In the area around Portsoy, F2 folds are locally dominant. Those folds have steeply plunging axes, which are colinear with a very strong stretching lineation attributed to thrusting and focussed along the Portsoy Shear-zone.

The D3 deformation, which post-dates the peak of metamorphism and main growth of porphyroblasts east of Boyne Bay, has limits that effectively coincide with the andalusite isograd. Large-scale F3 folds are characteristically open to close and monoclinal in form. Associated finely spaced cleavages and tight crenulation cleavages occur in the more-pelitic units and small-scale open to tight fold structures are well seen in the more-banded units. The Turriff Syncline and Buchan Anticline have been tentatively attributed to the D3 phase by several authors. However, west of Whitehills, smaller scale D3 structures have easterly to south-easterly dipping axial planes and a westerly vergence. It is difficult to correlate these D3 structures with the open and upright character of the Turriff Syncline, which is more compatible with major D4 structures elsewhere. Numerous sets of minor kink and brittle folds in the area, notably in the pelitic lithologies, are attributed to later events.

Steeply dipping beds on the western limb of the Turriff Syncline are the result of a monoform, regarded as a major fold closure pre-dating the metamorphic peak by Sutton and Watson (1956), who named the structure the *Boyndie Syncline*. However, Read (1923, 1955), who concentrated firstly on the stratigraphy and secondly on the regional structural interpretation, portrayed the syncline merely as a perturbation on the top limb of the Banff Nappe. Subsequently Johnson (1962) and Fettes (1971) recognized two fold phases in the Whitehills area and allocated the Boyndie Syncline to the secondary phase, which they termed D3. They argued that the syncline folds the metamorphic isograds and hence post-dates the metamorphic peak. Treagus and Roberts (1981) argued that F1 folds consistently face upwards along the coast section and favoured a D1 age for the Boyndie Syncline. The structural evidence and metamorphic pattern would be compatible with formation of the steep zone during or prior to D1, followed by superimposition of the metamorphic pattern and D3 deformation. This would accord with other coastal sections where F3 folds appear to be superimposed on a stepped profile.

The Boyne Line as envisaged by Read (1955) underlies the Banff Nappe and separates it from the Argyll and Appin group succession to the west; it is a 'lag' rather than thrust structure, i.e. younger rocks are juxtaposed over older rocks (Figure 6.3)b, (Figure 6.26). Ashworth (1975) argued strongly against Read's model, preferring Horne's original idea of sedimentary facies variations to explain the absence of the Boyne Limestone Formation to the south (Horne, in Read, 1923, p.72). Most authors agree that later faulting is also present. However, the presence of biotite-grade mylonitic rocks at Old Hythe and the local deformation patterns do suggest that it is the site of a steep shear-zone, possibly with lateral movement. That said, there is no metamorphic hiatus and moderate structural continuity is retained across the section. The structure may well be linked to the Portsoy Shear-zone that crops out to the west but there is no need to invoke a Boyne Line *sensu* Read (1955).

Between the putative Boyne Line and the Portsoy Shear-zone, Sturt *et al.* (1977) and Ramsay and Sturt (1979) recognized a complex structural history in the Cowhythe Psammite Formation and allocated the migmatitic gneissose rocks to a pre-Dalradian basement unit formed in the Neoproterozoic. They maintained that the contact of the migmatitic semipelite at the base of the Cowhythe Psammite is visibly discordant with the structurally underlying calcareous psammitic and semipelitic succession to the west along the *Portsoy Thrust*, thus resurrecting Read's concept of an allochthonous succession in Buchan. However, most workers regard the gneisses as migmatized equivalents of the upper parts of the Argyll Group (see 1.1.3 in *Introduction*).

The Portsoy Shear-zone shows evidence of a complex and lengthy tectonic history (Goodman, 1994), as discussed on a regional basis in section 1, *Introduction*. The main problems associated with the structure are to reconcile its identities as an initially steep lineament, a subsequent shallow dipping shear-zone, and a steep fault/shear-zone along which preferential uplift later occurred. Although evidence for these three manifestations is present on the coast section, it is unclear as to how and where the different elements might be projected at depth or farther south to Deeside and beyond. Local and regional stratigraphical patterns imply that a lineament could well have been active at the time of Argyll Group sedimentation (Fettes *et al*., 1991). The main tectonic activity was focussed in mid-Ordovician time at around 470 Ma when thrusting to the west-north-west and associated deformation, metamorphism and fluid flow, occurred roughly coeval with intrusion of basic and ultrabasic bodies (Baker, 1987; Oliver, 2002). The overprint of kyanite after andalusite to the west of the shear-zone reflects a pressure increase of *c.* 2 kbar at this time, consistent with an increase in overburden of 6–7 km (Beddoe Stephens, 1990). Later steep shear-zones, along which granitic veins are intruded in parts, are well seen around Portsoy and show foliations and geometries indicative of dextral shearing.

