British Geological Survey
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Geology of the Huntly and Turriff Districts

Sheet description for the 1:50 000 geological sheets 86W (Huntly) and 86E (Turriff) (Scotland)

Geology and Landscape Scotland

Open Report OR/15/026

BRITISH GEOLOGICAL SURVEY

GEOLOGY AND LANDSCAPE SCOTLAND

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Keywords

Report; Geology, Huntly, Turriff.

National Grid Reference

SW corner 34338, 82923
Centre point 36309, 84315
NE corner 38281, 85705

Maps

Sheet 86W, 1:50 000 scale, Huntly; Sheet 86E, 1:50 000 scale, Turriff

Front cover

Huntly Castle, Aberdeenshire, from the north-east, showing the magnificent 17th century heraldic doorway of Old Red Sandstone (P001147)

Bibliographical reference

Gunn, A G, Mendum, J R and Thomas, C W. 2015. Geology of the Huntly and Turriff Districts. Sheet description for the 1:50 000 geological sheets 86W (Huntly) and 86E (Turriff) (Scotland). British Geological Survey Open Report, OR/15/026.

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Foreword

This report summarises the results of detailed geological remapping and related studies undertaken by the Geological Survey in the Huntly and Turriff districts of North-east Scotland. It provides an account of the geology to accompany the published 1:50 000 geological maps sheets 86W (Huntly) and 86E (Turriff). The districts occupy a tract of generally rolling country, which ranges from about 50 to 200 m above sea level in its eastern part, to more elevated hilly country, commonly reaching over 300 m and 400 m above OD, in its western and southern parts. The drainage is dominated by the sinuous incised valley of the River Deveron and its main tributaries, the rivers Isla and Bogie, except for the southern part of the Turriff district, which is drained by the headwaters of the River Ythan. Agriculture and forestry are the dominant economic activities, with tourism and whisky distilling also significant.

The Huntly and Turriff districts are underlain mainly by Dalradian metasedimentary rocks of Neoproterozoic age that have been strongly deformed and metamorphosed during the Grampian event of the Caledonian Orogeny. The Dalradian rocks have been intruded by igneous intrusions that range from large plutons to small pods and dykes. Granite sheets and pods were emplaced at about 600 million years (Ma), followed later by small ultramafic and mafic bodies. However, the main intrusive igneous event occurred in the Early to Mid Ordovician at 474 to 470 Ma, coeval with the Grampian event. It resulted in the emplacement of mafic and ultramafic plutons, commonly zoned; the Insch Pluton includes monzonites and syenites in its upper zone. Dioritic and granitic bodies are associated with the plutons.

The major structural feature is the north-north-east-trending Portsoy Shear Zone, which traverses the Huntly district. This steeply easterly dipping zone is coincident with a major regional lineament, which separates stratigraphically discrete packages of Dalradian rocks with different tectonometamorphic histories. The shear zone has also facilitated and in part controlled the emplacement of the Huntly and Knock mafic-ultramafic plutons. The Dalradian metasedimentary rocks contain both Buchan and Barrovian metamorphic zonal assemblages. Folding and shearing have caused local repetition of lithological units, but overall the Dalradian sequence becomes younger eastwards until the broad hinge of the regional Turriff Syncline is reached in the central part of that district. Here, the youngest Dalradian rocks are exposed and metamorphic grade is low (biotite grade). Farther east older Dalradian rocks again crop out and the Buchan metamorphic isograds are re-crossed such that the rocks contain andalusite and sillimanite.

Following the Grampian orogenic event the area was uplifted, and during the Early Devonian fluvial and lacustrine Old Red Sandstone rocks were deposited in the northerly trending fault-bounded basins, namely the Turriff and Rhynie basins. In Strath Bogie a basaltic andesite lava unit linked to the Rhynie chert occurs within the Rhynie Basin succession. Subsequently, a Middle Devonian conglomerate-dominated sequence, linked to the Orcadian Lake farther north, was deposited unconformably on the older succession in the Turriff Basin.

In the Turriff district deep Tertiary weathering profiles and local fluvial sands and gravels are preserved, testifying to only limited erosion by the later Quaternary glaciations. The Devensian glacial and postglacial history of the districts was dominated by an ice sheet derived from the highland areas farther to the south-west. The related glacial and postglacial superficial deposits form a pervasive if generally thin cover over much of the bedrock. Till derived from the Moray Firth is present in the north-eastern part of the Turriff district. Eastward migration of glacial meltwater gave rise to channels that in places have significantly influenced development of the Holocene fluvial drainage pattern.

The Huntly district has been the focus of several periods of exploration since 1970 for platinum group elements, copper and nickel linked mainly to the mafic-ultramafic plutons and their metamorphic aureoles. The limited drilling and more extensive ground magnetic surveys, in combination with geochemical studies and gravity modelling, have provided detailed information as to the nature, distribution and origin of prospective areas. No economic deposits have been delineated to date. However, this BGS report and the geological maps provide a sound foundation for existing and any future commercial and/or conservation-related developments.

Acknowledgements

The original geological survey was carried out by mainly by J Horne between 1880 and 1884, with minor contributions from J S Grant Wilson and LW Hinxman. Detailed revision was undertaken by H H Read between 1917 and 1919 and the resultant 1:63,360 scale Sheet 86 (Huntly) and related memoir were published in 1923. The more recent mapping in the districts took place in the late 1980s and early 1990s, as part of the wider East Grampian Project. It has concentrated mainly in the Huntly district, where, the Department of Trade and Industry (DTI) funded detailed mapping and investigations by BGS in areas thought likely to be prospective for minerals, work complemented by the DTI Mineral Reconnaissance Programme. However, the bulk of the mapping and related work in the Huntly andTurriff districts was funded by the Department of Education and Science as part of its remit to provide geological data, maps and reports to underpin the UK infrastructure and economy. The Forestry Commission and other landowners within the Huntly and Turriff districts are thanked for their cooperation and assistance.

The mapping and related geological studies have resulted in significant revision of the geology, culminating in publication of the accompanying 1:50 000 Sheet 86E (Turriff) and 86W (Huntly) maps in 1995 and 2000 respectively. The solid geology was compiled from 1:10 000 maps produced by A G Gunn, J R Mendum, S D Redwood, D Stephenson, C W Thomas and D Gould, and from other map and data sources held in the archives of the British Geological Survey. A G Gunn compiled the data on mineral reconnaissance work on the mafic igneous intrusions. M Styles undertook detailed petrographical work in the mafic-ultramafic igneous rocks, and E R Phillips and B Beddoe-Stephens undertook petrographical work on the Keith Granite and the metamorphic rocks, respectively. T A Fletcher is thanked for making available his data on the Littlemill–Auchincrieve area. The concealed geology was described by K E Rollin and J R Mendum. D Gould contributed to the description of the basic igneous rocks and D Ball described the hydrogeology. The sheet description was initially compiled by C W Thomas and A G Gunn and edited subsequently by D Woodhall. More recently the text has been further revised and significantly updated by J R Mendum.

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Summary

This report describes the geology of the Huntly and Turriff districts that were mapped as part of the East Grampian Project, a major regional study carried out by the British Geological Survey in the 1980s and 1990s. This East Grampian area, totalling some 8500 km^2, had been mapped originally by the Geological Survey between 1885 and 1920, but coverage was very variable, based in part on one-inch-scale field slips. The academic community had largely neglected the area due to its generally poor inland exposure and complex geology. In consequence, the Dalradian stratigraphy and structure, the role of the mafic-ultramafic plutons, and the nature and timing of the Grampian orogenic event, were unclear.

The introductory chapter sets the scene both topographically and geologically. It briefly describes the main geological units represented in the districts and relates them to the geological history, with particular emphasis on the Grampian event of the Caledonian Orogeny. A section on the history of research describes the efforts of the early surveyors, notably H H Read, in delineating the nature and extent of both the bedrock and Quaternary units. Studies in the latter part of the 20th century have focussed on the mafic-ultramafic plutons, the nature of the Buchan metamorphism, and the search for economic minerals, in part linked to geophysical surveys. More recently, tectonic models that attempt to explain the geometry and timing of the Grampian event in north-east Scotland have been promulgated.

Chapter 2 describes the Dalradian stratigraphical succession but firstly explains the terminology used. Not all lithological units have been assigned to formations; some have only been assigned to subgroups or to groups. This partly due to the poor exposure, but also reflects the locally varied stratigraphy and the considerable structural complications. Grampian and Appin Group rocks are restricted to the north-western part of the Huntly district where they lie in the footwall of the Portsoy Shear Zone. Semipelite is the dominant lithology but the sequence contains significant quartzite, pelite (in part graphitic), metalimestone and calcareous units. This shallow marine shelf sequence has a generally coherent stratigraphy, except around Keith where metalimestone and semipelite units cannot be simply correlated. Appin Group rocks are overlain by quartzite of the Islay Subgroup (Argyll Group) and subsidiary pelitic units of the Easdale Subgroup, but in several places the stratigraphical sequence is truncated by the westernmost thrusts of the Portsoy Shear Zone. Within and adjacent to the shear zone are pelitic units attributed to the Argyll Group, which show affinities with Easdale Subgroup units elsewhere. Here they are host to several mafic-ultramafic intrusions. They are succeeded eastwards by migmatitic psammite and semipelite (Crinan Subgroup), in turn overlain by a mixed quartzite, psammite and pelite unit with thin metalimestones. This last unit, the Whitehills Grit Formation, and its semipelite-dominated lateral equivalent, the Clashindarroch Formation, belong to the Southern Highland Group, and appear to truncate the underlying Argyll Group succession progressively to the south-west. The more typical turbiditic Southern Highland Group rocks, mainly arenite (psammite) and pelite, are represented by the Macduff Formation, which underlies the south-east part of the Huntly district and most of the Turriff district.

Chapter 3 describes the Devonian Old Red Sandstone outliers, now preserved in the fault-bounded Turriff and Rhynie basins. These northerly trending basins were infilled by fluvial and lacustrine sediments derived from erosion of the uplifted Caledonian Orogen. The sequence consists of conglomerates, sandstones and minor siltstones.

Chapter 4 describes the nature of the weathering profiles and products that developed under subtropical conditions in the Palaeogene and Neogene, and the isolated exposures of distinctive quartz gravels that occur in Buchan. These deposits are preserved due to the limited erosion beneath the ice sheets that spread across the districts during the Quaternary. Blue-grey clayey till, derived from offshore in the Moray Firth, has been transported east-south-east into the northern part of the Turriff district. Elsewhere fawn, pale grey, or orange-brown till that reflects the underlying bedrock was deposited from a generally cold-based Grampian ice sheet that advanced

slowly from the south-west. Glacial meltwater channels are a distinctive geomorphological feature, particularly in the Turriff district, now commonly occupied by misfit streams.

Chapter 5 describes the igneous rocks, a major feature of the Huntly and Turriff districts. They range from Neoproterozoic foliated granite, found in the Keith area, to the Early to Mid Ordovician age mafic-ultramafic plutons and related intrusions that dominate around Huntly and Knock and form the southern boundary to the districts (Insch Pluton). The later Ordovician granitic intrusions and sparse late Carboniferous quartz dolerite dykes are also described. The oldest mafic-ultramafic rocks, the Succoth-Brown Hill type, are dominated by clinopyroxene and are mineralogically and chemically distinct from the gabbros, norites, peridotites, etc of the Huntly, Knock and Insch plutons. They are now altered, deformed and metamorphosed; their age of emplacement is not known but they predate the main Grampian deformation event. The Ordovician mafic-ultramafic plutons exhibit cumulate compositional layering that ranges from dunite, peridotite, troctolite and olivine-gabbro (Lower Zone) to norite and gabbro (Middle Zone) and olivine ferrogabbro, monzonite and syenite (Upper Zone). The full sequence is best represented in the Insch Pluton. In contrast, in the Huntly and Knock plutons Lower Zone cumulate rocks exhibit steeply dipping layering and occur in separate disconnected bodies. The cumulate rocks show evidence of contamination and minor modification. Middle Zone lithologies are mainly represented by granular gabbros and norites that have been pervasively recrystallised and are commonly foliated. Contaminated and xenolithic gabbros and norites are abundant both within and marginal to the Huntly and Knock plutons. Pressure and temperature estimates of 4.5 kb and up to 900°C have been obtained from the contaminated and hornfelsed rocks showing that localised partial melting occurred. The generally poor exposure, combined with the variable and interleaved nature of the igneous and metasedimentary rock types, and the structural complexity, have necessitated the use of borehole data and geophysical surveys to decipher their geology. Other sheeted mafic bodies occur farther east around Marnoch, and also west of the Portsoy Shear Zone. The relationships of these amphibolitic gabbros and metadolerites to the main plutons are unclear, but their lithologies and field relationships suggest that they were emplaced roughly coeval with the main bodies. Small granitic pods and dykes occur within and adjacent to the mafic-ultramafic plutons, and larger diorite and granite bodies are also present. Isotopic age determinations suggest that they were emplaced only a short time after the main mafic-ultramafic plutons.

Chapter 6 highlights the main anomalies and features shown by the regional gravity and magnetic data. The data is used to erect 2D and 3D models that attempt to reconcile gravity and magnetic profiles with the main features of the geology and thus to extend the geological interpretation to deeper crustal levels. The geophysical modelling suggests that the Insch Pluton extends to about 2.5 km, but the Huntly Pluton is limited to relatively shallow depths (< 1 km). Gravity data is used to model the thickness of the Old Red Sandstone sequence in the Turriff Basin, suggesting that it ranges from 800 m in the north to 1400 m farther south.

Chapter 7 describes the regional and detailed structure of the Huntly and Turriff districts, which is dominated by the Portsoy Shear Zone. This steeply east-south-east-dipping structure shows evidence of a long history and marks the western extent of the Ordovician mafic-ultramafic plutons. Its trace corresponds to a lineament across which the Dalradian sequence shows distinct facies and lithological variations. Subsequently, it appears to have acted as a major thrust zone that transported the upper parts of the Dalradian succession to the west-north-west. There is evidence for later lateral transcurrent movements and faulting. Exposures of shear zone/fault rocks are sparse, but ductile shear zones occur both within the mafic-ultramafic plutons and in places farther west. A further shear zone, the Keith Shear Zone, tracks across the north-west part of the Huntly district. The textures, fabrics and lineations in the granites within this moderately south-east-dipping shear zone show clear evidence of thrust movement to the west-north-west. Shear zones are also present at or adjacent to the northern margin of the Insch Pluton. The structures and fabrics in the Dalradian rocks were formed during two main deformation and related metamorphic events; one predates emplacement of the Ordovician mafic-ultramafic plutons, the other postdates emplacement. The early deformation is linked to few if any large-scale folds, but has resulted in a pervasive cleavage and metre- to kilometre-scale folding. The secondary deformation is linked to large-scale folding that controls the distribution of stratigraphical units but is only seen in the higher grade rocks below the andalusite isograd. Related cleavage development ranges from penetrative, to locally developed, to absent. Within the Portsoy Shear Zone several deformation phases can be identified locally, but their interrelationships and correlation to the regional pattern is unclear. Two boreholes, drilled by Drumnagorrach Farm illustrate the variable pattern of deformation and its relationships to the mafic-ultramafic intrusive rocks. The regional structure of the Turriff district is largely governed by the late-stage open Turriff Syncline, which has a broad hinge zone and folds the metamorphic isograds. Models for the structural evolution of north-east Scotland and the role of the Portsoy Shear Zone during the Grampian event are discussed. The role and pattern of faulting is also described. North-west-trending faults offset elements of the Portsoy Shear Zone and parts of the Huntly and Knock plutons and north-trending faults have controlled the development of the Devonian half-graben basins. East-north-east-trending faults are generally interpreted as late Carboniferous in age.

Chapter 8 describes the pattern of metamorphism that developed in the Dalradian rocks during the Grampian orogenic event. The mineral assemblages range from chlorite and biotite grade (greenschist facies) at shallow exposed levels in the Turriff district up to sillimanite + K feldspar (upper amphibolite facies) at deeper crustal levels adjacent to the Ordovician mafic-ultramafic plutons. In the marginal and contaminated zones of the Huntly and Knock plutons granulite facies conditions were attained and partial melting occurred locally. Here igneous intrusion overlapped with peak metamorphic conditions. The metamorphic mineral assemblages have been divided into two facies series, namely the lower pressure Buchan series, and the medium pressure Barrovian series. Buchan assemblages occur east of the Portsoy Shear Zone and Barrovian assemblages to the west. However, there is evidence of Barrovian overprinting of Buchan assemblages (kyanite after andalusite) in the footwall of the Portsoy Shear Zone, implying a marked pressure increase attributed to west-north-west-directed thrusting across the shear zone. The Insch Pluton show good evidence of a metamorphic aureole on its northern side, manifest as biotite, cordierite and andalusite development in the slate hills. The earliest formed metamorphic assemblages ranged from Buchan to Barrovian from east to west, and developed shortly after the first main deformation. Subsequent thrusting and development of the second major structures were accompanied by a Barrovian overprint, but this is absent from rocks at shallow crustal levels. Many of the assemblages have been partially or even wholly retrogressed.

Chapter 9 describes the Applied Geology of the districts. It summarises the geological resources, namely hard rock (aggregate), building stone, limestone and dolomite, slate, sand and gravel, brick clay, peat and metalliferous minerals. Although there has been extraction of many of these materials in the past, most are not currently exploited. The search for metalliferous minerals has not resulted in any identifiable economic deposits and exploration has now ceased, although concentrations of Ni and Cu were found. The hydrogeology of the Huntly and Turriff districts is also described. Groundwater flow in the bedrock is invariably fracture and fissure controlled. Superficial deposits, particularly sands and gravels, do form more permeable local aquifers. Springs are numerous and have been used for water supply for generations. Since the introduction of the Deveron Water Scheme and provision of a mains supply the use of local groundwater sources has declined markedly.

Chapter 10 lists the multiple sources of information on the geology of the districts held by the British Geological Survey. The sources are listed under numerous subject headings and subheadings to assist with searches. Note that much of the data and map information is now available in digital formats

1 Introduction

The Huntly and Turriff districts lie in the central and western parts of Buchan in north-east Scotland. The economy of the region is based largely on agriculture and forestry, with tourism and whisky production also important. The scenery is typically gently rolling, with the Turriff district forming part of the Buchan plateau, lying between 100 m and 200 m above OD. The districts are drained by the River Deveron and its tributaries, notably the rivers Bogie and Isla, except for their south-eastern part, which is drained by the River Ythan. The drainage pattern in part reflects the routes followed by glacial meltwaters across the districts as they moved generally from west to east. Higher hill ground occurs mainly within the Huntly district, particularly in the west and south, culminating in the Tap o'Noth (563 m), a prominent sentinel overlooking Strathbogie. These higher areas are given over largely to forestry and hill farming.

This account summarises current knowledge of the geology of the districts. Although bedrock exposure is distinctly limited across most of the area, recent BGS mapping has clarified and refined the Dalradian Supergroup stratigraphy in an area that was previously poorly understood. The presence of precious metals, notably nickel, copper, platinum group elements (PGE) and gold, within and associated with the major mafic-ultramafic intrusions, is of potential economic importance. Hence, the recent research into the mafic-ultramafic rocks and results from the prospecting and exploration are highlighted and discussed.

The geology of the Huntly and Turriff districts is dominated by metasedimentary rocks of the mainly Neoproterozoic Dalradian Supergroup and the Ordovician gabbro-peridotite plutons of Huntly, Knock and Insch (Table 1, Figure 1). Note that the western part of the Insch Pluton is here termed the Boganclogh sector. The presence of representative units of much of the Dalradian succession, the mafic-ultramafic intrusions, and the regionally significant Portsoy Shear Zone (PSZ), are all important with regard to the Late Proterozoic to Early Palaeozoic evolution of Scotland leading up to and immediately following the Early to Middle Ordovician Grampian Orogeny. The districts lie partly within the type area for low pressure, high temperature 'Buchan' series metamorphism but the Dalradian rocks to the west of the PSZ were also subjected to moderate pressure, medium to high temperature Barrovian metamorphism.

Lower Devonian sandstones, siltstones, mudstones and andesitic lavas occur in the Bogie Outlier, the northern extension of the larger Rhynie Outlier, which crops out in Strathbogie in the southern part of the Huntly district. The larger but poorly exposed Turriff Outlier, which consists of Lower Devonian conglomerates, sandstones and siltstones, overlain by Middle Devonian conglomerates, underlies an area extending north from Fyvie to Turriff and Cuminestown. Post-Devonian rocks are absent. Superficial deposits include the possible Pliocene age deposits of the Buchan Gravels Formation near Turriff and Fyvie, the abundant Pleistocene glacial and postglacial deposits, and more recently formed peat and alluvium.

Table 1 Geological succession of the Huntly and Turriff districts.

SUPERFICIAL DEPOSITS (DRIFT)					
Quaternary	Flandrian				Peat, alluvium, river terrace deposits
	Late Devensian				Glaciolacustrine deposits, glaciofluvial sand and gravel, diamicton: till, moranic deposits and glacially deformed weathered rock
Palaeogene/ Neogene				Buchan Gravels Formation, undivided: gravel with white clayey matrix	Windy Hills Gravels Member: gravel, sand and micaceous clay

Age	Supergroup	Group	Subgroup	Formation	Member/lithology
BEDROCK					
Sedimentary and volcanic rocks					
Devonian	Orcadian Old Red S'stone Supergroup				
Mid Devonian		Inverness Sandstone Group		Gardenstown Conglomerate Formation	Conglomerate and breccia with subordinate sandstone and minor shale
Early Devonian		Crovie Sandstone Group undivided			Sandstone and shale with minor conglomerate
		Rhynie Group		Dryden Flags Formation	Mudstone and siltstone
				Tillibrachty Sandstone Formation	Sandstone and conglomerate
		Lavas			Andesite, basaltic, commonly vesicular
Metasedimentary and metavolcanic rocks					
Neoproterozoic to early Cambrian	Dalradian Supergroup	Southern Highland Group		Macduff Formation	Psammite, semipelite and minor pelite, with rare calc-silicate laminae
					Hill of Foudland Pelite Member: pelite and semipelite, commonly slaty
				Whitehills Grit Formation	Quartzite, schistose pelite and rare, thin impure metalimestone
				Clashindarroch Formation	Semipelite and pelite, with minor coarse psammite and quartzite
					Garnel Burn Pelite Member: pelite, schistose
		Argyll Group		Unnamed units within or adjacent to Portsoy–Duchray Hill Shear Zone	Semipelite and pelite with minor psammite and metalimestone, and inclusions of mafic igneous rocks
					Pelite and semipelite with minor psammite, metalimestone and quartzite
			Units unassigned to subgroups	Aberdeen Formation	Psammite and semipelite. migmatitic
				Strichen Formation	Pelite and psammite, calc-silicate ribs, largely migmatitic
				Blackwater Formation	Grumack Hill Quartzite Member: quartzite
					Corinacy Pelite Member: Pelite, schistose to phyllitic, with psammite
				Beldorney Pelite Formation, undivided	Pelite, semipelite and psammite
			Crinan Subgroup	Cowhythe Psammite Formation	Psammite and semipelite, migmatitic and gneissose, with some quartzite units
			Easdale Subgroup	Unit unassigned to a formation	Semipelite and metalimestone with calc-silicate rocks
				Castle Point Pelite Formation	Pelite and semipelite with thin calc-silicate and metalimestone lenses
			Islay Subgroup	Durn Hill Quartzite Formation	Quartzite with tillite lenses developed locally near base
		Appin Group	Units within Keith Shear Zone unassigned to Subgroups		Semipelite, schistose
				Keith Limestone Formation (poss part of Blair Atholl Subgroup	Semipelite, schistose to gneissose, with limestone
					Cuthill Limestone Member: metalimestone
			Blair Atholl Subgroup	Unit unassigned to a formation	Semipelite with some metalimestone and quartzite beds
				Fordyce Limestone Formation	Pelite and semipelite, schistose, with thin limestone and calc-silicate rock
					Limehillock Limestone Member: metalimestone with thin semipelite and pelite beds

			Ballachulish Subgroup	Tarnash Phyllite and Limestone Formation	Semipelite with metalimestone and calc-silicate rock; prominent white limestone unit common near base
				Corryhabbie Quartzite Formation	Orthoquartzite
				Mortlach Graphitic Schist Formation	Pelite and semipelite
					Dufftown Limestone Member: metalimestone with thin pelite beds
			Lochaber Subgroup	Pitlurg Calcareous Flag Formation	Calcareous psammite and semipelite with with thin tremolite laminae; rare quartzite beds
					Drummuir Calcareous Member: Semipelite, flaggy, with thin calc-silicate rock and metalimestone beds
				Findlater Flags Formation	Semipelite, schistose, commonly flaggy in upper part; psammite and semipelite with local thin quartzite beds dominant in lower part
		Grampian Group		Cullen Quartzite Formation	Bellyhack Quartzite Member : quartzite, massive

1.1 GEOGRAPHY AND PHYSIOGRAPHY

The principal settlements are the market towns of Huntly and Turriff, although there are numerous outlying villages and hamlets. Although generally the area is one of low to moderate and rolling relief, elevations locally exceed 300 m. The lowest point of the districts lies in the lower part of the Deveron valley at around 15 m above OD. The highest point is Tap o' Noth (564 m) in the south-west part of the Huntly district, which overlooks the Clashindarroch Forest where the Kirkney Water and its tributaries effectively dissect a 'plateau' topography that attains 380 to 430 m above OD. Brown Hill (483 m), Clashmach Hill (375 m), The Balloch (366 m) and Knock Hill (430 m) form prominent rounded hills in the higher western part of the Huntly district. Further east and north, the gently undulating Buchan plateau at 130 to 160 m above OD, is incised by the major river valleys of the Deveron and Ythan and their tributaries. In the southern parts of the districts lie the 'Slate Hills' that stretch westwards from Core Hill (245 m) to the Hill of Rothaise (261 m), the Hill of Tillymorgan (381m), the Hill of Foudland (467 m) and Knockandy Hill (434 m).

The River Deveron and its principal tributaries, the Bogie and the Isla, form the main river system, draining the northern and western part of the districts. The Deveron follows a meandering, typically deeply incised course between Milltown of Rothiemay [NJ 548 481] and Turriff, from where it turns sharply north to reach the sea at Banff Bay. The River Ythan drains the central and south-east part of the Turriff district. It follows a similarly meandering course eastwards passing through the narrow Fyvie Gorge. Many of the broad tributary valleys contain only small burns, e.g. the Idoch Water between Turriff and Cuminestown, reflecting their origins as glacial meltwater channels.

1.2 GEOLOGICAL HISTORY

1.2.1 Dalradian

Dalradian metasedimentary rocks ranging from the Grampian Group through to the Southern Highland Group are represented within the district. The stratigraphical successions of the uppermost Grampian Group, Appin and Argyll Groups record deposition of sandstones and siltstones, mudstones and limestones under mainly shallow water marine conditions on slowly rifting and subsiding continental crust, probably between about 750 and 510 million years ago (Ma) (Neoproterozoic to Cambrian). Diamictites, interpreted as glaciogenic ('tillites') in origin, occur at the base of the Durn Hill Quartzite Formation and mark the start of the Argyll Group sequence.

Ahough undated, they are considered to have been formed during the global Marinoan glaciation which took place about 630 Ma. They are correlated with similar glaciogenic deposits elsewhere in the Scottish Highlands, and in Greenland, Norway and Spitsbergen. Shallow marine shelf sediments pass up into deeper water sandstones, siltstones and mudstones in the middle part of the Argyll Group and this facies is dominant in the overlying Southern Highland Group. These younger arenites, semipelites and pelites were largely deposited from turbidity currents in continental edge fan systems which developed as the crust thinned and fractured as a result of the lithospheric extension of the Rodinian supercontinent. The continental crust eventually ruptured between about 600 and 550 Ma ago, to produce the continents of Laurentia and Gondwana with the consequent formation of the Iapetus Ocean.

Subsequent tectonic activity focussed at the continental margins, notably in Ordivician times, prior to closure of the Iapetus Ocean in the early Silurian. This activity, which included collision between the Laurentian continental margin and microcontinents, island arcs, spreading ridges, etc resulted in the Grampian Orogeny in Scotland and Ireland between about 500 and 450 Ma. During this event, Dalradian sediments were pervasively deformed and metamorphosed, and intruded by igneous bodies that ranged from ultrabasic to granitoid in composition.

1.2.2 Pretectonic granites

Pretectonic granite bodies occur in the north-western part of the Huntly district, linked to the Keith–Portsoy Shear Zone. They form lenticular bodies and sheets and are mostly foliated, coarse-grained biotite-muscovite granites with potash feldspar augen. The main intrusions stretch from Keith north-eastwards to Lurg Hill {504 575) with outlying bodies farther north-east by Boggierow [575 652] in the Portsoy district (Sheet 96W) and farther south-west on Hill of Mulderie [383 517] and on the Hill of Bellyhack [389 424] in the Glenfiddich district (Sheet 85E). The emplacement of these granites has been dated at 600 Ma (Barriero, 1998).

1.2.3 Caledonian igneous intrusions

Synorogenic intrusions

The mafic and ultramafic intrusions (Table 2) of the North-east Grampians Basic Subsuite (part of the Scottish Highlands Ordovician Suite) underlie extensive areas of the Huntly district and are a key feature of the geology of the Huntly and Turriff districts. Read (1919) divided these mafic-ultramafic intrusions into an 'Older' group that he interpreted as predating the regional metamorphism, and a 'Younger' group, emplaced approximately synchronous with the climax of regional metamorphism at about 475 to 470 Ma (Carty, 2001; Dempster et al., 2002; Condon and Martin, cited in Oliver et al., 2008 as a personal communication). Both groups are currently regarded as of Ordovician age but the 'Older' group intrusions are undated and some at least may be of Cambrian or Neoproterozoic age. In the Huntly district small intrusive basic and ultrabasic bodies of the 'Older' group are widespread along the PSZ. They have undergone multiple phases of recrystallisation, deformation and alteration during metamorphism and shearing.

Intrusions of the 'Younger' suite crop out more extensively. The Huntly and Knock gabbro-perdotite plutons underlie a total area of approximately 65 km^2. Only the northern part of the larger Insch Gabbro-peridotite Pluton crops out along the southern edge of the districts but this underlies some 75 km^2. A small part of the Boganclogh sector of the Insch Pluton outcrops in the south-west corner of the map, but covers an area of less than 5 km^2. These intrusions range in composition from peridotite through gabbro and norite to quartz syenite. In contrast to the 'Older' Basics, they preserve various magmatic features with deformation generally restricted to discrete shear zones or marginal areas.

The distinction between the 'Older' and 'Younger' Basic intrusions can be unclear in the proximity of the regional shear zones. Detailed studies of some of the larger 'Older' intrusions, such as the Succoth–Brown Hill Ultramafic Intrusion, have shown that they differ petrologically and geochemically from the 'Younger' Huntly and Knock plutons and show evidence of a more complex geological history (Gunn et al., 1996).

Late-orogenic intrusions

Late- to post-orogenic granitic intrusions include those at Aberchirder, Avochie, Carvichen and Kennethmont, the latter being the largest of these (Stephenson and Gould, 1995). Most are biotite granites, although Kennethmont also includes a quartz-diorite and granodiorite phase.

1.2.4 Old Red Sandstone Supergroup

Erosion accompanied and followed uplift of the Grampian terrane in Late Ordovician and early Silurian times. Subsequently, sedimentary rocks belonging to the late Silurian to Middle Devonian Old Red Sandstone Supergroup were deposited in fault-bounded, continental basins under tropical semi-desert conditions.

Within the Huntly and Turriff districts, these rocks are represented by two separate successions. Conglomerates, breccias, sandstones and siltstones belonging to the Crovie and Inverness Sandstone Groups crop out in the Turriff Outlier which extends north from Fyvie to the Banffshire coast. Conglomerates, sandstones and mudstones, belonging to the Rhynie Group, crop out in Strathbogie, these rocks forming the northward continuation of the Rhynie Outlier, well known for its Early Devonian plant and fish remains and preserved hot spring system. The late Silurian to Early Devonian was a period of considerable volcanic activity in Scotland. Within the Huntly district volcanic rocks are represented by andesitic lavas interbedded with the sedimentary rocks in the northern part of Strathbogie.

1.2.5 Cenozoic superficial deposits

Although sedimentary rocks of Late Palaeozoic and Mesozoic age may have been deposited within the Huntly and Turriff districts after the Devonian, none are preserved, reflecting the fact that the area has undergone net erosion for nearly 400 Ma. The only preglacial, post-Devonian sediments present within the district are unconsolidated, white to cream clayey and pebbly quartz gravels of the probable Pliocene age known as the Buchan Gravels Formation. This formation crops out in a few small outliers north-east and south-south-east of Turriff and in a rather larger outlier east of Fyvie at Windy Hills. The deposits are probably remnants of more widespread fluvial deposits of Palaeogene age which have subsequently been removed by erosion during the Palaeogene/Neogene uplift which affected Scotland. The Palaeogene/Neogene was also a time of intense weathering during a warm climatic period.

Towards the end of the Neogene at about 2 Ma, the climate deteriorated leading to episodic glaciation of Britain during the Pleistocene. Pleistocene superficial deposits within the Huntly and Turriff districts result mostly from the last major Late Devensian glaciation, which comprised the Dimlington Stadial that occurred between approximately 26 000 and 13 000 years ago, and the subsequent Windermere Interstadial between 13 000 and 11 500 years ago.

The superficial deposits are dominated by widespread but commonly thin and even patchy tills and locally developed spreads of glaciofluvial sand and gravel. Glacial meltwater channels were developed extensively and have strongly modified the former river pattern. There is only sparse evidence of features and deposits that resulted from the pre-Late Devensian ice sheets. Early in the Dimlington Stadial, the Moray Firth ice sheet transported dark grey, clay-rich till containing rafts of Jurassic mudstones and Quaternary marine sediments onshore to the south and south-east as far as Turriff. This ice stream also diverted the inland ice sourced in the Grampian Highlands eastwards and southwards, as shown by recorded striations and distribution of both local and far-travelled erratics. A later phase of north to north-eastward movement by this East Grampians ice sheet is indicated by north-trending striae and the distribution of troctolite and gabbro erratics from the Huntly intrusion (Read, 1923; Merritt et al., 2003). Till resulting from the East Grampians ice sheet occurs mainly to the north in the Portsoy and Banff districts (Sheets 96W and 96E

Table 2 Timing and relationships of the major deformation and metamorphic events, and the emplacement of igneous intrusions**.**

Age (Ma)	Deformation and metamorphic events	Igneous intrusions
295	East and east-north-east-trending faulting	Quartz-dolerite dykes
400		
	North-west-trending faulting	
450		
	Dextral strike-slip movement on Portsoy Shear Zone	
	D3 deformation	
		Kennethmont Granite
	Localised shearing	Aberchirder, Avochie, Carvichen and other small foliated granites
470	Extensional shearing focussed on the PSZ	Huntly, Knock and Insch plutons and related smaller intrusions
	Metamorphism (M2)	Metadolerite sheets
	D2 deformation: folding, thrusting and shearing	
	D1 deformation and Metamorphism (M1)	
500		Succoth–Brown Hill and related intrusions
600	Faulting, minor shear zones, coincident with rifting of Rodinian Continent prior to break-up and formation of Iapetus Ocean	Keith–Portsoy Granite

respectively). The presence of ice in the Moray Firth during deglaciation resulted in the formation of marginal lakes and as a result the bulk of meltwater was diverted eastwards via a series of glacial meltwater channels. Classic examples include the Fyvie Gorge, occupied now by the River Ythan, and the valley of the Idoch Water. The courses of the Deveron and Ythan rivers and their tributaries were also considerably modified by the glacial meltwaters.

Recent superficial deposits comprise river alluvium in the valleys of the rivers and larger streams, and patches of peat locally developed to the north and west of the River Deveron and to the east of Fyvie and Cuminestown.

1.2.6 Structure and metamorphism

The regional scale tectonic pattern in the north-east Grampian Highlands is dominated by a suite of major shear zones. The largest structure is the steep north-north-east-trending Portsoy Lineament which runs southwards from Portsoy and traverses the Huntly district in its western part (Figure 1). This structure initially acted as a major control on Dalradian sedimentation patterns, but during the Grampian Orogeny it acted as a regional shear zone. This Portsoy Shear Zone (PSZ) also limits the distribution of 'Older' and 'Younger' mafic and ultramafic intrusions (Ashcroft et al., 1984; Fettes et al., 1986, 1991). The shear zone was the locus of considerable deformation during and after emplacement of the 'Younger' basic intrusions, such as the Huntly and Knock plutons (Table 2). The lineament forms the western boundary of the Buchan block, a tectonic unit with distinctive geophysical and structural features compared to the other parts of the Grampian Highlands. Shear zones are also developed along the margins of, and more rarely transect, many of the 'Younger Basic' plutons – notably Huntly, Insch, and farther south-east Belhelvie.

