MACDUFF TO WHITEHILLS – BUCHAN TYPE REGIONAL METAMORPHISM

N. F. C. HUDSON & T. E. JOHNSON

PURPOSE

To examine the metamorphic isograds and mineral assemblages of the western part of the classic Buchan type regional metamorphic terrain and the sedimentology and structure of the Southern Highland Group rocks.

ACCESS

A small vehicle (car or minibus) may be parked close to each locality, all of which occur on the rocky foreshore. If using a coach, this may be sent from Scotstown (Locality 2) to await the party at Whitehills Harbour (Locality 10), involving a walk of 3.5 km (Fig. 1). The area is covered by OS 1:50 000 Landranger sheet 29 (Banff & Huntly) and 1:25 000 Explorer sheets 425 (Huntly & Cullen) and 426 (Banff, Macduff & Turriff) and the BGS 1: 50 000 sheet 96E (Banff). Although the excursion can be done in half a day, it probably deserves a full days attention to make the most of some spectacular but reasonably complicated rocks – a hand lens is strongly recommended. A lowish tide is preferred for locality 1 and required for localities 2 and 6. Sedimentary structures are well preserved, even in the higher-grade rocks. These can be best understood if this excursion is preceded by Exc. 4 (Macduff).

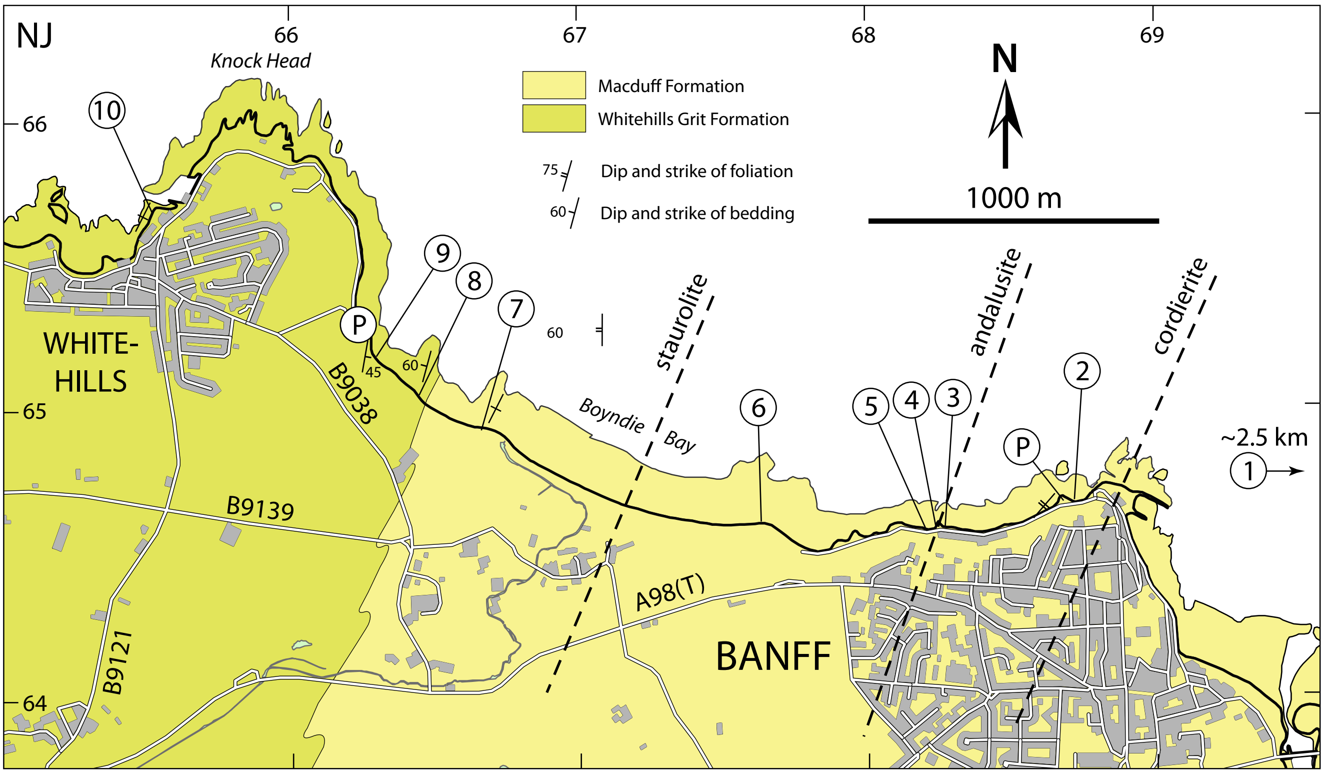

Fig. 1. Location map of the section from Banff to Whitehills. Locality 1 (Tarlair) is ~2.5 km to the east. Contains Ordnance Survey data © Crown Copyright and database right 2013 and British Geological Survey materials ©NERC 2013.

INTRODUCTION

