Southern Grampians Complex, Grampian Caledonides

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Contents

Southern Grampians Complex

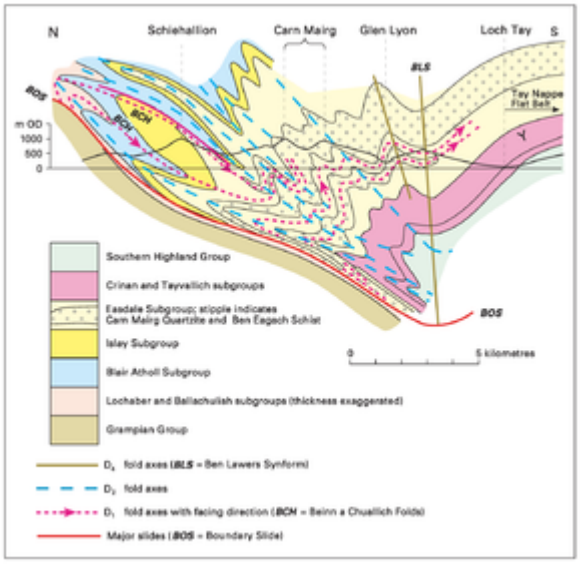
Highland Border Steep Belt and the hinge zone of the Tay Nappe

The existence of a belt of steeply dipping rocks along the Highland Border has long been known and is implicit in the early discussions of the area. However, it was not fully recognised and described until 1957 (Stringer, 1957). The *Aberfoyle Anticline* was first recognised by Henderson (1938) who used sedimentary structures to demonstrate opposing younging directions in 'grits' on either side of a core of slates. These criteria were also applied by Anderson (1947) to interpret outcrops of slate along the length of the Highland Border as the cores of similar structures, a correlation which has subsequently been shown to be erroneous in many places. However, it was Shackleton (1958) who used both sedimentary structures and cleavage-bedding relationships to demonstrate that the Aberfoyle Anticline is a downward-facing synformal anticline and interpreted it as the closure of the Tay Nappe. Subsequently, many detailed local studies have been made of key areas of the steep belt (from south-west to north-east: Simpson and Wedden, 1974; Paterson et al., 1990; Mendum and Fettes, 1985; Stone, 1957; Harris, 1962; 1972; Harris and Fettes, 1972; Harte et al., 1984).

Block diagram of major structures in the

Grampian Highlands. P915427.

D_1 recumbent fold in dominantly inverted gritty and pelitic metagreywackes. Collieston Formation, Southern Highland Group, Devil's Study, near Whinnyfold, Aberdeenshire. P002878.



Section across the Northern Fold Belt in the Schiehallion–Loch Tay area showing the combined effects of D1 and D2 folds. P915428.

In the Cowal and Bute area the strata steepen gradually on the south-eastern limb of the *Cowal Antiform*, but north-eastwards from here the bend becomes a sharp, monoclinal flexure, over which the *Flat Belt* of the Tay Nappe gives way to the *Steep Belt*. This flexure, which results in a downstep to the south-east of as much as 10 km, is known as the *Highland Border Downbend* (or *Monoform*). It has long been recognised as a secondary structure, either associated with the D_4 deformation or, more likely, with a slightly earlier phase of differential block uplift (Mendum and Fettes, 1985). It is possible that the downbend is sited over a reactivated basement lineament separating two major crustal blocks (Harte et al., 1984).

The hinge zone of the Tay Nappe was originally described as a single downward-facing anticline at Aberfoyle, but elsewhere it has been shown to be more complex. In the Ben Ledi area the hinge zone consists of two major synforms, the *Aberfoyle Anticline* and the *Benvane Synform*, separated by the *Ben Ledi Antiform* (Mendum and Fettes, 1985). These structures are all inferred to be of primary, D_1,

age since minor D_2 structures are not seen near the Highland Border in this area and only become overprinted on D_1 farther to the north-west. In the Dunkeld area, downward-facing folds are interpreted as lying on the north-western limb of the main Aberfoyle Anticline (Treagus et al., 1972; Harris and Fettes 1972).