East of the PSZ early upright to west verging folding and a single cleavage are present in the Southern Highland Group arenites and slates. Secondary folding occurs in areas of higher metamorphic grade, for example in the Fyvie Gorge, and in the 'Slate Hills', north of the Insch intrusion, where it postdates the main metamorphism.

Metamorphic grades range from greenschist facies in the structurally and stratigraphically higher part of the succession in the Turriff Syncline, to middle and upper amphibolite (sillimanite-potash feldspar) grade adjacent to the Portsoy Lineament and 'Younger Basic' intrusions. Mineral assemblages in pelitic rocks include cordierite and andalusite, minerals characteristic of low pressure, high temperature 'Buchan' type regional metamorphism. This phase of metamorphism was augmented by emplacement of the mafic-ultramafic intrusions at about 470 Ma.

To the west of the PSZ the Dalradian rocks show evidence of two phases of deformation and amphibolite facies metamorphism, resulting overall in north-west verging asymmetrical folds and accompanying shear zones. The earlier deformation phase was characterised by low to medium pressure amphibolite facies metamorphism and the later phase by a marked pressure increase, manifest locally by kyanite pseudomorphs after andalusite in the pelitic lithologies. The trace of the anastomosing north-north-east-trending Keith–Portsoy Shear Zone cuts across the north-west corner of the Huntly district (Figure 1). This zone was a locus for intrusion of granite sheets at about 600 Ma and was subsequently reactivated during the Grampian Orogeny as a site of significant north-west-directed shearing movements. The PSZ itself is a complex sheared and faulted zone that ranges in width from a few hundred metres to about 1.5 km on the coast at Portsoy. Its present steep nature reflects its later history where it appears to have acted as a zone of differential uplift.

1.3 HISTORY OF GEOLOGICAL RESEARCH

The sheet was originally surveyed for the Geological Survey by J Horne, J S Grant Wilson and L W Hinxman between 1880 and 1894. H H Read subsequently revised the mapping in considerable detail between 1917 and 1919 and the resultant 1:63 360 scale survey map of the Huntly district (Sheet 86) was published in 1923, along with the memoir for Sheets 86 and 96 (Read, 1923). Read published extensively on the geology of north-east Scotland and maintained an interest in the area throughout his working life. Revision and remapping have been carried out by the survey in the 1980s and 1990s as part of the East Grampian Project, whose aims were to produce a coherent bedrock geological map of north-east Scotland at a 1:50 000 scale. This work has made use of academic and economic studies and used geophysical and geochemical techniques where applicable.

The Huntly, Knock and Insch plutons have been the subject of many detailed studies despite their poor surface exposure. Read acknowledged the early work of Watt (1914) who described the petrography of the main constituent lithologies and contaminated marginal rocks of the Huntly Pluton. Shackleton (1948) postulated that Huntly Pluton was overturned based on the steeply dipping rhythmic cumulate banding of the mafic-ultramafic rocks in the Bin Quarry. He subsequently suggested (in discussion of Read and Farquhar, 1956) that the pluton was part of a single folded and boudinaged mafic-ultramafic sheet that underlay much of north-east Scotland. Stewart and Johnson (1960) and Stewart (1970) reviewed the evidence for a single sheet-like intrusion and concluded that whilst feasible, folding and deformation had occurred closely following emplacement while the sheet was still ductile. Weedon (1970) used the major and limited trace element chemistry and plagioclase feldspar compositions from the cumulate succession in the south-western part of the Huntly Pluton to conclude that there were significant breaks in the igneous sequence. This was confirmed by a drilling and trenching programme carried out by Munro (1970), which concentrated initially on defining the boundaries and general distribution of lithologies in the Huntly and Knock plutons and in the Portsoy Gabbro-serpentinite Intrusion-swarm. Subsequently Munro (1984) and Munro and Gallagher (1984) documented the distribution of cumulates and other elements of these intrusions in detail based on a comprehensive outcrop sampling, drilling and trenching programme carried out over many years. They concluded that the intrusions represented a much disrupted and variably deformed complex of partially layered mafic and ultramafic intrusions, but the evidence did not support their emplacement as a single body.

In the Insch Pluton, Sadashivaiah (1954) studied the dunite-troctolite cumulates from the eastern part of the intrusion. Read et al. (1961) described the differentiated sequence from the north-western part of the pluton that ranges from gabbro to syenite. Clarke and Wadsworth (1970) divided the Insch Pluton into Lower, Middle and Upper zones based largely on petrographical data backed up by some chemical analyses. Wadsworth (1986, 1988) later described the mineralogy of the Upper Zone and Middle Zone rocks in more detail. More recently, detailed major, trace element and isotopic studies by Hay (2002) have clarified the nature and origin of the basic magmas that gave rise to the Huntly, Insch and Belhelvie plutons.

The relationships between the intrusions of the North-east Grampians Basic Subsuite and the adjacent Dalradian metasedimentary rocks have also been the subject of considerable work. Fettes (1968, 1970) showed that in Southern Highland Group arenites and pelites lying north of the Insch Pluton the hornfels mineralogy and texture overprinted an early penetrative fabric, but were in turn overprinted by a secondary deformation and metamorphism. Droop and Charnley (1985) estimated pressure (P) and temperature (T) conditions from metamorphic assemblages in pelitic rocks in the inner hornfels of the Morven–Cabrach, Huntly, Knock and Belhelvie plutons. Using several geobarometers they obtained pressures of 4 to 5 kb and temperatures of 700°C to 850°C, implying that the plutons were all intruded at about the same crustal level (15 to 18.5 km). Later work by Droop et al. (2003) used more modern thermodynamic datasets to assess P-T conditions of the partially melted migmatitic rocks associated with the Huntly Pluton and the surrounding pelitic rocks. Their results corroborated the earlier work giving P values of 5 kb but higher T values for the migmatites of about 900°C.

The conditions prevailing during regional metamorphism in the wider Buchan region have been the subject of a number of studies since the 1960s. Hudson (1980, 1985) used a range of geobarometers and geothermometers to demonstrate an increase in pressure and temperature westwards from the central part of the Turriff Syncline to Portsoy. Subsequent work has further constrained general pressure conditions throughout the region (Baker, 1985; Beddoe-Stephens, 1990). Chinner (1966) interpreted sillimanite to result from a thermal overprint on the regional metamorphic pattern that related to depth of burial. Subsequently, Fettes (1970), Pankhurst (1970), and Ashworth (1975) suggested that the high temperature metamorphic effects, manifest as sillimanite, resulted from the high heat flow associated with intrusion of the mafic-ultramafic plutons. They postulated that their emplacement was approximately coeval with the peak of regional metamorphism. Harte and Hudson (1980, 1985) delineated two stages of sillimanite growth, one related to the regional metamorphism and the other associated with the basic masses. However, they believed that development of the ‘regional’ and ‘contact’ sillimanite occurred at approximately the same time.

The pseudomorphing of andalusite by kyanite west of the PSZ was first noted by Elles (1931) and subsequently studied by Chinner (1980), Chinner and Heseltine (1979) and Beddoe-Stephens (1990). Beddoe-Stephens used several geothermometers to elucidate the pressure and temperature conditions under which the inversion from andalusite to kyanite occurred. He showed that there was an increase in pressure of about 2 kb across the PSZ and interpreted this in terms of westerly directed thrusting across this structure as postulated by Baker (1987). In contrast, Dempster et al. (1995) suggested that the superimcumbent load imposed by the emplacement of the mafic-ultramafic intrusions may have been responsible for this pressure increase.

The role of the Portsoy Lineament and Shear Zone was not recognised during the original surveys. Read (1923) placed the main dislocation, the Boyne Line, farther east and interpolated its extension southwards into the Huntly district where it was position was defined by sparse exposures of gneissose and schistose lithologies. Elles (1931) first recognised a major dislocation in the Dalradian succession farther west at the junction of the Portsoy Limestone Formation and Cowhythe Psammite Formation in Links Bay by Portsoy. She termed this structure the Portsoy Thrust. Subsequent work has shown that there is a major shear zone, the Portsoy Shear Zone (PSZ), some 1.5 km wide, exposed on the Banffshire coast at Portsoy. Its role in the geological history of north-east Scotland has been variously interpreted but most authors agree that it is a regionally significant structure with a long history of movement (Fettes et al., 1986, 1991; Goodman, 1994; Stephenson and Gould, 1995; Carty, 2001; Viete et al., 2010). Ashcroft et al. (1984) showed that the PSZ was part of a network of steeply inclined shear zones that bounded and transected the Buchan area of north-east Scotland, approximately coeval with emplacement of the North-east Grampian Basic Subsuite. Although the PSZ now dips steeply eastwards authors differ as to whether formerly it dipped more gently and was the site of regional westward thrusting (Baker, 1987; Beddoe-Stephens, 1990; Viete et al., 2010).

There have been widely differing interpretations of the nature of the protoliths and geological history of the Cowhythe Psammite Formation (‘Cowhythe Gneiss’). Read (1923, 1955) interpreted this unit as part of his Keith Division – older gneissose metasedimentary rocks with a more complex structural and metamorphic history that formed the autochthonous basement to the Banff Nappe. Ramsay and Sturt (1979) emphasised this structural and metamorphic complexity, and in combination with Rb-Sr isotopic data from the Inzie Head and Ellon gneisses that gave Neoproterozoic ages (Sturt et al., 1977), they suggested that this unit represented allochthonous pre-Caledonian basement, thrust westwards along the Portsoy Thrust. Oliver (in Viete et al., 2010) obtained a U-Pb SHRIMP age of 1012 ± 10 Ma from zircon overgrowths in a migmatitic leucosome from the western part of the Cowhythe Psammite Formation, suggesting that Grenvillean basement is present. Viete et al. (2014) obtained more detailed U-Pb SHRIMP ages from 55 small euhedral zircons, typically with prominent oscillatory zoning, sampled from both the leucosome and mesosome of the migmatitic pelite. The zircons gave concordant ages between 1025 and 975 Ma, with a mean $^{206}Pb/^{238}U$ age of 1003± 6 Ma age, interpreted as dating the migmatisation. Inherited ages ranged from 3000 Ma to 1000 Ma.

A more conventional model views the unit as an integral part of the Dalradian succession (Crinan Subgroup) that has undergone Caledonian deformation and high grade metamorphism largely as a result of its structural position in the immediate hangingwall of the PSZ (e.g. Stephenson and Gould, 1995).

The British Geological Survey published the regional Bouguer gravity and aeromagnetic survey maps in 1978 (Institute of Geological Sciences, 1978 a, b respectively). The results of a regional stream-sediment survey are summarised in the East Grampians geochemical atlas (British Geological Survey, 1991). The patterns of major and trace element abundances derived from the stream-sediment samples in the Huntly and Turriff districts generally reflect the underlying rock units, despite the extensive cover of superficial glacial deposits (mainly till). Hence Ca, Mg, Fe, V, Cr, Ni and Co concentrations are enhanced over the mafic-ultramafic plutons, and K and Ga depleted. In contrast, the Southern Highland Group rocks show enhanced B, Li, Ti and Ga concentrations but low Zr and Ca values. Granitic rocks show enhanced concentrations of K, Rb, Be and Li. The correspondence of stream-sediment and hence till geochemistry with the underlying bedrock suggests that the subglacial till was formed largely in situ.

Both geophysical and geochemical data have been employed to facilitate the delineation of geological boundaries and the nature and extent of units in the poorly exposed Huntly and Turriff districts. Bouguer gravity modelling was used to provide some estimates of the thickness of both the Devonian sequence in the Turriff Outlier (Ashcroft and Wilson, 1976). Leslie (1984) used ground magnetic surveys and pitting to model the north-eastern contact of the Insch Pluton and its aureole. Similarly Fettes et al. (1991) combined geological and geophysical methods (mainly detailed ground magnetic surveys) to delineate the nature of the PSZ and the Dalradian stratigraphy to the south-west of Huntly. Gunn et al. (1996) combined detailed ground magnetic surveys, and limited new gravity data with borehole information to elucidate the nature of the Succoth–Brown Hill Ultramafic intrusion. This last work linked to an assessment of the amount and nature of platinum group elements associated with the ultramafic and mafic intrusions. The potential for economic quantities of platinum group and other elements has attracted several mineral companies to north-east Scotland, commencing in the 1970s. The companies undertook extensive geophysical surveys, notably of magnetic susceptibility, and drilled considerable numbers of boreholes in the Huntly and Knock Plutons and adjacent migmatitic rocks. Fletcher used material from prospective boreholes to study the mineralogy of the Huntly and Knock plutons and associated mineralisation (Fletcher, 1989; Fletcher and Rice, 1989). However, to date, no economic deposits have been found.

The Quaternary deposits and features of north-east Scotland have been studied for over 150 years, commencing with the pioneering work of Thomas Jamieson who reconstructed the glacial history of the region based mainly on the stratigraphical record (e.g. Jamieson, 1858, 1906). Jamieson's mantle was taken over by Alexander Bremner who published numerous papers in the early 1900s focussed particularly on the glacial meltwater channels formed during ice retreat (e.g. Bremner, 1934, 1942). The significant early work by Jamieson and Bremner, their models of Late Devensian glaciation, and the work of later workers on the Quaternary geology of north-east Scotland were summarised in Merritt et al. (2003), who provided a comprehensive account of the Cenozoic geology and landscape evolution of north-east Scotland.

2 Dalradian Supergroup

The Dalradian metasedimentary rocks within the Huntly and Turriff districts are dominated by those assigned to the youngest constituent group, the Southern Highland Group. These rocks occupy most of the ground east of the Huntly and Knock mafic-ultramafic plutons and north of the Insch Pluton (Figure 1). The oldest Dalradian rocks belong to the Grampian Group and crop out only in a small area in the west of the Huntly district. Successively younger rocks, assigned to the Appin and Argyll Groups, crop out in the Huntly district, where they are cut by the major shear zones and the mafic-ultramafic intrusions.

The terminology used to describe the Dalradian stratigraphy and lithologies in the literature is somewhat confusing. Some formation names refer to their undeformed protolith rock type, e.g. Fordyce Limestone Formation, but others highlight their metamorphic character, e.g. Mortlach Graphitic Schist Formation, and yet other their parting characteristics, e.g. Findlater Flag Formation. Unfortunately, a single rational scheme based on simple criteria cannot be easily applied to the Dalradian succession and the varied names reflect the field appearance and characteristics of the individual formations. Given that there is no satisfactory alternative scheme, and to maintain continuity with the previous literature, such idiosyncratic lithostratigraphical names are used here, with minor rationalisations.

However, the recently approved BGS lithological schemes for igneous, metamorphic and sedimentary rocks are generally followed throughout this sheet explanation. The lithologies in the Huntly and Turriff districts vary from low grade deformed arenites (sandstones) and argillites (mudstones and siltstones) in the turbiditic Southern Highland Group to their recrystallised and gneissose metamorphic equivalents that retain no trace of their former bedding, typically seen in some Argyll Group rock units. Hence, with increasing metamorphic grade, arenites become psammites, and argillites become pelites or semipelites, dependent on their mica content. The arenites range from quartz arenites (>95% quartz) to the sub-feldspathic (5–25% feldspar) and feldspathic (25–100% feldspar) varieties. Sub-lithic and lithic arenites (>50% rock fragments) are rare. Note that quartz arenites are generally termed quartzites and even in their recrystallised metamorphic state they retain this name. If the matrix percentage rises to over 15 per cent in siliciclastic arenaceous rocks, they are termed wackes and some of the Dalradian turbiditic succession undoubtedly contains feldspathic and possibly locally quartz wackes. As no modes are available for many of the arenites/wackes, in this account they are generally termed arenites or psammites. The pelitic and semipelitic rocks are more susceptible to deformational and metamorphic processes even in the lowest grade rocks. Here they are invariably slaty at low metamorphic grade (greenschist facies) and as the grade rises they are phyllitic and schistose. Hence, in this account they are referred to as pelites and semipelites throughout. The carbonate rocks should be termed metacarbonates, metalimestones, etc but the term limestone is still used here, both in the lithostratigraphical formation names and in places, also in the text.

2.1 GRAMPIAN GROUP

Cullen Quartzite Formation

The Grampian Group is represented by a small outcrop on the Hill of Shenwall on the border of sheets 85E (Glenfiddich) and 86W (Huntly) at around [NJ 440444]. There are no exposures and the outcrop is defined by the presence of boulders and white-weathering debris of massive pinkish quartzite. This outcrop, together with a more extensive outcrop on the Hill of Bellyhack on sheet 85E, occurs in the core of the Ardonald Anticline. The rocks are assigned to the Cullen Quartzite Formation on the basis of their stratigraphical position below the Findlater Flag Formation and are termed the *Bellyhack Quartzite Member*.

2.2 APPIN GROUP

2.2.1 Lochaber Subgroup

The Lochaber Subgroup is represented in this district by two formations, both of which comprise dominantly flaggy psammites and semipelites. The noncalcareous Findlater Flag Formation is overlain by the Pitlurg Calcareous Flag Formation, which includes beds of calc-silicate rock and locally impure metalimestones. The junction of the formations is relatively sharp; in the field it is identified by incoming of a pale greenish grey colour, characteristic of most lithologies in the Pitlurg Formation. In thin section, the colour is seen to be due to the presence of abundant fine-grained tremolitic amphibole.

Findlater Flag Formation

There are two outcrops of this formation in the district. The larger one, around the Burn of Aultmore, encompasses almost all of the rocks below and to the north-west of the Keith Shear Zone and is continuous with the type locality around Findlater Castle on the Banffshire coast some 12 km to the north-east. The smaller outcrop lies farther south in the core of the Ardonald Anticline. Lithologies are similar in both outcrops and consist predominantly brown-weathering, grey, thinly banded micaceous psammites and semipelites. Most exposures are distinctly flaggy, but the semipelites are typically schistose, commonly with a marked crenulation cleavage (S3). The semipelites are garnetiferous in places, particularly in the higher parts of the formation.

In the Burn of Aultmore and its tributaries there are several beds of grey to off-white, flaggy, micaceous quartzite and some more massive white quartzites in which cross-bedding is commonly visible. All of the quartzites have thin fissile micaceous partings. The highest exposed part of the formation, immediately beneath the Keith Shear Zone, is more predominantly semipelitic with abundant schistose micaceous beds.

Pitlurg Calcareous Flag Formation/Cairnfield Calcareous Flag Formation

The main outcrop of the Pitlurg Formation is around the eastern closure of the Ardonald Anticline, which includes the type locality of the Den of Pitlurg [NJ 425 452 (in sheet 85E) to NJ 452 453]. Here, there are excellent exposures on the steep sides of a deep, boggy glacial meltwater channel that has been excavated along an E–W strike fault. The formation consists typically of flaggy calcareous psammites and semipelites that show a strong colour banding on a scale of 1 to 2 cm in shades of grey and pale green. Micaceous partings occur throughout, normally muscovite rich but commonly also with biotite. Near the base are persistent beds of schistose garnet-biotite semipelite similar to those in the underlying Findlater Flags. The formation becomes more calcareous towards the top and in places there are quite thick sequences of pale green and spotted calc-silicate rocks and thin beds of impure cream and pale grey metalimestone.

In the area to the south of Keith (mainly in Sheet 85E), the upper part of the Pitlurg Formation is dominantly semipelitic, but with numerous beds of calc-silicate rock and impure metalimestones. Most of the metalimestones are thinly banded, some with pelitic interbeds, but others are pale grey to white, coarsely crystalline and massive. This sequence is termed the *Drummuir Calcareous Member*. Along strike to the north-east, along the Burn of Drum in the present district, there are grey, flaggy semipelites with phyllitic partings and thin beds of psammite. These have been assigned to the Drummuir Member but here the semipelites are less calcareous and lack metalimestones, making the correlation somewhat uncertain.

Beneath and to the north-west of the Keith Shear Zone, flaggy calcareous rocks above the Findlater Flags are considered to be laterally equivalent to the Pitlurg Formation but, because they have a distinctly different field appearance, they are termed the *Cairnfield Calcareous Flag Formation*. Both the Pitlurg and the Cairnfield Flag formations contain flaggy, colour-banded, amphibole-bearing rocks, but they differ in the mode of occurrence of the amphibole. Whereas the Pitlurg Flags generally contain disseminated fine-grained amphibole, visible only in thin section, the Cairnfield Flags include beds of coarse-grained amphibole-rich rock, with the amphbole clearly visible in hand specimen and forming crystals up to several centimetres long in places. The Cairnfield Calcareous flags project into the Huntly district in only two small outcrops around [NJ 445 522] and [NJ 489 580], neither of which is exposed.

Apart from the discrete beds of metalimestone, few of the lithologies in the Pitlurg and Cairnfield Calcareous Flag formations contain any appreciable carbonate minerals. Typical thin sections show fine-grained equigranular quartz and colourless prismatic amphibole, varying in proportions from band to band, together with lesser amounts of phlogopite. The amphiboles range from tremolite to tremolitic hornblende to magnesio-hornblende and show hardly any enrichment in either sodium or iron (Stephenson, 1993). Overall the mineralogy suggests a protolith high in calcium, magnesium and aluminium, with variable amounts of silica, such as would be found in dolomitic marl. Sedimentary bedforms throughout this part of the Dalradian sequence suggest deposition in shallow water, possibly on a marine continental margin (Anderton, 1988). The magnesium-rich carbonates are most likely to have been precipitated from seawater in restricted lagoons, subject to evaporation in a tropical environment. Stephenson (1993) has argued that the observed colour banding may effectively be primary, reflecting seasonal variations in the amount of silica and aluminium brought into the lagoons as clastic material from a nearby mature landscape with lateritic soils.

2.2.2 Ballachulish Subgroup

Mortlach Graphitic Schist Formation

The base of the Ballachulish Subgroup throughout the north-east Grampian Highlands is marked by a relatively abrupt change to a more pelitic and graphitic background lithology, the Mortlach Graphitic Schist Formation, within which are calc-silicate beds, similar to those of the underlying formation, and beds of metacarbonate rock. At, or close to the base of this formation throughout much of the area is a persistent bed of massive metalimestone, termed the Dufftown Limestone Member, which has been quarried extensively in several localities. In the Huntly district, the Mortlach Graphitic Schist Formation crops out only sparsely near its western margin around the eastern closure of the Ardonald Anticline, in an inferred anticlinal core in the Glen of Coachford, and in small outcrops around Dunnyduff.

The Dufftown Limestone Member is well exposed in the disused Blackhillock Quarry [NJ 440 481] in sheet 85E, and in long-abandoned quarries to the south of Alehousehillock [NJ 459 449 to 461 442]. It can be traced farther south-west around the nose of the Ardonald Anticline and west along its southern limb by small exposures, shallow overgrown pits, and lines of springs. The metalimestone is up to 30 m thick, although tight to isoclinal folding is developed in places, implying at least some local tectonic thickening. Typically it is pale bluish grey and coarsely crystalline with a pronounced banding and locally developed dark pelitic partings.

The metalimestones are overlain directly by black graphitic pelites, which are best exposed at the top of the quarry faces at the Blackhillock and Alehousehillock quarries. Elsewhere its presence is revealed mainly from debris in soil and till. In places thin quartz-rich laminae indicate bedding, but mostly the pelites are schistose with a strong crenulation cleavage (S3), itself deforming an earlier spaced cleavage (S2). Small garnets are common and staurolite locally present. Outcrops assigned to the Mortlach Graphitic Schist in the Burn of Drum, around [NJ 441 497], are atypical lithologically, being phyllitic to slaty, paler grey and more semipelitic. Their correlation with the main Mortlach Graphitic Schist outcrop is uncertain but they seem to be continuous with lithologically similar outcrops to the north-west of the Drummuir Fault in the adjacent Glenfiddich district (Sheet 85E).

Corryhabbie Quartzite Formation

The Corryhabbie Quartzite crops out almost continuously throughout the north-east Grampian Highlands from Deeside to just east of Keith in the Huntly district. It forms two parallel outcrops around the eastern closure of the Ardonald Anticline, where the repetition is interpreted as due to westward thrusting. In its northward extension across the north-west-trending Cairnie Fault, it forms an extensive outcrop underlying most of Balloch Forest defining a complex anticlinal fold closure. A further outcrop, structurally beneath that of the Balloch, extends from the Cairnie Fault, through Dunnyduff to the River Isla and, across the Isla faults, ending in an anticlinal closure on Gallow Hill [NJ 483 526]. Outcrops of highly sheared quartzite within the Keith Shear Zone at Greenbog [NJ 472 545] and between Goukstone [NJ 489 560] and Clochmacreich [NJ 494 580] are lithologically similar to the Corryhabbie Quartzite, but there are no further outcrops to the north. Although this unit can be traced along the Dalradian outcrop from Donegal through the Grampian Highlands, it is not present in Sandend Bay, some 10k m along strike to the north-east. Hence, it must either lens out or have been excised tectonically to the north-east of Keith.

In other areas in the Grampian Highlands, including the adjacent Glenfiddich district (Sheet 85E), there is commonly a striped transitional unit or units of micaceous psammite, which intervene between the underlying graphitic pelite and the quartzite. However, in the Huntly district, the true boundary between the formations is not seen; it is either not exposed, as on the southern limb of the Ardonald Anticline and the Glen of Coachford, or it is inferred to be a tectonic dislocation. There is no sign of striped transitional lithologies as clasts in the subsoil or till of any of the unexposed areas and we infer that the boundary is relatively sharply defined in this district. The tectonised lower boundary of the quartzite is well seen in the east face of Blackhillock Quarry [NJ 4415 4816], where layers of dark green to white clay with shattered quartzite fragments occur. Elsewhere, as in the Burn of Ardonald around [NJ 462 448], there are schistose muscovite-rich quartzites or flaggy quartzites close to the quartzite margin.

Much of the mapping of the Corryhabbie Quartzite is based upon the tracing of ridges of high ground that are commonly littered with angular blocks of white-weathering massive quartzite The typical lithology, well seen for example in Cairdshill Quarry [NJ 443 482] and in a small quarry on the south side of Both Hill [NJ 4438 4050], is a white to fawn, massive, indurated orthoquartzite. Bedding traces are typically well seen due to a pinkish brown weathering of very thin heavy mineral layers. Cross-bedding is common and graded bedding and slump features are seen locally. Way-up criteria are clearly seen at the two quarries mentioned above, but normally are more indistinct. At Cairdshill Quarry there are micaceous interbeds and layers of pale green clay material. Thin, coarse-grained, gritty feldspathic beds occur only rarely, e.g. in the quarry on Gallowhill [NJ 4842 5253].

The upper boundary of the quartzite is exposed in the Burn of Tarnash [NJ 4436 4918], where there is a sharp junction with flaggy to phyllitic, banded semipelites and micaceous psammites of the overlying Tarnash Phyllite and Limestone Formation. Elsewhere the upper boundary is inferred. In places, it seems to cut across the overlying strata and has been interpreted as a tectonic dislocation, as in Mill of Wood Burn [NJ 4555 5050], on the north-west side of Gallow Hill, and on the north-west side of Meikle Balloch Hill.

Tarnash Phyllite and Limestone Formation

This formation is only well exposed in burn sections east and north-east of Keith. The low relief areas that surround The Balloch are mostly underlain by this formation, but most are till-covered and cultivated. The type section lies in the lower part of the Burn of Tarnash around Bridge of Tarnash [NJ 4438 4894] and in its south-eastern tributary, the Birken Burn. Further sections occur in the lower part of the nearby Herrick's Burn, farther north in limited parts of the Burn of Paithnick, by the Mill of Paithnick [NJ 4817 5383], and the Lime Burn, downstream from Bridge of Bridgend [NJ 5146 5526]. It consists of mid grey to fawn, flaggy to fissile, thin- to medium-bedded, phyllitic, micaceous and highly micaceous psammite and semipelite with prominent metalimestones, and some thin psammite beds. The micaceous psammites are commonly calcareous and locally contain abundant thin bands and lenses of cream to pale green calc-silicate rock, which in parts show well-formed dark green tremolitic amphibole laths. The metalimestones are dominantly calcitic and range from the typical white weathering, pale grey to white and cream, fine-grained, crystalline varieties to white/grey, laminated and thinly banded types, and more rarely to coarsely crystalline, pure white types. They are typically 20 to 30 cm thick but range from 1 cm up to 2 m. A 4 to 8 m-thick, cream to grey, dolomitic metalimestone (in part metadolostone) near the base of the formation forms the prominent waterfall in the type section in the Burn of Tarnash. Rarely thin quartzite beds occur within the sequence.

The formation is internally tightly folded so that estimates of its stratigraphical thickness are problematical. It is probably between 150 and 200 m thick in the Tarnash area, but may be thicker farther north where it is dominantly semipelitic. Generally it passes upwards with rapid transition into dominantly schistose and commonly graphitic, pelites and semipelites that form the lower part of the Fordyce Limestone Formation. Near Balnamoon [NJ 4821 5556], it passes up into directly into the Limehillock Limestone Member, a thick blue-grey metalimestone normally found in the central part of the Fordyce Limestone Formation.

Ailnack Phyllite and Limestone Formation

A poorly exposed outcrop of semipelites, micaceous psammites and thin metalimestones stretches along the eastern side of The Balloch, south-south-west from the valley of the Isla through Auldtown [NJ 494 487] and Botary Mains Farm [NJ 470 450] to reach the western margin of the district at Westfolds [NJ 437 414]. The Burn of Cairnie provides a cross-section though the formation, but even here the exposure is dominated by the numerous metadolerite sheets. A prominent grey metalimestone occurs in the upper part of the sequence. Although these beds occupy a similar stratigraphical position to the Tarnash Phyllite and Limestone Formation, they are attributed here to the laterally equivalent Ailnack Phyllite and Limestone Formation as they form a laterally contiguous outcrop with that unit to the south. A small tight elongate periclinal synform enclosed by the Corryhabbie Quartzite Formation that underlies most of The Balloch contains semipelite, micaceous psammite and a prominent metalimestone unit in its hinge area. This is interpreted as a fold outlier of the Ailnack Phyllite and Limestone Formation.

2.2.3 Blair Atholl Subgroup

Rocks attributed to the Blair Atholl Subgroup are mainly schistose pelites and semipelites, in part graphitic, and with abundant thin beds of grey, crystalline metalimestone and more lenticular calc-silicate rock. A thick unit of blue-tinged, pale to dark grey crystalline metalimestone is present in many places and this distinctive lithology can be correlated readily with other Blair Atholl Subgroup limestone formations farther south-west. The subgroup is characterised by consistent lithologies and represents a period of widespread, stable, shallow marine shelf conditions. The rocks in the Huntly district are termed the Fordyce Limestone Formation, and link northwards to their type area. However, in some parts of the district lack of exposure prevents the separation of Blair Atholl and Ballachulish subgroup rocks and the metalimestone-bearing pelitic rocks are termed Blair Atholl Subgroup Undivided, as Blair Atholl Subgroup rocks are thought to form the bulk of the outcrop.

Fordyce Limestone Formation

This unit crops out west of the Portsoy Lineament in the Limehillock, Edingight and Burn of Paithnick areas north of the River Isla, where it is folded into a kilometre-scale, east-north-east-plunging syncline-anticline-syncline pattern. South of the River Isla the formation crops out in the core of a recumbent synformal structure on the lower north-west flank of Meikle Balloch Hill. Its type area lies farther north, and good sections through the formation are rare in this district. Coherent exposures are seen in the Mill of Wood Burn [NJ 457 503], in parts of the Burn of Braco around [NJ 498 524] and [NJ 5055 5366], and in the Burn of Paithnick and its tributaries, the Bowie and Balnamoon burns, e.g. around [NJ 4812 5402]. The formation consists of dark to silvery grey, fissile, slaty to schistose, commonly graphitic, muscovite-biotite pelite and semipelite. It is locally calcareous and commonly pyritic. Micaceous psammite, commonly finely interbedded with semipelite, and rarely feldspathic psammite, occur in its upper part, notably around Langley [NJ 5160 5674] and Brambleburn [NJ 5101 5639]. Typically, the unit contains abundant metamorphic porphyroblasts of brown to grey staurolite, small red garnets and locally prominent grey kyanite laths up to several centimetres long. Beds of blue-grey, crystalline metalimestone, ranging from a few centimetres to several metres thick, are common within the formation, and a thick central unit is termed the *Limehillock Limestone Member*. It is a pale to dark grey, typically coarsely crystalline metalimestone that varies from massive to thinly banded with abundant chert and pelitic interbeds. This metalimestone unit correlates with Blair Atholl Dark Limestone formations, such as the Inchrory Limestone that crops out farther south. It forms one of the most persistent lithostratigraphical markers in the Dalradian succession.

The metalimestone is commonly exposed in small and medium sized quarries, from where it has been obtained mainly for local use in liming the agricultural land. Many of these quarries are now disused or infilled but are recorded near to the following farms; Mains of Edingight [NJ 5144 5622], Fortry [NJ 5064 5355], Muiryfold [NJ 4904 5193], Mains of Auchoynanie [NJ 4575 5005], Goukstone [NJ 4915 5616] and Nethertown of Windyhills [NJ 5017 5610]. Note that some of the quarry locations cited here are some distance from the farm itself. At the type locality adjacent to the large, now flooded, Limehillock Quarry [NJ 5155 5190], the unit consists of grey, flaggy to blocky and in parts massive, thin- to medium-bedded, crystalline metalimestone intercalated with thin beds of graphitic pelite and calcareous semipelite. Impure pelitic and psammitic beds and lenticular calc-silicate bands are also abundant. The sequence dips at about 50° to the south-east and totals some 120 m in thickness, but it exhibits tight folding and a notable down-dip extension lineation, testifying to its strongly deformed state. The outcrop is bounded on its south-east side by the Portsoy Lineament/Shear Zone.

The overall thickness of the Fordyce Limestone Formation ranges between about 300 and 400 metres in this district, but the formation thickens northwards. Thicknesses measured from cross-sections are between 330 and 370 m, but such estimates neglect the effects of internally folding and the strong deformation.

The upper contact of the formation with the overlying Durn Hill Quartzite Formation (Islay Subgroup) is not exposed in this district but float and sub-outcrop on the south-east slope of Lurg Hill roughly define its location here. Sparse outcrops on the north-west slope of Sillyearn Hill locally constrain its position and show that the contact must be relatively sharp, marked by a change from graphitic pelite and semipelite to either micaceous psammite or to quartzite with minor interbedded semipelite. The contact on the south-east slope of Sillyearn Hill is indicated by the marked change in slope and the numerous springs.

Blair Atholl Subgroup, undivided

In the valley of the River Deveron, between Aswanley and Cairnborrow, a dominantly semipelitic succession intervenes between the Corryhabbie Quartzite and the quartzite at the base of the Argyll Group (Kymah Quartzite). This succession is truncated to the east by the western elements of the Portsoy Shear Zone. As there is no evidence for tectonic excision of any units within this succession, it has been assigned to the Ailnack Phyllite and Limestone Formation and the Blair Atholl Subgroup (undivided); the boundary between the two units on the map is arbitrary. This succession is intruded by many concordant sheets of metadolerite and metabasalt (see Chapter 5), which account for most of the exposures within its area of outcrop. Exposures of metasedimentary rock mostly consist of schistose micaceous semipelite, banded in places, with some interbedded psammite. At Blairmore School [NJ 4366 3982] a grey impure metalimestone shows signs of baking adjacent to a metadolerite sheet. More extensive exposures of metalimestone and metadolerite, which show complex contact relationships, occur just to the west of the present district, in the River Deveron section around the Haugh of Glass [NJ 424 393].

2.2.4 Appin Group unassigned

Within the Huntly district there are areas of Appin Group rocks that form distinct units, even formations, but then cannot readily be assigned to a particular subgroup. These lithological units mostly have structural boundaries, but their generally poor exposure commonly prevents the determination of their relationships to the known succession. Where the exposure is very poor the rocks can merely be allocated to the Appin Group and comments made as to the possible underlying lithology and its probable affinities. These units are shown on the 1:50 000 map as Appin Group - Unassigned. In this area and in the Glenfiddich district to the west they include the Keith Limestone Formation.

Keith Limestone Formation

The Keith Shear Zone is a zone of deformation up to 1 km wide, marked by a strong foliation and a prominent lineation, locally with associated asymmetrical shear indicators. It dips south-east at between 25° and 40° and cuts across the north-west corner of the Huntly district between the outskirts of Keith [NJ 44 51] and Clochmacreich [NJ 49 58]. The zone is characterised by the presence of several parallel lenticular sheets of foliated metagranite whose outcrops are coincident with the main thrusts. The metasedimentary background lithology is dominantly semipelite, with one thick and several thin metalimestone beds, best exposed in the vicinity of Keith itself in the Glenfiddich district (Sheet 85E). These metasedimentary rocks within the shear zone, collectively termed the Keith Limestone Formation, are lithologically similar to other Appin Group units, but their exact stratigraphical position is uncertain.

The semipelites are typically bluish to purplish grey to dark grey, medium- to coarse-grained and schistose, with both a strong foliation and a penetrative, down-dip stretching lineation. Garnet, muscovite and biotite are obvious in most samples. Close to the sheets of metagranite, porphyroblasts of pink feldspar are developed and the semipelite becomes gneissose, with quartzo-feldspathic augen, similar to those in the metagranite. The boundary between metasedimentary rock and metagranite appears gradational and is difficult to determine precisely in places. Thin beds of flaggy, micaceous, quartzose psammite are present locally.