The rocks exposed along the coast between Macduff and Whitehills constitute a series of metamorphosed coarse grits, graded turbidites and interbedded pelites belonging to the Southern Highland Group of the Dalradian (Whitehills Grit and Macduff Formations locally). They are predominantly right way up and have a regionally consistent younging direction towards the east with local inversions due to folding.

The rocks were regionally metamorphosed during the early Ordovician Grampian event at *c.* 470 Ma, which resulted in the widespread growth of andalusite and cordierite throughout the NE Dalradian (Harte & Hudson, 1979). The presence of these minerals implies low-pressure, high-temperature metamorphism, termed 'Buchan type' by Read (1952). Buchan type metamorphism needs an additional source of heat compared to Barrovian type metamorphism (which is characterised by the growth of garnet and kyanite), the latter of which is generally considered to result from 'normal' continental collision (such as in the Alps or the Himalaya). Barrovian type metamorphism characterises the bulk of the Dalradian to the south and west.

The rocks cropping out between Macduff and Whitehills show the effects of two deformation events, though the later one is less well developed at the eastern end of the section. These are usually correlated with the regional D1 and D3 deformation events recognised in the more extensively deformed Dalradian rocks to the west of Boyne Bay (Johnson 1962, Fettes 1971, Treagus and Roberts 1981), although in detail these workers have differences of opinion (see also Viete *et al.*, 2010).