Minor structures in rocks of low metamorphic grade in the Steep Belt and in much of the adjacent parts of the Flat Belt are very much influenced by lithology. Pelites develop axial planar slaty cleavages, but in the meta-greywackes, which constitute most of the Southern Highland Group, spaced cleavages fan around fold closures. Increased deformation during subsequent phases flattens the spaced cleavage and induces a finely striped rock so that, where folding is tight, as in the lower structural levels of the Tay Nappe, it is difficult to recognise the multiple origin of the dominant foliation (Harris et al., 1976). Bedding is generally not discernable, except where distinct lithological changes occur, and outcrops are commonly dominated by abundant minor folds and composite cleavages. Where NE–SW-trending D_4 folds are present, they are usually accompanied by a strong crenulation cleavage, best seen in the more pelitic or strongly foliated rocks. This cleavage dips north-westwards at moderate to subvertical angles.

Tay Nappe

The history of development of the Tay Nappe is a matter of continuing discussion and is central to all interpretations of the overall evolution of the Grampian Highlands. It is generally agreed that the recumbent structure now seen is not necessarily the fold as initially formed, but is the result of flattening, tightening and extension of the original D_1 anticline during D_2 and, where present, D_3 deformation. The resulting, essentially parallel-sided, flat-lying nappe has a large amplitude in the south-west, but diminishes towards the north-east (P915427). Bedding and the composite foliation resulting from the primary (D_1 to D_3) episodes are essentially parallel. Later NE–SW-trending secondary folds and other structures on both a major and a minor scale were subsequently imposed on the nappe. The major folds are commonly of large amplitude and open in style, for example the *Ben Lawers Synform*, but can be sharply defined locally such as in the Highland Border Downbend. Late cleavages and foliations associated with these folds cross-cut the primary structures at a high angle and trend NE–SW.

In the South-west Highlands the nappe has the form of a broad arch, known as the *Cowal Antiform* ((P915427), block A). This is modified by two conjugate monoformal structures, probably both related to the pre-D_4 block uplift: the *Highland Border Downbend* to the south-east and the *Tarbert Monoform* to the north-west (Roberts 1974). Exposure levels are entirely within the lower, inverted limb of the nappe, except to the north-west of the Tarbert Monoform, where the core of the Tay Nappe is brought down below the level of erosion to crop out as the *Ardrishaig Anticline*. Here the fold limbs, primary axial planes and associated cleavages all dip steeply to the north-west and constitute part of the *Knapdale Steep Belt* (Roberts, 1974a). This is the only area in which the core of the Tay Nappe is exposed.

North-east from Cowal, the crest of the Cowal Antiform flattens and the inverted lower limb of the Tay Nappe forms the *Flat Belt* which dominates so much of the Southern Highlands ((P915427), blocks B, C and D). The Flat Belt is sharply limited on its south-eastern side by the Highland Border Downbend, but the Tarbert Monoform dies out north-eastwards and the core of the nappe lies above the present level of erosion. The north-western limit of the nappe is here defined by a steeply dipping zone of downward-facing folds which must include, in part, the hinge zone of any major antiformal syncline originally underlying and complementary to the Tay Nappe. This zone is termed the *Ben Lui Fold Complex* in block B (Roberts and Treagus, 1979) but the zone widens north-eastwards in blocks C and D with the addition of many tight, upright folds of a later generation

(D_2/D_3) which will be described as the *Northern Fold Belt* ((P915427), blocks B, C and D).

Late broad, upright, NE-trending D_4 folds affect the north-western part of the Flat Belt ((P915427), blocks B and C). Of these, the best developed are the *Ben Lawers Synform* (Treagus, 1964) and its complementary, lower amplitude *Loch Tay* (or *Ben More) Antiform* to the south-east (Watkins, 1984; Harte et al., 1984). The somewhat tighter *Sron Mhor Syncline* may be of the same generation but it is closely associated with the steeper structures of the Northern Fold Belt and was probably initiated as an earlier structure (P915427, block D).