The *Cuthill Limestone Member* is a massive, colour-banded, mid grey crystalline metalimestone that has a proven thickness of up to 28 m in Keith itself. It probably extends east-north-east into the present district along the crest of the broad ridge at Drum, but there are no exposures. Thinner metalimestones, also massive and colour-banded, occur structurally beneath the Cuthill Limestone. One of these, a banded impure metalimestone with lenses of dark pelite, was formerly quarried in the present district at [NJ 4438 5135], but the small quarry is now completely infilled.

The Cuthill Limestone is similar in lithology and thickness to the Dufftown Limestone of the Ballachulish Subgroup in its type area, and in the adjacent Glenfiddich district (Sheet 85E) it crops out in a structural position that could be interpreted as supporting such a correlation. However, analyses of the Cuthill Limestone show geochemical characteristics that are unlike metalimestones of the Ballachulish Subgroup, but more typical of those in the Blair Atholl Subgroup (Thomas, 1989). To emplace Blair Atholl Subgroup rocks in the Keith Shear Zone would involve considerable tectonic transport and complex structural geometry. The structurally adjacent succession, immediately above the Keith Shear Zone, is the Drummuir Calcareous Member of the Pitlurg Formation at the top of the Lochaber Subgroup. This member does comprise a general lithological association of semipelites with thin metalimestones, similar to that of the Keith Limestone Formation. However, it contains no thick developments of metalimestone and is characterised by generally impure metacarbonate rocks that would be expected to show geochemical affinities with Ballachulish rather than Blair Atholl metalimestones. The conflicting evidence and in particular the geochemistry of the metalimestones, which has proved to be a good stratigraphical ‘indicator’ elsewhere in the north-east Grampian Highlands (Thomas, 1989, 1999), precludes any detailed correlation of the Keith Limestone Formation with other established Appin Group formations.

The River Isla, between Bridge of Montgrew and Grange, flows through a broad alluvial plain in which there are no rock exposures. Straight banks on either side of the alluvium suggest fault control (the Isla fault system). The ground between the faults is interpreted to be underlain by easily eroded metasedimentary rocks, which, by comparison with surrounding known lithologies, are probably mostly semipelites. Similarly, mainly unexposed ground within the Keith Shear

Zone, forms a 200 m to 600 m wide zone north of the River Isla, stretching north-north-east from Mains of Glengarrack [NJ 455 526], across Foggy Moss and into the Portsoy district to the north. This area is also probably underlain by schistose semipelites. Sparse notes by the original surveyors recorded folded and weathered schists, commonly muscovite-rich. A significant metalimestone bed was recorded by the original surveyors adjacent to the B9018 road at [NJ 492580] at the northern margin of the Huntly district. Their structural setting requires that these areas are part of the Appin Group, and they may belong to the upper parts of the Ballachulish Subgroup and/or the lower part of the Blair Atholl Subgroup. However, they cannot be assigned to a particular subgroup or individual formation with any confidence. In part they may also be equivalent to the Keith Limestone Formation.

2.3 ARGYLL GROUP

2.3.1 Islay Subgroup

Durn Hill Quartzite Formation

This basal formation of the Islay Subgroup underlies Knock Hill, the ridge of Sillyearn Hill, and the south-east flank of Lurg Hill. Exposure is poor, although the nature of the unit is seen in the relatively abundant float blocks. The basal contact of the unit with the Fordyce Limestone Formation is commonly marked by springs, particularly along the Sillyearn and Knock hills, reflecting the fracture-dominated nature of the quartzite and its local role as a permeable aquifer. The formation consists mainly of white to cream, pink-purple and fawn, medium- to coarse-grained, indurated quartzite and feldspathic quartzite. Tabular planar cross-bedding with high foreset-bedding angles is present in boulders on Sillyearn Hill, and is common in the quartzite north and south of the Huntly district. The lowermost units of the formation are exposed in a small quarry by Cairdshill Farm at [NJ 5063 5137], where leached muscovitic semipelite beds are interbedded with grey to purple-tinged, white to fawn, blocky, lineated, fine- to coarse-grained quartzites. More biotite-rich semipelites are seen in a similar situation in minor tributaries of the Lime Burn on the north-west side of Sillyearn Hill. On Lurg Hill there is evidence for grey to green-grey micaceous and highly micaceous psammite at or near the base of the formation, parts of which are unbedded with rare scattered clasts (mostly quartz). This lithology resembles that of the 'Boulder Bed', a metadiamictite, which occurs as a lenticular unit either at the base of the quartzite or within its lower part. Adjacent to Langley Farm is a large angular boulder of vesicular and possibly pillowed, partly carbonated, amphibolitic metabasic rock. It contains some irregular more mafic patches, a crude banding and some included quartz pebbles. Similar pillowed mafic lavas are associated with the quartzite and the underlying 'Boulder Bed' in the Glenlivet district (Sheet 75E) in the Kymah and Muckle Fergie Burn sections respectively.

The Durn Hill Quartzite reaches a thickness of about 55 m on Knock Hill, although its upper contact is not exposed. However, possible structural duplication by thrusting and/or folding may occur here as parts of the Portsoy Shear Zone pass through the central part of the hill. The upper contact of the quartzite with the overlying Castle Point Pelite Formation is either a fault or a slide in the Huntly district. Further north on the Banffshire coast in the Portsoy district (Sheet 96W), this boundary is marked by a rapid transition.

2.3.2 Easdale Subgroup

Castle Point Pelite Formation

This formation is composed of dark grey, schistose, biotite-rich, locally graphitic pelite and semipelite. It underlies the almost completely drift covered, low relief area of Glen Barry, where it is intruded by elements of the Knock Pluton and the Portsoy mafic and ultramafic intrusions. It generally lies to the east of the Portsoy Shear Zone and hence its lower contact is likely sheared or faulted. Near the northern margin of the district, north-west of Barnyards of Badenyouchers [NJ 540 571], it also crops out west of the trace of the shear zone, but again its lower contact with the Durn Hill Quartzite is faulted. The bulk of evidence for the nature of the formation comes from shallow boreholes and pits excavated by AMAX in connection with the wider investigations into copper and nickel mineralisation by Exploration Ventures Ltd. in the 1970s (see Chapter 9). A few of the deeper boreholes drilled by Aberdeen University to investigate the nature of the North-east Grampian Basic Subsuite ('Younger Basic') intrusions (Munro, 1970; Munro and Gallagher, 1984) also penetrated the Castle Point Pelite formation. One of these near Drums of Muirake Farm at [NJ 5544 5721] recorded 6 metres of sillimanite-bearing gneiss beneath 2 metres of sandy drift deposits. The semipelite is locally calcareous to the north with thin calc-silicate rock lenses and impure metalimestone interbeds.

The transition upwards from the Castle Point Pelite Formation into the Cowhythe Psammite Formation is not exposed but is obscured by numerous metabasic pods and sheets and probably by dislocations. On the Banffshire coast section in the Portsoy district numerous metacarbonate, semipelite, quartzite and graphitic pelite units constitute the Portsoy Limestone Formation. This unit has been intruded by numerous metabasic and ultramafic intrusions and is strongly deformed and folded. Such rocks appear to be largely missing in the Huntly district. Concealed serpentinised ultramafic pods around Ordiquhill and Gordonstown may signify the presence of a major lineament that marks the eastern edge of the regional Portsoy Shear Zone. This zone also shows evidence of middle to upper amphibolite grade metamorphism, related to the intrusion of the North-east Grampian Basic Subsuite.

2.3.3 Easdale Subgroup unassigned

Partly calcareous semipelitic and subsidiary pelitic lithologies, metalimestones and calc-silicate rock lenses are recorded from two BGS boreholes sited adjacent to the Portsoy Lineament near Drumnagorrach at [NJ 5241 5242] and [NJ 5198 5205]. Similar lithologies are also recorded from other boreholes at the southern and western edges of the Knock intrusion. In parts the rocks appear to be fragmentary on a millimetre to centimetre scale, possibly reflecting an initial sedimentary brecciated limestone-siltstone/mudstone protolith. The metasedimentary rocks are strongly deformed, hornfelsed, and have been metamorphosed mainly at middle amphibolite grade. They are typically interleaved with variably foliated metagabbros, metanorites, serpentinised ultramafic rocks and quartz-feldspar pegmatites. They are attributed to the Easdale Subgroup but their relationship to the Castle Point Pelite Formation is unclear.

2.3.4 Crinan Subgroup

Cowhythe Psammite Formation

This unit, formerly termed the Cowhythe Gneiss (Read, 1923), crops out to the east of the Castle Point Pelite Formation. It is also very poorly exposed in the Huntly district. It underlies a broad swathe that stretches south-south-west from Gordonstown [NJ 564 566] and Finnygaud [NJ 604 545] in the north, to Milltown of Rothiemay [NJ 547 484] and the Huntly Pluton in the south. The formation consists of mid to dark grey, commonly gneissose micaceous psammite, biotite-rich semipelite and pelite with abundant quartz-feldspar segregations. Calc-silicate rock is not common in the sparse exposures but has been intersected in boreholes close to the Knock and Huntly basic-ultrabasic plutons and in the xenolithic gabbroic bodies that punctuate the Cowhythe Psammite outcrop. Quartzose psammite with thin semipelitic partings is recorded both in old quarries [NJ 5882 5637] and in float on Meikle and Little Brown Hill. Coarsely gneissose segregated semipelite was recorded from a now-infilled quarry near Starmires Farm at [NJ 5864 5594].

2.3.5 Crinan/Tayvallich Subgroup

Strichen and Aberdeen Formations

Rocks assigned to the Crinan and/or Tayvallich Subgroup, formerly termed the Old Meldrum Gneisses (Read, 1923), crop out at the eastern end of the Insch Pluton, in the south-east corner of the Turriff district. Again, the succession is generally poorly exposed. Its extent on the north-eastern margins of the Insch Pluton has been clarified by geophysical and pitting work by Aberdeen University workers (e.g. Leslie, 1981). Small troctolite and gabbroic intrusions lie within the metasedimentary succession and may indicate that mafic rocks occur more widely at shallow depths here.

In the stream section just north of Mill of Easterton [NJ 7775 3085] parts of the Strichen Formation are moderately well exposed. Lithologies range from coarsely schistose semipelite and pelite to migmatitic semipelite with patchy segregations and a gneissose foliation defined by the quartz-feldspar leucosome. Some rocks contain what appear to be ‘xenoliths’ of pelitic material with ghosted margins. The rocks are strongly deformed and sheared in places. In thin section sillimanite, cordierite and andalusite are present and the widespread occurrence of foxy, red-brown biotite suggests that most of the rocks are hornfelsed. Read (1923) reports the occurrence of a garnet-cordierite-biotite-green spinel-quartz-plagioclase rock with scattered magnetite around [NJ 810 293]; this is probably a contaminated igneous rock or a partial melt restite.

2.3.6 Argyll Group unassigned

Lithologies typical of Argyll Group successions elsewhere in the Dalradian occur immediately to the east of the Portsoy Shear Zone and are dominated by locally graphitic pelites and semipelites with thin psammitic beds. Thick turbiditic units of gritty psammite and massive gritty quartzite occur as local lenses, and metalimestones and calc-silicate rocks are generally thin and impersistent. Although formations have been erected and members recognised, they cannot be traced laterally for any distance and do not directly correlate with Argyll Group successions elsewhere in the Grampian Highlands (Fettes et al., 1991). Hence, it is inappropriate to assign them to subgroups within the Argyll Group.

Beldorney Pelite Formation

The type area for this formation lies in the immediately adjacent part of the Glenfiddich district (Sheet 85E), where good exposures occur in the River Deveron around Beldorney Castle [NJ 421 369]. The dominant lithology is black, phyllitic or slaty, commonly finely laminated pelite that passes into schistose semipelite in parts. Thin psammite beds and quartzose psammite lenses are common. In the Huntly district the formation extends along the western parts of the Portsoy Shear Zone, from Westerpark [NJ 437 382] north-eastwards to the area around Ruthven [NJ 506 470]. The best exposures of the typical pelitic and semipelitic rocks occur in the River Deveron below Bogforth [NJ 472 404], and in the Burn of Cairnie around [NJ 480 448], between Newton and Cairnie. In these exposures coarse-grained schistose muscovite-biotite-garnet semipelites are common, some with conspicuous tourmaline and possible kyanite. At a remarkable exposure in the River Deveron at [NJ 4720 4041] thin (about 5 cm) tightly folded beds of hard, massive, unfoliated quartz-plagioclase-garnet rock occur within schistose semipelite. The beds contain up to 50 per cent, clear, pinkish purple euhedral garnets up to 5 mm in diameter. They may represent a basic metavolcanic or possibly metasomatic protolith.

The Beldorney Pelite Formation is also exposed in the Burn of Aswanley, upstream of [NJ 4467 3920]. Here the north-west margin of the formation, adjacent to a metagabbro at the western limit of the Portsoy Shear Zone, is marked by a grey, gritty feldspathic psammite that can be traced north-eastwards along a ridge, almost to the River Deveron. The psammite contains some pelitic interbeds and quartzose psammite lenses and locally has a strong foliation. Farther to the north a strongly deformed micaceous psammite with some gritty feldspathic beds occupies a similar position, adjacent to the western limit of the shear zone. Good exposures of this psammite, with interesting deformation structures associated with the shear zone (see Chapter 6), are seen on the south bank of the Burn of Cairnie, below Newton [NJ 478 449].

Blackwater Formation

The Blackwater Formation crops out on the south-eastern side of the Succoth–Brown Hill intrusion and hence is outwith the main zone of deformation in the Portsoy Shear Zone. The lower part of the formation occurs in adjacent areas of the Glenfiddich district. It comprises a mixed sequence of gritty psammites, schistose pelites and abundant metavolcanic rocks; compositonal changes in the latter are used to define three members (Gunn et al., 1990; Fettes et al., 1991). Only the upper part of the formation, comprising two members, occurs in the Huntly district, the lower members having been cut out by the shear zones and the Succoth Fault that bound the Succoth–Brown Hill intrusion.

The *Corinacy Pelite Member* crops out from the south-eastern slopes of the Deveron valley, on the western edge of the Huntly district at [NJ 436 355], to the valley of the Collonach Burn, near Wellheads [NJ 486 396]. The member is dominantly pelitic, ranging from schistose to phyllitic and slaty. The pelites are graphitic in part and in the Dry Burn [NJ 436 358] they contain a dark grey, ovoid, phosphatic nodule, about 4 cm x 3 cm x 2 cm, with impurities of amorphous iron and manganese. Andalusite is common, either as dark grey blobs or as large, euhedral crystals of white-weathering chiastolite up to 2 cm long. Some rocks also contain garnet and staurolite. In the adjacent Glenfiddich district sheets of metabasalt are abundant in the lower part of the member, but are less abundant higher up. Thin lenticular beds of gritty psammite are present throughout the member, but become thicker and more persistent towards the top, where they locally form distinct low ridge features [NJ 485 380]. In addition to the lithologies already described, the boreholes by Wellheads [NJ 486 395] (see Chapter 9) intersected graphitic quartzite, chert, intraformational breccias and a 5 m-thick metalimestone.

The *Grumack Hill Quartzite Member* occurs only in the south-western part of the Blackwater Formation outcrop and is cut out to the east by the east-north-east-trending Long Slough Fault. It forms persistent positive features on the north-west flank of the watershed ridge, south-east of the Deveron valley. The buff-grey to off-white massive quartzites are purer than the psammites in the underlying Corinacy Pelite Member, although some gritty beds occur locally. Mixed quartzitic and pelitic debris on top of the features suggests that the member may include significant interbeds of phyllitic pelite.

Formation unassigned

Typical Argyll Group semipelites with minor metalimestone extend to the north and north-east, through poorly exposed ground between Wellheads [NJ 486 395] and Littlemill [NJ 518 474]. This approximately 1 km-wide outcrop lies between sheared metagabbro bodies that may be a drawn-out extension of the Succoth–Brown Hill intrusion, and the western margin of the West Huntly cumulate body. Although the semipelites may possibly be a continuation of the Corinacy Pelite Member (Blackwater Formation) to the south, or the Beldorney Pelite Formation farther west, they lie within the Portsoy Shear Zone. Hence, they are separated from both pelite units by major dislocations, making any such correlations suspect.

Good sections are seen in the road cutting on the north side of the Deveron valley, east of Milton of Cairnborrow between [NJ 478 407] and [NJ 483 406], and in the Burn of Cairnie between [NJ 487 446] and [NJ 495 449]. Here, the rocks are schistose semipelites, dominated by muscovite, biotite and garnet, with some thin beds of gritty psammite. Samples from the eastern end of the Cairnborrow section are spotted and one contains fibrolite mats replacing biotite and white mica, possibly after cordierite. In the part of the Burn of Cairnie adjacent to the Huntly intrusion, the rocks are gneissose and heterogeneous, suggesting partial melting and/or intermixing with basic magma. Blue-grey, fine-grained metalimestone is well exposed in a line of old pits on the south side of the Hill of Cuternach [NJ 479 418].

2.4 SOUTHERN HIGHLAND GROUP

Rocks assigned to the Southern Highland Group occupy more than half the area of the Huntly and Turriff districts (Sheet 86W/E), forming the major part of the wide outcrop of these rocks which extends northwards into the Banff district (Sheet 96E) and up to the coast. Read (1923) estimated that they covered an area of 'over 200 square miles' (about 520 km^2) in north-east Scotland. Southern Highland Group rocks are bounded to the west mainly by the Cowhythe Psammite Formation (Argyll Group), but also by the Huntly Pluton around Huntly itself. Near the southern margin of the Huntly and Turriff districts they are transected by the Insch Pluton, and to the east they underlie the Old Red Sandstone of the Turriff basin.

Southern Highland Group rocks consist almost entirely of metamorphosed wacke sandstones, arenites and mud rocks, although very coarse arenites and microconglomerates occur locally in several large lenses. Though rare, thin units of calc-silicate rock and one or two thin metalimestones occur in the western part of the crop.

The Group is divided up into three formations as follows (youngest to oldest):

Macduff Formation

Whitehills Grit Formation /Clashindarroch Formation

Although they differ lithologically, the older two formations are considered, at least in part, to be stratigraphically equivalent, and to interdigitate in the ground south-west of Huntly. Rocks of the carbonate-bearing Whitehills Grit Formation (formerly the 'Whitehills Group' of Read, 1923) crop out to the west of the Macduff Formation, north of Huntly, where they overlie the Cowhythe Psammite Formation.

The base of the Clashindarroch Formation is marked in places by the Garnel Burn Pelite Member. This schistose, highly magnetic pelite unit is laterally equivalent to other magnetic pelitic and semipelitic lithologies mapped at this stratigraphical level in other districts, e.g. the Longshank Gneiss Formation in the Ballater district (Sheet 65E) (British Geological Survey, 1995).

The Macduff Formation forms much the greater part of the Southern Highland Group outcrop on Sheets 86E and 86W. Although the formation is a broadly uniform sequence of metaturbidites, in its lower part a major pelite unit, the Hill of Foudland Pelite Member, forms the prominent, east–west trending line of hills (the 'Slate Hills') immediately north of the Kennethmont and Insch Intrusions. Also in several places within the formation generally lenticular but moderately thick units of conglomeratic to microconglomeratic arenites can be mapped.

The Southern Highland Group rocks in much of the Turriff district are disposed in the broad open Turriff Syncline (Read, 1955). The wide complex axial zone of this large-scale structure trends roughly 008°, with its trace lying close to the western edge of the Turriff outlier. However, south of grid line 40, bedding and S1 cleavage swing to strike north-east and then east-north-east to become near parallel the northern margin of the Insch Pluton. Here, the trace of the syncline is unclear and it may well decline in amplitude as it is traced to the west-south-west. The Boyndie Syncline, defined by Sutton and Watson (1956), is effectively a large-scale, east-facing monoform defined by the Knock Head Grit Member on the Banffshire coast section. In the Turriff district its southerly continuation is not well defined and no kilometre-scale monoform structure can be readily identified. The steep limb of the monoform may be represented by the numerous steep and subvertical dips seen in gritty arenites and microconglomerates close to the western boundary of the Macduff Formation and farther south-west in the Whitehills Grit Formation. However, local reversals of dip and changes in younging direction imply that medium-scale F1 folds are present in the succession as seen on the coast section around Banff and Macduff. These generally upright structures commonly have steeply dipping limbs.

The Turriff Syncline is reflected by the metamorphic zonation (Read, 1955). Chlorite and biotite-grade greenschist facies metasedimentary rocks lying in the core of this structure pass both to the east and west into schistose cordierite- and andalusite-bearing lower amphibolite facies pelites and semipelites within the Macduff and Clashindarroch formations. These schistose, dominantly pelitic and semipelitic rocks were formerly referred to as the 'Fyvie Schists' and 'Boyndie Bay Group', respectively, and were defined by Read (1923) as separate units from the 'Macduff Slate'. However, they are lithologically similar and now recognised as a partly metamorphic transition. In the south-east part of the Turriff District, andalusite- and cordierite-bearing rocks of the Macduff Formation overlie gneissose and migmatitic pelites, semipelites and psammites assigned to the Strichen Formation. However, gneissose rocks are absent to the south-west of Huntly where the Clashindarroch Formation overlies metasedimentary rocks assigned to the Argyll Group.

Whitehills Grit Formation

This formation includes andalusite- and tourmaline-bearing semipelite and pelite, gritty quartzites and psammites, and rare metalimestones and calc-silicate rocks. The andalusite-bearing pelitic rocks are highly schistose, with grey commonly elongate porphyroblasts some several millimetres across. The formation crops out in a narrow zone between 0.8 and 4 km wide, stretching from south-west of Huntly, around Brawlandknowes [NJ 507 369], north-north-east to Aberchirder [NJ 625 525], and thence northwards into the Portsoy and Banff districts (Sheet 96W and E) to its type section on the coast immediately west of Whitehills. Exposure inland is generally poor and restricted to isolated outcrops, as noted by Read (1923).

In the area between Marnoch [NJ 597 502] and Drumblade [NJ 585 400] in the Huntly district, a thick lens composed mainly of quartzite occurs within the Whitehills Grit Formation. Its lenticular form is interpreted here to represent original facies variations and may possibly be a large sand channel form. Read (1923, p. 53) records that the quartzite ranges from fine-grained to gritty and even pebbly. Near its southern extent it is exposed in a small quarry in Cruchie Wood [NJ 5827 4313] where white, fine- and medium-grained quartzites and psammites with thin schistose pelitic partings locally show cross-bedding and ripple marks. Metalimestones and calc-silicate rocks, though rare, are characteristic features of the Whitehills Grit Formation that help in distinguishing the unit from the Clashindarroch Formation. Read (1923) recorded 'broken whitish limestones' near Auchingoul [NJ 610 486]. Thin beds of metalimestone are also exposed in the River Deveron near Marnoch Lodge (NJ 604 496], and in the River Bogie and the railway cutting at around [NJ 525 370] just east of Bucharn [NJ 521 369].

Clashindarroch Formation

The Clashindarroch Formation is almost wholly restricted to the Clashindarroch Forest area in the south-western part of the Huntly district and south-eastern part of the Glenfiddich district (Sheet 85E). The formation is lithologically similar to much of the overlying Macduff Formation, but typically it is more semipelitic. However, its base is marked by the *Garnel Burn Pelite Member*, a distinctive schistose, biotite-rich, andalusite-bearing pelite that contains several per cent of fine-grained magnetite and hence is highly magnetic. As a result this member can be traced readily from the Daugh of Corinacy [NJ 402 311] north-east over Grumack Hill in the Glenfiddich district and into the Huntly district on the ridge north-west of Red Hill [NJ 437 340]. Its outcrop only appears to extend north-east in the Clashindarroch Forest as far as [NJ 450 356] where it is truncated by the Succoth Fault. Farther along strike to the east-north-east the base of the Clashindarroch Formation is marked by coarse, gritty and locally conglomeratic psammite units that form the crests of Muckle Long Hill [NJ 460365] and Hill of Bogairdy [NJ 485 366]. These psammite units die out laterally and the main semipelitic lithologies of the Clashindarroch Formation lie directly on rocks assigned to the Corinacy Pelite Member (Blackwater Formation, Argyll Group) on the west side of Clashmach Hill [NJ 498 385]. In this area, the Clashindarroch Formation appears to underlie the Whitehills Grit Formation, although at least in part the contact is faulted. Relationships farther to the north-east are obscured by the Huntly Pluton. However, it is possible that the elongate mass of semipelite shown at the base of the Whitehills Grit Formation in the Fourman Hill area, and described above, is an outlier of the Clashindarroch Formation.

Conglomeratic psammites occur in several places, most notably north-west of Whitestones [NJ 480 355] and on the south-east flanks of Craigend Hill at about [NJ 458 342]. In the extreme south-west corner of the Huntly district, parts of the Clashindarroch Formation lie within the contact metamorphic aureole of the Boganclogh sector of the Insch Pluton. They have been metamorphosed into very hard, compact, fine-grained cordierite-and-andalusite-bearing pelitic and semipelitic hornfelses.

Macduff Formation

Read (1923) termed this unit the Macduff Group, but more recently it has generally been called the 'Macduff Slate Formation' (e.g. Harris et al., 1994), with the emphasis on its pelitic lithologies. Although slaty pelite and semipelite are locally abundant, there is a range of terrigenous, clastic lithologies in the formation and the term 'slate formation' is thus somewhat of a misnomer.

The Macduff Formation is very well exposed along the Banffshire coast section but exposure inland is poor and individual exposures are generally isolated. It is considered to be a turbiditic sequence, exhibiting classic turbidite fan facies (Kneller, 1987; Trewin, 1987). It includes dropstones and debris flow diamictites, which are well exposed at Macduff and have been interpreted as glacigenic in origin (Sutton and Watson, 1954; Hambrey and Waddams, 1981; Stoker et al., 1999). Such lithologies and features have not been recognised within the Huntly and Turriff districts. The formation is considered to have been deposited in deep water in a continental slope setting. Material was derived from an adjacent marine continental margin and shelf which may have undergone periodic active glaciation.

The dominant lithologies are fine- to coarse-grained siltstones and wacke sandstones, with subordinate pelites, arkosic gritty sandstones and rare quartzites. Pebbly zones, microconglomerates and very coarse grained gritty sandstones are locally important.

Coarse-grained gritty feldspathic arenites containing clasts of semipelite up to several tens of centimetres across are seen in Strathbogie at [NJ 5128 3378], to the south on Birch Hill [NJ 51 33] and immediately east of the River Deveron in Logg Wood at [NJ 6437 4736], near Inverkeithny.

Very coarse-grained arenites and microconglomerates were recognised as distinct units by Read and shown on the original (1923) 1: 63 360 scale geological map of Sheet 86. These lithologies consist of interbedded coarsely gritty arenite and pebbly conglomerate with a coarse-grained sand matrix. The pebbles consist mostly of vein-quartz, although Read (1923) also reports the presence of feldspar, quartzite and granitic lithologies. The pebbles are well-rounded and are up to 3-4 cms in diameter. One of these coarse-grained units extends west-south-west from near Culdrain House [NJ 515 338] for some 4 km. At its eastern extent its outcrop possibly terminates against the fault that forms the western side of the Old Red Sandstone Strathbogie Inlier. The best exposures occur in Kirkney Water and on the steep north-facing bank opposite the northern end of Birch Hill [NJ 5096 3293]. To the west, the conglomerate unit lenses out on northern side of Slouch Hill [NJ 4815 3279]. A further major occurrence of gritty arenite and conglomerate outcrops just to the south-east of Bainshole [NJ 611 351]. It is well exposed in a small quarry 400 m east of Bainshole. This unit can be traced intermittently east-north-east across the Glens of Foudland over some seven kilometres towards the Glenmellan–Logie Aulton area to about [NJ 658 381]. Here, it is a massive, coarse-grained gritty arenite and pebble conglomerate, interbedded with strongly cleaved semipelite. As the unit is poorly bedded and generally fractured and weathered, little internal detail can be discerned. The unit may continue along strike to the west-south-west to link with outcrops in the Burn of Stodfold at [NJ 5871 3375]. Blocks of conglomerate are numerous hereabouts. Many are fractured and contain slickensided surfaces, indicative of local faulting. The pebbles, composed predominantly of vein-quartz, are rounded to well-rounded and up to 5 cm in diameter. To the east of Burn of Stodfold, the conglomerate can be traced over the hillside across the fields for about 1 kilometre.

The most extensive continuous development of pelite and semipelite within the Macduff Formation occurs in the 'Slate Hills' near the southern margin of the sheet, just north of the Insch Pluton and Kennethmont Intrusion. These distinctive slaty pelitic lithologies, termed the *Hill of Foudland Pelite Member*, lie mainly within the contact aureole of the Insch Pluton and show varying degrees of contact metamorphism (see Chapter 8 – Metamorphism). Their cleavage generally dips steeply southwards, and the due to their massive and partly hornfelsed nature they form generally positive relief features.

Exposure of the pelitic rocks is enhanced considerably by the extensive abandoned slate quarries throughout the 'Slate Hills', most particularly on Hill of Foudland [NJ 603 332] itself. The slates were exploited from a narrow zone either just within or just outwith the onset of hornfels textures. Here the pelitic rocks were recrystallised, making them harder and more durable, and yet they were still fissile enough to split along the S1 slaty cleavage to form slates. However, clean bedrock faces are relatively rare in the workings. Much of the abundant loose material is inferior quality slate material, back-fill, and ruins of dwellings, all linked to the uncontrolled nature of slate exploitation in numerous small quarries in the 19th century. The rocks vary from generally poorly to well-cleaved pelites and semipelites with thin siltstone and fine-grained sandstone laminae. They are generally massive in the southern part of the member, where they are more strongly hornfelsed. Way-up is generally difficult to determine and the slates do show complex medium-scale F1 folds, at least locally. Farther northwards the member becomes less pelitic and small-scale sedimentary structures are present in more sandy beds, some of which do indicate a more consistent way-up. The pelitic rocks pass northwards into coarse-grained arenites and wackes with subsidiary pelitic interbeds.

Small, dark green, lath-shaped chloritoid porphyroblasts are abundant in places in the pelites. Greenish-grey, highly cleaved pelites containing chloritoid are found both on the west side of Strathbogie on the summit ridge of the Hill of Kirkney [NJ 505 316], and on the east side on the Hill of Corskie [NJ 547 327]. Chloritoid is also recorded from pelitic rocks on the hills of Foudland and Tillymorgan (Leslie, 1988) and in small exposures at the eastern end of Wishach Hill around [NJ 577 332].

South across Hill of Kirkney towards Glen of Noth, spots and small porphyroblasts of cordierite and andalusite begin to appear in the pelites due to contact metamorphic effects of the Insch Pluton (Boganclogh Sector). At the south-western end of the Hill of Kirkney, the pelitic rocks are thoroughly recrystallised into very hard, weakly to moderately foliated, massive, cordierite-andalusite hornfelses. The foliation is best developed on the outer margins of the hornfelsed zones.

Calc-silicate rocks: Calc-silicate-bearing rocks have been found several localities in the south-west corner of the Huntly district. They occur as thin laminae generally less than 5 cm thick and are interbedded with medium-bedded, dark grey, fine-grained micaceous psammites and semipelites. Though conspicuous where present, they are not abundant in the Macduff Formation. The calc-silicate laminae are creamy-white in colour, flecked with green amphibole and pink grossular garnet. In thin section, the general assemblage is plagioclase + quartz + garnet + hornblende ± zoisite ± sphene ± biotite ± white mica. Calcite or other carbonate minerals are absent. The assemblage accords with that recorded by Hudson (1985) for calc-silicate rocks from the coast section west of Banff. Such assemblages are only stable in the presence of very water-rich fluids. This is consistent with their presence in micaceous psammites and semipelites, for which equilibrium fluids have $\mathbf{a}_{H_2O}$ (water activity) ≈ 1.

The Fyvie Gorge and Foredoun Burn sections

Within the Huntly and Turriff districts, the best-exposed sections through the Macduff Formation occur in the River Ythan section in the Fyvie Gorge and in the lower part of the tributary Fodoun

Burn that joins the Ythan at Fyvie. Both sections afford good exposures of the Macduff Formation, here disposed in large, upright folds (see also Chapter 6). The Fyvie Gorge is an over-deepened glacial meltwater drainage channel within which the diminutive River Ythan is now somewhat of a misfit. The Fyvie Gorge section extends over about 6.5 km from Ardlogie [NJ 780 373] in the west of Braes of Gight [NJ 828 387] in the east. Exposure is also reasonably good in the gorge of the Fordoun Burn, particularly at about 1.5 km south-west of Fyvie, around a prominent bend at about [NJ 755 372].

The rocks vary from pelite and semipelites to dark, greenish-grey, coarse-grained, gritty, wacke sandstones with arenites and rarer pinkish arkosic sandstone beds. Units are generally thinly to thickly bedded, except for some massive, coarse-grained units that attain in excess of 2 m thickness and in part probably comprise amalgamated beds. Graded bedding is common in the thinner and finer grained arenites, allowing elucidation of the major fold structures in these areas (See Section 7.8.1. Other sedimentary structures present in these rocks include ripples, load casts, loading structures and trough cross-lamination, all of which can help to determine way-up.

The more aluminous pelitic lithologies commonly contain porphyroblasts of cordierite and andalusite, which are typically weathered out, giving the weathered surface a honeycomb texture. They also show a strongly developed schistosity in places, with the fabric (S2) wrapping the porphyroblasts.

3 Old Red Sandstone Supergroup

Rocks of Devonian age that form a small part of the Old Red Sandstone Supergroup crop out in the Turriff Outlier and in the Rhynie and Bogie outliers in Strathbogie, south of Huntly (Figure 1).The Turriff Outlier occupies an approximately 4 to 8 km-wide half-graben which extends for a further 10 km north-eastwards to the coast at Gardenstown and Gamrie in the Banff district (Sheet 96E). It contains units of the Upper Devonian Crovie Sandstone Group and the Middle Devonian Inverness Sandstone Group, separated by an unconformity that is well seen on the Banffshire coast (Read, 1923, Archer, 1978; Trewin et al., 1987). The western boundary of the outlier is defined by the Afforsk Fault (Read, 1923), a major structure that dips steeply to moderately eastwards. Two subsidiary parallel, approximately north–south trending faults define a horst and a further fault-bounded outcrop immediately to the west of the main basin. This last outcrop extends through the eastern part of Turriff itself. The succession through the Old Red Sandstone rocks of the Turriff Outlier is shown schematically in Figure 2. Note that the Gardenstown Conglomerate Formation (Inverness Sandstone Group) is locally directly unconformable on the Macduff Formation in the southern part of the outlier. The overall thickness of the succession has been estimated from gravity modelling as between 800 m in the north and 1400 m in the south (see Chapter 6 – Concealed Geology).

The Bogie Outlier forms a narrow northern extension of the larger Rhynie Outlier, which outcrops mainly in the adjoining Alford district (Sheet 76W) to the south (Gould, 1997). In Strathbogie the outlier is fault bounded on its western side between Newnoth [NJ 518 302] and Mains of Collithie [NJ 515 352].

The northern tip of the main Rhynie Outlier is terminated by a fault which extends from just west of Newnoth, east-north-eastwards up the Glen of Cults between Knockandy Hill [NJ 550 314] and Hill of Corskie [NJ 540 324]. To the north of this Glen of Cults Fault, erosion has removed the upper part of the succession, including any overstep of the Tillbrachty Sandstone Formation to the west across the north–south trending Strathbogie Fault. The Strathbogie section of the Rhynie Outlier was originally thought to be bound to the west by a significant fault giving rise to a half-graben structure similar to that of the Turriff Outlier. There is little doubt that the western margin of the outlier is faulted, but the significance of this fault in relation to the structure of the outlier has been called into question by Trewin and Rice (1992). Their borehole investigations of the outlier around Rhynie suggest that rocks of the Tillybrachty Sandstone Formation lie unconformably on the Macduff Formation on the western side of the outlier. This is the interpretation shown on the 1:50 000 map of the Alford district (Sheet 76W), which has been continued northwards. If correct, it implies that the Rhynie Outlier has a synclinal structure modified by coeval faulting (Gould 1997; fig. 24b). The age of the sequence in the Rhynie inlier, notably that of the Rhynie Chert, has been estimated from detailed assessment of the spore assemblage as early Praghain to early Emsian (Wellman, 2006). Recent isotopic ages give contrasting results. Mark et al. (2011) obtained an $Ar^{40/}Ar^{39}$ age of 403.9 ± 2.1 Ma from orthoclase feldspar in a hydrothermal vein from the Rhynie Chert. However, Parry et al. (2011) have reported an ID-TIMS U-Pb zircon age of 411.5±1.3 Ma from the nearby andesitic lavas that relate to the fossilised sinter (hot spring) deposits preserved at Rhynie.