The position of the Keith Shear-zone on the coast section is marked by strong planar and linear fabrics and localized migmatization of Islay Subgroup rocks around Foul Hole just west of Portsoy. Shear-sense indicators imply top-to-west movement. The shearing post-dated both lithification of these rocks and intrusion of the Keith–Portsoy Granite and was most likely associated with the Grampian Event in mid-Ordovician time. Just inland, at Boggierow, the granite has been reliably dated at *c.* 600 Ma and is interpreted as having been intruded into an early lineament that was subsequently re-activated as the shear-zone, thereby providing a minimum age for its initiation. A full appraisal of the shear-zone and its associated intrusions, incorporating evidence from outwith this GCR site, is given in section 1.2.1 in *Introduction*.

Farther west in the Appin Group rocks, two phases of penetrative deformation are seen, manifested as folding and related planar and linear fabrics. These structures are particularly clear in the pelitic and metalimestone lithologies, but it is uncertain whether they should be attributed to D1 and D2, D2 and D3, or D1 and D3. By analogy with deformation chronologies farther south they are generally attributed to D2 and D3. In fact, Peacock *et al.* (1968) showed that to the south-west of Cullen, the penetrative early fabrics and folds attributed to D2 post-date an earlier bedding-parallel schistosity that they termed S1.

13.3.3 Regional metamorphism

The Cullen–Troup Head section remains one of the classic areas for studying the nature of the relatively low-pressure and high-temperature Buchan-type metamorphism (Read, 1952). Many studies have documented the transition from greenschist facies in the Macduff–Gardenstown area to lower and upper amphibolite facies in the Portsoy and Fraserburgh areas (Johnson, 1962; Chinner, 1966; Fettes, 1971; Hudson, 1980, 1985; Hudson and Harte, 1985; Johnson *et al.*, 2001a, 2001b). The occurrence of upper amphibolite-facies assemblages (sillimanite-potash feldspar) in the Cowhythe and East Head area and granulite-facies assemblages east of Fraserburgh Bay (see the *Cairnbulg to St Combs* GCR site report) was shown by Ashworth (1975) and Johnson *et al.* (2001b) to relate to mafic intrusions of the North-east Grampian Basic Suite. Pressure and temperature conditions ranged from 1.2 kbar, 400°C in the lowest biotite-grade rocks to 1.8 kbar, 490°C at the andalusite isograd and 3.3 kbar, 545°C at the sillimanite isograd (Hudson, 1985). The higher grade rocks reached 4.2 kbar, 630°C, values consistent with pressure–temperature estimates derived from the hornfels mineralogy of larger mafic intrusions (Droop and Charnley, 1985).

The Buchan metamorphic peak occurred following the D1 deformation but mainly prior to the later D3 event (Johnson, 1962, 1963). Porphyroblasts overgrow generally planar S1 fabrics, but thin-section studies from several rocks in the Inverboyndie area show that cordierite overgrowths also occurred synchronous with D3 deformation (Phillips, 1996). A later phase of retrogressive metamorphism characterized by chlorite and sericite (muscovite) is found in many of the rocks, in parts associated with late-formed structures.

The metamorphic pattern has influenced both the original lithological divisions and former tectonic models for the Buchan area. Read (1923) defined several lithological units on the basis of their metamorphic features. Thus, the former Boyndie Bay ‘group‘, west of Banff, which is characterized by andalusite schists, is now regarded as merely the lower part of the Macduff Formation. Similarly, to the south-east, the Macduff Formation grades downward into the ‘Fyvie Schist’, which is characterized by andalusite and cordierite porphyroblasts giving a ‘knotted‘ appearance and is now placed in the Methlick Formation. He also erected the Boyne Line on the basis of a supposed metamorphic hiatus between his overlying ‘Banff division’ and underlying ‘Keith division’ rocks. However, Ashworth (1975) dismissed the evidence for a metamorphic hiatus and showed that the metamorphic zones appeared to be superimposed on the early-formed structural pattern. Hence, he rejected the concept of both the Boyne Line and the Banff Nappe.