Towards the north-east the amplitude of the Tay Nappe is considerably reduced ((P915427), block E). In the Glen Esk area a broad late antiform, the *Tarfside Culmination*, exposes a wide zone of non-inverted strata, apparently beneath the Tay Nappe, which Harte (1979) assigned to a separate *Tarfside Nappe*. According to Harte the axial zone of the fold separating the two nappes has been replaced by a slide, the *Glen Mark Slide* ((P915427), block E). On the coast section north of Stonehaven, a generally flat-lying sequence is 'down-bent' (D_4) and becomes overturned to the south-east, with downward-facing D_1 structures (Booth, 1984; Harte et. al., 1987). It is not certain how this sequence, which may be right-way-up, relates to the Tay Nappe.

To the north of Aberdeen the Tay Nappe can no longer be identified with any certainty ((P915427), block F). The rocks are mostly right-way-up and it is not clear whether the inverted limb has been cut out by major thrusting, or whether, more simply, the nappe structures have a much smaller amplitude in this area (Harte et al., 1984). However, in the coast section around Collieston the beds are regionally inverted and there are abundant small- to large-scale recumbent, isoclinal D_1 folds with a maximum amplitude of about 1 km ((P002878); Read and Farquhar, 1956; Mendum, 1987). These folds plunge gently to the north, face eastwards and may represent a subdued equivalent of the nappe (Ashcroft et al., 1974). The folds, and their accompanying spaced cleavage, are refolded by a later set of near-coaxial, tight folds which postdate porphyroblast growth and hence are assigned to D_3.

Ben Lui Fold Complex and the Northern Fold Belt

From Dalmally north-eastwards to Strathtummel, a progressively widening zone of steeply inclined strata intervenes between the Flat Belt of the Tay Nappe and the Boundary Slide. Since the axial plane of the anticlinal Tay Nappe appears to be above the level of erosion throughout this area, early workers considered that the underlying major synclinal axial plane and fold closure (the'righting fold') must lie within this zone. In the critical area around Ben Lui the contact between the Ardrishaig Phyllite and the Ben Lui Schist can be traced around a fold closure from an inverted to a non-inverted limb. This antiformal syncline was termed the 'Ben Lui Fold' by Bailey (1922) who proposed that it is the D_1 syncline beneath the Tay Nappe.

Subsequent work by Cummins and Shackleton (1955) supported Bailey's view, but a more detailed study by Roberts and Treagus (1964; 1975) showed that the folding is more complex. Beneath the D_1 Ardrishaig Anticline, the *Ben Lui Fold Complex* consists of three recumbent elements, the *Dalmally Syncline*, the *Ra Chreag Anticline* and the *Ben Lui Syncline*, all of which were shown to be later, D_2 (or possibly D_3) structures. This tripartite structure has been traced north-eastwards to lower Glen Lyon (Roberts and Treagus, 1979), beyond which the individual folds lose their identity. In the Balquhidder area, Watkins (1984) has proposed that a large-scale recumbent fold exists, which he has tentatively correlated with the Ben Lui and lower Glen Lyon D_2 folds. Many folds in the Schiehallion area and associated folds in Strathtummel with SE-dipping axial planes ((P915427) and (P915428)) appear to belong to the same generation of D_2 folds, which in places are seen to fold the axial planes of major D_1 folds such as the *Beinn a Chuallich Folds* and the *Creag na h'Iolaire*

Anticline (Roberts and Treagus, 1979; Treagus, 1987). It was these NW-overturned folds, together with the SE-facing Tay Nappe, which led to the model of a 'mushroom' structure of nappes diverging from a root zone in the *Tummel Steep Belt*, comparable to the Loch Awe Syncline (Sturt, 1961; Rast, 1963; Harris 1963). The demonstration that the D_2 folds to the north-west of the steep belt refold SE-facing D_1 structures associated with the Tay Nappe makes this interpretation untenable.