The lithostratigraphical descriptions that follow are mostly based on those of Read (1923).

3.1 TURRIFF OUTLIER

3.1.1 Crovie Sandstone Group

Rocks considered to be of Early Devonian age (Praghian to Emsian; Westoll, 1977) in north-east Scotland are assigned to the Crovie Sandstone Group. They outcrop in a narrow strip up to 1.7 km wide along the eastern margin of the Turriff Outlier between Meikle Gourdas [NJ 775 415] in the south and east of Byth House [NJ 818 564] in the north-east corner of the Turriff district. There is no continuous section through the sequence, merely isolated exposures in burns, small quarries and pits.

The basal unconformity is only exposed on the roadside a little north-west of Keithen [NJ 795 452] (Read, 1923). Here a thin basal breccia, composed mainly of angular to subangular clasts of gritty arenite and semipelite, patently derived from the underlying Macduff Formation, is overlain by red sandstones and conglomerates that in turn pass up into red sandstones. The rocks all dip to the west at between 20° and 40°. A thicker development of the basal breccia and conglomerate unit has been interpreted to occur between Cuminestown [NJ 804 503] and New Byth [NJ 822 540] but outcrop is poor and the unit may well be lenticular. The basal breccia and conglomerate is succeeded by dull red to reddish grey sandstones with thin shale partings that form the bulk of the sequence. Pebbly lenses and clay galls occur locally. An example is recorded some 900 m south-west of Byth House at [NJ 8115 5572] where in a small quarry red clay galls are concentrated along bedding planes in coarse-grained micaceous sandstones. Dips in the sandstones are generally lower than in the underlying conglomerates, varying between about 10° and 25°. Given an overall dip of 20° the overall sequence can be estimated at about 500 m thick around Byth House.

3.1.2 Inverness Sandstone Group

Gardenstown Conglomerate Formation

The Crovie Sandstone Group succession is unconformably overlain by conglomerates and breccias of the Gardenstown Conglomerate Formation of the Inverness Sandstone Group. These rocks dominate in the Turriff Outlier, overstepping the Crovie Group in the southernmost part of the outlier to lie directly on the Macduff Formation. In general, bedding dips gentle westwards, normally between 10° and 30°, but steeper dips do occur in parts, notably adjacent to the west-bounding faults where bedding dips locally exceed 60°. The unit becomes more sandstone rich in the ground around Wood of Delgaty [NJ 760 500], where Read (1923) recorded about 35 m of dull red sandstone intercalated with breccia and conglomerate. The sandstone thins to the south towards Hatton Castle [NJ 758 469]. Exposures recorded by Read in several former quarries around the Water of Idoch show sandstones in beds 0.3 to 1 m in thickness with thin beds of conglomerate and scattered pebbles. The sandstones are locally interbedded with thin beds of purple shales. The sandstones indicate a general fining upwards sequence in the Gardenstown Conglomerate Formation; any pre-existing fine-grained lithologies have subsequently been removed by erosion.

3.2 BOGIE OUTLIER

3.2.1 Rhynie Group

Tillybrachty Sandstone Formation

Much of the following text is based on observations made by Read (1923), and others therein, based partly on exposures which are no longer visible. The base of the Lower Devonian Tillybrachty Sandstone Formation occurs in the Glen of Cults [NJ 535 315] where it is marked by a thin (0.7 m) conglomerate unit resting unconformably on rocks of the Macduff Formation. The conglomerate includes abundant local clasts and is overlain by green and dark grey calcareous shales with nodules and thin beds of limestone probably resulting from caliche development in a semi-arid environment. These shales contain fragmentary fossil plant remains, identified by Kidston as resembling *Pachytheca* (Read, 1923, p.180). The plant remains occur at a similar stratigraphical horizon to that of the Rhynie Chert Member (Dryden Flags Formation) that occurs 5 km to the south-west and whose flora was described in detail initially by Kidston and Lang (1917, 1920a, b, 1921a, b). The green and grey shales are overlain by red laminated sandy shales and friable red sandstones.

Included within the Tillybrachty Sandstone Formation are andesitic lavas. Although only locally developed south of the Glen of Cults fault, they form the bulk of the succession to the north of the fault. They extend up the valley of the Bogie to near Mains of Collithie [NJ 516 352] fringed on their eastern side by a very thin strip of sandstone and shale. In 1990 the A97 was realigned on its west side immediately north of Kirkney Bridge [NJ 518 336] by Culdrain, exposing deeply weathered andesitic lavas lying beneath purple and green volcaniclastic and tuffaceous sandstones. This indicates that the lavas are interbedded with locally derived sandstones. The lavas were known locally as 'cork rock' because of their vesicular character and light weight. The extent of the lavas can be discerned from the distribution of fragments in the fields between Newnoth [517 302] and Mains of Collithie. The lavas are typically highly altered by weathering or hydrothermal activity. Rice et al. (1995) obtained a fresher sample of andesitic lava from a small quarry by the A97 near Whitelums at [NJ 521 324]. They also recorded the presence of associated volcaniclastic rocks that show features typical of hyaloclastites. The lava consists of sparse microphenocrysts of both plagioclase feldspar (An_{48}–An_{53}) and chloritic pseudomorphs after olivine in an ophitic matrix composed of calcic augite, abundant ilmenite laths and largely devitrified interstitial glass. Geochemical analysis showed it to be a basaltic andesite belonging to the high K calc-alkaline series. The lava also shows high LILE/HFSE ratios (e.g. Ba/Nb – 32, Rb/Nb – 3, Th/Nb – 0.56, La/Mb – 2.63) and a high Zr/Nb ratio. These features are typical of subduction-related magmas and the andesite is geochemically similar to calc-alkaline lavas near Montrose (Rice et al., 1995).

Read (1923) noted that andesitic lavas appear to predominate, but he also described a dark green olivine basalt from the Whitelums area [NJ 520 322]. In thin section the rock consists of sparse large plagioclase phenocryts (labradorite) in an ophitic matrix of augite, plagioclase and highly altered olivine. Iron oxide is not common. Read considered the rock to represent a mafic sill intruded into the lavas, but noted that its field relationships could not be seen.

South of the outcrop of lavas, conglomerate is exposed in the River Bogie some 200 m southwest of Candy [NJ 530 303]. The conglomerate is composed of pebbles of locally derived arenite, slaty pelite and red sandstone and was interpreted by Read (1923) to overlie the lava sequence.

Dryden Flags Formation

The Tillybrachty Sandstone Formation is overlain by very poorly exposed sandstones and shales of the Dryden Flags Formation. These are better known from their type area in the Rhynie district to the south, where they host the famous Rhynie Chert deposits (Archer, 1978; Rice and Trewin, 1988). Here they contain dessication cracks, mudflake breccias and caliches indicative of semi-arid lacustrine environments on an alluvial plain. Read (1923) documented grey to reddish grey, flaggy micaceous sandstone and shales that were exposed by the River Bogie, adjacent to Haremire farmhouse [NJ 525 300], and just east of the bridge on the minor road opposite Smithston at [NJ 521 215].

3.3 ENVIRONMENTAL SETTING

During Early and Mid Devonian times Scotland lay some 30° to 25°S of the equator and formed part of a large continental mass termed Laurussia that incorporated much of North America, Greenland and northern Europe. Climatic conditions were subtropical and sedimentation was typically terrestrial to lacustrine, occurring in fault-controlled sedimentary basins, formed during the major uplift that marked the last phase of the Caledonian Orogeny. The resulting Old Red Sandstone Supergroup rocks in north-east Scotland formed in small restricted basins whose sedimentary fill was mainly conglomerates, sandstones and siltstones. The common occurrence of caliche limestones testifies to the presence of palaeosols and there is other evidence of the periodic emergence of the succession, e.g. dessication cracks, plant remains, rip-up mud clasts.

The Turriff Outlier contains basal lithologies that reflect their local derivation and deposition in alluvial fans. The sandstones were deposited by a northward flowing river system that prograded farther north into an impermanent lake. The overlying conglomerates and sandstones of the Middle Devonian Gardenstown Conglomerate Formation were probably deposited in alluvial fans from high energy rivers, again probably flowing northwards. The presence of an Achanarras fish fauna near Gamrie on the coast shows that the Orcadian Lake did cover parts of the area at the time of maximum transgression but at other times alluvial conditions prevailed (Trewin and Thirlwall, 2002).

The Lower Devonian sandstones and shales of the Rhynie/Bogie outlier were also deposited in a fault-controlled basin dominated by alluvial fan systems that here gradually gave way to a dominantly lacustrine environment. Again palaeocurrents appear to have flowed northwards. The Tillybrachty Sandstone Formation contains conglomeratic lenses and is an immature, poorly sorted unit probably indicative of deposition from flash floods on outwash fans. The overlying Dryden Flag Formation represents a dominantly lacustrine and alluvial plain environment. Thin andesitic lava flows were extruded locally in the basin during deposition of this unit and the fossil sinter deposit that is the Rhynie Chert Member represents extensive localised hot spring activity. Despite the semi-arid conditions and tropical latitudes the environment was locally biologically very active, as shown by the plant flora and mainly arthropod fauna preserved at Rhynie and the abundant bioturbation of the sands, silts and muds by burrowing organisms.

4 Cenozoic superficial deposits

4.1 PALAEOGENE/NEOGENE

4.1.1 Palaeogene/Neogene gravels and deep weathering

Within the Huntly and Turriff districts are occurrences of unconsolidated deposits that appear to predate the Pleistocene glacial and glaciofluvial deposits. Their exact age is uncertain but they are considered to be largely of Palaeogene and Neogene age. They include the Buchan Gravels Formation and spreads of intensely and deeply weathered bedrock (saprolite) that can be divided into two distinct types: clayey gruss and sandy gruss (Hall, 1986). Clayey gruss resulted from deep weathering under humid, warm climatic conditions, probably during the Miocene. Comparison of the saprolite mineralogy with that of North Sea sediments suggests that highly kaolinitic weathering mantles formed prior to the Pliocene in north-east Scotland (Hall et al., 1985). The sandy gruss resulted from less intense weathering under humid temperate conditions and is considered to be Pliocene to Early Pleistocene in age. The deeply weathered rocks are best developed in the south-east part of the Turriff district on the higher metamorphic grade Strichen Formation and on parts of the Insch Pluton and related mafic intrusions.

Buchan Gravels Formation

The highly distinctive quartzite and quartz-rich gravels of the Buchan Gravels Formation are known from three localities in the Fyvie and Turriff areas. Of these, the outcrop of the *Windy Hills Gravel Member* at Windy Hills [NJ 795 395], 3 km north-east of Fyvie, is the largest, extending over about 2 km^2. The others, at Wood of Delgaty [NJ 745 508], 2 km north-east of Turriff, and Dalgatty Forest [NJ 737 459], 4 km south-south-east of Turriff, cover a combined area of less than 0.5 km^2. The deposits at Windyhills have been worked piecemeal as a resource for aggregate, generating considerable exposures, whereas at the smaller localities exposure is very poor. Hence, much of what is known about the formation comes from the Windy Hills outcrop, for which there are several detailed accounts (Flett and Read, 1921; Read, 1923; Kesel and Gemmell, 1981; McMillan and Merritt, 1980; Gordon and Sutherland, 1993). A detailed account of the geology of the Windy Hills Gravel Member is given in Merritt et al. (2003).

At Windyhills, some 14 m of dominantly quartzite and quartz gravel is interbedded with white quartz sand and micaceous silt overlying kaolinised pelites (Hall et al., 1989; Kesel and Gemmell, 1981; Koppi, 1977). The quartzite and quartz pebbles are highly rounded, relatively fresh, and some show chatter marks, whereas the sparse granite and psammite clasts are generally decomposed to kaolinitic sand. A few flint pebbles are also present, some of which have been reported to contain Late Cretaceous fossils typical of the Chalk (Christie, 1831; Jamieson, 1865), although subsequent work has failed to confirm the presence of these fossils. Very rare chert clasts, including some of possible Early Cretaceous age, have also been reported (Flett and Read, 1921; Hall, 1987).

Considerable topographical change has taken place since the deposition of the gravels. Inversion of relief means that the gravels now occur on benches at elevations of around 110 to 125 m above OD, high above the current valley floors of the lower Deveron, the Idoch meltwater channel, and the middle part of the Ythan valley.

Clast imbrication, rare cross-bedding and channel forms outlined by ground penetrating radar indicate deposition of the gravels by water moving approximately north-eastwards approximately parallel to the current course of the nearby River Ythan (Kesel and Gemmell, 1981; Merritt et al., 2003; McMillan and Merritt, 1980). Although Flett and Read (1921) argued for a marine origin, the evidence indicates that the Windy Hills Gravel Member is fluviatile in origin, deposited in a pre-Quaternary river course. A glaciofluvial origin has also been proposed, consistent with the presence of quartz grains with surface textures suggestive of a phase of glacial transport and with the presence of striated metamorphic clasts (Hall, 1983; Kesel and Gemmell, 1981).

This may be apply to the quartzite gravels at the south-west end of the outcrop, which have been modified during the Pleistocene by glacial erosion, local deposition of overlying till, and by periglacial disturbance.

Paleogene/Neogene deep weathering deposits

Deeply weathered bedrock and other deposits generated by weathering are widespread but not abundant in the Huntly and Turriff districts, except locally in the south-east part of the Turriff district. The deposits appear to predate the Pleistocene, and show features compatible with their formation under humid tropical and then temperate conditions during the Neogene. This period of intense weathering coincided with the uplift in north-east Scotland, which began in the early Palaeogene and continued into the Early Pleistocene.

Deep weathering affects almost all rock types to varying depths (Fitzpatrick, 1963). The distribution of weathered bedrock is governed mainly by rock type, structure, topography and the variable intensity of glacial erosion. The mafic-ultramafic igneous rocks of the Insch Pluton and the Aberchirder biotite granite are widely and deeply weathered. In contrast, Southern Highland Group rocks and Devonian sandstones and conglomerates are less significantly affected (Hall, 1986), although geophysical surveys suggest that in parts of the Turriff outlier alteration extends down to 10 m (Ashcroft, personal communication to A Hall, 1983). Beds of quartzo-feldspathic psammite within the Dalradian quartzites are frequently kaolinised.

Rocks in shear zones in the low relief depression at the eastern end of the Insch Pluton are weathered to depths of about 50 m (Leslie, 1984). Similar depths of weathering may also occur along the northern margin of the Insch depression and beneath the floor of the Drumblade depression (Ashworth, 1975). Boreholes in the Knock Pluton east of Ruthven also reveal 20 to 30 m of weathered basic igneous rock, although weathering depths are highly variable (Hall, 1983, fig. 12.6.iv).

'Scarp-foot' zones of enhanced weathering occur along the northern margin of the Insch depression at the foot of the Slate Hills (Hall, 1986, fig. 5). Glacial erosion was variably effective but did result in the stripping of weathered rock in some areas. Ice-moulding generally increases eastward along the Insch depression and the distribution of weathered rocks becomes more restricted, although numerous deep pockets and zones still remain. Similarly, weathered rock profiles appear to be less commonly preserved north of Huntly in the area affected by the relatively vigorous eastward flowing Moray Firth ice stream. Outcrops of fresh rock are also more abundant in this area in addition to the fewer occurrences of weathered rock.

Very intense weathering during the Miocene produced clayey gruss that is dominated by kaolinite and illite and small amounts of hematite. Examples of this degree of weathering are known only from the pelitic rocks beneath the Buchan Gravels and silicate clasts within the gravels themselves (Hall et al., 1989; Koppi, 1977). Koppi (1977) also described a highly weathered biotite-bearing feldspathic psammite from Clashindarroch Forest at [435 305], just within the Glenfiddich district.

Within the Huntly and Turriff districts, most saprolites are sandy grusses with low fines, considered to have formed under the humid temperate conditions in the Pliocene and during warmer periods of the Pleistocene (Hall et al., 1985). The clay mineralogy of grusses is closely controlled by bedrock composition. Granitic saprolite clay mineral assemblages are dominated by kaolinite and white mica (Hall et al., 1989), whilst basic igneous saprolites contain a wide range of clay minerals. Plagioclase feldspar and hornblende in the Insch Pluton are largely unaffected by weathering. Pyroxene alters first to iron oxides and then vermiculite, whilst biotite weathers to hydrobiotite and vermiculite and, locally, kaolinite and gibbsite (Basham, 1974). Kaolinite and mica clays predominate in weathered metamorphic quartzo-feldspathic rocks, but the presence of ferro-magnesian minerals results in an increased smectite content (Hall et al., 1989).

Deep weathering profiles are highly variable (Hall, 1983). Weathering of igneous rocks normally leaves a residual coarse grit, with or without core stones. Weathering of metamorphosed pelitic and psammitic rocks results initially in deep blocky disintegration with the progressive development of fines as weathering becomes more intense. Borehole intersections of the weathering profile and the bedrock show that typically there is a gradational contact. However, in rare cases a sharp contact is observed (Hall, 1986).

4.2 QUATERNARY

Quaternary superficial deposits are dominated by those formed as a result of main Late Devensian glaciation between about 26 000 and 13 000 years BP (before present) (Merritt et al., 2003). Note that most of the ages quoted in the Quaternary section relate to calibrated years BP (taken as 1950). Uncalibrated radiocarbon (^{14}C) ages are also quoted here, but they have not been adjusted and recalibrated. Radiocarbon years can be converted graphically to calibrated years (BP), but the adjustments can be complex and may result in a spurious accuracy. Where ages lie at or above the limit of ^{14}C dating (c. 50 000 years BP), as in the two instances cited below, no advantage is obtained by their conversion. Regional setting and timing

The Huntly and Turriff districts lie in a region which underwent complex glaciation and deglaciation during the Quaternary, dominated by ice sheet build-up, movements and subsequent decay in the Late Devensian between about 26 000 and 10 000 years BP (Sutherland and Gordon, 1993; Merritt et al., 2003). Interaction between separate Late Devensian ice sheets, one cold-based and sourced in the Cairngorms, the other wet-based and occupying the Moray Firth, occurred to the north and east of Turriff, with the Moray Firth ice stream transporting and depositing large rafts of Pleistocene marine sediments and Jurassic clays on the mainland (Figure 3). A cold, dry interstadial possibly occurred between about 21 000 and 18 000 years BP as has been documented in the Fennoscandian ice sheet (Sejrup et al., 2000). Amelioration of the climate during the Windermere Interstadial (13 000 to 11 000 years BP) was interrupted by the Loch Lomond Stadial about 11 000 years BP. This period of intense cold lasted about 1000 years until the start of the Holocene (10 000 years BP). Permafrost conditions were re-established, leading to the formation of ice wedges, periglacial solifluction deposits and frost shattering.

4.2.1 Pre-late Devensian deposits

Evidence of interstadial deposits that pre-date the Late Devensian glaciation is rare in Scotland, but in 1980 a drainage contractor discovered organic deposits beneath the till in a drainage ditch by Crossbrae Farm at [NJ 753 512]. The site was first described in Hall (1984) but further excavations in 1992 (10 pits in total) resulted in more extensive studies (Whittington et al., 1998). The pits reveal topsoil over a brown and red diamicton up to 2.5 m thick, which in the more north-easterly pits is underlain 0.4 to 1.2 m of pale brown-grey, crudely bedded sandy quartz and quartzite gravel. In two of these pits the gravel overlies a unit up to a metre thick, consisting of pale grey, disturbed, laminated medium-grained sand lying above organic sand material and sandy peat. A thin, lenticular, sandy peat bed forms the base of the unit and lies on weathered sandstone bedrock. This lower organic unit has a maximum thickness of 55 cm and is termed the Crossbrae Farm Peat Bed (Merritt et al., 2003). Pollen analysis has revealed that dwarf shrub tundra vegetation with *Betula nana* and *Salix herbacea* was formerly abundant. The spike heath, *Bruckenthalia spiculifolia* (Ericaceae), found presently in the Balkans, has also been identified. Forty coleoptera taxa including *Olophnum boreale*, *Acidota quadrata* and *Boreaplius hinningianus* have been reported from the bed (Whittington et al., 1998). At the present day none of the beetles are found in the British Isles but all are found in northern Fennoscandia. Based on the overlap of the climatic envelopes of 23 coleoptera species the mean temperatures of the warmest and coldest months are estimated at 10°C ± 1°C and -9°C ± 3°C respectively. Two samples of the peat were subject to radiocarbon age determination and gave uncalibrated 'humic carbon' ages of 44 030 +910/-820 ^{14}C yr BP and 47 180 +1390/-1190 ^{14}C yr BP, and 'humin carbon' ages of >53 630 ^{14}C yr BP and >61 900 ^{14}C yr BP, respectively (Whittington et al., 1998). These ages are interpreted as minima for the Crossbrae Farm Peat Bed with possible contamination by younger carbon in groundwater. Correlating the Crossbrae site with other interstadial peat sites at

Camp Fauld, Burn of Benholm, Sel Ayre, Fugla Ness and Allt Odhar suggest that the peat formation may date from the Early Devensian Brørup or Chelford Interstadial, equivalent to OIS 5c (95 to 104 ka). The overlying glaciofluvial gravel is interpreted as of probable Late Devensian age, but may be older, as glacial deposits farther east at the Howe of Byth, and farther west in the vicinity of Tiendland, have been ascribed to cold stages in Oxygen Isotope Stages 4 and 3 (Merritt et al., 2003).

4.2.2 Late Devensian glacial deposits

Superficial deposits of Pleistocene age within the Huntly and Turriff districts are dominated by tills with subordinate glaciofluvial deposits.

The glacial, glaciofluvial and glaciolacustrine deposits can be divided into two groups: the East Grampian Drift Group and the Banffshire Coast Drift Group (Merritt et al., 2003) (Figure 3). These were formerly referred to as the 'Inland Series' and the 'Blue-grey Series', respectively (Sutherland, 1984; Hall and Connell, 1991) and also roughly equate with the 'Upper or Northerly' and the 'Lower or Southeasterly' drifts of Read (1923).

Deposits of the Banffshire Coast Drift Group generally underlie deposits of the East Grampians Drift Group and were probably laid down early in the Late Devensian before the East Grampians ice sheet had expanded towards the Buchan coastline (Figure 3).

Although tills are widely distributed, they only attain significant thicknesses in the northern and northeastern parts of the Huntly and Turriff districts. Over the remainder of the area, the till cover is patchy and thin and much of the superficial material is weathered bedrock. The tills are diamictons characterised by poor sorting of clasts in a dense and cohesive sandy, silty and clayey matrix.

Glaciofluvial deposits are concentrated particularly in the valleys of the rivers Ythan, Deveron and Idoch Water and are generally terraced (see also Chapter 9, Applied Geology).

East Grampian Drift Group

These deposits occur over the whole of Sheet 86 and generally were sourced locally from the East Grampian ice sheet. In the Huntly and Turriff districts they consist generally of thin to very thin (< 2 m), typically sandy diamictons, derived mostly from disturbed, weathered bedrock. The uppermost metre has commonly been severely disturbed by periglacial activity. The diamictons strongly reflect their local bedrock albeit with a small eastward or southeastward overlap. They range from typically yellow-brown to grey, sandy tills in the northern part of the Huntly district to dark brown, more clayey tills, full of arenite and slaty pelite fragments, in the areas underlain by the Macduff Formation. The Old Red Sandstone gives rise to a red-brown sandy till. Read (1923) recorded that in Strath Isla west of Meikle Balloch the till is a dark-grey clayey diamicton, derived from the local graphitic pelite unit.

Although the tills are of local derivation, reflecting the largely cold-based nature of the ice sheet, the distribution of erratics implies a more complex pattern of ice movement. Read (1923) documented the nature and extent of erratic blocks across north-east Scotland and drew attention to the distribution of the olivine-gabbro and troctolite that form the western part of the Huntly Pluton around The Bin and Dunbennan Hill. A prominent train of these mafic boulders can be followed northwards as far as Portsoy. Blocks of gabbro and troctolite 2 m to 3 m across are found on the summit of Knock Hill (430 m above OD), and about 735 m north-east of the summit at 249 m above OD, an erratic block known as the Cloven Stone measures 4 m x 3 m x 1.2 m. Similar metre-sized boulders occur on the south-west flanks of Knock Hill. On Sillyearn Hill (quartzite) erratic gabbro and troctolite boulders are also prominent. A prominent ovoid boulder called the Gillymule Stone sits some 275 m south-south-east of Edingight Wood. Erratic mafic boulders are also common in the low ground around Knock, but these may be derived more locally from the gabbros and troctolite of the underlying Knock Pluton. In addition to the obvious northward carry of the Huntly mafic rocks, Read (1923) also documented their northwestward carry to near Cairnie and the Glen of Coachford. The Huntly olivine-gabbros are also found as erratic blocks southeast from The Bin in Strathbogie. Southeastward transport in the southern part of the Huntly district is also shown by spotted slaty pelitic rocks, derived from the aureole of the Insch Pluton, which Read (1923) recorded as occurring as striated blocks in the till overlying the igneous rocks of the pluton. Read (1923) also pointed out that erratics of the prominent garnetiferous cordierite-sillimanite-bearing pelitic hornfels that outcrops immediately southeast of Knock Hill are found farther to the north-north-east.

The erratic blocks were probably incorporated into the basal or lower parts of the ice sheet and hence reflect the ice sheet flow patterns over time. Some may have been derived during earlier glaciations and redistributed in the Late Devensian. Many may have originally been corestones, particularly where derived from the lower relief areas. The distribution of erratics agrees moderately well with information on ice movement directions derived from striae (Read, 1923, Fig.11).

Glaciofluvial deposits associated with the Late Devensian ice sheets only rarely occur in the Huntly and Turriff districts. Eskers are sparse but an excellent example occurs immediately west of Gartly church [NJ 527 350] where two narrow bedded sand and gravel ridges trend approximately 010°, The more easterly known as The Riggin is some 1.3 km long and up to 10 m high. The more westerly ridge, known as Little Riggin, is about 750 m long. Read (1923) recorded that eskers are also found in the parish of Alvah, where disconnected elongate mounds of very coarse gravel trend northwards. A near-continuous feature runs from approximately 375 m west of Rosyburn [NJ 667 560] north for about a kilometre. The northward continuation runs from Fattahead [NJ 661 577] to Mallyrust [NJ 662 596] but lies within the Banff district.

North-east of Huntly lying on both sides of the Knightland Burn is an area some 4 km long by 1 to 1.5 km wide where clays have been worked for brick and tile manufacture at the former Kinnoir Brickworks in the 18th and early 19th centuries. Around Longmoor Wood the clays pass into sands that underlie the low ground of the Corse of Kinnoir [NJ 550 434] and can be traced westwards to the River Deveron where gravels are present. This low-lying area is interpreted as the site of a former late glacial lake (Read, 1923).

The apparently weathered nature of the tills and their overall thinness, together with the dearth of glaciofluvial deposits, has been taken by some workers to indicate that central areas of Buchan are 'moraine-less', and thus were unglaciated during the Late Devensian (e.g. Synge, 1956; Hall and Connell,1991).

Banffshire Coast Drift Group

Deposits of this drift group lies at depth in the northern and eastern parts of the Turriff district and have all been assigned to the Whitehills Glacigenic Formation (Merritt et al., 2003). They are dominated by brown weathering, bluish grey, clayey tills that locally are up to 9 m thick but in this district normally only attain few metres in thicknesses. The tills commonly include abundant fragmentary and occasionally striated shells that are the remains of deeper water mollusca, whose living relatives are found in the colder boreal waters of the North Atlantic. Good sections occur in several places beside the Burn of King Edward [NJ 722 561] and were originally described in detail by Jamieson (1858, 1865, 1906) and summarised by Read (1923). A good section was formerly exposed about 100 m south-west of the old bridge on the Banff-Turriff road. Here Jamieson reported up to 8 m of glaciofluvial sand and gravel (with ice-wedge casts) overlying 9 m of dark grey pebbly mud with striated shells in its basal part. This diamicton, termed the 'Shelly Boulder-clay' by Read (1923), following Jamieson (1865), is now known as the Castleton Member (Merritt et al., 2003). It overlies a 60 cm-thick layer of brown shelly sand, interstratified with over 3 m of stone-free dark grey silt that contains crushed and decayed arctic shells with a few whole specimens apparently in situ. Jamieson viewed this lower shelly silt and sand as an in situ deposit thus requiring sea level to be at over 45 m above current OD at some stage during the Quaternary. Read (1923) favoured an interpretation that viewed the whole sequence as erratic and hence transported from the Moray Firth. This model fitted well with the presence of large and small rafts of Jurassic mudstones and Quaternary marine clays in the till, also derived from the floor of the Moray Firth.

Merritt et al (2003) reported a more recent excavation of the river bank 200 m south-east of the original locality at [NJ 7236 5604]. This confirmed the original succession of terrace gravel over dark grey muddy diamicton, resting in turn on over 6 m of intercalated brown sand, grey silt and mud and dark-grey muddy diamicton. Shell fragments occur in varying concentrations and states of preservation throughout the sequence. Whole shells, including specimens of *Lunatia pallida*, and valves of *Arctica islandica* and *Mathoma balthica* were recoverd from the sand layer at 12 m depth. The basal contact of the sequence was not found, but in a pit beneath the adjacent flood-plain of the burn at [NJ 7234 5602] the lower muddy diamicton rests on coarse glaciofluvial gravel and on Devonian bedrock. In addition, the sequence is distorted and steeply dipping in parts, suggestive of glacial disturbance. Merritt et al. (2003) provide a full list of the mollusca recovered from both recent and older excavations at the King Edward sites, and at Gardenstown and Gamrie. They noted that the taxa represented were very similar but pointed out that only two species, *Tachyrhynchus reticulata* and *Serripes greenlandicus,* can be classed as truly arctic to sub-arctic. One species (*Yoldiella lucida*) is a deep water taxon and two others, *Polinices nanus* and *Turritella communis*, are boreal taxa. However, most of the listed mollusca have also been found in the Windermere Interstadial Clyde Beds of western Scotland. Hence the listed mollusca are typical of a non-arctic, interstadial offshore fauna. This data supports Read's hypothesis that the shelly tills, muds and sands were transported by the Moray Firth ice stream onshore from the bed of the Moray Firth (Read, 1923).

At King Edward five Arctica shells were collected for determination of amino-acid ratios from a till exposure 200 m north-east of Jamieson's section. Ratios ranging from 0.073 to 0.095 (mean value 0.078 ± 0.010) were obtained (Miller et al., 1987). Uncalibrated AMS radiocarbon ages of > 44, 200 and >41,500 ^{14}C years BP were obtained from two of the analysed shells. On the basis of this data Merritt et al. (2003) assigned the Castleton Member of the Whitehills Glacigenic Formation to the interval between 40 and 80 ka BP. They pointed out that this age is consistent with the faunal evidence of interstadial conditions and that the marine muds and sands were thus originally deposited on the floor of the Moray Firth during the late stages of the Early Devensian or in the Mid Devensian (OIS stage 4 or 3).

4.2.3 Sequence of Late Devensian glaciation

Although there has been considerable debate about the extent of glaciation over the of Buchan region, which includes the Huntly and Turriff districts, the current view is that the area was overwhelmed by ice during the Late Devensian (Peacock and Merritt, 1997; Whittington, et al., 1998).

During an early phase of Late Devensian glaciation, ice belonging to the Moray Firth ice stream, derived largely from the Northwest and Central Highlands, flowed south-east across the north-eastern part of the Turriff district (Figure 3). This general south-eastward-directed flow was caused by the presence of Scandinavian ice in the North Sea. This large ice mass deflected the Moray Firth ice stream onshore, where it deposited dark grey, clay-rich tills and associated large rafts of Jurassic mudstones and Quaternary sea-floor sediments derived from the floor of the Moray Firth. Erratics derived from inland sources include granitic rocks derived from plutons to the west of the Buchan region, such as the Auldearn Granite Pluton near Nairn and the Inchbae Augen Gneiss (Read, 1923).

The dark tills occur at depth north of a line between Turriff, Blackhills and Deskford, indicating the minimum extent of the incursion of Moray Firth ice. A raft of Lias clay enveloped in till was found when the railway cutting was made at Plaidy [NJ 730 550]. This mass was large enough for a brick pit to operate in the late 19th century (Jamieson, 1859; Jamieson, 1906).

Dark grey clay-rich till and beds of sand and gravel occur in the King Edward Burn (Read, 1923). These sediments contain cold water to arctic marine shells. These are commonly fragmented and striated, but locally appear undisturbed. Sutherland (1981) suggested that certain of the shelly sediments are in situ marine deposits of Mid Devensian age. However, temporary excavations near Castleton Bridge [NJ 722 561] have shown, extensive shearing and disturbance within similar sediments and it is likely that these materials represent glacitectonic rafts (Peacock and Merritt, 1997, 2000).

Later in the Late Devensian, local East Grampian ice covered the Huntly and Turriff districts, flowing to the north and northeast. This is indicated by striae orientated north and north-east that locally are superimposed on older easterly striae, e.g. at Rothiemay [NJ 541 498], and at Alvah, in the Banff district (Read, 1923). The train of basic igneous erratics that has been documented north and north-east of the Huntly Pluton, apparently extending as far as the coast, testifies to the extent of this ice sheet (Read, 1923). The presence of basic igneous erratics at > 400 m above OD on Knock Hill indicates an ice sheet of considerable thickness. The only significantly thick tills that have been attributed to this ice movement occur mainly in the coastal zone outwith Sheet 86 (Peacock and Merritt, 2000). Read (1923) regarded this north to north-easterly ice flow as the final ice movement within the Huntly and Turriff districts, but complex movements of the margin of the Moray Firth ice lobe have been deduced from localities along the Moray Firth coast (Peacock and Merritt, 1997, 2000).

The system of large meltwater channels which extends from Gardenstown to Turriff and the associated high level terraces around King Edward and Turriff show that Moray Firth ice extended to the present coastline, even at a relatively late stage in the deglaciation of the Huntly and Turriff districts. This ice dammed the lower Deveron system, resulting in the deposition of silts (Kirkburn Silts Formation) in the resulting lakes. Meltwaters from the Deveron catchment were diverted into the Ythan via the Towie Spillway, south-south-east of Turriff, where they deposited the only extensive spreads of glaciofluvial sand and gravel within the Huntly and Turriff districts.

This model of glaciation in the north-east Grampians is almost certainly over-simplified and relates only to the Late Devensian. Thus, no account is taken of pre-Devensian glacial events and their possible role in the distribution of erratics. Read (1923) provided a thorough account of the distribution of erratics, but it is possible that certain blocks were not attributed to their true sources, due to the poor exposure. Drift thicknesses are limited over much of the district due to nondeposition and few multiple till sequences are known. The relative age of the two periods of main ice movement rests on evidence of crossing striae at just two sites and on the stratigraphical relationships seen in the till sections exposed at Boyne Bay and at Gardenstown in the Portsoy (Sheet 96W) and Banff (Sheet 96E) districts, respectively (Peacock and Merritt, 1997, 2000). Deglaciation occurred under cold, dry 'periglacial' conditions over a long period, during which time there was considerable cryoturbation and gelifluction (Sutherland, 1984).

4.2.4 Windermere Interstadial and Loch Lomond Stadial deposits

The Windermere Interstadial was a period of milder climate which began around 13 000 years ago, but was terminated by climatic cooling at around 11 000 years ago. It was succeeded by a further cold period, the Loch Lomond Stadial, which persisted for only about 1000 years. Organic and inorganic deposits from these two periods are known for a number of sites in the Huntly and Turriff districts and pollen analysis indicates the presence of a tundra vegetation cover of mainly grasses and sedges, with some dwarf birch and willow. Ice cover was not re-established in these districts but corrie glaciers were present in the Cairngorms and a significant ice sheet formed farther west in the Grampian Highlands.

Almost continuous vegetation cover was established during the Windermere Interstadial, following the final retreat of the Late Devensian ice sheets from north-east Scotland. Peats and organic muds from this period and the later Loch Lomond Stadial are known from excavations at Woodhead, Fyvie [NJ 788 384] (Connell and Hall, 1987), Fisherie Green [NJ 791 589] and North Gorrachie [NJ 7385 5857] (Whittington et al., 1998).

The Loch Lomond Stadial was a period of intense cold that resulted in permafrost conditions in north-east Scotland. Ice wedge casts are commonly present in sand and gravel quarries and at least some these structures formed during this period (Gemmell and Ralston 1984). Examples have been noted in gravel pits south of Turriff [NJ 736 493] and elsewhere (Connell and Hall, 1987; Galloway, 1961). Involutions and vertically orientated clasts, rotated as a result of freeze-thaw action, are also widespread in gravel pits in the Turriff area (Connell and Hall, 1987). However, the finest example of rotated clasts in the districts occurs in the quartzite gravels at Windy Hills (see above). Here, the entire upper metre of the deposit locally consists of sub-vertically orientated clasts.