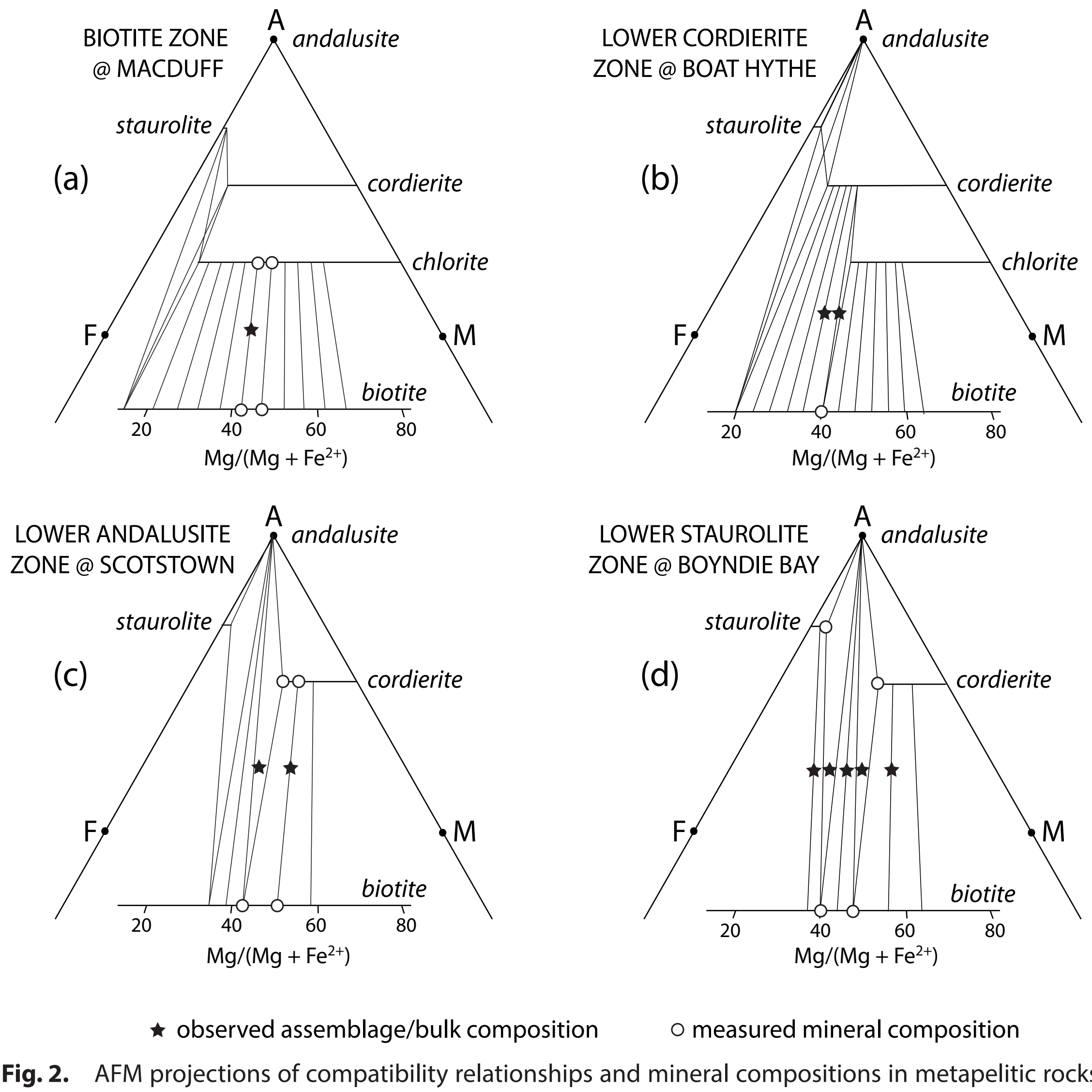

Fig. 2. AFM projections of compatibility relationships and mineral compositions in metapelitic rocks containing muscovite, quartz and H_2O (see Hudson, 1980). Cross tie-lines in (a) and (b) represent potential univariant reactions in rocks more Fe-rich than observed.

Study of the microstructures in these rocks, particularly of oriented trails of inclusions within metamorphic porphyroblasts, suggests that the porphyroblast phases grew after the development of the early structures (D1) and during or after the later ones (D3; Johnson, 1962). The regional isograds established at this time were subsequently folded into a major open NNE–SSW trending (presumably D4) structure termed the Turriff Syncline by Read (1923). The Turriff syncline now contains the lowest grade rocks in its core, with higher-grade rocks cropping out on its limbs at structurally deeper levels.

The Macduff to Whitehills section traverses the western limb of the syncline so that the metamorphic grade increases from east to west, progressing from biotite zone at Macduff through cordierite and andalusite zones at Banff into staurolite zone to the west of Boyndie Bay. A kyanite zone is encountered close to Portsoy (Exc. 3), broadly coinciding with the westerly transition from Buchan type to Barrovian type metamorphism. Though somewhat specialised, Fig. 2 illustrates compatibility relationships in the simplified metapelite chemical system K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O (KFMASH) at various localities, to which reference can be made where appropriate.

Fig. 3. Looking north through the natural arch (the 'Eye of the Needle') near Tarlair swimming pool (locality 1). The best examples of load casts occur straight through the arch (i.e. on the seaward side) and cross-bedding is particularly well displayed in exposures through the arch and to the left, although both are inaccessible at high tide. Graded bedding and bedding-cleavage relationships are clearly seen high up on the left wall of the inner arch (see Fig. 4). Excellent examples of graded bedding and slump folds occur in low-lying exposures on the opposite side of the prominent ridge (out of frame to the left).

ITINERARY

Locality 1. Biotite zone at Tarlair [NJ 7189 6463]

The excursion is best begun with a visit to view rocks of the biotite zone that exhibit spectacular sedimentary structures and bedding–cleavage relationships. From the A98 in Macduff turn down Moray Street and follow it right (east) onto High Shore. Continue almost to Tarlair swimming pool, parking just before a prominent ridge of rocks. Walk through the gap to the arch (the 'Eye of the Needle'; Fig. 3).