Farther to the north-east, in the Glen Shee area, a structure known as the *Kirkmichael Fold* has long been identified as a continuation of the Ben Lui Syncline (Bailey, 1925; Read, 1935; 1955). However, this too has subsequently been shown to be a complex D2 structure, similar in profile to those of the Strathtummel area (Upton, 1986).

In the area around Schiehallion and Strathtummel ((P915427), block C) the Appin and Argyll group rocks, the Boundary Slide and the underlying Grampian Group undergo a dramatic swing of strike which is a major feature of even small scale maps (e.g. P915411). This displacement is caused by large, steeply plunging, north-trending late folds termed the *Errochty Synform* and the *Bohespic Antiform* (Rast, 1958; Thomas, 1980; Treagus, 1987). Thomas considers these folds to be D_4 structures (his D_3), whereas Treagus regards them as later (his D_4, and hence D_5 in the overall scheme). The two folds have contrasting geometry, consisting of a tight synform and a broad, open antiform. Such changes in fold geometry commonly occur at the junction of materials of contrasting competence, in this case the thick psammites of the Grampian Group and the multi-layered pelites and quartzites of the Appin Group. A similar geometry occurs in a fold pair of similar age farther to the west, in the Loch Rannoch area. These fold pairs have a symmetrical spatial relationship to the major NNE-trending Loch Tay, Bridge of Balgie and Tyndrum faults, and Treagus (1987) considers that there may be a relationship between ductile shearing, the late folds pairs and later brittle faults. Whatever age is assigned to these fold pairs they do not represent the latest deformation in the area, since their axial traces are themselves folded locally by NW-trending folds, the most important being the *Trinafour Monoform.*

Boundary Slide

The Southern Grampians Complex is separated from the structurally underlying Central Grampians Complex by a slide which can be traced almost continuously from Dalmally to Glen Tilt. This zone of highly schistose or platy rocks, varying in thickness from 500 to 2000 m, includes several planes of dislocation and has been termed the *Boundary Slide* (Roberts and Treagus, 1977c).

A 'Boundary Slide' was first recognised in the Strathtummel area by Anderson (1923) and was described in detail in the Schiehallion area by Bailey and McCallien (1937) and by Rast (1958). It was subsequently equated with major slides in the South-west Highlands to become part of the 'Iltay Boundary Slide' (MacGregor, 1948; Rast, 1963). For most of its length the slide forms the boundary between successions with markedly different lithological associations, formerly assigned to the Moine and the Dalradian. No correlations were attempted between these successions on early maps (e.g. Bailey, 1934). Consequently the slide assumed a fundamental importance as a major dislocation separating two major tectonostratigraphical units, the Ballappel Foundation and the Iltay Nappe. Correlation across the slide involves a comparison of widely separated successions in the Appin area and in Perthshire. Unsatisfactory attempts at correlation by Anderson (1948; 1953) and Voll (1964) were followed by the more generally accepted correlation of Rast and Litherland (1970). This seemed to confirm that a considerable hiatus is represented by the slide since, in several areas, large sequences of the Appin Group and Islay Subgroup appeared to be absent. However, recent mapping has revealed that attenuated sequences of the Lochaber and Ballachulish subgroups are present in most areas (Treagus and King, 1978; Roberts and Treagus, 1979; Treagus, 1987). The attenuation may be due to a variety of factors other than sliding, and the presence of near-complete

successions along much of the length of the Boundary Slide has therefore lessened its significance as a structural boundary in most current interpretations.

Roberts and Treagus (1977c) regard the Ballachulish Slide of the Western Grampians Complex as part of the Boundary Slide, although correlation between the Glencoe and Dalmally areas is speculative on account of the intervening Etive Granite. From Dalmally eastwards the slide is well defined by a zone of strongly deformed rocks which intervenes between the Easdale Subgroup and underlying rocks of the Lochaber Subgroup (Roberts and Treagus, 1979). From Beinn Dorain eastwards through Glen Lyon, additional, structurally lower slides separate the Lochaber Subgroup from the underlying Grampian Group.