Frost shattering of rock is also widespread. Some shattering predates the last glaciation, as with the shattered quartzite as Newbigging [NJ 527 591], which is overlain by till (Galloway 1958). Shattering is particularly well developed on the Durn Hill Quartzite, for example, at Gallowhill [NJ 484 525] and it reaches a reported depth of 8 m on Sillyearn Hill [NJ 507 514] (Galloway 1958). The phyllitic semipelitic rocks around the headwaters of the Ythan and in the Glens of Foudland also show shattering to depths of 3 to 5 m (Galloway 1958).

Periglacial mass movement deposits are also widespread. In an old quarry at Cadgers Road [NJ 662 344], up to 3.5 m of head is exposed, developed on a surface slope of 12°. The upper 2 m consists of tabular pelite clasts, in parts up to 30 cm in diameter, but mainly less 5 cm, in a matrix of fine sand and silt. The basal metre contains larger blocks and forms an open-work scree deposit. Numerous examples of solifluction deposits occur in the district, for example, at Bruckhills [NJ 692 379], near the headwaters of the Ythan [NJ 630 379], at Woodside [NJ 612 407], and at Gallows Hill [NJ 685 437] (Galloway, 1958). These deposits are typically 1 to 2 m thick, with a well-developed clast fabric orientated near parallel to the slope. However, they lack morphological expression and generally form a smooth blanket of reworked till and weathered and shattered rock.

Evidence that significant solifluction occurred during the Loch Lomond Stadial is provided by the soliflucted tills that overlie Windermere Interstadial peats. Examples are seen at Woodhead, Fisherie Green and North Gorrachie, and similar relationships occur at several localities outside the districts (Connell and Hall, 1987).

4.2.5 Flandrian

Flandrian deposits formed during the last 10 000 years in the Huntly and Turriff districts consist mainly of peat and recent river alluvium, with some fine-grained deposits developed in minor enclosed basins. Spreads of alluvial materials are most extensively developed beneath the floodplains of the main river systems of the Deveron, Idoch Water and the Ythan.

Peat was extensively developed over much of the Huntly and Turriff districts and was notably abundant on ground to the north-east of Fyvie and north of the Deveron in the Huntly district. However, most of the mosses have been locally and commercially exploited and the peat areas reclaimed for agriculture, resulting in significant depletion of the former peat deposits (see also Chapter 9, Applied Geology). Read (1923) recorded that the peat moss lying immediately north-east of Windyhills around [NJ 804 405] was stated to be 6 to 7 m deep in its centre. He also noted that a moss once stretched along the southern margin of the Slate Hills from Kennethmont to Old Meldrum but now only small relic patches remain unreclaimed. Wartle Moss [NJ 723 325] constitutes the largest remaining moss but even this has been worked down to the water table.

5 Intrusive igneous rocks

Intrusive igneous rocks are a major feature of the Huntly and Turriff districts (Figure 1). The Ordovician mafic and ultramafic igneous intrusions that constitute the North-east Grampian Basic Subsuite, a member of the Scottish Highlands Ordovician Suite, form a significant and distinctive element of the geology of this part of Scotland (Figure 4). The Huntly, Knock and Insch gabbro-peridotite plutons form the major intrusions but there are numerous smaller bodies and a wide development of contaminated mafic rocks and interleaved metasedimentary and mafic-ultramafic rocks. The syn- to late-tectonic plutons are also important as potential hosts of economic deposits of nickel, copper and platinum-group elements (PGE). Academic studies and commercial exploration programmes since the 1960s have complemented work by BGS and led to an improved understanding of the nature and origins of the mafic and ultramafic intrusions in the region (Gunn, 1997).

Read (1919, 1923) divided the mafic-ultramafic igneous rocks of the district into two main categories: an ‘Older Series’ that were intruded prior to regional deformation and metamorphism; and a ‘Younger Series’ that postdated these events (Figure 4). The ‘Older Series’ included ultramafic, mafic and felsic intrusions that were generally highly deformed and pervasively metamorphosed. They outcrop as discontinuous concordant sheets and pods in a belt that runs south-south-west from the Banffshire coast at Portsoy for over 30 km. They have been designated here as the Succoth–Brown Hill type intrusions. Read’s ‘Younger Series’ included a similar range of compositions, here dominated by the mafic and ultramafic rocks of the Huntly, Knock and Insch plutons.

Igneous rock nomenclature used in this report is based upon the latest BGS Rock Classification Scheme (Gillespie and Styles, 1999; Gillespie et al., 2012).

5.1 PRETECTONIC GRANITES

5.1.1 Keith–Portsoy Granite

Several lenticular bodies of foliated augen granite ranging from a few metres to 350 m thick have been intruded into Appin and Argyll group metasedimentary rocks in the north-west part of the Huntly–Turriff district. They form part of a more extensive network of sheets and lenses of granite that extends from a kilometre west of Portsoy, south-westwards to beyond Keith [NJ 433 505], approximately coincident with the anastomosing south-east-dipping Keith Shear Zone. The main outcrops were previously known as the ‘Windyhills Granite’ (Read, 1923).

The granite bodies are mostly poorly exposed, and typically form yellow-brown, cream and grey, weathered, friable, rounded masses with wide jointing. However, in parts they are represented by collections of subangular to rounded, relatively unweathered boulders. The best exposures are found in the Bowie Burn, around [NJ 4865 5633], in the Burn of Aultmore between [NJ 4602 5294] and [NJ 4596 5251], and around Over Windyhills [NJ 4923 5672] and Nethertown [NJ 4928 5725] farms, from where they extend up the western flank of Lurg Hill [NJ 507 575].

Where fresh and unfoliated, e.g. on parts of Lurg Hill, the rock is a grey and pink mottled, macroporphyritic, granite with minor muscovite. More commonly it is strongly foliated with a marked down-dip extension lineation, with conspicuous feldspar augen (after phenocrysts) and abundant muscovite. Pink potash feldspar megacrysts, up to 30 mm long, are ubiquitous and smaller subsidiary plagioclase megacrysts also occur in parts. The granite typically contains abundant small grey, fine-grained dioritic and metasedimentary xenoliths. The pervasive foliation is defined by aligned biotite, muscovite, recrystallised elongate to ribbon quartz, and by the preferred orientation of the feldspar megacrysts. It strikes north-east and dips generally south-east at 25° to 40°, subparallel to the margins of the granite sheets, and the bedding and regional cleavage. Where granite sheets intrude semipelites, their margins are commonly diffuse, and the semipelites share a similar fabric and extension lineation with the granite. In some areas pink feldspar porphyroblasts are locally developed in semipelitic rocks marginal to the granite, e.g. in the Burn of Aultmore at [NJ 4590 5334].

Eight representative samples were collected from fresh exposures the along its outcrop of the Keith–Portsoy Granite. The localities selected stretched from the Banffshire Coast south-west via Boggierow Quarries (Sheet 96W – Portsoy district) to Lurgbrae in the Huntly district and Muldearie, Keith, Glass and the Hill of Bellyhack in the Glenfiddich district (Sheet 85E). The samples were analysed at BGS in Keyworth using X-Ray Fluorescence Spectrometry on fused glass beads for the major elements, and pressed powder pellets for the trace elements. Full sample locations and analytical values are given in Appendix 1.The sample from the Banffshire coast section (GX 1717) was taken from a discordant lenticular granite dyke where it cuts an amphibolitic mafic sheet. Its geochemistry shows that the granite has assimilated a limited amount of mafic material in that it exhibits markedly low SiO_2, K_2O, P_2O_5 and Rb values and elevated TiO_2, Al_2O_3, Fe_2O_3, MgO, Na_2O, CaO, SO_3, and Cu, Sr and Zr values. As such it is atypical for the granite and is excluded from the discussion below and from Table 3 that shows the mean composition of the Keith–Portsoy granite in comparison to that of Ben Vuirich and published mean values for the major typological classes of granitic rocks.

Table 3 Whole-rock geochemistry (mean values) of the Keith–Portsoy Granite, Ben Vuirich Granite, and the major typological classes of granite.

.[1]: mean of 7 samples. [2]: mean of 33 samples (from Tanner et al., 2006). [3]: mean of 578 S-type granites, 991 I-type granites, 421 felsic I-type granites and 148 A-type granites (Whalen et al., 1987).

	Keith–Portsoy[1]	Ben Vuirich[2]	S-type[3]	I-type[3]	Felsic I-type[3]	A-type[3]
SiO_2	70.80	72.30	70.27	69.17	73.39	73.81
TiO_2	0.59	0.60	0.48	0.43	0.26	0.26
Al_2O_3	13.92	12.96	14.10	14.33	13.43	12.40
FeO	3.51*	3.26	2.87	2.29	1.32	1.58
MnO	0.04*	0.06	0.06	0.07	0.05	0.06
MgO	1.08	0.74	1.42	1.42	0.55	0.20
CaO	1.21	1.51	2.03	3.20	1.71	0.75
Na_2O	2.72	2.88	2.41	3.13	3.33	4.07
K_2O	4.88	4.22	3.96	3.40	4.13	4.65
P_2O_5	0.16	0.16	0.15	0.11	0.07	0.04
Rb	185	152	217	151	194	169
Sr	165	162	120	247	13	48
Ba	533	720	468	538	510	352
Y	33	48	32	28	34	75
Zr	271	359	165	151	144	528
Nb	19	20	12	11	12	37
Ni	10	20	13	7	2	<1
Cr	43	26	nd	nd	nd	nd
V	33	34	56	60	22	6

*Measured as Fe_2O_3 and Mn_3O_4

The high SiO_2 content (70.25 to 71.68 wt%; mean 70.80%) and restricted compositional range make it difficult to establish a clear lineage for the Keith–Portsoy Granite samples, and the absence of certain elements from the dataset, notably Ga, an important discriminator for A-type granitic rocks, precludes a full assessment of the typological affinity. However, the mean values for the Keith–Portsoy granite samples suggests it can be best described as exhibiting mild A-type characteristics, or characteristics transitional between A-type and felsic I/S-type granites. The granite has a high-K, peraluminous character, bordering on shoshonitic. On the Nb/Y diagram the analyses plot just in the within-plate field (Figure 5). As such, it displays notable compositional similarities with the Ben Vuirich Granite Pluton (Table 3), the 'type' intrusion of the approximately 600 Ma Vuirich Suite (Tanner et al., 2006). Its similar composition and age (see below) suggest the Keith–Portsoy intrusion is part of the Vuirich Suite, a swarm of generally small, extension-related, broadly A-type granitoids that can be found stretching from the Appalachians to Scotland. Its sheet-like nature, strong foliation, and concentration in a roughly planar zone suggests that its emplacement, which occurred prior to the main regional deformation, was controlled by a pre-existing lineament. That zone was subsequently the focus for ductile shearing; granite samples from boreholes around Keith show distinctive asymmetrical augen 'tails' that imply that this later shearing was north-west directed (see Chapter 6 – Structure). The related foliation and lineation correspond to the main secondary deformation phase in this area, here termed D2.

A concordant zircon U-Pb age of 599.9 ± 2.5 million years (Ma) was obtained from acicular euhedral zoned zircons separated from a foliated Portsoy Granite sample taken from Boggierow Quarries, about 1.6 km south-west of Portsoy. More internally complex, partly inherited zircons separated from a more strongly foliated granite sample from a borehole in the Keith area gave a discordant U-Pb age with a lower intercept at 600.8 ± 2.5 Ma and an upper intercept age at 1491 ± 25 Ma (Barriero, 1998). The lower intercept age agrees with that obtained from the Boggierow sample, and confirms that the granite was intruded at about 600 Ma. The upper intercept suggests that the granite formed by partial melting of lower to middle continental crustal material previously subjected to a major tectonometamorphic event at around 1500 Ma.

The Neoproterozoic intrusion age for the Vuirich Suite granites corresponds to a period of rifting that marked a significant phase in the progressive thinning of the Rodinia supercontinent. The intrusion of the Vuirich Suite granites occurred coeval with voluminous localised basic magmatism, whose manifestation is well seen in the Tayvallich area of the south-west Highlands. These events took place some 30 to 50 Ma prior to rift-drift transition that signalled the formation of the Iapetus Ocean and formation of the separate continents of Laurentia and Gondwana (Dalziel, 1997). In Scotland this last event marked the onset of dominantly turbiditic sedimentation, now manifest by Southern Highland Group metasedimentary rocks.

5.2 PRETECTONIC MAFIC–ULTRAMAFIC ROCKS

In the Huntly district, lenses, pods and sheet-like bodies of mafic and ultramafic rocks crop out discontinuously within, or close to, the Portsoy Shear Zone between Brown Hill [NJ 440 367] and Drumnagorrach [NJ 522 525]. These rocks are considered to be pretectonic and are referred to here as the Succoth–Brown Hill (S-BH) type, after the large ultramafic intrusion of that name that lies some 4.5 km west-south-west of Huntly and extends south-westwards into the adjacent Glenfiddich district (Sheet 85E) (Styles, 1994, 1999) (Figure 4).

Several small deformed and metamorphosed ultramafic bodies also occur mainly peripheral to the western part (Boganclogh sector) of the Insch Pluton. This concentration is termed the Boganclogh margin type, and is also interpreted as pretectonic (Styles, 1994, 1999).

5.2.1 Succoth–Brown Hill type

The Succoth–Brown Hill mafic-ultramafic intrusion forms a poorly exposed elongate pod underlying an area of approximately 14 km^2 (Gunn et al., 1990, 1996). The boundaries of the intrusion are not exposed, but are interpreted as probably shear zones or faults. About 70 per cent of the complex is composed of metagabbroic rocks. The remainder consists of ultramafic rocks disposed in two belts along the northern and southern margins, the rocks along the latter being largely serpentinised.

The metagabbroic rocks exhibit wide textural variation and include highly deformed, heterogeneous types, homogeneous, medium-grained variants with gabbroic texture and fine-grained, foliated mafic types (Plate 1). Penetrative foliations and mylonitic fabrics have mostly near vertical or steep east or south-east dipping orientations, probably reflecting the margins of the intrusion. Coarse-grained ultramafic intrusive rocks comprise variably altered and recrystallised clinopyroxene-rich and olivine-rich lithologies. Primary igneous features are poorly preserved as a result of later deformation, metamorphism and alteration. However, relatively undeformed modal layering that dips south-east at 30 to 40° is present in pyroxene-rich rocks in exposures near Red Burn [NJ 3448 8382].

It is not possible to deduce an original igneous 'stratigraphy' for the intrusion based on the distribution of rock types due to the deformation and the tectonic nature of the marginal zones and contacts. Magnetic and topographical data indicate that many of the units are discontinuous, their present extent being controlled by the occurrence of shear zones and later faulting. Elongate screens of quartzite have been mapped in the western sector of the intrusion. These may have been emplaced tectonically or may indicate that the igneous rocks were originally intruded as sheets.

Smaller bodies of S-BH type also occur at Whitehill [NJ 518 460], Brownhill [NJ 506 460] and about a kilometre north of Roadburn [NJ 513 453]. These intrusions lie within and adjacent to a major north-west-orientated faulted zone that effectively separates the Huntly and Knock plutons. Their external boundaries are inferred to be tectonic; north-east-trending shear zones occur parallel to the long dimension of the bodies and they are transected by the later north-west-orientated brittle faults. At Whitehill, heterogeneous, texturally diverse metagabbroic rocks are dominant, with subordinate discontinuous elongate pods and sheets of predominantly clinopyroxene-rich ultramafic rocks. Deformation fabrics are generally steeply dipping and lie subparallel to the mapped margins of the intrusions. Locally preserved primary igneous features indicate that these rocks were originally mafic and ultramafic cumulates. Relict igneous layering is preserved at Whitehill quarry [NJ 5186 4628] where thin, olivine-rich layers occur within clinopyroxenite.

In the Brownhill intrusion and its south-western extension towards Cairnie, the metagabbroic rocks are highly sheared within the PSZ, locally exhibiting a strong foliation. South of Cairnie, towards the River Deveron, metagabbroic rocks crop out in discontinuous sheets and lenses, one of which can be traced southwards into the Succoth–Brown Hill intrusion, These bodies lie close to the south-western corner of the Huntly pluton.

Serpentinised ultramafic rocks are found at several other localities within the PSZ. At the Hill of Milleath [NJ 470 425] sheared serpentinites, possibly metawehrlites, are poorly exposed on a prominent hill over an area of about 0.3 km^2, forming an elongate pod about 1.2 km in length. A smaller pod of foliated serpentinite crops out adjacent to Ballochburn [NJ 489 479] at the western margin of the PSZ, close to the south-western corner of the Knock Pluton. The rock type here was originally rich in clinopyroxene, similar to the ultramafic rocks of the Succoth–Brown Hill intrusion. A further elongate body of ultramafic rocks up to 250 m wide, defined by ground magnetic survey data, extends from south of Drumnagorrach [NJ 5203 5251] in a south-westerly direction for about 1.8 km, again, along the western margin of the PSZ. Mineralogical studies indicate that these rocks were originally dunites and clinopyroxenites similar to those found in the Succoth–Brown Hill Intrusion. Many show evidence of an early stage mylonitisation under amphibolite-facies conditions.

Petrographical studies reveal certain common features within the S-BH type bodies:

i. The ultramafic rocks are mainly clinopyroxene rich, originally either clinopyroxenites or olivine-clinopyroxenites. Subordinate wehrlites and dunites also occur.
ii. The order of primary crystallisation is either clinopyroxene-olivine-plagioclase or olivine-clinopyroxene-plagioclase.
iii. The mafic rocks were originally gabbros, but contain no evidence of original olivine or orthopyroxene.
iv. All the rocks exhibit evidence of multiple phases of recrystallisation and alteration. Primary magmatic textures are rarely preserved.

Microphotographs of typical S-BH type rocks are shown in Plate 3 (v, vi).

The pretectonic mafic and ultramafic rocks are also characterised by their distinctive mineral chemistry. In the ultramafic rocks of the Succoth–Brown Hill intrusion, clinopyroxenes, and the amphiboles which replace them, are rich in Ca and Mg, with Mg# around 90. Olivine compositions range from around Fo_{80} to Fo_{92}. Although plagioclase ranges widely in composition (An_{90}-An_{32}), compositions are typically greater than An_{80} and, in some cases, even exceed An_{90}. Styles (1994, 1999) has shown that the ultramafic parts of the other S-BH type bodies in the region have comparable mineral chemistries.

5.2.2 Boganclogh margin-type ultramafic rocks

Small bodies of serpentinised and sheared dunite and harzburgite, which occur along the northern margins of the Insch Pluton, notably along the Boganclogh sector, are included in the Boganclogh margin type (Styles 1994, 1999). In the Huntly district, elongate pods occur 1 km west of Old Merdrum [NJ 458 298], and at Leith Hall Home Farm [NJ 541 303 to 550 304]. A large body occurs on the Mount of Haddoch at the north-west corner of the Insch Pluton (Boganclogh Sector), but only just extends into the Huntly district at [NJ 434 297]. The rocks were originally harzburgites with subsidiary dunites, but most were completely serpentinised and recrystallised during shearing, destroying any original igneous fabrics.

The harzburgites contain orthopyroxene crystals up to 6 mm long, set in a groundmass of serpentinised olivine. These large orthopyroxenes have been deformed, resulting in bent crystals with some recrystallisation to finer-grained aggregates. The proportion of orthopyroxene varies from very low in the dunitic rocks up to about 20 per cent in the harzburgites. In some specimens, the olivine has almost completely altered to antigorite (serpentine), and the orthopyroxene to bastite (serpentine), or locally to amphibole. Where the serpentinites have been strongly deformed, the antigorite has recrystallised to define a strong planar fabric and secondary iron oxide has been streaked out, giving the rock a banded appearance. No mineral analyses have been obtained for these rocks in the district, but they are petrographically similar to the ultramafic rocks along the southern margin of the Boganclogh intrusion, which contain olivines of $Fo_{92–89}$ and interstitial orthopyroxenes of En_{92}.

5.3 SYNTECTONIC MAFIC-ULTRAMAFIC ROCKS

Intrusive rocks of the North-east Grampian Basic Subsuite form several major plutons, intrusion-swarms and sills in the East Grampian region. They are interpreted as having been intruded at or near the peak of metamorphism during the Early Ordovician and have been termed the ‘Younger Series’ (Read, 1923), the ‘Younger Basic’ suite (Fettes and Munro, 1989) and also the ‘Newer Gabbros’. The Huntly and Knock gabbro-peridotite plutons lie entirely within the Huntly district, and parts of the Insch Gabbro-peridotite Pluton also crop out along much of the southern margin of the Huntly and Turriff districts.

These intrusions are composed of a wide range of mafic and ultramafic lithologies of both cumulate and non-cumulate origin. Previous studies have focused mainly on the cumulate rocks, which consequently are better known than the non-cumulate rocks. Subsidiary intermediate and felsic lithologies are also present, notably in the insch Pluton. Clarke and Wadsworth (1970) established a zonal classification for the cumulate rocks of the Insch Pluton based upon phase layering:

Upper Zone (UZ)	- UZc: syenite
	- UZb: olivine monzonite, olivine monzodiorite
	- Uza: olivine ferrogabbro
Middle Zone (MZ)	- norite, gabbro, quartz-biotite-norite
Lower Zone (LZ)	- dunite, peridotite, troctolite, olivine-norite, olivine-gabbro

Associated cryptic variation in mineral chemistry indicates progressive fractionation of the magma upwards through the zonal sequence. This framework has been adopted by other workers as a basis for comparison between the intrusions in the region and for studying their petrogenesis.

5.3.1 Huntly Gabbro-peridotite Pluton

The Huntly Gabbro-peridotite Pluton underlies approximately 40 km^2 around the town of Huntly. The external boundaries and internal structures of the intrusion are very poorly exposed. Major parts of the western margins of both the Huntly and Knock plutons are bounded by north- to north-east-trending shear zones that form part of the PSZ (Figure 4). The Central Huntly Shear Zone, that branches off the PSZ a few hundred metres south of Whitehill, transects the central part of the Huntly mass. Farther north the zone is coincident with the eastern flank of the Knock intrusion for at least 3 km. Evidence for shearing at the western boundary of the Huntly body comes from boreholes near Cairnford at [NJ 4861 4080] and at Drumdelgie [at around NJ 486 422] (Munro, 1984). At Drumdelgie sheared and crushed cumulates occur close to metasedimentary rocks that lack evidence of hornfelsing, indicating tectonic juxtaposition. At the north-western boundary of the pluton mylonitic and foliated rocks with some brecciated zones make up a complex sheared margin and are exposed in sporadic exposure along the Burn of Cairnie to the south of Midtown [around NJ 492 444].

Ground magnetic surveys across the eastern and south-eastern margins of the intrusion suggest that magnetic gabbroic rocks, inferred to be olivine-bearing cumulates, are intercalated with a mixed nonmagnetic assemblage of altered and contaminated gabbroic and metasedimentary rocks. The northern boundary of the intrusion is inferred from magnetic and topographical discontinuities to be defined by faults trending north-west and east-north-east. Faults orientated approximately west-north-west and north-west also define much of the south-western margin of the intrusion. A gas pipeline trench extending for almost 7 km from the River Deveron at [NJ 485 405] towards the south-south-east to [NJ 545 379], about 650 m south of Cairn Hill, provided useful control on the position of the southern contact (Munro, 1984; Munro and Gallagher, 1984). Along most of its length the trench exposed non-hornfelsed migmatitic metasedimentary rocks, locally mylonitic, but gabbroic rocks were recorded in a short section south of Craigwillie, around [NJ 51 39].

A wide variety of rock types have been identified within the Huntly intrusion reflecting primary magmatic variations, subsequent contamination, and later deformation and alteration. Four principal groups of rocks are recognised:

i) cumulate rocks
ii) modified cumulate rocks
iii) contaminated igneous rocks
iv) pegmatitic rocks

Internal boundaries between these groups are not exposed, but their positions can be inferred locally from topographical features and magnetic data. The olivine cumulate rocks produce the highest magnetic field intensity and as a result their contacts can be defined relatively accurately. In contrast the other rock types (modified cumulates and contaminated/xenolithic lithologies) have generally low magnetic susceptibilities.

Cumulate rocks

Mafic and ultramafic intrusive igneous rocks displaying cumulate textures are widely distributed in the Huntly pluton (Figure 6a). They may be recognised in hand specimen by their euhedral, commonly equigranular, medium-grained textures. The principal mafic rock type is olivine-gabbro, with minor troctolite, olivine-melagabbro and rare anorthosite. Ultramafic rock types are subordinate to those of mafic composition, but include plagioclase-bearing peridotite and mela-troctolite with minor developments of dunite, peridotite and pyroxenite. The cumulate rocks locally display excellent primary igneous textures, principally layering and crystal lamination.

In the Huntly pluton cumulate rocks form several apparently discrete bodies. Some of these are defined on the basis of single outcrops or boreholes, locally supported by magnetic survey data. The largest outcrops are termed the West Huntly and East Huntly cumulate bodies, but smaller bodies also occur close to the eastern and southern margins of the pluton (Figure 6a).

West Huntly: the West Huntly body is the best known because of the relative abundance of natural exposures, and its outcrop in disused quarries, along forest tracks, and in boreholes drilled by BGS, the University of Aberdeen and by commercial exploration companies.

The cumulate rocks crop out over approximately 7 km^2, mainly in Dunbennan Wood [NJ 495 415] and the Bin Forest [NJ 510 430], where they are cut by a number of faults. Boreholes through a narrow north–south band of ultramafic cumulate rocks close to the western margin of the body intersected a sheared contact, although local hornfelsing of the country rocks is evident. Olivine-gabbro is the dominant rock type of the West Huntly body with subordinate troctolite, melatroctolite, mela-olivine-gabbro and rare thin bands of anorthosite. Olivine-orthopyroxene-gabbro occurs in the eastern parts of its outcrop.

Crystal lamination and igneous layering are common. The layering ranging from less than a centimetre up to several metres thick, and generally trends between north and north-north-east and dips steeply or near vertically (Plate 2). In the northern part of the body in the Bin Forest the layering dips to the west, whereas in its southern part around Dunbennan Hill, it dips to the east. Modal layering, reflecting the variations in the proportion of plagioclase to the mafic constituents, is the most widespread form, but grain size, phase and textural layering are also locally developed. Pseudosedimentary structures are locally preserved in the layered sequences. These include scour features, current bedding, and rip-up clasts. These features, together with the cryptic variation in mineral compositions and graded layering, all indicate a younging direction to the east. The northern section, in the Bin Forest, is thus interpreted as being overturned. Cyclic units, marked by repetitive phase layering with the onset of olivine crystallisation, are present on the metre scale, but larger scale cyclic units cannot be identified with confidence.

The primary magmatic features of the West Huntly cumulates are most clearly displayed in the disused Bin Quarry [NJ 498 431] and in Sinsharnie Quarry [NJ 490 440].

East Huntly: In the East Huntly body cumulate rocks underlie about 3 km^2 straddling the River Deveron to the north-east of the town of Huntly (Figure 4a). Coarse-grained olivine-gabbro and troctolite are the main rock types. Layering and other primary magmatic features are rarely observed: a small exposure on the north-west flank of Hill of Mungo [NJ 547 427] displays indistinct layering and crystal lamination with a north–south trend and near vertical attitude.

The western and southern margins of the body are marked by a sharp transition to a distinctive gabbro containing coarse ophitic clinopyroxene. To the north the cumulate rocks appear to become intercalated with increasing amounts of metasedimentary rocks. To the east they pass into granular gabbroic rocks comparable with those on the eastern flank of the West Huntly cumulate body.

Bridges: high amplitude ground and airborne magnetic anomalies delineate an elongate body of cumulate rocks about 800 m long and 100 m wide at Bridges [NJ 563 425], close to the eastern margin of the Huntly Intrusion. Two boreholes defined an eastern strip of ultramafic cumulates in contact with a western band of troctolites and gabbros. About 400 m to the south-east of Bridges at Costlyburn [NJ 564 416] another small body of gabbroic cumulate rocks is indicated by magnetic survey data and borehole evidence.

There is very little ground control on the distribution of mafic lithologies in the south-eastern part of the Huntly intrusion. Ground magnetic survey data indicate the presence of intercalated bodies of magnetic and nonmagnetic rocks in this sector. High amplitude magnetic anomalies are interpreted to be due to olivine cumulates, probably olivine-gabbro. Locally recrystallised and sheared noritic cumulates have been recovered in shallow boreholes at locations where the magnetic field intensity is low. It is suggested that this margin of the intrusion is characterised by intercalated gabbroic, noritic and metasedimentary rocks, in variable proportions, reflecting either the original intrusive form of the body or modification by shearing, or possibly a combination of both.

Craigwillie: A small isolated body of medium- to coarse-grained leucocratic gabbroic cumulates is exposed to the south-west of Craigwillie [NJ 511 396], close to the southern margin of the intrusion. Near vertical grain-size layering is well developed and trends nearly north–south. Exposure in a gas pipeline trench about 100 m to the south revealed foliated gabbroic rocks. These isolated exposures are interpreted as a small body of cumulate rocks bounded by shear-zones.

Mineralogy of cumulate rocks

The primary order of crystallisation is normally olivine-plagioclase-clinopyroxene-orthopyroxene; grain size ranges mainly from medium- to coarse-grained. Poikilitic textures, defined by pyroxene oikocrysts enclosing or partly enclosing plagioclase or olivine chadacrysts, are common. Ortho-cumulate (75–85% cumulate minerals, 25–15% groundmass) and meso-cumulate (85–93% cumulate minerals) textures are widely observed, but adcumulates (93–100% cumulate minerals) are recorded only locally. Crystal lamination, defined by the alignment of primary crystals, is widely present especially in the western part of the West Huntly cumulate body.

Mineral composition data for cumulus olivine, plagioclase and clinopyroxene show a clear pattern of increasing fractionation in the West Huntly body from west to east. Olivine compositions range from Fo_{85} to Fo_{74}, although local reversals in the general pattern do occur in association with some peridotitic units that show complex mixing textures. Cumulus plagioclase compositions range from An_{77} to An_{68} and mirror the changes in olivine compositions. Cumulus clinopyroxenes are mainly augite with a similar trend of Fe enrichment from west to east in the West Huntly body.

Mineral compositions in the East Huntly body are generally more evolved than those in West Huntly, but a similar west to east fractionation trend can be tentatively identified. Mineral composition data from the other minor bodies of cumulate rocks in the Huntly intrusion are sparse but overlap with those from the East Huntly body.

Modified cumulate rocks

Extensive, but poorly exposed areas of the Huntly and Knock plutons appear not to be underlain by cumulate rocks, but such rocks have received little attention prior to the work of Fletcher (1989). Subsequently, field mapping, BGS Mineral Reconnaissance Programme surveys, and re-evaluation of EVL borehole data, show that these 'non-cumulate' rocks consist of a variety of rock types including modified cumulates and contaminated gabbroic rocks (Figures 6b, c). Each type commonly has textural affinities with adjacent units and irregular or gradational contacts.

West Huntly: the relationships between modified and unmodified cumulate lithologies are best seen in the West Huntly body. Cumulate rocks that display a range of igneous textures pass eastwards in the Bin Forest into rocks, firstly with an anhedral granular character and then through a range of intermediate types. This transition is best observed on the eastern flanks of the Bin between the Bin Quarry and the summit, but is also discernible in the eastern part of

Dubenan Wood. Towards the east orthopyroxene appears as a cumulus phase, accompanied by an increase in olivine grain size. Aggregates of olivine crystals, up to 2 cm across, give rise to a glomeroporphyritic olivine-gabbro with a distinctive spotted appearance that can be mapped as a discontinuous band up to 50 m wide. Farther east these rocks become increasingly fine grained and develop an anhedral granular texture (Plate 3). Orthopyroxene becomes an increasingly important constituent and olivine gradually disappears. These rocks, termed granular gabbros, outcrop in a band about 1 km wide on the eastern flank of the Bin Forest. They comprise a heterogeneous group, composed mostly of fine-grained gabbroic and leucocratic noritic rocks. They are commonly partly or wholly recrystallised and show amphibolite-facies mineralogies. Although relict primary igneous textures are found locally, a foliation is widely developed and mylonitic fabrics are seen sporadically.

A large area underlain by granular gabbroic rocks extends from the east side of Dunbennan Hill eastwards under the town of Huntly and northwards from there in a band less than 1 km wide towards Haddoch [NJ 534 447]. In this area sporadic exposures of heterogeneous, fine- to medium-grained noritic rocks with minor clinopyroxene are found. Biotite is a common constituent, locally forming abundant coarse plates.

The best exposures of modified cumulates occur in two sections in the River Deveron north of Huntly, at Gibston – between [NJ 514 405] and [NJ 520 408], and near Huntly Castle – between [NJ 531 408] and [NJ 537 409]. Granular gabbroic rocks show discordant, possibly intrusive relationships to cumulate and ophitic gabbroic rocks in Battlehill Quarry [NJ 539 395] and in the Pirriesmill road cutting on the A96 Huntly bypass between [NJ 5315 3929] and [NJ 5330 3926]. Good exposures are also present to the east of the East Huntly cumulate body on and around the Hill of Mungo.

Linear topographical features and discontinuous north-trending aeromagnetic lineaments provide evidence for shear zones running through the central part of the Huntly intrusion. Field evidence for the shear zones is provided by sinuous mylonitic zones in fine-grained granular norites in a disused quarry south of Haddoch [NJ 5335 4440] and in the conspicuous north-trending foliation developed in recrystallised leucocratic gabbros near Robieston Croft [NJ 529 419].

East Huntly: in this area the transition westwards from cumulate rocks to granular gabbros is marked by the abrupt appearance of a distinctive ophitic variety of olivine-gabbro and by orthopyroxene-gabbro characterised by the presence of oikocrysts of clinopyroxene up to 3 cm across. These rocks have been termed ‘patchy cumulates’ by Fletcher (1989). Their texture varies from granular to cumulate over short distances and within individual exposures the two types may be interlayered. These transitional rocks occur in a narrow north-trending strip, 100 to 200 m wide, on the eastern side of the line of hills that include Backwood Hill [NJ 533 438], Crow Wood [NJ 535 425] and Deerpark Wood [NJ 536 420], all underlain by granular gabbroic and noritic rocks. To the south the ophitic rocks underlie a wider area and have been mapped in faulted contact with xenolithic rocks in the River Deveron at [NJ 5372 4088], close to its confluence with the River Bogie. They are widely observed in scattered exposures and as loose blocks in the southern part of Kinnoir Wood [NJ 540 410], on the Hill of Bruntstane [NJ 549 407] and the Hill of Greenfold [NJ 552 414], and in the intervening lower ground to the west.

Ophitic gabbros are also inferred to underlie a broader zone, 700 to 800 m wide, in the central part of the Huntly intrusion, although ground control in this area is poor. Gabbros with coarsely ophitic clinopyroxene, giving them a distinctive spotted appearance, crop out in the south at Gibston [NJ 516 411] and on the lower eastern slopes of Ordiquhill around [NJ 526 432]. Granular gabbros also outcrop sporadically within this zone. The ophitic gabbros marginal to the olivine-gabbro cumulates in East Huntly and elsewhere in the central part of the intrusion are mainly medium- to coarse-grained, although veins and irregular areas of pegmatitic gabbro are commonly developed. Variations in pyroxene content, crystal form and grain size locally produce weak layering. Both interlayered and gradational contacts with cumulate rocks and granular gabbros are observed locally.

Mineralogy of modified cumulate rocks

Cumulate and modified cumulate rocks in the Huntly intrusion belong to the Lower and Middle Zones of Clarke and Wadsworth (1970).

In the West Huntly body the eastward transition from rocks with cumulus textures to anhedral granular varieties is associated with the appearance of orthopyroxene. The transition is accompanied first by the development of glomeroporphyritic olivine-gabbro, followed farther east by the disappearance of olivine and the passage into finer grained varieties of granular gabbro. The compositions of cumulus mineral phases in the modified cumulate rocks show a continuation of the eastward trend of increasing fractionation. Olivine compositions vary from Fo_{77} in the west to Fo_{50} in the granular gabbros in the east, with a corresponding change in plagioclase composition from An_{70} to An_{47}. Iron enrichment trends in clinopyroxene and orthopyroxene are also present across the same area. The ophitic gabbros (patchy cumulates) in the eastern and central parts of the intrusion are characterised by relatively evolved mineral compositions with olivine in the range Fo_{72}-Fo_{62} and plagioclase between An_{69} and An_{56}.

Increasing physical alteration of the rocks is accompanied by mineralogical and lithological changes eastwards across the West Huntly body. There is an overall reduction in grain size associated with recrystallisation of original pyroxene and plagioclase producing rocks of granular character with mainly equant mineral grains. A secondary planar fabric or foliation is also commonly developed. The highest degrees of physical alteration and the greatest development of foliation in the intrusion occur adjacent to and within the Central Huntly Shear Zone, and on the eastern and western margins of the East Huntly cumulate rocks, away from the main cumulate bodies.

Contaminated and xenolithic igneous rocks

Contaminated rocks underlie a broad north–south tract, up to 1.5 km wide, in the central part of the Huntly Pluton (Figure 6c). They also form a series of bodies, commonly occupying high ground, within the Cowhythe Psammite Formation to the east of the mapped boundaries of the Huntly and Knock plutons. With the exception of a small area at Cuttle Hill [NJ 50 47] near the south-west corner of the Knock Pluton, contaminated igneous rocks are largely absent from the western side of the intrusions.