These rocks appear virtually unmetamorphosed in the field, although tiny (<1 mm) porphyroblasts of biotite are visible in some of the dark, fine-grained metapelites with the aid of a hand lens. The rocks exhibit a diverse selection of sedimentary structures that are of particular use in providing way-up criteria, in particular load casts, cross bedding and graded bedding (Fig. 4). All show that the rocks are right-way-up (i.e. the youngest rocks are at the top). Bedding-confined slump folds are also common. Such features record gravity-driven soft-sediment deformation (i.e. occurring prior to their complete lithification), perhaps triggered by seismic activity.

The rocks have a prominent slaty cleavage, which is axial-planar to a series of upright anticlines and synclines. The eroded core of one of these anticlines occurs at the location of the swimming pool to the east. Its presence may be inferred from consideration of the bedding and cleavage orientations at the natural arch. The bedding dips moderately towards the west, while the cleavage has a much steeper dip, indicating an antiformal closure to the east (Fig. 4).

Fig. 4. Looking north at exposures high on the west wall beneath the arch. Graded bedding in thinly bedded westward-dipping metaturbidites shows the rocks are right way up. The relationship between bedding and the steep cleavage indicates an anticlinal closure to the east (at the swimming pool).

Locality 2. Lower cordierite zone at Boat Hythe, Banff [NJ 6870 6465]

Proceed via the A98 from Macduff to Banff and follow the minor road (North Castle Street; signposted 'Hospital, Harbour') leading to Scotstown. Continue past the harbour and round to the left and park in the bay on the rocky promontory [NJ 6866 6465]. Either descend the steps on the west side of the car park or climb over the railings and onto the rocks (in both cases be careful as the rocks can be very slippery), then walk eastwards along the beach. These exposures are under water at high tide.

The promontory is formed by a metamorphosed gritstone that is repeated by a small syncline on Meavie Point, the next promontory to the east directly north of the harbour. The core of the syncline occurs within metagreywackes that crop out in the small bay (Boat Hythe). The metagreywackes contain sparse small (< or << 2 mm) cordierite porphyroblasts (now altered to pinite, a fine-grained intergrowth of chlorite and white mica), which appear as dark spots on wave-washed surfaces. Around Meavie Point, cordierite may also be found, but it does not occur further east. This shows that the cordierite isograd runs somewhere through the harbour and that the metamorphic grade increases towards the west.

Cordierite is an aluminous mineral and forms only in aluminium-rich rocks (i.e. the metapelites and metagreywackes). The complete mineral assemblage in metapelitic rocks here is generally cordierite–biotite–muscovite–quartz with or without plagioclase and other minor accessory minerals (Fig. 2b). Rare primary chlorite occurs in some rocks close to the isograd. The isograd results from a continuous KFMASH reaction chlorite + muscovite = cordierite + biotite + H_2O involving an up-temperature migration of the tie triangle cordierite–biotite–chlorite towards more MgO-rich compositions (compare Fig. 2a & b).

Careful examination of the rocks at Boat Hythe reveals rare, thin (usually less than 4 cm thick) calc-silicate layers containing hornblende–garnet–quartz–plagioclase ± epidote, which were presumably originally thin calcareous shale beds. The assemblage garnet–biotite–quartz occurs in adjacent impure metapelites. Garnetiferous calc-silicates also occur in exposures to the east of Banff Harbour below the cordierite isograd, but equivalent compositions have not been found at Macduff and it is not possible to establish the position of a garnet isograd for these compositions.

Locality 3. Upper cordierite zone, Scotstown [NJ 6825 6456]

Walk (or drive) west along the road towards Scotstown and descend to the pebble beach opposite the last block of cottages. Low wave-washed exposures near the bottom of the pebble beach contain dark oval porphyroblasts of cordierite that can be 5 mm or more in diameter (Fig. 5). Many of these rocks contain fresh (paler and glassy) cordierite, although this mineral commonly exhibits partial alteration to (darker and dull) pinite, in particular around the margins of porphyroblasts, but also in their core.

The rocks at this locality are hard and show little sign of any cleavage, characteristics more often associated with hornfelses produced by contact metamorphism (i.e. close to igneous intrusions). However, the porphyroblasts may contain trails of oriented inclusions (visible only in thin section), which attest to the previous presence of a fabric in these rocks. The destruction of the earlier fabric in the matrix may be interpreted as a result of near static recrystallisation accompanying porphyroblast growth.