Within the Portsoy Shear-zone the metamorphic mineralogy is undoubtedly complex. By the Portsoy swimming pool (at [NJ 5844 6648]), graphitic pelite shows apparent andalusite (chiastolite) porphyroblasts. However, in thin section a different picture emerges. Large andalusites are partly pseudomorphed by blocky kyanite, set in platy to felted muscovite. Ragged early staurolite with sigmoidal inclusion trails and smaller, later, more-euhedral porphyroblasts are also present. Garnets are ragged and show evidence of partial dissolution. The biotite-rich fine-grained schistose matrix is deflected around the andalusites but platy muscovite and kyanite overgrow this fabric locally. Fibrolitic sillimanite also occurs, which on textural evidence pre-dates growth of small kyanite blades (Beddoe-Stephens, 1990). Although the mineralogy gives us a record of at least parts of the lengthy metamorphic history of this rock, it is difficult to unravel which mineral associations were in equilibrium at each stage.

West of the Portsoy Shear-zone, porphyroblast growth occurred at several times. Garnet and biotite formed both prior to and synchronous with formation of the S2 fabric; the metamorphic minerals are wrapped by the later amphibolite-facies schistosity and show some resorption or alteration (Peacock *et al*., 1968). Beddoe-Stephens (1990) showed that the Buchan-type assemblages were present in this area but were subsequently overprinted under higher pressure conditions during the D3 deformation (see the *Auchindoun Castle* GCR site report). It is this event that deformed the Keith–Portsoy Granite, implying thrusting to the west-north-west, probably with movement focussed along the Portsoy and Keith shear-zones.

13.4 Conclusions

The coast between Cullen Bay and Troup Head provides the longest continuous section across the strike of the Dalradian succession in Scotland. It extends from the top of the Grampian Group to the highest preserved beds of the Southern Highland Group and is the type section for the Argyll and Southern Highland groups of the North-east Grampian Highlands. It records the progression from deposition in a shallow marine gulf in an intracontinental rift that became a series of fault-bounded deeper sedimentary basins on a continental shelf heralding the opening of the Iapetus Ocean, to deposition from turbidity currents in major sub-marine fans on the subsiding shelf and continental slope.