These rocks owe their origin to partial or complete assimilation of material of sedimentary origin and constitute a highly variable group. Several subgroupings may be distinguished locally, but variation is great and even on the scale of a single outcrop, several distinct lithologies may be identified. The rocks appear to have a close spatial association with granular recrystallised gabbroic rocks.

Contaminated gabbroic rocks are mainly medium-grained with considerable variation in texture and mineralogy (Plate 3). Orthopyroxene-bearing rocks predominate, the principal rock types being orthopyroxene-gabbro, clinopyroxene-norite and norite. They are commonly leucocratic containing more than 70 per cent plagioclase, with subordinate biotite, amphibole, garnet and Fe-Ti oxides. Minor quartz, cordierite, olivine, sillimanite, orthoclase, zircon, apatite, sphene, pyrite and pyrrhotite are present locally. They may have sharp or gradational contacts with xenolithic variants and recrystallised cumulates.

Xenolithic gabbros are highly contaminated heterogeneous rocks closely associated with other varieties of contaminated rocks and granular gabbros, forming either irregular patches or, locally, discordant dyke-like bodies. They are commonly medium to coarse grained and typically leucocratic. They contain locally abundant biotite and garnet, together with variable amounts of amphibole, orthopyroxene, cordierite, quartz, sillimanite, spinel, graphite, sulphides and apatite. The xenoliths are up to 2 m in size and may have sharp or diffuse boundaries. Internally they may be little disrupted or may be partly digested. Xenoliths are dominated by pelitic, semipelitic, quartzitic and calc-silicate lithologies, with subsidiary vein quartz, granite and graphitic pelite.

In the central Huntly zone contaminated rocks are well exposed at Boddum Hill [NJ 510 418], Ferny Knowe [NJ 510 423], Ordbrae [NJ 504 419] and Bin Moss [NJ 51 42]. Foliated variants occur at two localities within this zone. The first is on a knoll 300 m west of Gibston [NJ 513 411] where a strongly foliated and recrystallised leucogabbro containing quartz and aggregates of biotite and amphibole is cut by thin vertical mylonitic zones that trend approximately north–south and comprise fine-grained plagioclase, quartz and biotite. The second is a similarly foliated orthopyroxene-gabbro, spotted with biotite, which crops out about 2.5 km to the north, close to Roadburn, at [NJ 515 438]. Xenolithic variants are well exposed on elevated ground at Clean Hill [NJ 516 423], on the north-west flank of Ordiquhill [NJ 518 436], and at Thief's Rock and Horse Rock [around NJ 522 440].

Xenolithic and contaminated gabbroic rocks are inferred to underlie the area around Cumrie [NJ 520 445] and Hill of Cormalet [NJ 525 451] at the northern end of the central Huntly zone. Exposure is rare in this sector but numerous, widespread large float blocks support the interpretation. The detailed mineralogy of these rocks has been documented by Droop et al. (2003) and is described in the section on Metamorphism.

Good exposures of contaminated igneous rocks occur in the River Deveron to the north of Huntly where granular gabbros appear to be cut by xenolithic gabbroic rocks and locally gneissose contaminated rocks. An apparently intrusive relationship between xenolithic rocks and granular gabbros is also observed on the western flank of Ord Hill [NJ 503 424]. From this point a discordant body of xenolithic rocks, 70 to 80 m wide, can be traced discontinuously for at least 500 m in a west-south-westerly direction towards the River Deveron.

A highly varied assemblage of heterogeneous, locally veined, brecciated or foliated, hornfelsed metasedimentary rocks and contaminated xenolithic gabbroic rocks crop out in small bodies along the eastern flanks of the Huntly and Knock intrusions. They are exposed at Hill of Kinnoir [NJ 555 435], Elry Knowe [NJ 554 460], and between Barlatch Wood [NJ 554 471] and Milltown of Rothiemay [NJ 548 485]. Internal and contact relationships are not observed in outcrop.

In addition to the contaminated igneous rocks described above there are significant areas where there is limited evidence of interleaved or mixed gabbroic and metasedimentary rocks (Figure 6c). In the poorly exposed south-east part of the Huntly Pluton ground magnetic data and limited shallow drillhole intersections imply that the area is underlain by a mixture of gabbroic and noritic cumulate rocks (see above) with intervening areas of metasedimentary rocks. Similar lithologies are interpreted along parts of the north-eastern faulted margin of the Huntly Pluton, e.g. west of Haddoch [NJ 534 446], again in very poorly exposed ground. A further area of mixed gabbroic and metasedimentary rocks lies within the olivine-gabbro cumulates near the western margin of the Huntly Pluton.

Pegmatitic rocks

Pegmatitic dykes and sheets of gabbroic composition have been mapped at three localities in the eastern part of the Huntly intrusion: in a north-west-trending body cutting xenolithic rocks on the Hill of Kinnoir [NJ 555 436]; in a body of similar orientation cutting granular gabbros in Mungo Wood [NJ 551 430]; and in a body trending east-north-east in ophitic gabbros at the south end of Coniecleugh Forest [NJ 535 422] (Figure 6d). These bodies are up to 40 m wide and are composed of 1 to 10 cm crystals of plagioclase, pyroxene and ilmenite. Locally they contain xenoliths of granular gabbro. Elsewhere, they are cut by veinlets of granular gabbro or pyroxenite.

Irregular discordant bodies of graphite- and sulphide-bearing orthopyroxene-rich pegmatites occur in the West Huntly cumulate body. Two such bodies, up to 3.5 m wide, are exposed in the Bin Quarry [NJ 49 43]. They are heterogeneous in texture and composition. The principal silicate mineral is orthopyroxene, but some zones are highly feldspathic. The graphite and sulphide contents are also highly variable, each locally comprising up to 50 per cent of the rock. The wallrock adjacent to these bodies is altered over distances of up to 0.5 m with the development of biotite and chlorite. Rocks of this type have also been recorded from the River Deveron near Huntly Castle [NJ 538 410] and intersected in boreholes drilled in Dunbennan Wood and the Bin Forest.

5.3.2 Knock Gabbro-peridotite Pluton

The Knock Pluton underlies an area of approximately 25 km^2 and lies to the north of the Huntly Pluton from which it is separated by a fault-bounded enclave up to 3 km wide (Figure 4). The enclave is poorly exposed and consists of low-lying ground underlain by Argyll Group metasedimentary rocks that have been intruded by several small mafic and ultramafic bodies. Natural exposure in the Knock Pluton is also sparse and information has been largely obtained from drilling and ground magnetic surveys conducted by Aberdeen University, EVL and BGS.

The Knock Pluton comprises a complex sequence of interlayered lenses and sheets of cumulates, modified cumulates, and contaminated and metasedimentary rocks. The sheets are discontinuous and steeply dipping. The lenticular form of some units is interpreted as typical and has been used as the basis for extrapolation of the varied lithologies over many parts of the pluton where other evidence is unavailable. The external boundaries of the intrusion are not exposed but the boreholes at Drumnagorrach, Claymires and in the south-eastern sector near Clashman Hillock [NJ 539 481] and Woodside indicate that the contacts are complex and commonly sheared. Elsewhere the positions of the external contacts are inferred mainly from ground magnetic survey data. Evidence from numerous boreholes indicates the presence of localised shear zones throughout the intrusion, with deformation apparently most intense in its south-eastern sector.

The complexity of the external contacts is demonstrated by exposures on Cuttle Hill [NJ 500 474] close to the south-west corner of the intrusion. The high ground here is underlain by granular, contaminated and locally xenolithic gabbroic rocks, locally strongly foliated. Two boreholes a few hundred metres to the west and north-west of Cuttle Hill intersected ultramafic, olivine-gabbro and gabbro cumulates up to 30 m thick within a banded sequence of metasedimentary rocks and contaminated and xenolithic gabbroic rocks. A strong foliation and shear zones are present in these sections, although the metasedimentary rocks are hornfelsed adjacent to their contact with the igneous rocks in one of the boreholes.

The nature and position of the eastern margin of the pluton is also difficult to delineate. Available evidence suggests that a single contact seems unlikely and that the proportion of metasedimentary material increases towards the east. Boreholes, sparse exposures and ground magnetic survey data provide some local information on the nature of this contact. A series of boreholes drilled near Glenburn Cottage [NJ 532 480] showed that cumulate lithologies passed eastward with a sharp transition into xenolithic gabbros and mica schists and gneisses. Approximately 1.4 km to the north near Claymires [NJ 533 494] boreholes intersected a sheared contact between clinopyroxene-norite and a sequence of biotite-gneiss and psammite to the east. Magnetic survey and borehole data also indicate that the northern boundary of the Knock Pluton is complex and has been a locus of deformation and shearing.

Cumulate rocks

Cumulate rocks in the Knock Pluton are dominated by troctolites and norites. The former occur mainly in the north-western section of the intrusion whereas the latter are more widespread in its central and southern parts. Boundaries of the cumulate bodies are defined chiefly on the basis of ground magnetic data, although borehole evidence indicates the common intercalation of different rock types. Olivine-bearing cumulates, troctolites, and subordinate olivine-gabbro, dunite and anorthosite underlie some 3 km^2 in the western and north-western parts of the intrusion. Layering and crystal lamination are widely observed in float boulders but in-situ exposures are rare. Munro (1984) reported laminated troctolites at Upper Fowlwood [NJ 5270 5270] with a vertical lamination striking north-east. Troctolite and olivine-gabbro cumulates were also reported from a borehole about 600 m farther to the south-east. The general north-east strike of magnetic features in this part of the intrusion may reflect primary magmatic structure or may reflect deformation features associated with the Portsoy Shear Zone.

The main tract of noritic and other orthopyroxene cumulates extends for more than 4 km in a north-easterly direction from near Ruthven [NJ 507 470] to near Parrock [NJ 530 510]. In the south-eastern part of the intrusion a narrower belt of orthopyroxene-bearing cumulates runs south-westwards from Cairnhill [NJ 532 487] for about 2 km. In this last body a sequence of at least 5 layered units, each 10 to 25 m in thickness, was reported by Fletcher (1989) from a borehole near Glenburn Cottage, about 750 m west of Clashman Hillock. These units range from orthopyroxenite to norite and clinopyroxene-norite and exhibit clear cumulate textures.

Modified cumulate rocks

In contrast to the Huntly intrusion, modified and granular cumulates are not widely recognised in the Knock Pluton (Figure 5a,b). A poorly defined tract of granular gabbros and norites has been mapped close to the western margin over a distance of about 3.5 km, running south-westwards from Upper Fowlwood [NJ 527 530]. These mainly fine-grained rocks are partly or wholly recrystallised and amphibolitised and are heterogeneous, commonly foliated, and locally mylonitic. Remnants of primary igneous textures are sporadically observed. No contacts are exposed and relationships with adjacent rock types are unknown.

Compositions of cumulus minerals in the cumulate and modified cumulate rocks of the Knock Pluton are comparable with those from the East Huntly body. Olivine compositions lie in the range Fo_{80} to Fo_{61}, plagioclase from An_{80} to An_{49}, and orthopyroxene from En_{72} to En_{56}. On this basis they may be assigned to the Lower and Middle Zones of Clarke and Wadsworth (1970).

Contaminated igneous rocks

Extensive bodies of contaminated and xenolithic gabbroic rocks occur widely along the eastern and northern margins of the Knock mass (Figure 6c). Borehole evidence indicates complex interleaving of these rocks with cumulate lithologies and metasedimentary rocks, but it is rarely possible to delineate individual bodies with confidence. The contaminated igneous rocks have generally low magnetic susceptibilities, making them indistinguishable from the metasedimentary rocks where there is no exposure. In some marginal areas a heterogeneous assemblage of gabbroic and metasedimentary rocks is recorded. Such rocks appear to mark an irregular, at least partly deformed, transition between the intrusive igneous rocks and the surrounding metasedimentary rocks. A similar transition is inferred along the eastern margin of the Huntly intrusion on the basis of ground magnetic survey data and sparse borehole evidence.

Close to the delineated north-eastern margin of the Knock intrusion, contaminated gabbroic rocks are locally well exposed in discrete outlying bodies underlying the Bo Hill–Craigbourach area [NJ 560 515 to 566 528], by Ternemny [NJ 555 527], and around Barry Hill and Wether Hill [NJ 571 531 to 560 544]. These rocks comprise texturally and mineralogically varied, fine-grained biotite-bearing norites and orthopyroxene-gabbros which are locally xenolithic. Leucocratic, typically coarser grained varieties are widely observed to vein the other rock types, locally giving rise to apparent gneissose or migmatitic textures.

Contaminated, locally xenolithic gabbroic rocks crop out between Cuttle Hill [NJ 501 473] and Flooders [NJ 502 478] at the south-western corner of the Knock intrusion. They are commonly rich in biotite and locally strongly foliated. Deep drilling by EVL a few hundred metres to the west revealed a sheared and interbanded section through xenolithic gabbro, troctolite and metasedimentary rocks.

Enclaves of predominantly foliated, gneissose and commonly hornfelsed pelite and semipelite have been mapped within the main Knock intrusion in three areas, notably around Auchencrieve [NJ 523 480] where there is good borehole control. The enclaves are inferred to be narrow and lenticular, but in parts they are at least a kilometre in length. They are intercalated with variable, but subordinate, amounts of xenolithic, contaminated and cumulate gabbros. Locally, rafts of metasedimentary rock with maximum dimension exceeding 100 m have been identified from boreholes in the southern part of the Knock intrusion. However, in this area it is difficult to demonstrate an origin by assimilation of metasedimentary material rather than structural incorporation as a result of later shearing.

5.3.3 Rothiemay and Avochie intrusions

Ultramafic rocks underlie an area exceeding 1 km^2 in the south-east corner of the Knock Pluton around the Bridge of Isla [NJ 530 467]. The best section is exposed in a railway cutting to the north-west of Rothiemay station [NJ 531 460]. Peridotite, melatroctolite and wehrlite are the dominant lithologies, with minor olivine-gabbro and troctolite. They commonly exhibit cumulate textures, layering and crystal lamination that trend approximately north-north-east and dip towards the west-north-west at about 50º.

In thin section olivines from the Rothiemay cutting have a distinctive rounded crystal shape. A poikilitic texture is locally well developed with large interstitial pyroxene plates. Small-scale modal variation gives rise to millimetre-thick layers of dunite, wehrlite and melatroctolite. The rocks show no significant evidence of deformation or metamorphism and are interpreted as local variants of Huntly-type cumulates. The mineral chemistry of the mafic and ultramafic rocks at Rothiemay is similar to that shown by the West Huntly cumulates but exhibits slightly more magnesian compositions. Most olivine compositions lie between Fo_{80}-Fo_{85}, and locally attain Fo_{90}.

In the Avochie area, again at the south-east corner of the Knock Pluton, a sequence of mafic and ultramafic igneous rocks up to 400 m wide extends from just north-west of Dykehead [NJ 537 461] north for about 900 m to the River Deveron near Smithy Croft [NJ 535 470]. Gabbro, olivine-melagabbro, troctolite and melatroctolite, comparable with Huntly-type cumulate rocks, form in the eastern part of this sequence. Sparse borehole and surface observations indicate that the western and northern sections of this zone are underlain by foliated amphibolitic gabbros and xenolithic gabbros. A small body of dominantly ultramafic rocks occurs around Midplough Farm and the site of Avochie Castle [NJ 536 435], adjacent to the cumulate and contaminated gabbroic rocks. The ultramafic rocks range from poikilitic wehrlites, similar to those at Rothiemay, to clinopyroxenites with interstitial olivine, comparable to those from the Whitehill and Succoth–Brown Hill bodies. The exact relationships between the different rock units around Avochie are not known but the contact is interpreted as a ductile shear zone.

5.3.4 Insch Gabbro-peridotite intrusion

The Insch Pluton, which here includes a small part of its western Boganclogh sector, crops out over an area of about 80 km^2 in the southern part of the Huntly and Turriff districts. The northern contacts of the pluton are tectonic, characterised generally by shear zones, but locally controlled by faults (Leslie, 1981, 1984). However, a contact metamorphic aureole is preserved along the entire northern margin of the Insch Pluton; its width is variable, in part due to later east–west shearing. The aureole is some 300 m wide adjacent to the Boganclogh sector at the western margin of the district, but broadens rapidly to about 3 km at the western margin of the Bogie Devonian outlier.

The northern contact of the Insch intrusion trends generally east–west, except in the south-east part of the Turriff district where it has been is displaced by several significant faults (Leslie, 1984). From Slack [NJ 579 311] to south of Largie [NJ 611 312] the contact is an eastward continuation of the northern margin of the Kennethmont Complex. It truncates the subzone boundaries within the Insch intrusion and also the north–south fault which runs from Brankston south towards the Alford and Inverurie districts (Gould, 1997). In the vicinity of Largie [NJ 611 312 to 619 320], its north-east-trending margin may be an essentially intrusive contact.

The main displacements of the contact that occur south-east of Cross of Jackson [NJ 749 326] occur across north-east-trending faults, the largest of which displaces the pluton margin from near Lightnot [NJ 795 302] south-west to just south of Newton of Saphock [NJ 775 284]. The contact metamorphic aureole cannot be recognised in this sector, as a consequence of the higher grade of regional metamorphism. Contaminated and xenolithic mafic rocks also occur locally (e.g. near Newton of Saphock), indicating interaction between the country rock and the intrusion.

Cumulate rocks

Lower Zone: Lower Zone rocks are confined to small, isolated fault-bound outcrops of dunite and troctolite around Meldrum House [NJ 810 290] and Whigabuts [NJ 815 303] in the extreme south-east of the Turriff district.

The 1 km-wide belt of strongly foliated mafic rocks that separates the Lower and Middle Zone rocks in the Inverurie district crosses the south-east corner of Sheet 86E between [NJ 810 282] and [NJ 820 288]. As these rocks have been extensively recrystallised during amphibolite facies metamorphism, they cannot be readily assigned to the Lower or Middle Zones.

Ultramafic cumulates in the south-eastern part of the Turriff district are petrographically similar to Lower Zone cumulates in the main part of the Insch intrusion (Ashcroft and Munro, 1978). They are dunites and troctolites with cumulus crystals up to 4 mm across. The composition of the cumulus olivine (Fo_{87-77}) is significantly less magnesian than in the Boganclogh-margin ultramafic rocks, and plagioclase compositions range from An_{84} to An_{78}.

In the Den of Wraes, north of Slack [NJ 576 317], a small elongate body of ultramafic rock occurs in Dalradian country rocks. The rock has been extensively amphibolitised, but originally was a poikilitic wehrlite or melanocratic olivine gabbro. Olivine compositions are Fo_{72-70}, the actinolite has Mg# 81-86, and the kaersutite amphibole has Mg# of 76. The rock resembles the ultramafic cumulates from Rothiemay, at the south-east margin of the Knock Pluton.

Middle Zone: Middle Zone rocks underlie about 35 km^2 in the southern and eastern parts of the Insch Pluton in Sheet 86 and consist of cumulate norites and granular gabbros, intermixed on scales of 1 to 100 m (Wadsworth, 1988). The mapped trace of the Middle–Upper zone boundary indicates that the cumulate pile dips north at a low angle (probably <10°). Poorly developed modal layering dips at 10° to 50° to the west, north-west or north.
The rocks comprise three intimately associated varieties (Wadsworth, 1988):

a) orthopyroxene-clinopyroxene-plagioclase-ilmenomagnetite cumulates,

b) fine-grained granular gabbros

c) porphyritic granular gabbros

Types a and b dominate the Middle Zone sequence. The cumulate rocks are relatively coarse-grained (2 to 4 mm) adcumulates. Cumulus pyroxenes show little or no zoning and plagioclase compositions are variable. There is little preferred orientation of cumulus grains or rhythmic variation in mineral proportions. Apatite is a cumulus phase in some norites.

The fine-grained and porphyritic granular gabbros differ only in that the latter contain abundant plagioclase phenocrysts. The granular gabbros are finer-grained (0.5 to 1 mm) than the cumulate rocks, and have textures varying from granoblastic to a granular mosaic of polygonal crystals. The transition from granular to cumulate gabbros may be sharp or can occur over some 5 to 10 m. Where visible contacts are sharp, there is no sign of one type chilled against the other. However, in general, contact relationships suggest that the granular gabbro intrudes cumulate norite. The quartz-biotite-norites that form the Middle Zone in the central part of the Insch Pluton crop out in the Huntly district over a very small area adjacent to the eastern contact of the Kennethmont Complex near Glanderston [NJ 589 289].

Although the mineral compositions are not particularly evolved, the Middle Zone rocks in the Turriff district are apparently at high ‘stratigraphical’ levels within the zone. However, Wadsworth (1988) showed that cryptic variation within the Insch Middle Zone norites was only loosely related to position within the overall outcrop, probably due to the numerous faults and shear zones present.

Upper Zone: olivine ferrogabbros of UZa outcrop in the northern part of the Boganclogh sector of the Insch Pluton in the Huntly district. East of the Devonian Rhynie Outlier Upper Zone rocks of the Insch Pluton consists mainly of olivine ferrogabbros, with subordinate olivine monzonite and syenite, assigned to UZb and Uzc respectively. These higher subzones are confined to small areas around Coldhome [NJ 595 300] on Sheet 86W and on Fallow Hill [NJ 638 316] in Sheet 86E.

The apparently concordant boundary between the Middle and Upper Zones, marked by the incoming of cumulus iron-rich olivine, is the first marker horizon in the main part of the Insch intrusion. In the Turriff district it can be traced for over 11 km east-north-east from [NJ 641 287] to [NJ 752 318], where it is truncated by a north-north-west-trending fault. There are a few granular rocks in UZa, but they are not known from the UZb and UZc subzones. Rapid upward iron enrichment occurs in the olivines and pyroxenes of the Upper Zone, while the plagioclase, though more sodic than in the Middle Zone, continues to show a wide range of compositional zoning within individual crystals.

Where fresh, the olivine-ferrogabbro of UZa is a dark, blue-black, tough rock with only poor mineral layering. Their typical mineralogy is olivine + plagioclase ± clinopyroxene ± orthopyroxene + ilmenomagnetite + apatite, and the ferrogabbros are ortho- to mesocumulates. Pyroxene, especially orthopyroxene, is less abundant than in the Middle Zone rocks.

Olivine monzonite and subsidiary olivine monzodiorite (UZb) overlie the olivine-ferrogabbro on Fallow Hill [NJ 636 317] and north of the Shevock Burn near Foggieburn [NJ 587 297]. These rocks are very similar in appearance to the olivine-ferrogabbro, except for the euhedral crystals of orthoclase, scattered through the rock. This roughly coincides with the reduction in An content of the plagioclase to below 50 per cent and the appearance of zircon is a cumulus phase. Hence, the more plagioclase-rich UZb cumulates are olivine-monzodiorites rather than olivine-monzogabbros.

Syenite (UZc) crops out over an area of 3 km^2 to the north of Wardhouse [NJ 593 290], and forms the summit of Fallow Hill [NJ 637 316]. The syenite is considerably more leucocratic than the UZb rocks. Orthoclase perthite is more abundant than plagioclase. Clinopyroxene is present in some specimens, but it is generally replaced and/or overgrown by amphibole, and biotite is always present. Apatite and zircon form small euhedral crystals.

The Upper Zone rocks of the Insch Pluton show a single trend of cryptic variation very similar to that shown by other highly differentiated tholeiitic layered intrusions. The most notable feature is the overlapping Mg/Fe ratios between the most evolved Middle Zone rocks and the least evolved Upper Zone rocks. Hay (2002) used the major and trace element chemistry and cumulate mineralogy of the Insch Middle and Upper Zone rocks to show that there was straightforward upward differentiation to extreme compositions. No evidence of magma replenishment was found implying that the intrusion was closed during its final stages of crystallisation.

Contaminated and xenolithic rocks

These rocks are present where the original intrusive contacts of the Insch Pluton are preserved, and are also found around enclaves of metasedimentary rocks within the intrusion. The best developments are at Newtown of Saphock [NJ 776 283], Easter Saphock [NJ 775 283] and Mill of Boddam [NJ 624 303]. In the Middle Zone rocks of the eastern part of the Insch Pluton contamination is indicated by the occurrence of quartz-biotite-norites. These are typically associated with cordierite norites, which Gribble (1967, 1968) has shown to be derived from an Al-rich dioritic partial melt produced by the assimilation of Dalradian pelitic metasedimentary rocks. Read (1966) recorded black xenoliths of norite, together with pelitic and quartzose metasedimentary xenoliths, all within friable but fresh outcrops of olivine-ferrogabbro by the Mill of Boddam and in the neighbouring Kellock Burn. The norite consists of hyperthene, plagioclase feldspar and abundant iron oxide and locally shows relict mineralogical layering. It is generally coarse-grained but contains well-defined, medium- to fine-grained patches that vary in shape from irregular to elongate and even streaky. The dark grey to blue-black pelitic xenoliths range from 1 to 30 cm in length and are typically composed of cordierite, green spinel, plagioclase and biotite (± hypersthene). Cordierite-spinel hornfels, in places containing sillimanite is also present and shows alteration to diaspore. The siliceous xenoliths are grey and fine-grained and range up to 75 cm long. They consist of recrystallised quartz, with sparse skeletal hypersthene, iron oxide and feldspar.

5.3.5 Geochemistry

Hay (2002) carried out a detailed geochemical and isotopic investigation of the representative samples of the Insch (33 samples), Huntly (40 samples) and Belhelvie (38 samples) plutons. She also analysed 12 samples of Dalradian metasedimentary rocks. The resultant data was used to characterise the nature of the magmas and magmatic processes, the frequency of major influxes, level and type of magma contamination, and the origins of the mafic and ultramafic magmas. Her conclusions are summarised below.

Fractional crystallisation trends in differentiated igneous intrusions are normally illustrated by Harker diagrams showing the relative enrichment or depletion of major and trace elements concentrations against SiO_2, or in mafic rocks, MgO. Such trends are difficult to assess in cumulate rocks as their major and trace element concentrations are controlled by the cumulus mineralogy and nature of the post-cumulus material. Indeed, Hay (2002) showed that the major and trace element trends in individual plutons were readily explained by the nature of their cumulate mineralogy and post-cumulus material. All the plutons show increasing magmatic differentiation with 'stratigraphical' height and only the Huntly Pluton shows evidence of at least one new magma influx in its Lower Zone. The fractional crystallisation follows a tholeiitic trend and the lack of primary amphibole suggests that the magma was comparatively anhydrous.

The whole-rock geochemistry of the West Huntly granular gabbros is compatible with Middle Zone cumulates, implying little overall geochemical change during their textural modification. In contrast, the East Huntly granular gabbros and quartz-biotite-norites show more varied whole-rock geochemistries that reflect their marginal positions. The Insch Middle Zone norites show more evolved mineral compositions than the Huntly and Belhelvie Middle Zone rocks. They also have higher trace element contents, notable Ba, Zn and the LREEs, and higher $^{87}Sr/^{86}Sr$ ratios, all pointing to greater magma contamination in the Insch Pluton. The Insch Middle Zone trends continue into the Upper Zone sequence, which shows a straightforward upward differentiation to more extreme compositions implying that the intrusion was closed during the final stages of crystallisation.

The occurrence of orthopyroxene as a cumulus mineral prior to clinopyroxene suggests that crustal basement gneiss material was assimilated into the magma at an early stage, prior to emplacement. The Huntly and Insch fine-grained granular gabbros and gabbronorites require <5 per cent of contamination but the Insch porphyritic granular gabbronorites require between 5 and 20 per cent of crustal contamination. The Huntly Pluton shows evidence of contamination by the adjacent Dalradian Argyll Group metasedimentary rocks, particularly in its eastern upper part.

The most primitive Huntly and Belhelvie cumulates and the Insch non-cumulate rocks have Sr-Nd-O isotopic characteristics that imply their magmas were mantle derived, but their mineral compositions suggest that they were more evolved than primitive mantle magmas. Insch and Huntly samples plot within or close to the mantle array and the calculated parent magmas are slightly LREE-enriched. They are also enriched in LILE such as Ba and Rb and depleted in the HFSE, notably Nb and Zr. Together with their robust La/Yb ratios of >0.95, these features imply a subduction-related origin. The source magmas could have originated from the same depleted mantle source with some minor contamination by <1 per cent of subducted oceanic sediment.

5.3.6 Emplacement model

Cumulate rocks have been identified in several discrete bodies over a wide area in the Huntly Pluton. They comprise mainly olivine-gabbro with minor troctolite and peridotite. The order of primary crystallisation in these rocks is generally olivine-plagioclase-clinopyroxene-orthopyroxene. In the Knock Pluton, troctolite and norite cumulates are dominant, but the order of crystallisation is marked by the early appearance of orthopyroxene, before clinopyroxene. These rocks are inferred to have been produced by differentiation along the tholeiitic trend from a primary subalkaline basaltic magma. The assimilation of aluminous metasedimentary material may explain the onset of orthopyroxene crystallisation in West Huntly and its early appearance in the Knock Pluton.

Mineral chemistry data indicate that the majority of the cumulate rocks in the Huntly and Knock intrusions belong to the Lower and Middle Zones of Clarke and Wadsworth (1970). However, in contrast to the Insch Pluton, there is no overall coherent igneous 'stratigraphy' within the Huntly mass. In the West Huntly body both cryptic variation patterns and way-up indicators in the layered rocks suggest that the base of the intrusion now corresponds to the western margin with younging upwards towards the east. However at Bridges, similar rocks that also show relatively primitive compositions, young towards the west. Hay (2002) has suggested that these layered cumulate rocks in the eastern part of the Huntly Pluton may represent roof cumulates. Alternatively they may be indicative of large scale folding within the intrusion (Fletcher, 1989). In the Knock Pluton microchemical data for plagioclase suggests that the base of the intrusion lies along the western contact, similar to Huntly. However borehole evidence from Drumnagorrach demonstrates the complex nature of the western margin of the Knock body with numerous mafic sheets and contaminated mafic rocks juxtaposed with highly foliated amphibolitised metabasic rocks, probably derived from the gabbros.

Major areas of the Huntly Pluton are underlain by cumulate rocks in which the primary igneous textures have been partially or wholly eliminated as a result of recrystallisation to finer grained granular lithologies. In some zones a pervasive planar foliation or cleavage has also been superimposed. These rocks are separated from the layered cumulate sequences by narrow belts of transitional rocks, mostly glomeroporphyritic olivine-gabbros or ophitic gabbros, which have been less strongly recrystallised. The origin of the granular gabbroic rocks in the 'Younger Basic' intrusions has been discussed by several workers (Read and Haq, 1963; Clarke and Wadsworth, 1970; Wadsworth, 1988; Fletcher and Rice, 1989; Gillespie et al., 1994; Hay, 2001). Various mechanisms for their formation have been proposed, but in the Huntly and Knock plutons we attribute the recrystallisation to shear-related deformation of the hot, ductile rock either immediately following or during the later stages of magma crystallisation.

Contaminated gabbroic rocks are widespread in both the Huntly and Knock plutons, with large areas of xenolithic rocks predominant towards their eastern margins. These rocks are derived from the assimilation of large quantities of metasedimentary rocks, preserved on a large scale either marking the roof zone of the intrusion or as a result of an emplacement mechanism that led to incorporation of a large amount of sedimentary material along this boundary. Elsewhere, for example in the central part of the Huntly Pluton, slow cooling of the magma allowed relatively complete digestion of the sedimentary xenoliths leading to the development of contaminated gabbros.

In summary, the distribution of lithologies in the Huntly and Knock plutons was controlled by a combination of magmatic processes involving magmatic fractionation and contemporaneous contamination associated with emplacement coeval with deformation and shearing. In the Huntly Pluton shearing was focused along north–south zones leading to widespread recrystallisation and associated grain size reduction, loss of primary igneous textures, and the development of a pervasive foliation in the most strongly deformed areas. Shearing and deformation were more widely distributed in the Knock Pluton resulting in the general obliteration of primary magmatic features and the lack of continuity of individual units along strike. Active shearing associated with the Portsoy Shear Zone at or close to the time of emplacement (Chapter 7) would also explain several unusual features of the Huntly and Knock plutons including:

i. the distribution and mineral chemistry of cumulate rocks

ii. the variable occurrence of granular gabbroic and noritic rocks

iii. the complex nature of the intrusion margins on both the western and eastern flanks

iv. the apparent shallow extent of the Huntly body implied by geophysical models.

5.3.7 Geochronology

Hay (2002) obtained Sm-Nd whole-rock and mineral separate data that she used to define isochrons for samples from the Huntly and Insch plutons. The best data from the Insch Pluton, from a Middle Zone cumulate rock, gave a crystallisation age of 482 ± 9 Ma (MSWD = 0.26). Sm-Nd ages of 474 ± 12 Ma (MSWD = 2.4) and 467 ± 15 Ma (MSWD = 0.18) were obtained from the Huntly Pluton, interpreted to date crystallisation of a Middle Zone granular gabbro and a Lower Zone cumulate rock respectively. Dempster et al. (2002) obtained a U-Pb TIMS zircon age of 470 ± 9 Ma from a syenogabbro from the Upper Zone of the Insch Pluton, again interpreted as a crystallisation age. They also presented a $^{207}Pb/^{206}Pb$ SHRIMP zircon age of 472 Ma from a clinopyroxene-bearing monzonite from the Morven–Cabrach Gabbroic Pluton. The low Pb and non-measurable U content and the presence of apatite and opaque oxide inclusions in the acicular zircons prevented more detailed analysis. These ages correlate well with U-Pb TIMS zircon ages of 474.3 ± 2.1 Ma and 471.5 ± 3 Ma from the Portsoy Gabbro-serpentinite Intrusion-swarm, obtained by Condon and Martin (cited in Oliver et al., 2008 as a personal communication) and Carty (2001) respectively. Carty et al. (2012) interpreted the age of the Portsoy gabbro emplacement as 471.3 ± 0.6 Ma, based on U-Pb TIMS analysis of three concordant fractions from magmatic zircon and also presented U-Pb titanite ages of 465.1 ± 0.9 Ma and 456 ± 4.5 Ma. When combined with data from the metamorphic porphyroblasts and fabrics, they proposed a model that D2 deformation and thrusting accompanied gabbro emplacement and was followed by rapid uplift. It seems clear that emplacement of these mafic and ultramafic intrusions of the North-east Grampian Basic Subsuite occurred during a short-lived episode of basic-ultrabasic magmatism during the Early Ordovician.

5.3.8 Comparison with pretectonic mafic-ultramafic intrusions

A comparison of lithological, mineralogical, deformational and geophysical features of the syntectonic mafic-ultramafic intrusions and the ‘Older’ pretectonic bodies, leads to the conclusion that they are not related (Table 4). Petrographical studies of rocks from the Succoth–Brown Hill type intrusions strongly imply that they have undergone a longer and more complex history than the Huntly and Knock plutons. This led Gunn et al. (1996) to propose that the Succoth–Brown Hill type bodies were emplaced at an earlier time. The relative proportions and chemical compositions of mineral phases present and their crystallisation sequences also suggest that the intrusions were formed from magmas with different compositions. Furthermore, a marked structural discontinuity between the two types of intrusion is suggested by their contrasting geophysical features. Aeromagnetic and regional Bouguer gravity anomalies across the Portsoy Shear Zone confirm the presence of a major structural break along the south-west side of the Huntly intrusion. This area is also associated with a marked change in the regional strike of the Dalradian succession from north-east to north. In addition, the high-grade sillimanite-bearing schists and gneisses marginal to the Huntly and Knock plutons have not been reported from around the Succoth–Brown Hill intrusion (Beddoe-Stephens, 1990). This may be the result of movement along a late structure, or, if the S-BH Intrusion represents an older phase of intrusive activity, thermal contact effects may have been destroyed by the subsequent regional metamorphism.

Table 4 A comparison between the mafic-ultramafic rocks from Succoth–Brown Hill Intrusion, Boganclogh margin of the Insch Pluton, and Huntly and Knock plutons.