Some of the metaturbidites at this locality show the effects of intense soft-sediment deformation, particularly bedding plane confined folds, and are presumably slump horizons. Calc-silicate pods have the same mineral assemblage as at locality 2 but are coarser-grained. Pink garnet and green hornblende are easily identified.

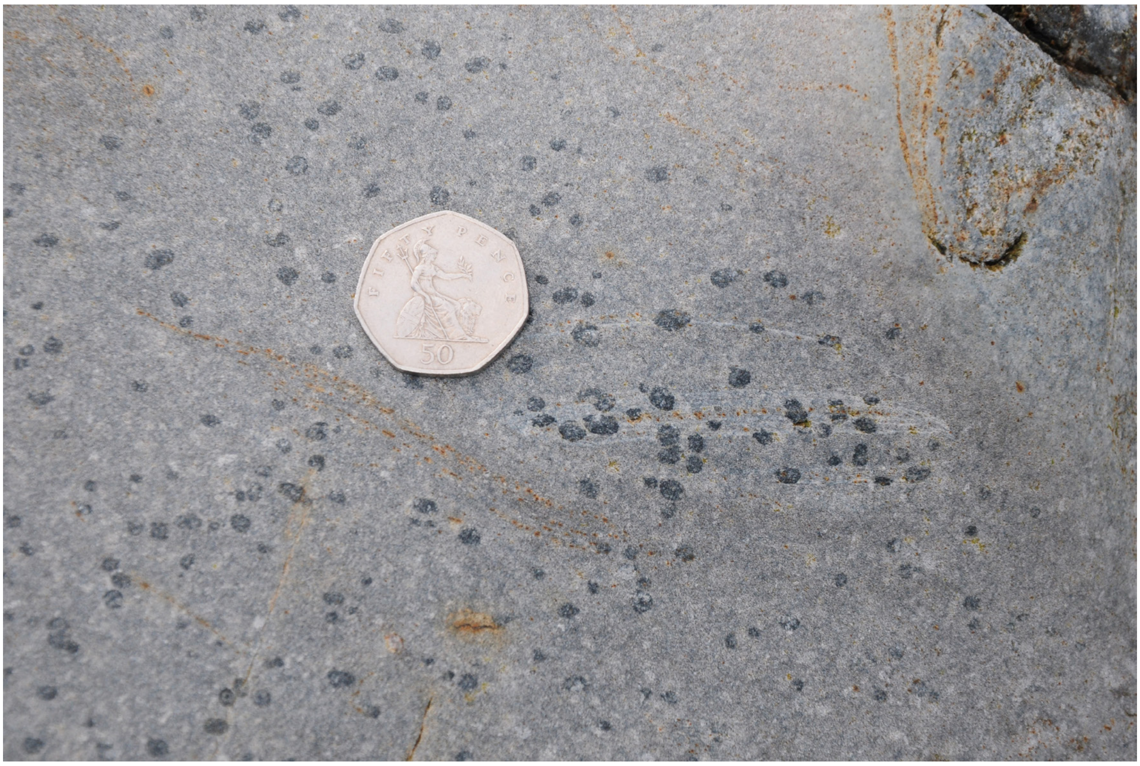

Fig. 5. Metaturbidites containing ovoid porphyroblasts of cordierite (locality 3). The paler glassy porphyroblasts are fresh; darker spot are pinitised pseudomorphs rich in chlorite and white mica.

Locality 4. Deformed porphyroblasts, Scotstown [NJ 6821 6455]

Just west of the last cottage at Scotstown a prominent metagritstone forms a promontory running out to sea. Near the wall by the road on the west side of this promontory a metapelitic horizon shows a prominent cleavage, a feature which was not present at locality 3. The rock here is rich in very dark green (almost black) chlorite porphyroblasts and contains pseudomorphed cordierite porphyroblasts (now composed entirely of chlorite and muscovite), which appear to have been flattened slightly in the cleavage (cf. Johnson 1962). There is little doubt that these flattened pseudomorphs were once composed of cordierite as rocks a little further west contain similar pseudomorphs with unaltered cordierite cores. It would seem that the cleavage at this locality deforms and therefore postdates the cordierite porphyroblasts. It would also seem to be associated with retrogressive chlorite growth.