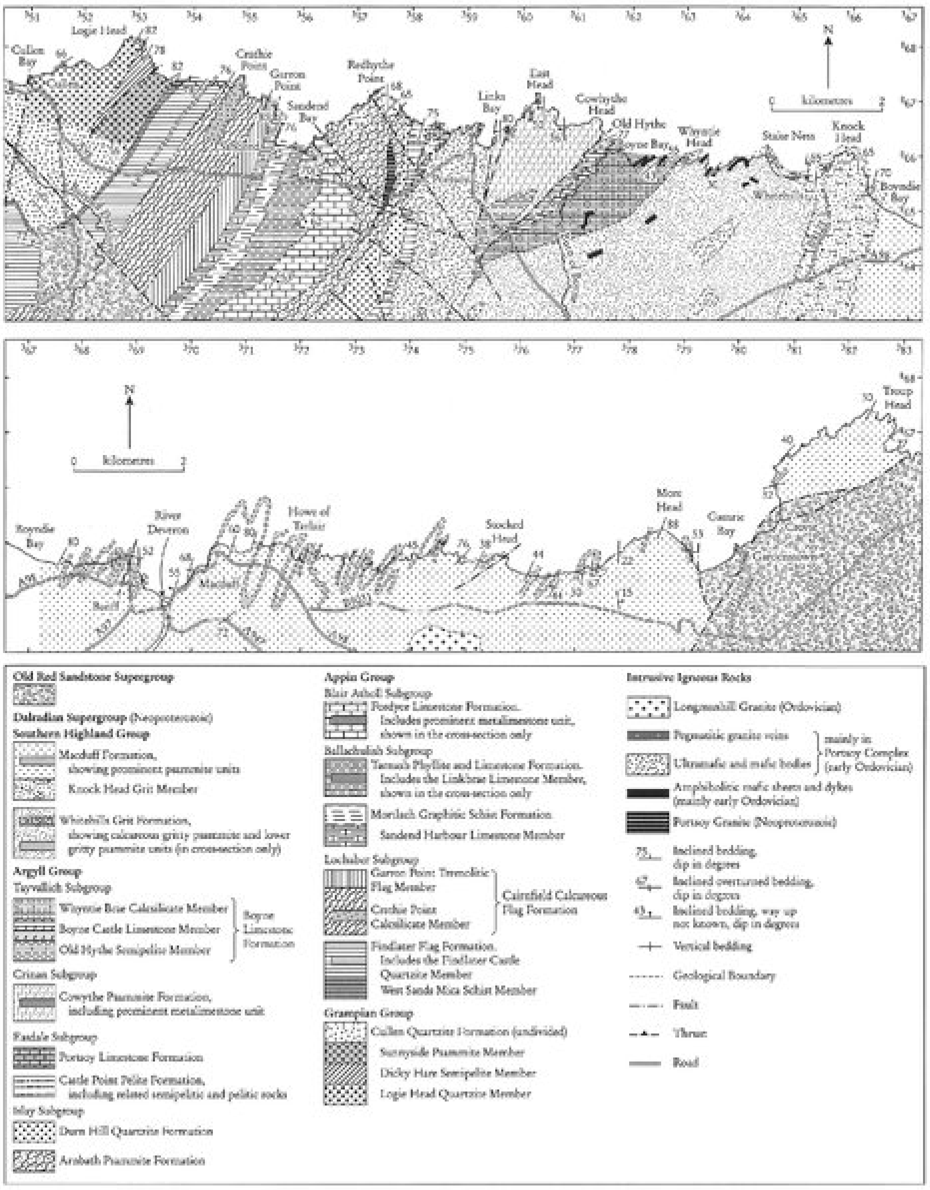
The coast also provides a near-complete structural and metamorphic transect across the Dalradian outcrop. The beds are basically the right way up and range from steeply dipping in the west to regionally shallow dipping in the core of the Turriff Syncline to the east. The succession is interrupted by several major dislocations, each of which probably marks the site of a fundamental structure with a long history extending back to the time of sedimentation. The Keith Shear-zone intersects the coast west of Portsoy; it does not remove or repeat much of the succession but it does include granite dated at 600 million years old. At Portsoy, a 1 km-wide zone of shearing that involves various 470 million year-old mafic and ultramafic intrusions marks the position of the Portsoy Shear-zone and the Portsoy Lineament. The latter structure seems to have acted as a controlling feature at the time of sedimentation, and through the deformation, metamorphism and magmatism of the Grampian Event. It separates the so-called Buchan Block to the east, which exposes higher stratigraphical levels and exhibits higher-level structures and low-pressure regional Buchan-type metamorphism, from structurally and stratigraphically lower level, higher pressure rocks to the west that seem to be a continuation of the sequences and structures typical of the Central Grampian Highlands.

The nature and origin of the Buchan Block and of its boundaries have been a constant source of discussion. It has clearly been decoupled at times from the adjacent terranes and possibly from the lower parts of the originally underlying Dalradian rocks; it has even been suggested that it might have been a separate allochthonous terrane with an entirely different sedimentological, structural and metamorphic history to the remainder of the Grampian Terrane. However, within this GCR site it could be argued that elements of both the stratigraphy and the structure are continuous across the Portsoy Shear-zone and relics of the Buchan metamorphism have been identified up to 10 km farther west, casting doubt on suggestions of large-scale regional displacement.