In the Schiehallion area the zone of strongest deformation is coincident generally with a porphyroblastic muscovite-schist with small quartz blebs which corresponds to the Beoil Schist of Bailey and McCallien (1937). This schist, which has a thickness of up to 95 m, was regarded as a tectonic schist by Rast (1958; 1963) and can be shown to transgress both Grampian Group and Appin Group sequences according to Thomas (1980). However, Treagus and King (1978) and Treagus (1987) argue that the Beoil Schist is a true stratigraphical unit within which the maximum deformation has been focussed. Despite this difference of opinion over local detail, there is no doubt that the slide zone does transgress the stratigraphy on a regional basis and that the total displacement may be several kilometres (Treagus, 1987).

Early isoclinal folds are truncated by the Boundary Slide and there is no doubt that it is folded extensively by later structures. Thomas (1980) considers that the dislocation was initiated during the formation of the primary nappes but that it was reactivated in places during later deformation. The strong platy or schistose fabric present throughout the zone is regarded by Treagus (1987) as an intense development of the regional schistosity developed during nappe formation, which he regards as a D_2 phase. Most of the slides within the zone occur on the short limbs of D_2 folds and result in an overall movement, in a thrust sense, towards the north-west. This fact is clearly contrary to the overall concept of the dislocation as an extensional slide related to the primary nappe formation and has not been fully explained. It may be that slides, initiated during basin development and early tectonism, were subsequently reversed during later movements (Soper and Anderton, 1984; Anderton, 1988).

A Boundary Slide has been traced north-eastwards from Glen Tilt, through the Braemar area to the eastern end of the Cairngorm Granite (Upton, 1986). However, here its overall effect may be much reduced. Farther north, zones of high strain, locally accompanied by slides, are common at or below the Grampian Group/Appin Group junction in Strath Avon and the Hills of Cromdale (McIntyre, 1951). A major shear zone, to the west of and structurally below the better-known shear zones that mark the Portsoy Lineament, has also been identified recently; this *Keith Shear Zone* may continue the zone of dislocation to the north coast at Sandend Bay.

Banff and Buchan area

In the North-east Grampians the outcrop pattern is dominated by late, open, broad, upright folds with NNE-trending axes, principally the Turriff Syncline and Buchan Anticline (Read, 1955; Read and Farquhar, 1956). Exposure is generally poor and detailed sections are to be found only on the coast.

Structures on the east coast around Collieston have been described in relation to the Tay Nappe. Here the beds are inverted regionally and a major early fold closure must therefore occur between this section and the coast section at Fraserburgh, which is regionally the right way up. The axis of

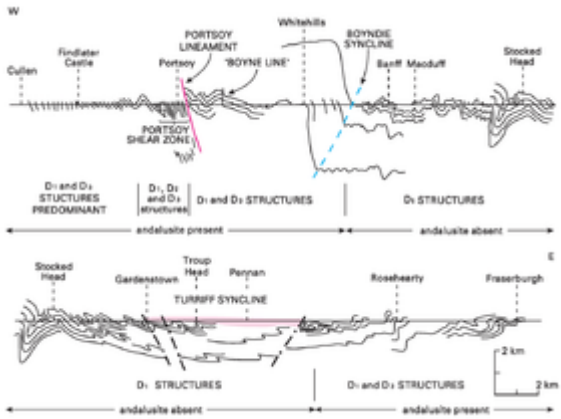
this fold cannot readily be traced; it lies in a complex sheared zone with high-grade metamorphism between Ellon and Inverallochy.

Along the north coast the rocks exhibit locally complex folding with steep dips over much of the section, but regionally they have been shown to be disposed in a broad, gentle syncline (P915429). This *Turriff Syncline* was recognised as a relatively late fold by Read (1955), who considered that the succession, which is right way up on a regional scale, constitutes the upper limb of a major recumbent anticline which he termed the Banff Nappe. The western limb of the Turriff Syncline is steep due to a monoform, regarded as a major fold closure predating the metamorphic peak by Sutton and Watson (1956) who named the structure the *Boyndie Syncline*. Subsequent workers have regarded this as a later (D_3) structure related to the main Turriff Syncline, thereby devaluing its regional importance (Johnson and Stewart, 1960; Johnson, 1962; Fettes, 1970), although Treagus and Roberts (1981) have assigned it as an early (D_1) phase.