Locality 5. Lowermost andalusite zone, Scotstown [NJ 6818 6455]

Low waved-washed exposures some 20 m further west are lithologically similar to those at locality 3 and contain a number of well-preserved sedimentary structures including load and flame structures. Cordierite porphyroblasts are again prominent but are now accompanied by rare small andalusite porphyroblasts. These are generally smaller than the cordierite, much paler in colour (pale greyish white) and rectangular or irregular in shape. They are often easier to see if the rock surface is wet. Please do not hammer this locality as andalusite is rather rare near the isograd. A good place for collecting andalusite is described at locality 6.

The andalusite zone metapelitic assemblage is andalusite–cordierite–biotite–muscovite–quartz–plagioclase (Fig. 2c), the andalusite isograd being generated by the KFMASH continuous reaction cordierite + muscovite = andalusite + biotite + quartz + H_2O as the three-phase triangle andalusite–cordierite–biotite migrates from Fe- to Mg-rich compositions upgrade (Fig. 2b, c & d). These rocks, like those at locality 3, seem unaffected by the later deformation event seen at locality 4. However, some porphyroblasts contain trails of inclusions that can sometimes be followed a short distance into the rock matrix.

Looking out to sea a few tens of metres further west, a small anticline is clearly visible. This fold and the syncline described at locality 2 are typical of a series of anticlines and synclines that occur along this part of the section. Some workers have considered these to be F3 structures (Johnson 1962; see also Viete *et al*., 2010) whilst others (Fettes 1971, Treagus and Roberts 1981) have considered them to be of D1 age. The structural evidence relating to the folds themselves is equivocal. Flattened pseudomorphed porphyroblasts occur on the top of the fold near its hinge zone, but it is difficult to show conclusively that an earlier fabric exists. It is possible that two sets of coaxial structures occur in this section (Treagus & Roberts, 1981).

A little further west of the anticline, wave-washed exposures of calc-silicate near the bottom of the beach are associated with cordierite-bearing metagreywackes. The discontinuous, lenticular nature of some of the calc-silicate horizons may indicate that they formed diagenetically and represent metamorphosed calcareous concretions (Hudson & Kearns, 2000). Some of the thicker calc-silicate bands have a zonal arrangement of mineral assemblages. Marginal zones (as well as thinner calc-silicate layers at this locality) have the assemblage hornblende–garnet–plagioclase–quartz ± epidote, similar to that found at lower grade. However, the central parts of the pods are softer (weathering as deep hollows in the rock) and contain calcite, commonly accompanied by pale green clinopyroxene (diopside).

Fig. 6. Looking south at the hinge of the 'Boyndie Syncline'.

Continue to walk further west across a prominent coarse metapsammite unit and onto the raised exposures beyond, in which a synclinal hinge may be seen provided the tide is not too high. This is the core of the 'Boyndie Syncline', supposed to separate more shallowly dipping rocks to the east from subvertical rocks to the west (Fig. 6; Sutton & Watson, 1956).

Locality 6. Andalusite zone, east side of Boyndie Bay [NJ 6761 6459]

Continue westwards along the road as far as the parking area, passing exposures of steeply dipping rocks, and descend to the beach by the steps at the far end of the sea wall by the shelter. Andalusite-cordierite schists crop out amongst rather grotty seaweed covered exposures, which are covered at high tide. However, good samples of the andalusite zone metapelite assemblage can usually be collected from the boulders strewn along the base of the sea wall.

If on foot, walk westwards through Banff Links caravan park and cross the footbridge over the Burn of Boyndie. Follow the path and descend to the exposures at the edge of the grassy promontory, a walk of just over 1 km. If driving, return to the main road (A98) and head west towards Portsoy. Take the B9038 towards Whitehills, turning right shortly after the 'Welcome to Whitehills' sign. Drive down the steep narrow road to the car park at the bottom (Red Well) [NJ 6621 6527]. Walk eastwards along the path and continue to the furthest visible outcrops beneath the grassy promontory, a walk of around 600 m.

Fig. 7. Looking south at thin horizon of dark-coloured metapelite rich in andalusite and apatite between more massive beds of (relatively) Fe-rich metapelite containing porphyroblasts of andalusite and staurolite (locality 7). Load casts in the sandy layer to the left of the phosphatic horizon show these rocks young towards the west, opposite to the regional trend.