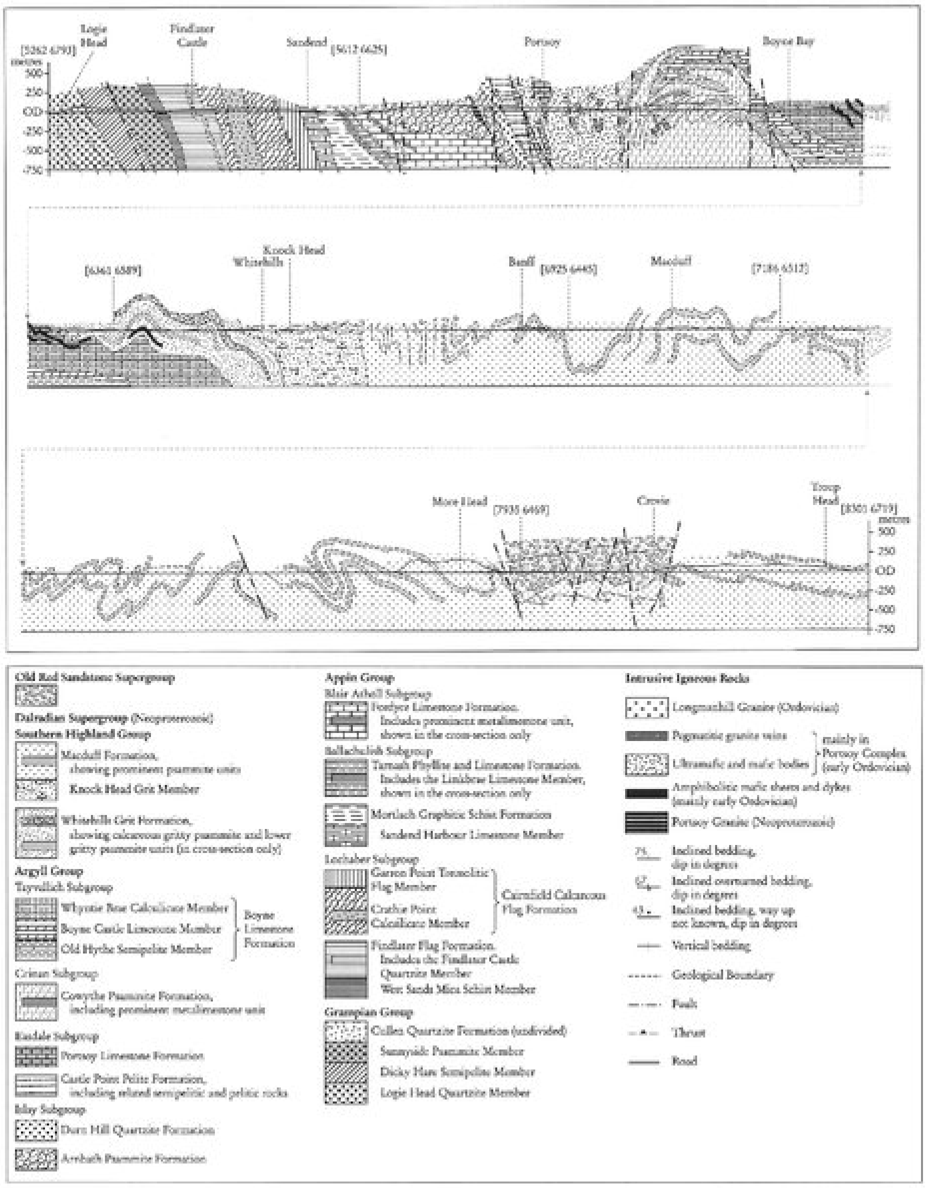
The coast section has contributed to speculation on the age of the Dalradian. At least the lower parts of the succession must be older than the 600 million year-old Portsoy Granite, and the highest parts have reportedly yielded some poorly preserved microfossils. An Ordovician age has been suggested, both from the microfossils and from the presence of glacigenic boulders that have been attributed to a late-Ordovician glacial period, but this interpretation cannot be reconciled with the dating of metamorphic events or the Dalradian succession elsewhere.

Most of this GCR site is well exposed and readily accessible, except for parts where the cliffs are particularly steep. With thick superficial deposits characterizing the hinterland this reference section is therefore extremely important in a national and possibly an international context. It has been the subject of more research and more publications than any other part of the Dalradian outcrop and is used extensively for teaching purposes. Yet there is so much about it that is still to be learned.

References



(Figure 6.25) Map of the coastal strip between Cullen and Troup Head, based largely upon BGS 1:50 000 sheets 96W (Portsoy, 2002) and 96E (Banff, 2002). Late-Caledonian minor intrusions are omitted for clarity.