	Succoth – Brown Hill Intrusion	**Boganclogh margin (Insch Pluton)**	**Huntly and Knock plutons**
Lithologies			
Ultramafic	Clinopyroxenite, wehrlite, dunite	Harzburgite, dunite, layered lherzolite	Dunite, peridotite, melatroctolite
Mafic	Gabbro	None	Olivine-gabbro, troctolite
Internal contacts	Tectonic	Tectonic	Magmatic, some tectonised
Magmatic features	Rare primary magmatic features	Rare primary magmatic features	Magmatic features commonly preserved
Deformation and alteration	Early high-temperature multi-phase recrystallisation and metamorphism; late alteration, commonly pervasive but little deformation.	Early high-temperature multi-phase recrystallisation and metamorphism; late alteration, commonly pervasive but little deformation	Simple deformation history. Deformation restricted to shear zones.
Mineral chemistry			
Mafic minerals	Mg# 95-75, most ca. 90	Mg# 95-90	Mg# 85-75
Plagioclase	In gabbro: >An_{80}; ranges An_{90-32} and locally >An_{90}		In gabbro: An_{75-55}
Crystallisation sequence	Clinopyroxene – olivine – plagioclase	Olivine –orthopyroxene – clinopyroxene	Olivine – plagioclase – clinopyroxene / orthopyroxene

It is not possible to quantify the age difference between the pre- and syntectonic intrusions on the basis of available evidence. As rocks within or adjacent to major shear zones have likely been affected by several deformation phases, possibly only separated by short periods of time, they commonly show complex deformational and metamorphic textures and mineralogies. These can be similar to those produced outwith the shear zone by several discrete regional metamorphic events. However, rocks adjacent to the Portsoy Shear Zone from the Knock area and from shear zones within the Huntly Pluton do not show complex textures, all the fabrics being essentially coplanar. The Succoth–Brown Hill type rocks may thus have been affected by an early regional metamorphic event prior to emplacement of the Huntly and Knock plutons, which show evidence of intrusion synchronous with or just following the peak of metamorphism.

The Boganclogh margin-type ultramafic rocks show evidence of a similar metamorphic and deformational history to the Succoth–Brown Hill type, and in the area to the north of Knock, in the Portsoy district (Sheet 96W), the two types occur close together. Styles (1999) suggested that these two groups together may represent a dismembered arc-root complex and uppermost mantle from beneath an exhumed volcanic island arc. Their association with regional shear zones, such as those which border or transect the Insch Pluton and the Portsoy Shear Zone, suggests that these features may represent long-lived crustal-scale structures along which magma emplacement was focused. The Succoth–Brown Hill type rocks were probably derived from a calc-alkaline magma with high initial contents of Ca and water leading to early crystallisation of clinopyroxene and formation of the characteristic clinopyroxenites (Styles, 1999).

5.4 OTHER MAFIC AND ULTRAMAFIC ROCKS

5.4.1 Marnoch-Essendrum mafic and ultramafic intrusions

Read (1923) showed a single outcrop of 'Older' gabbroic rocks extending from Pitfancy [NJ 602 435] northwards for about 8 km through Marnoch. However, the remapping and airborne magnetic survey data indicate a more complex situation. The principal exposures are in the River Deveron beneath, and to the west of, the Bridge of Marnoch [NJ 600 496 to 605 495]. Six sheets of coarse grained metagabbro, up to 100 m wide, have been delineated on the south bank of the river while only four are recognised on the north bank. This mismatch has been resolved by inferring an offset along an east–west fault along the river here.

Limited exposure and locally abundant boulders about 1 km to the west of Bridge of Marnoch indicate the presence of bodies of metagabbroic and subsidiary ultramafic rocks. The latter comprise amphibolitised clinopyroxene-olivine rocks. Both rock types show evidence of localised deformation, generally manifest as laterally discontinuous, small-scale shear zones.

To the south of Bridge of Marnoch there is sporadic evidence for the presence of similar rocks over a distance of about 9 km. Read (1923) reported exposures near Hillbrae [NJ 601 474] and in a small quarry at Pitfancy [NJ 5904 4358]. Elsewhere the presence of mafic and ultramafic intrusive rocks has been inferred from float and wall boulders, with boundaries defined mainly by airborne magnetic data. Where ground control is absent, it is possible that the magnetic anomalies may relate to interbedded magnetite-rich metasedimentary rocks rather than igneous rocks.

On the basis of limited petrographical and mineralogical studies by Styles (1999) these rocks cannot be grouped with either the pre- or syntectonic mafic-ultramafic intrusive rocks described above. They have been termed the Marnoch Mafic-ultramafic Intrusion-swarm and included within the North-east Grampian Basic Subsuite, but they are pervasively amphibolitised and appear to be unrelated to both the Insch, Huntly and Knock plutons and the Succoth–Brown Hill type intrusions. They also show no obvious relationship to the regional shear zones.

5.4.2 Metadolerite sheets west of the Porsoy Shear Zone

Generally concordant, sheet-like intrusions of metadolerite and metabasalt occur in a 1 to 2 km-wide zone, parallel to and north-west of the Portsoy Shear Zone. Mafic sheets are particularly common between Aswanley [NJ 437 395] and Coachford [NJ 465 455], but occur as far north-east as Netherton [NJ 497 489]. This major swarm lies adjacent to the Portsoy Shear Zone for some 56 km between Glen Fenzie, north Deeside, and the Huntly district.

The sheets are well exposed in sections along parts of the River Deveron and the Burn of Cairnie. Elsewhere, exposures are few, but where poorly exposed their presence is commonly indicated by float, particularly on the slopes of Both Hill [NJ 442 409] and Newton Hill [NJ 453 417]. Most sheets are several metres thick, but they vary from 1 m to over 100 m in width. The metadolerite and metabasalt are characteristically non-magnetic, precluding location of boundaries by magnetometer. The sheets represent crustal extension of over 20 per cent locally.

Where contacts with country rock are seen in this district, they are always concordant with bedding or regional foliation, although discordant contacts are recorded in upper Donside (Glenfiddich district – Sheet 75E). Contacts are usually sharp and some sheets have finer grained margins, but contact relationships are commonly obscured by shearing concentrated at the margins; contact metamorphic effects are rare.

Most of the sheets preserve igneous textures but some show a variably developed foliation, typically in discrete shear zones and at sheet margins. Many sheets are porphyritic, with plagioclase phenocrysts up to 5 mm wide comprising up to 30 per cent of the rock. Primary igneous phases have been replaced mimetically by an amphibolite-facies metamorphic assemblage consisting of amphibole (magnesio-hornblende), plagioclase (andesine-oligoclase with rims of albite), epidote, clinozoisite, titanite and ilmenite. Further recrystallisation and retrogression have resulted in widespread degradation of the igneous texture, with the development of plagioclase–quartz mosaics and an increase in epidote and clinozoisite. Whole-rock geochemical major and trace element analyses from the Donside mafic sheets show that they are subalkaline and relatively iron rich, with chemical compositions typical of continental tholeiites or within-plate basalts.

The age of the sheets is uncertain, but the available evidence favours emplacement after development of major folds, but prior to the peak of regional metamorphism. It seems most likely that they are part of the magmatic event that culminated in the emplacement of the major mafic plutons, occurred near the peak of metamorphism, and was linked to a major phase of contractional shearing across the Portsoy Shear Zone.

5.5 SYN- TO LATE-TECTONIC GRANITIC ROCKS

5.5.1 Avochie Granite

A small ovoid body, some 900 m long by 400 m wide, composed of white to grey, largely foliated, xenolithic, biotite granite, underlies the Hill of Avochie [NJ 541 466] and Brown Hill [NJ 543 470] on the east flank of the Deveron Valley and east of the Portsoy Shear Zone (Figure 6d). The steep, commonly subvertical foliation generally trends north to north-north-east but in the northern part of the body it trends north-west. In parts the granite displays a strong extension lineation, which in Avochie Quarry plunges 65° to the north-north-east. The granite is porphyritic (augened where foliated) in part and consists of turbid orthoclase, microcline, and subordinate oligoclase feldspar, biotite, quartz, and micropegmatite (Read, 1923). Feldspathic pegmatite veins and pods commonly cross-cut the granite.

5.5.2 Carvichen Granite

The Carvichen Granite forms a triangular shaped outcrop on the south-east edge of the Huntly Pluton (Figure 6d) encompassing Carvichen Cottages, [NJ 5408 3899], Cairnhill Farm [NJ 5445 3834] and Corsiestane Farm [NJ 5369 3864]. It consists of a white and grey to white and pink mottled, generally coarse-grained biotite granite with abundant metabasic and semipelite xenoliths. Like the Avochie Granite it is typically foliated and partly porphyritic, although potash feldspar megacrysts only reach about 1 cm in length. It is cut by coarse-grained, pink to white, pegmatitic leucogranite veins up to a metre thick, which are generally subhorizontal.

In thin section, potash feldspar megacrysts composed of turbid orthoclase and fresher microcline are commonly fringed by micropegmatite. The megacrysts lie in a matrix of quartz (with aligned inclusions), biotite, orthoclase and plagioclase feldspar (mostly oligoclase, some andesine). Primary muscovite is scarce and zircon, apatite and garnet are present as accessory phases. The quartz is recrystallised to fine-grained aggregates in parts.

5.5.3 Other granite intrusions

Small intrusions of foliated biotite-muscovite granite, lithologically similar to the Avochie and Carvichen bodies, occur as thin sheets or pods both within and adjacent to the Huntly and Knock Gabbro-peridotite plutons. Two small bodies of medium- to coarse-grained grey granite were formerly exposed in disused small quarries on the eastern bank of the River Bogie, immediately south of the Huntly Pluton at around [NJ 524 386], and some 460 m. South-south-east of Broadland Farm just west of the Huntly Pluton at around [NJ 483 410]. Read (1923) records that the granite contained large pink garnets at this latter locality. A similar lenticular body occurs farther north on Meikle Brown Hill [NJ 5702 5192].

In the Knock Pluton borehole evidence shows that foliated granite sheets cross-cut contaminated/xenolithic gabbros, norites, and hornfelsed metasedimentary rocks. The thickest bodies occur north of Waulkmill at [NJ 5150 4844] and [NJ 5157 4860] (Munro, 1970), and farther east near Auchincreive Farm [NJ 5223 4807] and by Cairnhill Farm at [NJ 5339 4858].

5.5.4 Foliated microgranite

A sheet of mylonitic feldspar-phyric microgranite forms a very distinctive marker over a distance of almost 8 km along the north-western margin of the PSZ. It outcrops between Backside [NJ 4109 3619] in the Glenfiddich district (Sheet 85E) and Terryhorn [NJ 468 402], close to the River Deveron in the Huntly district. Exposures occur in the Burn of Aswanley [NJ 448 391] and its outcrop is marked by the presence of abundant debris, including some large angular blocks, across Drumduan Moor [NJ 442 389] and on hillslopes to the north-east of Cairnagat [NJ 460 396]. The main sheet is up to 100 m thick and at least two thinner sheets are also present at Cairnagat.

This distinctive rock is pale pink and fine grained, with a very strong foliation although undeformed rocks occur close to the northern margin in the Burn of Aswanley. Scattered phenocrysts of dark pink feldspar (both microcline and plagioclase), up to 5 mm, form augen in the most deformed examples and biotite is conspicuous within the foliation. In thin section a strong mylonitic fabric is evident, with well developed tails on the feldspar augen and the foliation defined by biotite, muscovite and ribbons of fine-grained granular quartz.

5.5.5 Aberchirder Granite

A pale grey biotite granite intrusion forms J-shaped body centred on Aberchirder. The granite underlies an area of about 4 km^2 and is poorly exposed. It is cut by an east-north-east-trending fault that may also have partially controlled its emplacement. It is locally porphyritic and in parts shows some biotite alignment, possibly a combination of a weak igneous flow foliation and later minor tectonic effects. The granite intrudes greenschist-grade psammites and semipelites of the Macduff Slate Formation (Southern Highland Group) on its eastern side where a prominent hornfelsed zone containing cordierite and andalusite can be recognised. In a former roadside quarry at the south-east corner of Cleanhill Wood [NJ 6223 5173] a complex mixture of granite and hornfelsed pelite and gritty arenite of the Whitehills Grit Formation was documented by Read (1923). Cordierite and sillimanite were recorded.

Pankhurst (1974) obtained a Rb-Sr whole-rock isochron from the Aberchirder Granite giving an age of 444 ± 9 million years (Ma), which he intepreted as dating its subsequent uplift and cooling. Oliver et al. (2008) obtained a U-Pb zircon SHRIMP age of 450 ± 12 Ma that was interpreted as dating its intrusion. The Aberchirder Granite is similar in many respects to the Strichen, Longmanhill and Forest of Deer granites that give U-Pb zircon and monazite intrusion ages of about 475 to 465 Ma (Oliver et al. 2000), so it is likely that the Aberchirder Granite was intruded at about 460 Ma. The initial $^{87}Sr/^{86}Sr$ ratio of 0.7157 ± 0.0008 shows that the granite was derived from a crustal melt or was contaminated strongly by crustal material.

5.6 POST-TECTONIC DIORITIC AND GRANITIC ROCKS

5.6.1 Kennethmont Quartz-diorite-granite Intrusion-Swarm

The Kennethmont Quartz-diorite-granite Intrusion-swarm is the most northerly member of the Alford Subsuite of the Scottish Highlands Ordovician Suite. It consists of a roughly triangular main quartz-diorite body with separate granite bodies at its north-east and south-west end. Its northern half is poorly exposed and underlies an area of about 7.5 km2 in the Huntly district, sandwiched between the eastern sector of the Insch Pluton and the Devonian Rhynie outlier. The intrusion has been described by Read (1923), Sadashivaiah (1954), Read and Haq (1965), and Busrewil et al. (1975).

The northern contact of the Kennethmont intrusion is the western continuation of the northern tectonic contact of the Insch Pluton. Narrow discontinuous pods of serpentinite of Boganclogh margin-type occur at the margin as well as up to 500 m to the north, implying that the contact is marked by a wide zone of shearing. The contact zone is exposed over about 5 km between the north of Leith Hall [NJ 532 303] and the Shevock Burn at Slack [NJ 581 310]. The rocks to the north of the contact are sillimanite-bearing hornfelses similar to those along the northern contact of the Boganclogh sector of the Insch Pluton.

The relationships with the Insch Pluton are unclear. The eastern contact is difficult to define due to poor exposure and the similarity in appearance of some dioritic rocks of the Kennethmont intrusion and the adjacent finer-grained quartz-biotite-norites of the Insch Pluton. The contact runs south from the Shevock Burn near Slack [NJ 580 310] to near Glanderston [NJ 582 290], where it displaced about 100m eastwards by a fault. South of this fault diorites crop out in a small area on Hill of Glanderston [NJ 582 287].

The intrusion can be divided into three phases:

1) grey, fine- to medium-grained tonalite containing abundant diorite xenoliths. The xenoliths include patches and later veins of coarser-grained grey granodiorite and granite,
2) pink, coarse-grained quartz-syenite to syenogranite,
3) pink, medium-grained granite.

The relative age of phases 1 and 2 is not known, but phase 3 cuts both phases 1 and 2. Phase 1 is considered to represent a diorite which has been intruded and hybridised by possibly cogenetic granitic magma (Busrewil et al., 1975). The diorite xenoliths are typically subrounded to blocky. The abundance of xenolithic material is variable; in places the tonalite is merely the host material in a vein complex enclosing the dominant dioritic blocks. Phase 2 is of uncertain origin. Although the more granitic elements are more quartz-feldspar rich than any proven Insch Upper Zone rocks, the more syenitic lithologies show some similarities to the UZc syenites in the Insch Pluton. Phase 3 may be part of the suite of granite and pegmatite sheets and veins which intrudes most of the syntectonic mafic intrusions of the North-east Grampian Highlands, including the Insch Pluton. The three phases are included together in the Kennethmont Complex partly for historical reasons, and partly because of the difficulty of delineating the outcrop areas of phases 2 and 3.

Pankhurst (1974) obtained a Rb-Sr whole-rock isochron age of 453 ± 4 Ma, and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7145 ± 0.0001 for the pink granite (Phase 3). He suggested that the parental Kennethmont diorite magma might be related genetically to differentiates of the Insch magma. The Rb/Sr age for granite in the Kennethmont intrusion has been corroborated by a zircon evaporation age of 457 ± 1 Ma from a sample collected just south-west of the summit of Barr Hill at [NJ 5765 3052] (Oliver, et al., 1998). However, Parry (2004) has obtained U-Pb TIMS zircon and monazite ages of 472 ± 0.9 Ma and 471.5 ± 0.6 Ma respectively, from the Ord Hill Granite, a minor intrusion which cross-cuts the Boganclogh sector of the Insch Pluton west of Rhynie at [NJ 4876 2741]. This body and similar granitic minor intrusions appear to postdate the mafic and ultramafic units of the Insch Pluton and their hornfels.

5.6.2 Pegmatitic granites

Pegmatitic granites sheets and veins are present locally in the Huntly and Knock plutons (Figure 6d). They consist essentially of quartz, orthoclase (locally microcline), plagioclase (oligoclase-andesine), biotite and tourmaline. The pegmatitic bodies occur as low-angled sheets, lenticular pods and discordant steeply dipping dykes. A notably coarse grained example, 5 m thick and containing minor muscovite, is exposed near Ruthven at [NJ 5094 4707]. Pegamatites have been recorded in Battlehill Quarry [NJ 539 395], Haddoch Quarry [NJ 5336 4441] and also occur commonly in the foliated metabasic rocks and contaminated rocks of the Knock Pluton where they are up to a metre wide. Highly foliated examples were also intersected in a borehole at Drumnagorrach [NJ 5241 5242].

Granitic intrusions within the late-tectonic mafic-ultramafic intrusions

A distinctive cluster of pegmatitic granite and aplitic microgranite veins and sheets is restricted to the main mafic and ultramafic intrusions, particularly the Insch and Huntly plutons. Within the Turriff district, an aplitic microgranite body occurs near Wrangham [NJ 632 306], and a linear pegmatite body occurs near Loanend [NJ 720 290]. The thick quartz vein 400 m south of Jackstown [NJ 753 310] may also be related to this intrusive phase. These granitic rocks are possibly coeval with a granite pegmatite from Belhelvie (Aberdeen district) which has a Rb-Sr whole-rock isochron age of 467 ± 5 Ma (van Breemen and Boyd, 1972).

5.7 MINOR INTRUSIONS

A small number of quartz dolerite and tholeiite dykes assigned to the North Britain Late Carboniferous Tholeiitic Dyke Suite have been identified in the Huntly and Turriff districts. Exposures are rare, but the dolerite and tholeiite are characterised by very high magnetic susceptibilities, resulting in distinctive linear aeromagnetic anomalies (Gallagher, 1983). All have a general west-south-west to east-north-east regional trend, although some local sectors are orientated west-north-west to east-south-east or east to west.

The most southerly dyke in the Huntly–Turriff district, formerly exposed at in a large quarry at Auchinbradie [NJ 621 300] near Upper Boddam, consists of a 13 m-wide body of quartz-dolerite with a distinct chilled margin against spheroidally weathered UZa olivine-gabbros of the Insch Pluton (Read, 1923). Ground magnetic surveys and rare exposures indicate that the same dyke, locally offset by faults, may extend to the eastern edge of the sheet near Backmoss [NJ 821 325]. Another major dyke with a general west-south-west to east-north-east trend occurs in the Rothienorman and Fyvie area where Read (1923) reported four related exposures of dolerite; near Blackford House, 2 km west of Rothienorman at [NJ 701 356]; near Coshelly, 1 km south-east of Rothienorman at [NJ 730 352]; 900 m east-south-east of Hill of Petty Farm at [NJ 757 357]; and at Peth of Minnonie [NJ 792 363], 700 m west-south-west of St John's Wells. The dolerites generally exhibit spheroidal weathering and Read (1923) recorded chilled margins against the adjacent hornfelsed semipelite at the Peth of Minnonie Quarry.

A single lamprophyre dyke of probable Silurian or Devonian age was recorded by Fletcher (1989) from the Huntly Pluton at the Bin Quarry [NJ 4978 4301].

6 Concealed geology

Regional gravity and aeromagnetic data can provide both qualitative and quantitative information on the physical nature of subsurface geology. These potential fields integrate the effects of density and magnetisation structure throughout the upper crust and so contain a variety of frequencies that effectively represents the geological structure at various depths. Commonly, observed gravity and magnetic anomalies can be related directly to the surface expression of geological formations or structures and the data can be used to model the extension of these features at depth; models based on anomalies unrelated to the exposed geology are more speculative.

6.1 GRAVITY DATA

Bouguer gravity anomalies are derived from point observations of gravity, corrected for latitude, elevation and local terrain effects. In the Huntly–Turriff district, Bouguer gravity anomalies range from about -10 mGal in the north-west of the region over Argyll Group metasedimentary rocks west of the Portsoy Shear Zone (PSZ) to over 40 mGal in the south-west over the dense, iron-rich gabbros of the Upper Zone of the Bogancloch sector of the Insch intrusion (Figure 7). The positive anomaly associated with the Bogancloch sector extends north-west at least as far as the PSZ and appears to include the Succoth–Brown Hill mass to the north. Gunn et al. (1996) presented supplementary gravity data (14 new ground stations) from the Succoth–Brown Hill Intrusion that showed a closed positive 20 mGal Bouguer gravity anomaly over the body. When the regional field is subtracted a residual positive anomaly of 7 mGal remains, situated over Brown Hill and Evron Hill. The main part of the Insch intrusion is also associated with an elongate gravity maximum, which is displaced to the northern side of the mass by the effects of the adjacent low-density Bennachie Granite to the south.

There is a broad regional gravity high over the Dalradian strata of the Southern Highland Group of the Buchan region east of the PSZ but the Huntly intrusion itself is not directly associated with a significant gravity maximum. Given the relatively high density of exposed rocks in the Huntly intrusion, the lack of a significant anomaly suggests that the rocks of the Huntly intrusion do not extend to significant depths and the current exposed level may be close to the base of the intrusion.

Devonian strata in the Turriff basin are associated with a recognisable trough in the Bouguer gravity anomaly values, but at the eastern margin of the region, gravity values rise again towards a local maximum over the Maud intrusion of the North-east Grampian Basic Suite.

6.2 MAGNETIC DATA

Total field magnetic data (Figure 8) collected at 305 m above terrain along east–west flight lines approximately 2 km apart have also identified significant anomalies associated with the eastern and western (Bogancloch) parts of the Insch Pluton. Less prominent anomalies occur over some of the serpentinite masses along the PSZ. Magnetic data from a low-level helicopter magnetic survey carried out for mineral exploration by Exploration Ventures Limited (EVL) provides better resolution of some features. These data identify an east-north-east-trending feature north of the Insch Pluton associated in part with the Hill of Foundland Pelite Member, which is locally rich in andalusite and magnetite. Detailed ground magnetic data collected in the Huntly district as part of the mapping and mineral reconnaissance programmes have been used to constrain geological boundaries in some areas. The olivine-bearing cumulate lithologies do show greater susceptibilities and can be delineated from the granular gabbros and the contaminated and xenolithic mafic igneous rocks.

6.3 GRAVITY AND MAGNETIC MODELS

2D models

A model geological section has been generated from the regional geophysical data along the line of section A–B shown in Figures 7 and 8. Part of the model section shows the Huntly Pluton to be less than a kilometre thick whereas the Insch Pluton may extend to a depth of about 2.5 km (Figure 9). The Insch body is modelled with a density of 2.92 Mgm^{-3}, a bulk magnetic susceptibility of about 50.10^{-3} SI, and a small component (0.2 A/m) of natural remanent magnetisation (NRM) with an inclination of -26° and a declination of 149°. The thickness of the Huntly Pluton could be significantly increased if the bulk density of the mass was similar to the host strata. However, the gravity data suggest that the high density mafic and ultramafic rocks such as the West Huntly Cumulate body exposed on the Bin Hill cannot extend to great depth or certainly do not form a significant part of the intrusion at depth.

The main regional feature of the model is the nature of the crust beneath Southern Highland Group rocks east of the PSZ. At depths of about 8 km beneath the Buchan region, east of the Portsoy Shear Zone, Appin and Argyll Group strata are modelled on top of a high-density basement (2.78 Mgm^{-3}). Grampian Group strata are not modelled east of the PSZ. In contrast, the high density and high magnetisation basement, manifest as the regional magnetic anomalies near Lossiemouth and in the Inner Moray Firth, is confined to west of the PSZ.

2.5–3D models

The 2.5–3D models of the apparent density and magnetisation indicate that observed geophysical anomalies can be explained by reasonable values of density and susceptibility within the upper 4 km of the crust. In these models maximum apparent density contrasts over the Bogancloch sector of the Insch Pluton were close to 0.35 Mgm^{-3}, producing an implied density of 3 x10 Mgm^{-3}. This is very similar to measured values for the iron-rich gabbros and quartz-norites. Maximum apparent susceptibilities for the magnetisation model were close to 100 $x10^{-3}$ SI in parts of the Maud mass. In the Bogancloch sector of the Insch Pluton apparent susceptibilities up to about 60 $x10^{-3}$ SI through 4 km would be sufficient to explain the observed magnetic anomalies over the main mafic rocks. In the case of the Huntly Pluton, the lack of significant magnetic anomalies suggests that the mafic-ultramafic rocks might be no thicker than 1 km. In contrast, Gunn et al. (1996) constructed a 2.5D model for the Succoth–Brown Hill Intrusion constrained by the detailed magnetic and gravity data, borehole intersections and surface geology. If we model the intrusion as a series of steeply south-east dipping prisms and use an average density contrast of 0.175 Mgm^{-3}, the predicted maximum depth from surface of this ultramafic body is 2.5 km.

Turriff Basin

The Devonian Turriff Basin, with its fill of conglomerates and sandstone and faulted western boundaries, is reflected in the Bouguer gravity field as a trough with an amplitude of about 3 to 4 mGal. Ashcroft and Wilson (1976) interpreted a residual gravity anomaly of about 4 mGal over the basin in terms of a faulted wedge of Crovie Sandstone Group sandstone and shale overlain by coarse conglomeratic sedimentary rocks of the Gardenstown Conglomerate Formation, using a mean saturated density of 2.47 Mgm^{-3} based on measurements at 11 sites. They considered that this density value was affected by weathering. An observed increase in seismic velocity at the base of the weathered layer together with an estimate of density made from a gravity traverse suggested a mean density value closer to 2.60 Mgm^{-3}. Basin depths, modelled using a density contrast of 0.09 to 0.12 Mgm^{-3} were estimated at about 1 km in the northern part of the basin and about 1500 m in the southern part.

A revised residual field has been defined using a minimum curvature gridding algorithm and a subset of the observed gravity data from a grid of mesh size 2 km. All data on or immediately adjacent to the Devonian strata were removed so that the regional field was designed to exclude the effects of these strata. The resultant residual field has been modelled as a series of vertical contiguous prisms of mesh size 1 km and a density contrast of 0.15 Mgm^{-3}. After eight iterations the root mean square residual anomaly was less than 0.3 mGal. The estimated thicknesses of the Devonian succession are thus around 800 m in the north, but reach around 1400 m in the southern part of the Turriff Outlier (Figure 10). Both models are equally dependent on the magnitude of the density contrasts used and the magnitude of the residual field modelled. They both imply that the central parts of the basin are thicker, supporting Read's suggestion (1923) that there may be concealed faulting with the Dalradian–Old Red Sandstone interface stepped at depth.

7 Structure

The regional structure of the Huntly and Turriff districts is dominated by the Portsoy Lineament/Shear Zone whose trace crosses the north-west part of the district (Figure 11). This steep north-north-east-trending structure shows evidence of a long history. It divides complex folded and thrust Appin and lower Argyll group rocks to the west-north-west from upper Argyll and Southern Highland group rocks intruded by mafic-ultramafic plutons of the North-east Grampian Basic Subsuite to the east-south-east.

The rocks occurring west-north-west of the Portsoy Shear Zone (PSZ) show evidence of two main discrete penetrative deformation and metamorphic events, here designated D1 and D2. Note that these designations do not necessarily correlate with similarly labelled events elsewhere in the Dalradian outcrop. Indeed correlation of deformation and metamorphic events even across the PSZ is problematic. The primary D1 folding event and related cleavage formation were accompanied by low pressure–high temperature amphibolite-facies metamorphism. The secondary D2 event resulted in pervasive folding, generation of related cleavages, and formation of south-east dipping shear zones, all accompanied by intermediate to high pressure amphibolite-facies metamorphism. These secondary features dominate the structural pattern at 1:50 000 scale (Figure 11). Later deformation phases are manifest as locally prominent crenulation cleavages and open to close minor folding, but are less widely developed and mainly restricted to the more pelitic lithologies. Such late-stage features are common around the elongate domal structure termed the Ardonald Fold (Figure 11).

East-south-east of the PSZ two main penetrative deformation phases are also apparent in rocks lying below the andalusite isograd. There is evidence of a second deformation that immediately postdates the peak of low pressure Buchan metamorphism, but there is no evidence of an associated high pressure metamorphic event as found to the west of the PSZ. The overall structure in this eastern area is dominated by the late-stage Turriff Syncline, an open structure whose broad axial zone plunges gently north and whose trace is approximately coincident with the western edge of the Devonian Turriff outlier (Figure 11). The syncline is developed largely in the Southern Highland Group turbiditic sequence, but the detailed structural pattern is controlled by the earlier medium-scale folds (F1), and by alternating steep and more gently dipping zones that may reflect an underlying stepped basement profile. The Turriff Syncline folds the metamorphic isograds and exposes shallow structural levels in its broad hinge zone in the Aberchirder–Turriff–Ythanwells area. The rocks here show evidence of only a single fold phase (F1) and cleavage (S1), accompanied by greenschist-facies metamorphic mineralogies (chlorite and biotite zones).

The plutons of the North-east Grampian Basic Subsuite strongly influence the local structural pattern both within and to the east of the PSZ. They cross-cut the early pervasive F1 fold and S1 cleavage pattern, but are postdated by the secondary folding (F2) and related cleavage formation (S2). The Insch Gabbro-peridotite Pluton is bounded by approximately east-trending shear zones and the Huntly and Knock Gabbro-peridotite plutons contain numerous shear zones and exhibit complex relationships with the Portsoy Shear Zone. The Huntly and Turriff districts are also the site of two fault-bounded half-graben structures of Devonian age, the large Turriff outlier and the northern end of the Rhynie outlier (Figure 11).

7.1 HISTORY OF RESEARCH

Early work in the Huntly and Turriff districts, mainly by Read (1923) focused on the lithostratigraphy, the igneous rocks, and the relationships between the different geological elements, but did not specifically address the structure of the area. Subsequently, Read (1955) and Read and Farquhar (1956) subsequently described the overall structure of north-east Scotland in terms of a Banff Nappe, a large east-facing recumbent fold with gneissose 'Keith Division' rocks in its core and less-highly metamorphosed 'Banff Division' rocks on its upper limb. Read (1955) proposed that the upper limb was transected by a low-angle extensional structure that he termed the Boyne

Line. He interpolated this 'lag' structure south from Boyne Bay through unexposed ground on the eastern side of the Cowhythe Gneiss (Cowhythe Psammite Formation) outcrop until it intersected the Huntly Pluton. Read then showed it emerging from the south-west extremity of the Huntly intrusion to link with the prominent shear zone on the south-east side of the Succoth–Brown Hill Ultramafic Intrusion. He did not recognise the Portsoy Shear Zone, but was responsible for defining the Turriff Syncline and farther east the complimentary Buchan Anticline. Johnson and Stewart (1960) discussed the relationship of the mafic-ultramafic plutons to the overall structure of north-east Scotland and concluded that the main elements of the Portsoy, Knock and Huntly intrusions postdated the early deformation phase (Banff Nappe) but were deformed by a secondary phase. Sutton and Watson (1956) carried out a structural traverse of much of the Banffshire coast section and emphasised the importance of a large east-facing monoform, the Boyndie 'Syncline', which dominates the local structural pattern. The steep limb of this 'syncline' crops out between Whitehills and Macduff. They also concluded that the largely right-way-up Dalradian sequence showed evidence of much deformation but rejected the Read's hypothesis of the Boyne Line. Johnson (1962) also worked on the Banffshire coast section where he defined four separate deformation phases in the Dalradian rocks and related these to metamorphic porphyroblast growth. The main phases were designated D2 and D3, with the primary D1 being represented by rare tight to isoclinal minor structures and a near bedding-parallel first fabric (S1). Subsequently Fettes (1970, 1971) showed that the early S1 cleavage related to the main folding in the greenschist-facies Southern Highland Group rocks, but a secondary crenulation cleavage, which he termed 'S3' (here termed S2), was related to the Boyndie 'Syncline'. He found that farther south the trace of the S1 cleavage was distorted and partly truncated by the Insch Pluton but that the later cleavage (S2) postdated the associated hornfels. Treagus and Roberts (1981) later showed that the early F1 minor folds exhibit consistent upward facing across the Boyndie 'Syncline' and hence designated it a D1 structure. Munro (1970) and later Munro and Gallagher (1984) used shallow drilling and geophysical surveys to map out the elements of the North-east Grampian Basic Subsuite between Portsoy and Huntly. They recognised the sheared nature of many of the internal and external boundaries of the Portsoy, Huntly and Knock plutons. Leslie (1984) showed that the north-east part of the Insch Pluton is similarly controlled by and cut by several shear zones. Ashcroft et al. (1984) synthesised this approach by showing how the mafic plutons are closely associated with a network of shear zones in north-east Scotland.

The significance of the Portsoy Lineament/Shear Zone was first argued by Elles (1931), who identified a ductile thrust on the east side of Links Bay, by Portsoy. Ramsay and Sturt (1979) also adopted this interpretation but they resurrected the idea of the Banff Nappe, interpreting the gneissose lithologies in the Dalradian succession as basal lenses of mobilised basement. They used Rb-Sr whole rock isochron ages of 691 ± 39 (674*) and 724 ± 120 (707*) Ma from the Inzie Head and Ellon Gneisses respectively, to argue that the nappe had carried an allochthonous succession westwards. Garson and Plant (1973) argued that the distribution of ultramafic rocks along the Portsoy Lineament defined a crustal suture. Fettes et al. (1986) showed how the various lineaments in the Grampian Highlands had influenced both the early sedimentation patterns and the later tectonic development. The Portsoy Lineament is coincident with major lithostratigraphical changes but subsidiary north-west-trending lineaments are also present. Baker (1987) considered the metamorphic patterns of North-east Scotland and suggested that they are best explained by overthrusting of the Buchan block to the west along the Portsoy Shear Zone, with subsequent differential uplift causing the steepening of the structure. Beddoe-Stephens (1990) documented the pressure–temperature variations implied by the differing metamorphic mineral assemblages on either side of the PSZ in the Huntly-Dufftown area. He concluded that pressures had increased, by some 2 kb, on the western side of the PSZ, as a result of loading by westward thrusting of the Buchan block. Goodman (1994) reviewed the evidence for the nature of the Portsoy–Duchray Hill Lineament, noting its complex history and its role in dividing two areas of

* Ages in brackets are corrected for the now revised decay constant of $1.42 \times 10^{-11}\ a^{-1}$

differing structural and metamorphic history in the Grampian Highlands. Dempster et al. (1995) obtained Rb-Sr mica cooling ages in a traverse across the PSZ on the Banffshire coast section and showed that uplift occurred at around 460 Ma with the PSZ acting as a focus of differential movements. They also concluded that the PSZ had not acted as a major thrust zone and that the pressure overprint was possibly the result of magmatic loading following the injection of mafic and ultramafic intrusions along the Portsoy Lineament at about 470 Ma. Droop and Charnley (1985) concluded that the mineral assemblages from the inner parts of the metamorphic aureoles of the Huntly, Knock, Morven–Cabrach and Belhelvie plutons were all compatible with emplacement of the North-east Grampian Basic Subsuite at pressures of 4 to 5 kb, equivalent to an overburden thickness of 15 to 18.5 km. Droop et al. (2003) presented further detailed mineralogical and geochemical data from the regional and contact metamorphic rocks in and around the Huntly Pluton. They showed that peak metamorphic conditions resulted from intrusion of the mafic and ultramafic pluton and attained temperatures of 900 ± 50°C and pressures of 4.5 ± 1 kb. These conditions resulted in considerable partial melting of the adjacent Dalradian semipelitic country rocks.

7.2 LINEAMENTS

As noted above, the main lineament that crosses the Huntly district is the overall north-north-east-trending Portsoy Lineament. No lithostratigraphical units can be traced across the structure, although the well-exposed Banffshire coast section suggests that in broad terms, little, if any, of the stratigraphy of the middle Argyll and lower Southern Highland groups is missing, when compared with the coherent Perthshire succession. The coarse conglomeratic and gritty arenite at the base of the Clashindarroch Formation, lithological variations in the Whitehills Grit Formation, and the local extent and varied lithology of the members of the Blackwater Formation all suggest that there are significant local facies variations adjacent to the lineament. Clean quartzite units (Grumack Hill Quartzite) sit adjacent to graphitic pelite and semipelite (Corinacy Pelite) in which gritty arenite incursions are present. The basal unit of the Southern Highland Group that crops out at the western margin of the Huntly district is a magnetite-rich pelite. These units all suggest deposition within a relatively unstable locally deep-water restricted-basin environment situated roughly along the Portsoy Lineament in late Argyll Group times (c. 620-600 Ma). The lineament likely formed a locus for crustal thinning during the later stages of Dalradian sedimentation with possible local formation of oceanic crust. Intrusion of the Succoth–Brown Hill and related mafic and ultramafic intrusions postdated Argyll Group sedimentation, but these bodies may also be a feature of the slow stretching that seems to have characterised the Laurentian continental margin during Argyll–Southern Highland Group times.