Locality 7. Lower staurolite zone, west side of Boyndie Bay [NJ 6664 6490]

These rocks here are within the staurolite zone. Although staurolite is first found in the low exposures visible at low tide due east of here, fresh faces are largely obscured by seaweed and barnacles, and the staurolite isograd runs somewhere through Boyndie Bay (Fig. 1). These exposures (localities 7–9), which continue sporadically for several hundred metres northwest, show a variety of original sedimentary protoliths comprising mudstones (pelites), graded turbidite units, psammites and rare dark pelitic units rich in apatite, which were presumably phosphatic shales. Sedimentary structures providing way up criteria, principally graded bedding and load casts, are particularly clearly developed.

The mineral assemblages present in aluminous rocks (metapelites and muddy tops of metaturbidite units) vary depending on the chemical composition of the rocks. The metapelitic schists fall into two broad compositional groups, which depend on the ratio of ferrous iron (Fe^{2+}) to magnesium. Fe-richer rocks, which are the most common metapelitic lithology, have the main assemblage (excluding accessory phases) andalusite–staurolite–biotite–muscovite–quartz (Fig. 2d & 7), whilst rarer more magnesian rocks have andalusite–cordierite–biotite–muscovite–quartz (Fig. 2d & 8).

The staurolite isograd in muscovite-bearing rocks is formed by a continuous reaction andalusite + biotite + H_2O = staurolite + muscovite + quartz as the andalusite–staurolite–biotite triangle migrates to the right (towards the MgO apex) upgrade (Fig. 2b, c & d). This reaction is unusual in that it involves hydration. Manganiferous garnet is common as an additional mineral in most metapelitic rocks.

The rocks at locality 7 are metaturbidites, which show well-preserved partial Bouma sequences and load casts. Bedding is subvertical but way-up criteria show the rocks have a younging direction towards the west (Fig. 7), contrary to the regional trend, and lie on the steep western limb of an anticline. The metamorphic porphyroblasts are best developed in the aluminous metapelitic tops of these graded units, so that the part of the unit which was of finest grain size at the time of deposition became the coarsest part after metamorphism. Some of these metaturbidites also contain calc-silicate nodules of probable diagenetic origin with assemblages rich in hornblende and garnet (Hudson & Kearns, 2000).

The cordierite here has its usual round to oval shape, but it is commonly retrogressively altered to muscovite and chlorite. Andalusite generally forms elongate, apparently randomly-oriented porphyroblasts that stand proud of the matrix. Staurolite forms much smaller (< 1 mm) generally euhedral porphyroblasts toffee brown in colour. Importantly, some muscovite- and biotite-bearing layers contain porphyroblasts of andalusite, staurolite and cordierite. These rocks exhibit complex microstructural relationships and may have a more complicated tectonothermal history than previously thought (D. R. M. Pattison, personal communication).

The matrix of these rocks is significantly coarser in grain size than the matrix of rocks in the andalusite zone and biotite grains are sufficiently large to be identified as small black plates (a hand lens will help). A dark carbonaceous apatite rich band (4-5 cm thick) occurs at this locality and contains prominent pale andalusite porphyroblasts (Fig. 7), some of which have inclusion trails arranged in the chiastolite cross pattern.

Fig. 8. Relatively Mg-rich metapelites containing porphyroblasts of pale prismatic andalusite and dark ovoid cordierite. Graded bedding and load casts confirm that these beds young towards the west (top), opposite to the regional trend (locality 7).

Locality 8. [NJ 6643 6505]

Walk westwards across the beach to the next obvious outcrops. These rocks belong to the Whitehills Grit Formation close to its mapped contact with the overlying Macduff Formation (Fig. 1), although there is no clear lithological distinction. The first exposures encountered are metapelites containing several dark phosphate-rich bands. These give way to raised outcrops dominated by metamorphosed grits and psammites with thin layers of metapelite in which cordierite is particularly abundant. Some of the coarse-grained rocks contain clasts of bluish quartz, which suggest provenance from a granulite facies metamorphic terrain, for example the Lewisian foreland. The metamorphosed grits and psammites are followed by a metapelite–metaturbidite sequence.