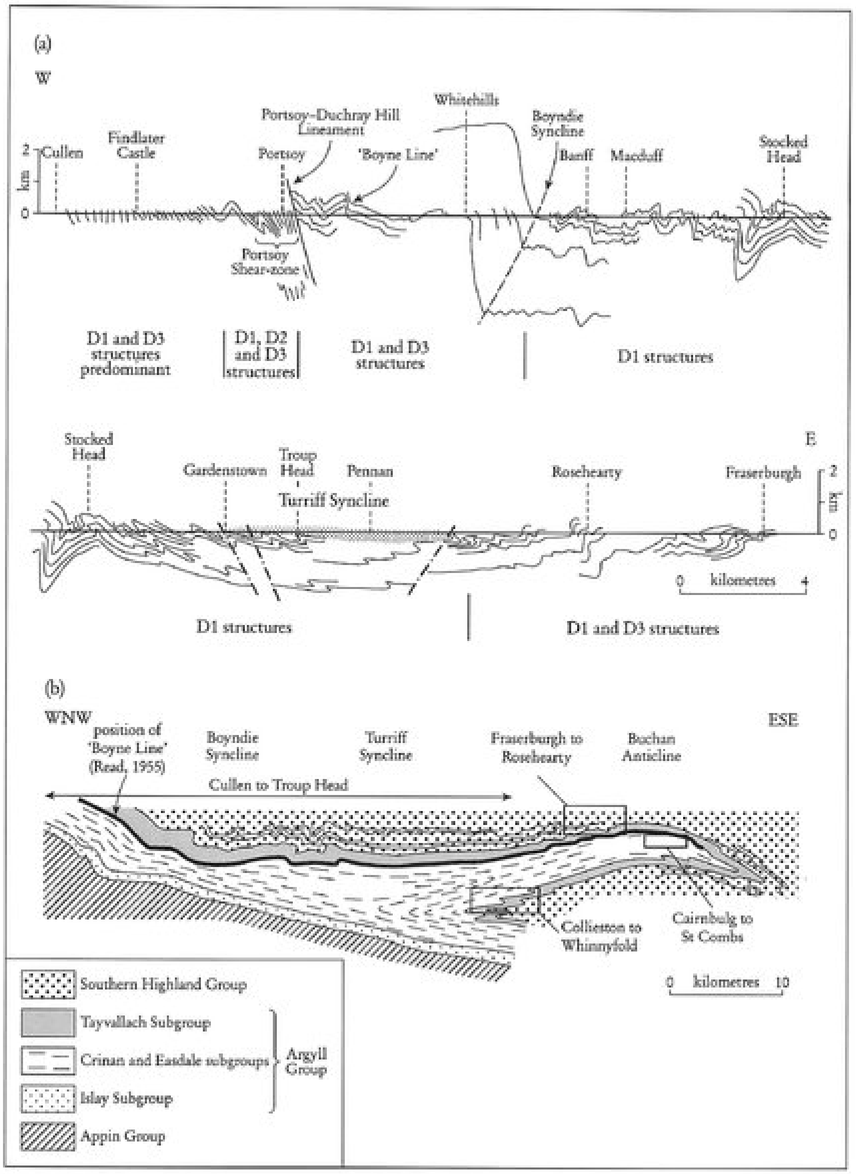
(Figure 6.26) Cross-section of the coast between Cullen and Troup Head, based largely upon sections accompanying BGS 1:50 000 sheets 96W (Portsoy, 2002) and 96E (Banff, 2002). Key as in (Figure 6.25).

(Figure 6.27) Ripples on bedding surface in the Findlater Castle Quartzite at Findlater Castle. (Photo: BGS No. P 008614, reproduced with the permission of the Director, British Geological Survey, © NERC.)

(Figure 6.28) View westwards from Portsoy Old Harbour towards Redhythe Point. The rocks of the near and middle distance are mostly highly deformed semipelites, quartzites, metalimestones and graphitic pelites within the Portsoy Shear-zone; note the very strong, steeply plunging lineation in the quartzite on the left. The second promontory away from the camera consists of serpentinized peridotite, worked and sold locally as 'Portsoy Marble'. (Photo: J.R. Mendum, BGS No. P 001134.)

(Figure 6.29) Andalusite porphyroblasts in the semipelitic part of the Knock Head Grit Member of the Macduff Slate Formation at Boyndie Bay. The hammer shaft is 35 cm long. (Photo: BGS No. P 221160, reproduced with the permission of the Director, British Geological Survey, © NERC.)

(Figure 6.30) Quartzofeldspathic boulder, interpreted as a dropstone from a floating iceberg in the Macduff 'Boulder Bed', Macduff Slate Formation, The Sclates, Macduff. Professor Janet Watson provides a scale. (Photo: J.R. Mendum, BGS No. P 726598.)



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