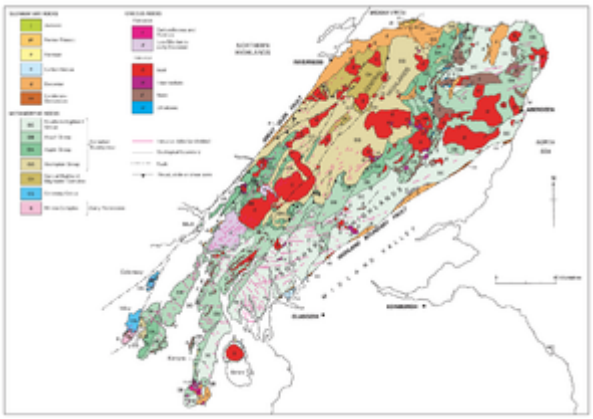
Despite the debate over the significance of the Boyndie Syncline, the overall structural and metamorphic sequences of this section are quite well understood due to several detailed studies of the minor structures (Johnson, 1962; Fettes, 1971; Treagus and Roberts, 1981). Early (D_1) structures face consistently upwards, developing a spaced cleavage in the psammitic rocks and a strong slaty axial planar cleavage in the more pelitic rocks of the Macduff Slate Formation. The attitude and style of the D_1 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 close to tight on the limbs. On both the western and eastern limbs the D_1 folds face to the north-west which is contrary to Read's (1955) model of a SE-facing Banff Nappe.

Post-D_1 structures are restricted to lower structural levels and hence are seen only on the western and eastern limbs of the Turriff Syncline. There is some confusion over the number of major phases which can be identified, and over their relationship to regional D_2 and D_3 as defined elsewhere. Both Johnson (1962) and Treagus and Roberts (1981) have identified separate D_2 and D_3 phases and their conclusions are incorporated in the following summary based upon that of Kneller (1987). D_2 folds and cleavages are recognised only to the west of the Boyne Limestone outcrop and to the east of Fraserburgh Bay. In the area around Portsoy, D_2 folds are locally the dominant folds. Here they are steeply plunging and have a very strong linear fabric attributed to thrusting associated with the Portsoy Lineament which has intensified and rotated the folds. The late, D_3 deformation, which postdates the peak of metamorphism and growth of porphyroblasts, has limits which almost coincide with the andalusite isograd (P915429). Large-scale D_3 folds are characteristically monoclinal. 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 major Turriff Syncline and *Buchan Anticline* have been tentatively attributed to the D_3 phase by most authors, although it is difficult to make exact correlations with the observed detailed D_3 structures and their overall open and upright character is more comparable with major D_4 structures elsewhere. Numerous sets of minor brittle folds in the area are attributed to later events.

To the west of the Turriff Syncline, a number of major zones of shearing and dislocation occur and these have been used to define the western edge of a distinct structural block, the Buchan Block, possibly decoupled from the main Dalradian terrane. On the eastern edge of the Cowhythe Psammite outcrop is a zone of highly deformed rocks with a strong down-dip extension lineation and development of thin mylonite. This zone marks the position of the *Boyne Line* of Read (1955) which was interpreted as a major slide underlying his proposed Banff Nappe. In this model movement on the Boyne Line was held responsible for the removal of any calcareous lithologies equivalent to the Loch Tay and Deeside limestones over much of the north-east Grampians, apart from the Boyne Limestone which is seen only in the north coastal section.



Cross-section along the Banffshire coast showing the main structural features and predominant deformation/fold phases. P915429.


Solid geology of the Grampian Highlands. P915411.