The rocks here dip at around 60 degrees toward the WNW and young towards the east, indicating they are inverted. If the bedding dip directions are followed carefully it is possible to locate the hinge zones of some open monoclines with axial planes dipping west. The schistosity here, formed by preferred orientation of muscovite and biotite, is folded by these monoclines (the schistosity orientation changes with the bedding) and is locally crenulated into microfolds.

Fig. 9. Typical massively bedded metapelite containing apparently randomly oriented porphyroblasts of pale andalusite and brown staurolite (locality 9).

Locality 9. [NJ 6628 6516]

Walking further west along the beach, the next prominent exposures comprise more massive beds of purplish-brown metapelite containing the assemblage andalusite–staurolite–biotite–muscovite–quartz–garnet–plagioclase (Fig. 9). A steep eastwards-dipping foliation is more clearly preserved in these rocks than elsewhere along the section, and is seen to refract through interbedded coarser-grained metapsammites. The rocks here are subvertical to eastward dipping and right way up.

Staurolite is easily identified as toffee brown porphyroblasts up to 2 mm across. Andalusite porphyroblasts are up to a couple of centimetres long and contain abundant inclusions. With a hand lens it is possible to follow oriented biotite within the matrix seemingly straight through the andalusite porphyroblasts, demonstrating that andalusite grew across, and largely postdates, this schistosity.

The metapelites here contain rare patches of pegmatite containing abundant coarse muscovite and pink andalusite (Fig. 10). These probably originate from Al_2SiO_5-saturated fluids derived locally from dehydration of the metapelites, and are not uncommon in the Dalradian (Thomson, 2007).

Locality 10. Whitehills [NJ 6551 6565]

Follow the track through the caravan path and around Knock Head, which is largely composed of metapsammites, to Whitehills. Find a parking spot just past the harbour and walk to outcrops at the bottom of the sloping sea wall. The rocks here, which are inaccessible at high tide, comprise a tightly folded package of metaturbidites. The folds are flat-lying and are considered to be F1 structures by Johnson (1962). They have been refolded by more upright F3. Andalusite and staurolite are conspicuously

Fig. 10. Pegmatite pod containing abundant muscovite and pink andalusite (locality 9).

developed in metapelitic horizons. Close to the highest point on the exposures, a calc-silicate pod contains idiomorphic garnet.

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Appendix – additional field photos

Top left – Ball-and-pillow load structures (running from bottom left to top right) formed at the junction between the sandy base and muddy tops of graded metaturbidite units (locality 1). ***Top right*** – Fine cross-laminations in metaturbidite units intercalated with thin metapelite layers (locality 1). ***Middle left*** – Graded bedding in metaturbidite units close to the high water mark on the western side of the rocky ridge at Tarlair (NJ 7188 6463). ***Middle right*** – Bedding-confined slump folds from the western side of the rocky ridge at Tarlair. ***Bottom left*** – Looking north towards the anticline a few tens of metres west of locality 5. ***Bottom right*** – Typical metaturbidite in the lowermost andalusite zone, Scotstown (locality 5). Small rectangular to irregular andalusite porphyroblasts occur alomng with abundant dark ovid cordierite porphyroblasts.

Top left – Wave-washed boulder typical of Southern Highland Group metagritstones. The quartz has a characteristic bluish colour suggesting it was dervied from granulite facies rocks. ***Top right*** – Looking west and down dip at layers and pods of pale calcareous metapsammite. Load casts show that the metasediments here are inverted and have a younging direction towards the east (locality 8). ***Middle left*** – Load casts at the junction between inverted graded metaturbidite units. Flame structures are particularly well developed in the darker metapelites (locality 8). ***Middle right*** – Abundant porphyroblasts of cordierite in metapelitic layers within an interbedded sequence of metapelites and fine metapsammites that together occur between thick metapsammites/gritstones (locality 8). ***Bottom left*** – A prominent cleavage (S1) in relatively massive metapelite layers is seen to refract through thin metapsammite horizons (locality 9). ***Bottom right*** – Layered calc-silicate pod containing abundant pale pink porphyroblasts of garnet from close to the high point of the exposures southwest of the harbour at Whitehills (locality 10). The pod sits within a graded metaturbidite, the metapelitic top of which contains abundant andalusite porphyroblasts.