Thrust-related fabrics at the western margin of the Cowhythe Psammite were attributed to a *Portsoy Thrust* by Elles (1931). From here a zone of sub-vertical mylonites, shear zones and faults extends westwards for over 1 km along the coast section around Portsoy. Earlier fold axes and lineations have been rotated so that they plunge down-dip adjacent to and within the zone, and locally a pervasive down-dip stretching lineation is present. Highly sheared basic and ultramafic igneous rocks occupy the centre of the zone and cross-cutting, but lineated, sheet-like granite bodies are present near the margins. This zone of shearing and dislocation, accompanied by igneous intrusions, can be traced inland in a general SSW direction from Portsoy to the Cabrach area (Ashcroft et al., 1984) and southwards to upper Glen Clova as the *Portsoy–Duchray Hill Lineament* (Fettes et al., 1986). Major stratigraphical discontinuities occur at the lineament (Fettes et al., 1991) and marked differences in metamorphic history on each side of the lineament indicate major westward overthrusting during the regional D_3 event (Baker, 1987; Beddoe-Stephens, 1990). Some geochronological and fabric evidence suggests that the Cowhythe Psammite, along with all the other gneissose units of the north-east Grampians, represent a pre-Caledonian basement complex (Sturt et al., 1977). Ramsay and Sturt (1979) suggested that all the rocks above the Portsoy Thrust constitute an allochthonous block, and that this consists of a Dalradian metasedimentary cover separated from underlying gneissose basement by a *décollement* along Read's original Boyne Line. Another interpretation, the one followed by this handbook, regards the gneisses as migmatised equivalents of the upper parts of the Argyll Group (Chapter 5), so that an almost continuous Dalradian succession is recognised in the area. Whilst recognising the importance of the Portsoy–Duchray Hill Lineament as a major tectonic, stratigraphical and metamorphic boundary, the Dalradian of the Buchan Block is here regarded as essentially autochthonous, as argued by Ashcroft et al. (1984).

To the west of the Portsoy–Duchray Hill Lineament, large isoclinal or near-isoclinal early folds are generally upward-facing and are overturned towards the north-west. Secondary folds, which can be shown to postdate the primary metamorphism, are commonly coaxial with the early folds and give rise to a dominant penetrative cleavage which is finely spaced, or to a tight crenulation in the more pelitic lithologies. Late folds, possibly related to uplift and basement block movement, locally exert a strong control on the outcrop pattern. Such folds are typically broad, near-upright and trend north–south or NE–SW such as the *Ardonald Fold* in the Dufftown area. Locally, penetrative spaced cleavages, minor chevron folds and kink bands are developed.

The western margin of this area, as shown in P915427, is marked by a major ENE- to NE-trending shear zone passing through Keith and projecting to the coast at Sandend Bay, although many of the structural features described above extend to the west of this zone into the Central Grampians Complex. This shear zone appears to be a continuation of the line of dislocation and stratigraphical attenuation at or around the Grampian/Appin group boundary to the south-west and is marked by an attenuated succession of Ballachulish Subgroup rocks. Within the shear zone are several foliated granites with a very strong ESE-plunging stretching lineation and asymmetrical fabrics that indicate overthrusting to the WNW.

One of the most striking features of both stratigraphical and structural maps of the Grampian Highlands (e.g. (P915411), (P915427)) is the 20 km-amplitude S-shaped 'knee-bend' in the strata in the area between Braemar and Tomintoul. The reasons for this major feature are obscure, since there are no obvious associated minor folds or regional cleavages. It is clearly a late structure, since all of the folds and dislocations described above, including the Portsoy–Duchray Hill Lineament, are folded around it. Such a large-scale structure must reflect deep crustal weaknesses and it probably results from crustal block movements in the later stages of the Caledonian Orogeny. Such movements may have been along NW–SE fractures which exerted some control on Dalradian sedimentation, although east–west-trending lines of Younger Granite intrusions appear to follow both axial traces of the 'knee-bend' and clearly indicate lines of crustal weakness.

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