A subsidiary lineament, here termed the Keith Lineament, stretches north-east and south-west from Keith; its outcrop here is restricted to the north-west corner of the Huntly district. The lineament is marked in part by the intrusive sheets and pods of the Portsoy and Keith granites which were emplaced at about 600 Ma. The Keith Lineament also appears to be coincident with considerable thickness variations and facies changes found in several of the Ballachulish and Lochaber subgroup units. The normally persistent Mortlach Graphitic Schist and Corryhabbie Quartzite formations are abnormally thin and show atypical lithologies around Keith possibly reflecting a local depositional high. A thin lens of sparsely vesicular amphibolitic metabasalt, marking the occurrence of local basic volcanism, crops out within the Corryhabbie Quartzite Formation south-east of Keith. It is exposed both at the junction of the Den Burn and Burn of Drum [NJ 4420 4925] and farther west at [NJ 4394 4914]. The locally variable nature of the Keith Limestone Formation (Blair Atholl Subgroup) is also attributed to activity on this lineament. Like the Portsoy Lineament, the Keith Lineament was reworked later during Grampian orogenesis, forming the locus of development of a significant shear zone.

7.3 EARLY DEFORMATION STRUCTURES

The most common early structural feature in most parts of the Huntly and Turriff districts is a pervasive slaty or continuous cleavage or schistosity (S1) that is generally orientated near-parallel to the bedding. In the low-grade, greenschist-facies, turbiditic Southern Highland Group rocks that lie in the broad hinge zone of the Turriff Syncline, S1 is the only penetrative structure present, and in places it is axial planar to open to tight, medium-scale folding (F1) typically with gentle northerly plunging axes. This early folding is best seen on the Banffshire coast between Banff and Gardenstown, but is undoubtedly present in the lower parts of the Deveron valley in the Huntly district. An exception to this F1 fold pattern is found farther south-east in the gorge section of the River Ythan, east of Fyvie where lithologically similar Southern Highland Group mixed arenites and schistose semipelites, have been metamorphosed under lower amphibolite facies conditions to give cordierite and andalusite. A penetrative early cleavage (S1) is prominent, but there is little evidence of F1 folding. In contrast secondary folding is well seen. Farther west to the north of the Insch Pluton, Fettes (1968, 1970) documented the regional pattern of the S1 cleavage, and showed that it predated pluton emplacement. In the Aberchirder area S1 strikes approximately north–south, but as the Insch Pluton is approached it swings progressively clockwise, to strike east–west around the northern end of the Rhynie outlier. Farther west again at the western end of the Boganclogh sector of the Insch Pluton the S1 cleavage swings back anticlockwise to strike north-east to south-west. Typically its dip ranges from about 75° to vertical.

The ‘Slate Hills’ lie along the northern flank of the Insch Pluton and stretch from Hill of Kirkney [NJ 502 315] in the west, via Wishach Hill and Hill of Foudland, to Hill of Tillymorgan [NJ 652 348] in the east. These hills are underlain by dominantly pelitic and semipelitic turbiditic units of the Macduff Formation (Southern Highland Group), termed the Hill of Foudland Pelite Member, and have an outcrop width of 1 to 2.5 km. The bulk of this pelitic unit has been hornfelsed by the Insch Pluton with ‘spotted slates’ typically developed. The ‘spots’ are mostly porphyroblasts of chlorite after biotite. Cordierite, andalusite and fibrolitic sillimanite are also present in the inner parts of the metamorphic aureole. The dominant structure in these pelitic rocks is normally a steep slaty S1 cleavage. Bedding is only seen locally and typically lies subparallel to the cleavage. It is difficult to recognise any small- and medium-scale F1 fold structures in these fine-grained slaty rocks but cleavage-bedding relationships do imply that they may be present in parts (see below for details). A second deformation phase, D2, is superimposed on rocks of the ‘Slate Hills’, overprinting the metamorphic aureole of the Insch Pluton (Fettes, 1970).

In the Appin and Argyll group units west-north-west of the Portsoy Lineament early structures are rarely seen. The complex structural pattern in the Dunnyduff Wood–Mill of Wood Burn area, 1 to 2 km east of Keith, may be partly a result of D1 and D2 folding and deformation, but evidence from outcrop only emphasises the pervasive nature of the D2 folding and cleavage. Also, in the area north of the River Isla only hints of earlier folding are seen. A closed ovoid fold interference pattern about a metre across was noted in close folded, staurolite- and kyanite-bearing graphitic pelites at [NJ 5125 5462] in the Lime Burn section. Metamorphic porphyroblasts, notably kyanite and staurolite here, show evidence of two discrete growth phases with the earlier phase preserving aligned inclusions which commonly lie at a high angle to the later cleavage. It seems that textural and mineralogical evidence of the early deformation phase is not as well preserved west of the Portsoy Lineament as it is in the lower grade areas that lie to the east.

7.4 SHEAR ZONES

The main shear zones in the district are the sinuous, broadly north-north-east-trending, Portsoy Shear Zone (PSZ), and the north-east-trending Keith Shear Zone (KSZ) (Figures 11, 12). Both zones appear to have reactivated pre-existing lineaments, and the PSZ also has a later faulting history that offshore affects rocks as young as Mesozoic.

7.4.1 Portsoy Shear Zone (PSZ)

The PSZ varies from a narrow complex zone of faulted, broken and foliated rocks to a 3 km-wide zone with discrete thrusts, mylonitic microgranite, and lenticular bodies of the older Succoth–Brown Hill type (clinopyroxene-dominated) mafic-ultramafic intrusions and serpentinised dunite and peridotite pods. Unfortunately most of the zone is unexposed in the Huntly district so that its constituent features here are not well known. The main elements of the zone are shown in Figure 11.

A partial cross-section through the PSZ is exposed in the Burn of Cairnie between [NJ 4846 4461] and [NJ 4756 4474]. At the east end of the section, partly garnetiferous, recrystallised striped and foliated amphibolite dips at 60° to 70° to the east-south-east. The amphibolite represents an early lenticular basic (gabbroic) body that has become highly sheared and recrystallised within the PSZ. It is succeeded westwards by schistose garnetiferous semipelite with abundant quartz pods and stringers. Minor quartzose psammite and some garnet-quartz bands are present. At [NJ 4780 4492] blocky, mid grey, fine-grained, mylonitic, highly micaceous psammite and subsidiary semipelite contain pink-orange fine-grained granitoid veins and pods. All these elements are highly deformed and the exposure is dominated by the very strong secondary cleavage, tight minor folding and a pervasive down-dip lineation. The beds have an overall dip of 20° to 30° to the east and east-south-east, with the cleavage near parallel, possibly with a slightly steeper dip. Fold axes are colinear with the lineation and both plunge 20° to 30° to between 093° and 100°. Farther west flaggy quartzites, locally with a pervasive cleavage and lineation are present. These structures and the ductile mylonitic rocks relate to westward thrusting. Evidence of other ductile fabrics linked to the PSZ is not abundant in the Huntly district, but is seen more extensively farther north. Mylonites are present in the Durn Hill Quarry in the Portsoy district and highly deformed ductile fabrics with a prominent, steep, down-dip extension lineation are seen within the PSZ on the coast section immediately west of Portsoy. Here, numerous distinct phases of deformation can be recognised, but they are largely confined to the PSZ and cannot be correlated readily with the regional deformation phases found outwith the shear zone.

In the south-west part of the Huntly district extending south-west from Terryhorn Farm [NJ 468 402] a sheet of pink, finely foliated, feldspar-phyric microgranite up to 100 m thick forms a distinctive marker within the Beldorney Pelite Formation (see Foliated Microgranite – section 5.5.4). The microgranite sheet lies near the north-western margin of the PSZ and typically carries a pervasive mylonitic foliation that dips steeply south-east subparallel to the sheet margins. In thin section this fabric is defined by aligned biotite, muscovite and ribbons of fine-grained granular quartz. Tails of recrystallised feldspar and quartz are well developed marginal to the feldspar augen, which in places show a marked asymmetry. The microgranite has apparently acted as a locus for ductile shearing along the PSZ or has possibly been intruded along the shear zone synchronous with thrusting.

In the Huntly and Knock plutons Munro and Gallagher (1984) documented the occurrences of deformed (sheared) mafic and ultramafic rocks. Information from drillholes, geophysical surveys and detailed mapping were used to interpret the pattern of deformation and location of shear zones both in and adjacent to the pluton. Both they and Fletcher and Rice (1989) noted that the mineral assemblages indicated that deformation and shearing had occurred under hydrous amphibolite-facies conditions. Amphibole, biotite, quartz, carbonate, garnet, graphite and sulphide are the characteristic minerals developed. Localised and intense hydrothermal alteration is also focused on the shear zones and late-stage veins contain the assemblages, chlorite-carbonate and serpentine-carbonate-pyrite. Fletcher and Rice (1989) also noted that kinematic indicators in deformed gabbros implied that the sense of movement across the shear zones was top to the west, i.e. at least some acted as thrusts.

Munro and Gallagher (1984) noted that the south-west margin of the Knock Pluton on the west flank of Cuttle Hill between [NJ 4995 4730] and [NJ 4975 4725] consisted of picritic and gabbroic cumulates, which in drillholes show increasing evidence of deformation towards the west.

Plagioclase crystals are bent and partly recrystallised to finer-grained aggregates, and olivine and pyroxene almost entirely replaced by amphibole and biotite in the foliated rocks. Narrow steep mylonite zones in gabbros are exposed near Ruthven at [NJ 506 477], and highly foliated 'flaser gabbros' recorded from drillholes farther east. One specimen from a drillhole at [NJ 524 478] was identified as a blastomylonitic diorite composed of small andesine megacrysts in a fine-grained quartzofeldspathic matrix. These features are all interpreted as lying within or being linked to the PSZ.

Two boreholes were drilled by BGS adjacent to the serpentinised ultrabasic knoll of Drumna Gorach, close to the north-west margin of the Knock Pluton and just south-east of the north-western margin of the PSZ. The holes NJ 55 SW 13 (Drumnagorrach No.1) and NJ 55 SW 14 (Drumnagorrach No.2) were sited at [NJ 5241 5242] and [NJ 5198 5205] (Figure 12) and reached downhole depths of 151.9m and 88.7 m respectively. They were inclined at 60° towards 295°. Drumnagorrach No.1 penetrated variably foliated and amphibolitised sheets of gabbronorite, granular gabbro, and minor olivine-gabbro. Below 136 m lies a +15 m thick sheet of medium- to coarse-grained amphibolitic gabbro with possible cumulate textures in its upper part. The sheet is only weakly foliated in its upper part but at lower levels contains localised shear zones and the foliation becomes progressively stronger and more penetrative. Interbanded hornfelsed semipelite with andalusite, cordierite and locally sillimanite is present in minor amounts in the upper part of the hole, and beds of calcareous semipelite with some calc-silicate pods and lenses up to 2 m thick are present in the lower parts. Thin serpentinite veins and slivers occur at the boundaries of some of the mafic sheets. Planar biotite-plagioclase-quartz pegmatite veins, up to a metre thick, first occur at about100 m depth, and are common below 135 m. Where only weakly deformed, they are slightly discordant, but in the lower parts of the amphibolitic gabbro sheet they are highly foliated, recrystallised, and finer grained.

In Drumnagorrach No.2, generally foliated and amphibolitic metagabbro and metanorite containing numerous discrete shear zones and serpentinised ultramafic (dunite) pods and veins are present in the upper 50 m. Below lies an 8 m transitional zone of intermixed contaminated mafic rock and hornfelsed semipelite, which passes downwards into interbanded semipelite (locally with sillimanite and garnet), metalimestone and calc-silicate rock that lies between 70 m and the base of the hole at 88.7 m.

Fletcher and Rice (1989) noted that the Knock Pluton was composed dominantly of Lower and Middle Zone mafic rocks, mainly troctolite and noritic cumulates (see Section 5.3.2,). Variations in plagioclase compositions suggested that the base of the body lies at its western margin. The Drumnagorrach boreholes show that the Knock Pluton adjacent to the PSZ is marked by numerous individual mafic sheets, mainly gabbronorites, biotite norites, granular gabbros, and contaminated mafic rocks. Typically, sheets are a few metres thick, but locally range up to 15 m. They show variable amounts of foliation development, with more intense foliations developed near the margins of individual sheets, particularly adjacent to serpentinite or metasedimentary rocks. In parts unfoliated or weakly foliated mafic sheets are in sharp contact with the adjacent pervasively foliated sheets. Similar lithologies are also typical of the disrupted eastern and sheared central parts of the Huntly intrusion; Fletcher and Rice (1989) argued that such lithologies characterise parts of the roof zone. The combination of Upper and 'Roof zone' lithologies, and their apparent intrusion coeval with shearing suggest that the PSZ was active at the time of emplacement of the Huntly and Knock plutons.

On the south-east side of the Knock Pluton the contact zone with gneissose semipelitic and psammitic rocks of the Cowhythe Psammite Formation was intersected in Borehole 81, sited by Claymires Farm [NJ 5330 4944] (Styles, 1992) (see Section 2.3.4). The foliated and amphibolitised gabbros, norites and contaminated mafic rocks of the pluton show local mylonitic zones, some silicification, and late-stage veining. The most deformed mafic rocks occur over the 20 m intersection adjacent to the contact. Munro and Gallagher (1984) interpreted this eastern margin as a shear zone and the information from the boreholes around Claymires Farm supports this iterpretation. The shear zone appears to pass southwards into the Huntly Pluton where it forms a central, steep, north-trending feature.

In the Huntly Pluton there is limited evidence of foliated or mylonitic rocks on the west side of the intrusion. Mylonitic hornfelsed rocks were recorded locally at [NJ 492 445] by Munro and Gallagher (1984), and Munro (1970) noted that cumulate rocks showing evidence of shearing and crushing occurred near Drumdelgie [NJ 484 422], in close proximity to non-hornfelsed metasediments. However, elsewhere, the western boundary of the pluton appears to be sharp, with little sign of contact lithologies, deformed mafic units, or hornfelsed metasediments. This suggests that this margin is marked by a very narrow, ductile shear zone, or in most places, by a late-stage brittle thrust or fault that may cut out or conceal any earlier ductile contact zone.

Munro and Gallagher (1984) and Fletcher and Rice (1989) both presented evidence for a central sheared zone in the Huntly intrusion that corresponds to the 600 m to 2 km wide, poorly exposed north-trending zone of granular orthopyroxene-gabbro and clinopyroxene-leuconorite. Within this zone, mylonitised mafic rocks are recorded locally at a small knoll [NJ 513 412] 1 km north-west of Huntly, and at Upper Robieston Farm [NJ 527 422]. At the former locality the shear zones are steep, but at the latter they form flat-lying zones 3 to 4 cm across in undeformed noritic rocks. More extensively foliated gabbroic rocks are seen in a quarry at [NJ 534 444]. Foliated xenolithic gabbros also crop out near the eastern margin of the Huntly Pluton at [NJ 557 445], and mylonitised mafic rocks were noted adjacent to the southern margin of the pluton at [NJ 512 395] and at [NJ 515 393].

The bulk of the evidence for the late stage movement history of the PSZ comes from the Banff-shire coastal section and from the western edge of the Morven–Cabrach Pluton in the Glenbuchat district to the south-west. Steep anastomosing shear zones and the overall geometry of the zone suggest that transcurrent movements, probably dominantly dextral, postdated the earlier thrusting across the PSZ. Such movements probably occurred during the Early or Mid Ordovician, as the metamorphic mineralogies in the steep shear zones remained at amphibolite grade. Some of the steep shear zones in the Huntly and Knock plutons (see above), and those affecting the Succoth–Brown Hill and Portsoy mafic-ultramafic intrusions, may relate to this episode. Some of the smaller serpentinite lenses and pods may also have been emplaced during this phase.

The age of intrusion of the North-east Grampian Basic Subsuite is dated at about 471 to 474 Ma (Dempster et al., 2002; Condon and Martin, cited in Oliver, 2008 as a personal communication; Carty, 2001; Carty et al., 2012). Pressure (P) and temperature (T) estimates based on the hornfels mineral assemblages (Droop and Charnley, 1985; Droop et al., 2003) imply that emplacement occurred at a crustal depth of 15 to 18.5 km (4 to 5 kb). These P-T conditions are compatible with estimates derived from metamorphic mineral assemblages in some of the sheared zones immediately west of the Huntly intrusion (Beddoe-Stephens, 1990). The distribution of shear zones and the disordered, complex internal structure of the component elements of the Huntly and Knock plutons can be reconciled if their intrusion occurred coeval with shearing and associated deformation. This would explain:-

- the presence of Lower Zone cumulates at both the western and eastern margins of the Huntly Pluton, and the local occurrences of smaller cumulate lenses within the intrusions
- the variable occurrence of granular gabbros
- the occurrence of basic sheets more typical of an upper or roof zone at the lower western margin of the Knock intrusion
- the apparent shallow overall thickness of the Huntly Pluton implied by both the detailed and regional gravity and magnetic data.

7.4.2 Keith Shear Zone (KSZ)

The Keith Shear Zone (KSZ) can be traced north-east across the north-western corner of the district, stretching from the eastern outskirts of Keith [NJ 44 51] to around Clochmacreich [NJ 495

580] (Figure 12). Farther north-east, on Sheet 96W, the zone is overlain unconformably by the Deskford Old Red Sandstone outlier. Between the ORS outlier and the Banffshire coast, exposure is poor, but the variably foliated granite sheets exposed in Boggierow Quarries, about 1.6 km south-west of Portsoy, exhibit similar features to those of the Keith area. They mark the continuation of the KSZ, which here lies within 1 km of the western margin of the Portsoy Shear Zone. The two shear zones possibly coalesce just offshore. South-west of the Huntly district, in Sheet 85E, the KSZ can be traced for 5 km to the south-western outskirts of Keith, but farther south and west its coherence, position, and even its continuation towards Drummuir are uncertain.

In the Huntly district the KSZ is generally poorly exposed. It is defined mainly the limited exposures and inferred outcrops of the foliated Keith–Portsoy Granite (see section 5.1.1). A few exposures of strained quartzite occur adjacent to the granite, e.g. at Greenbog [NJ 4720 5454], but the only section across the whole shear zone, albeit discontinuous, lies in the Burn of Aultmore between [NJ 4589 5336] and [NJ 4596 5252]. Better sections occur within the town of Keith and the shear zone has been intersected in several boreholes drilled in connection with the proposed bypass route south-west of the town, all in the Glenfiddich district (Sheet 85E). The outcrop width of the KSZ is between 500 m and 1000 m and it dips to the south-east at between 25° and 40°. Hence its true thickness ranges from some 210 m up to over 500 m. Asymmetrical tails on feldspar augen in borehole cores from the Keith area consistently indicate a top-to-north-west thrust sense of movement.

Rocks below the KSZ belong to the Lochaber Subgroup (Findlater Flag and Cairnfield Calcareous Flag formations) and those above range from topmost Lochaber Subgroup to Ballachulish and Blair Atholl subgroups (plus Islay Subgroup at Portsoy). Many of the gneissose semipelitic rocks and metalimestone units within the shear zone are of uncertain affinity, but have been assigned to the Appin Group and are designated as the Keith Limestone Formation. However, despite the local facies changes that occur in the vicinity of the KSZ, and the mapped dislocations and local increase in strain, there is no great disruption of the overall stratigraphy across the shear zone (c.f the PSZ), and there appear to be few significant differences in the metamorphic history or in maximum pressure and temperature conditions experienced on either side of the KSZ (Beddoe-Stephens, 1992).

Within the KSZ the deformation is concentrated in numerous anastomosing shears, most marked by separate sheets of granite, which exhibit intense planar and linear fabrics. There is an overall foliation defined by muscovite, biotite, and by recrystallised elongate quartz ribbons and feldspar augen, but in many outcrops the dominant fabric is a strong down-dip stretching lineation formed by rodded quartz and feldspar. Microscopic features of the less deformed metagranites include relics of the original igneous texture and textural features which suggest that some deformation possibly occurred during emplacement (Phillips, 1998). In the most intensely deformed rocks, igneous textures are completely overprinted by the planar to anastomosing foliation, which locally displays S-C geometry. The dominantly semipelitic metasedimentary rocks that separate the sheets and pods of foliated granite are also strongly foliated and show prominent down-dip lineations. In contrast, the metalimestones have been extensively recrystallised and commonly show little fabric. Intersection lineations and minor fold axes are also broadly parallel to the stretching lineation, both in the shear zone and locally in the footwall (Figure 13).

7.4.3 Nature of the PSZ and KSZ and their relation to deformation history

As noted above the Portsoy Shear Zone marks the site of an earlier lineament that has controlled the depositional pattern and thus the nature of the Dalradian stratigraphy, particularly within the Argyll Group. It also marks the western extent of geophysically distinct sub-Dalradian basement that may well reflect a fundamental difference between the Buchan area and the remainder of the Grampian Highlands. The structural and metamorphic history also differs considerably across the PSZ, although in the Huntly and Glenfiddich districts the boundary between the low P–high T Buchan-type metamorphism and the higher P–high T Barrovian-type metamorphism clearly lies to the west of the PSZ (Beddoe-Stephens, 1990). Unfortunately, the lack of inland exposure, complexity of the igneous and sedimentary sequences in the PSZ, and spatially variable nature of the ductile and brittle structures related to the PSZ in the Huntly district, all serve only to pose more questions about the history of this zone and its role in the wider tectonic evolution of the area. The borehole and limited outcrop evidence show that deformation and shearing have accompanied and in part controlled emplacement of the Ordovician North-east Grampian Basic Subsuite, dated at about 474 to 472 Ma.

Major westward shearing on the PSZ was proposed by Baker (1987) and Beddoe-Stephens (1990) to explain the marked change in metamorphic pressures demonstrated across the zone with the increase in pressure to the west of at least 2 kb. This westward translation is accepted here and must have taken place on a gently eastward dipping structure. Movement clearly post-dates the D1 deformation events both in the Buchan area and farther west as the D1 structures and metamorphic pattern are disrupted. If the movement along the PSZ and KSZ are linked, as seems likely, this thrust translation would relate to the main secondary deformation seen to the north-west of the PSZ. The steepening of the PSZ occurred subsequent to the main westward translation. However, a zircon U-Pb TIMS age of 468.5 ± 0.5 Ma from a variably deformed and steeply inclined pegmatitic granite vein at Portsoy Harbour implies that subvertical lateral movements occurred just after 470 Ma, i.e. only shortly after the main deformation. It is unclear as to how (or even whether) the secondary deformation found to the west of the PSZ relates to that to the east.

The discontinuous sheet-like nature of the porphyritic granite intrusions that comprise the approximately 600 Ma Keith–Portsoy Granite cannot be ascribed solely to the subsequent shearing and deformation. Emplacement seems to have been controlled by a pre-existing lineament, along which the lenticular granite sheets and pods were emplaced. The KSZ has subsequently reactivated this structure, which may well have been initiated during deposition of the Argyll Group sediments. This part of the Dalradian succession formed during a period of general crustal extension and localised instability, as shown by the presence of several small but deep rift basins, and the occurrence of widespread basic igneous activity. This was followed by continental break-up and the consequent opening of the Iapetus Ocean. Although emplacement of the Keith–Portsoy Granite was coeval with the extrusion of mafic lavas and intrusion of abundant dolerite sheets farther south-west around Tayvallich, regional considerations and global plate reconstructions suggest that the full rift–drift transition did not occur until around 570 Ma. Any small amounts of granitic magma generated by the crustal melting as continental extension progressively developed would likely migrate along pre-existing or newly formed lineaments.

The KSZ may have been active during early deformation of the Dalradian sequence, but the main foliation and lineation link to top-to-north-west ductile thrusting that formed part of the second major penetrative deformation phase (D2) found in this district, and with major shearing on the PSZ.

7.5 SECONDARY DEFORMATION STRUCTURES

On the Banffshire and Aberdeenshire coastal sections a second main penetrative deformation phase becomes apparent once the andalusite isograd is crossed. Note that this deformation has been termed 'D3' on the Banffshire coast but in this memoir it is termed D2. Minor scale secondary folding (F2) and a related crenulation cleavage (S2) are commonly developed, and the earlier F1 structures become progressively tightened. Concomitant with further increases in metamorphic grade to middle amphibolite facies (sillimanite grade) the rocks commonly are typically gneissose with a composite foliation, particularly the more pelitic lithologies. In the Huntly and Turriff districts it is not possible to recognise D1 structures in such high grade rocks, although they can still be identified in parts of the Banffshire coast section, e.g. in the Boyne Limestone and Cowhythe Psammite formations.

East of the PSZ there is evidence for a widespread secondary deformation phase that has resulted locally in open to tight, small- to medium-scale folding, commonly accompanied by a crenulation cleavage (S2). The S2 cleavage is found only in rocks of the andalusite zone and higher metamorphic grades and is mainly defined by growth of biotite. It is notably pervasive in the more pelitic lithologies. Fettes (1970) reported clear overprinting by S2 (N.B. termed 'S3' by Fettes and other authors) of both the first slaty cleavage (S1) and of the hornfels mineralogies in the Southern Highland Group rocks for up to 5 km north of the Insch Pluton. Here, S2 strikes generally north-east and dips moderately to steeply, mostly to the south-east; F2 minor fold axes typically plunge gently to moderately to the east (Fettes, 1968). In contrast, farther north by Aberchirder, both S1 and S2 cleavages strike north–south, and are subvertical. It is clear that D1 deformation predates the intrusion of the North-east Grampian Basic Subsuite but that D2 post-dates or is synchronous with the later phases of intrusion (Fettes, 1970). Where D2 deformation is well developed, e.g. north of the Boganclogh sector of the Insch Pluton, S2 cleavages and F2 folding are dominant. The S2 cleavage is generally still recognisable as a crenulation cleavage, but where strongly developed it forms the dominant parting in many of the pelitic rocks.

West of the PSZ secondary deformation (D2) structures are more complex. The major fold structures attributable to this deformation in the Huntly district include the Edingight and related folds, the Balloch Folds, and the Ardonald Fold (Figure 13). These structures are generally periclinal with hinge plunges varying from gentle to moderately to the north-east or east-north-east, and to the south-west. In concert with the shear zones they dominate the regional structural pattern. The D2 fold structures are accompanied by a penetrative crenulation or spaced cleavage defined by amphibolite grade mineralogies, including biotite, muscovite, garnet and kyanite. Following on from the work of Chinner (1980) and Harte and Hudson (1979), Beddoe-Stephens (1990) showed that rocks west of the PSZ had experienced a significant increase in pressure (up to 2 kb) at the time of the secondary deformation. This was demonstrable in some specimens where sheaves of kyanite have replaced chiastolite (andalusite), and the mineralogy used to calculate the P-T values formed part of the secondary fabric in the rock. Similar but less clear increases in P-T are also documented by Beddoe-Stephens (1992) across the KSZ. Hence the secondary deformation appears to be intimately related to activity across the major shear zones.

The main elements of the secondary deformation are the crenulation/spaced cleavage (S2), large-scale and minor folding (F2), and a locally prominent lineation (L2). L2 varies from an intersection to a prominent extension lineation (rodding), e.g. in and below the KSZ, and locally it is a mineral lineation. The orientations of these elements are shown in Figure 13.

The cleavage varies from a pervasive crenulation cleavage to a finely spaced (up to 1 mm wide) cleavage defined mainly by aligned biotite and muscovite growth and granular quartz and feldspar. In parts there has been differentiation into quartzofeldspathic and mica-rich lithons, separated by the S2 planes. Chlorite is commonly developed, both within the dominant S2 fabric, and as late porphyroblasts that cross-cut S2. Garnet, kyanite and staurolite growth is also documented in pelitic and semipelitic rocks, coeval with the formation of S2. The S2 cleavage varies in strike from north-north-east to east and generally has moderate to steep dips to the south-east and south respectively. In the area immediately south-east of Keith, in sections along the Burn of Drum and Herricks Burn, and around Denhead [NJ 437 491], S2 strikes east-south-east and dips gently to the south-south-west. The L2 lineations normally have a consistent down-dip plunge of 20° to 40° to the south-east in the foliated Keith Granite within the KSZ. Here, they are readily identified as extension lineations as they relate to the prolate form of the deformed felspar megacrysts. Outwith the shear zone the nature of the lineation is less clear and L2 are more generally intersection lineations linked with F2 folding. F2 fold axes mostly plunge gently to moderately to the north-east or south-west quadrants. A similar pattern is documented farther north-west in the Elgin district (Peacock et al., 1968).

In the Sillyearn Hill–Edingight [NJ 516 556]–Lurg Hill area the structure is dominated by the F2 Edingight fold, a large east-north-east-plunging, tight, north-west vergent antiform developed mainly in Blair Atholl Subgroup semipelites, pelites and metalimestones. Both limbs dip moderately to steeply south-east. Exposures in the fold hinge zone in the Edingight–Whiteley [NJ 524 566] area show minor F2 folds that plunge 20° to 45° to the east-north-east (062° to 078°). The fold is cut by a major north-west-trending fault and on its downthrown south-west side the fold is resolved into a series of anticlines and synclines, exposed in the Burn of Paithnick section. The Corryhabbie Quartzite Formation occurs in its core at Gallow Hill [NJ 483 525]. In this area F2 minor fold axes locally plunge south-west, although the overall structure still retains its regional north-east plunge. The south-east plunging L2 extension lineation is also prominent here. Complementary kilometre-scale Sillyearn and Lurg Hill synclines that preserve the Durnhill Quartzite Formation lie south-east and north-west respectively from the Edingight anticline. Good cleavage (S2)–bedding relationships from the hinge zone are seen in sections in the Lime Burn [NJ 513 550], and on the mainly overturned north-west limb in small stream sections by Westertown [NJ 509 553], Brambleburn [NJ 510 563] and Langley [NJ 516 567]. In some impure limestones the S2 cleavage is a pressure solution striping, and in some psammite units it forms a spaced cleavage. Exposures are poor around the Sillyearn Syncline but in the small quarry at Cairnhill [NJ 5063 5136] an L2 intersection lineation plunges 27° to 063° and S2 (032°/45°SE)–bedding relationships show that the quarry lies on the inverted south-east limb of the syncline. Farther north-east marginal to the flooded Limehillock Quarry [NJ 516 520], the S2 cleavage has a similar orientation to that in Cairdshill Quarry (027°/52°SE) but here a strong L2 lineation plunges approximately 40° towards 130°, i.e. approximately down dip on the S2 cleavage plane. Very tight F2 minor folds are present locally, possibly reflecting their close proximity of the PSZ. The F2 fold axes plunge near-parallel to the finite extension direction. On Lurg Hill the overall synclinal fold structure is complicated by the presence of lenses and sheets of the Keith–Portsoy Granite, and by the proximity of the KSZ to the north-west. F2 axes and L2 intersection lineations plunge 54° to 046° and 35° to 238°, but the strong pervasive S2 cleavage in the more pelitic units dips moderately to steeply south-east. The variable S2–bedding relationships found in the hinge zone of the Lurg Hill Syncline are compatible with the presence of minor F2 folding.

In the north-west corner of the Huntly district west of the KSZ the dominantly flaggy psammites and subsidiary semipelites of the Findlater Flag Formation show a strong S2 cleavage and generally weak, east to south-east plunging L2 extension lineation (commonly down-dip). There are few F2 minor folds, and those recorded are tight and reclined with axes that plunge gently to the east-south-east, e.g. in the Burn of Aultmore section at [NJ 4545 5509]. Later kink bands and minor chevron folds are also locally present.

The Balloch–Mill of Wood area is dominated by tight, kilometre-scale, north-north-west-vergent, overturned folds defined by the thick Corryhabbie Quartzite Formation. On The Balloch itself there are only sparse exposures of quartzite, but a coherent section is seen in the Paties Burn [NJ 483 503]. At the head of Paties Burn an elongate structural outlier of semipelite and psammite with a distinctive bluish grey metalimestone of Blair Atholl Subgroup affinity lies within the quartzite outcrop. This is interpreted as an F2 synclinal outlier. Farther south in the Glen of Coachford [NJ 465 466], Morlach Graphitic Schist Formation crops out in an anticlinal hinge zone in the quartzite. Limited S2–bedding relationships and the presence of anticlinal inliers and synclinal outliers imply that the quartzite is folded into a series of tight F2 periclinal folds in the area around The Balloch. At its western margin the quartzite is foliated and generally highly weathered, and parts of the Ballachulish Subgroup succession appear to have been cut out particularly along its northern part. A thrust is interpreted here on the attenuated overturned limb of a large F2 anticline. Structurally below is a tight syncline, the Dunnyduff Syncline, in graphitic pelite and metalimestone of the Fordyce Limestone Formation. A penetrative S2 slaty to crenulation cleavage is dominant and the F2 axes in the hinge zone plunge 20° to 081°. As the synclinal hinge is traced west-south-west its plunge swings to 42° to 108°, but the S2 cleavage dips relatively uniformly between 45° and 60° to the south-south-east. The hinge zone passes into the Corryhabbie Quartzite in Dunnyduff Wood [NJ 445 495] and here the Dunnyduff Syncline may well refold a tight F1 antiform. A thin antiformal inlier of Mortlach Graphitic Schist lies within the quartzite; its outcrop defining a small 'hook' that extends to the south-west. The quartzite is bounded to the north-west by a further thrust, but it is underlain by Lochaber and lowermost Ballachulish subgroup units that are well exposed in sections along the Burn of Drum and the Den Burn, immediately south-east of Keith. Here, the later F3 axes plunge gently to moderately south-east and locally gently north-west, and an S3 cleavage dips between 15° and 50° to the south. The presence of tight F2 folds can be inferred from changes in the S2–bedding relationships. The increasing strain as the KSZ is approached is matched by the rotation of fold axes and intersection lineations such that they plunge gently to moderately south-east. Farther south-east in the Herricks and Birken burn sections, L2 intersection lineations plunge 20° to 25° to the east-south-east, reflecting the increasing distance from the KSZ again.

South-west of the west-north-west-trending Cairnie Fault in the Huntly district is the eastern termination of a large elongate periclinal structure, termed the Ardonald Fold. This broad anticlinal structure stretches in an arc from Ardonald [NJ 455 442], west, west-south-west and finally south-west, across into the Glenfiddich district, extending to the head of Glen Rinnes. Grampian Group psammites and quartzites crop out in its core and Lochaber and lower Ballachulish subgroup units form the bulk of the exposed units in the antiform. Evidence for its complex history is best seen in the Glenfiddich district, where the Morthlach Graphitic Schist Formation lies in an apparently complementary synform to the north-west of the Ardonald Fold. Within the synform the S2 cleavage is folded and a further crenulation cleavage is present, whereas in the antiformal hinge zone of the Ardonald fold, S2 is axial planar. Hence the apparent complementary structures have at least partly different and probably composite histories. In the area around Whitehillock Farm [NJ 4464 4563] at the eastern end of the Den of Pitlurg, the flaggy, striped calcareous psammites, semipelites and calc-silicate rocks mainly dip moderately to steeply northwards. The S2 cleavage varies from steeper to shallower than bedding, and a prominent subhorizontal L2 intersection lineation is present. Later open folds (F3) and crenulations with a weak north-dipping crenulation cleavage also occur, particularly where the beds have shallower dips. F3 fold axes are coincident with L2. These relationships suggest that tight F2 folding is locally present and that the Ardonald fold is a composite structure with pre-D2, D2, and post-D2 elements. This may explain why its eastern termination is relatively abrupt, yet the recorded dips of the bedding are generally 20° or less. On the southern flank of the Ardonald Fold in the Huntly district exposures are very sparse but the beds dips moderately to steeply south-east. Thrusts related to the PSZ repeat parts of the Appin Group succession and metadolerite intrusive sheets are abundant. No large scale F2 folding appears to be present, although such fold structures do occur farther south-west in the Glenfiddich district.

7.6 LATE-STAGE DEFORMATION STRUCTURES

In several areas, coherent deformation features postdate the D2 structures, but these are only of local extent and cannot be correlated across the district. They are preferentially developed in the more pelitic lithologies, in the thinly bedded psammites and semipelites, and in the banded calc-silicate rocks. The most common late-stage structures are crenulation cleavages and associated open to close folding, or kink/chevron folds. Large scale open folds notably affect the S2 cleavage pattern only in the area between Keith, The Balloch, and Ardonald. In the PSZ and the partly sheared intrusions of the North-east Grampian Basic Suite, only minor late stage shear zones and fracture zones, characterised by low grade metamorphic assemblages, are present. In the very poorly exposed pelitic elements of the schistose and gneissose Castle Point Pelite and Cowhythe Psammite formations, late-stage crenulations result in a 'wavy' foliation/schistosity; a good example is exposed in a small quarry on Little Brown Hill at [NJ 5722 5129]. The range and orientation of late-stage structures is well seen on the Banffshire coast section on Sheet 96W between Links Bay and Old Hythe Bay (Cowhythe Psammite Formation), and immediately west of Portsoy (Castle Point Pelite Formation).

In the area west of the PSZ structural elements related to an apparently coherent D3 deformation event are present in parts. They are generally manifest as an S3 crenulation cleavage, an L3C lineation, and associated open to close, small- and medium-scale F3 folds. Figure 14 shows the orientation of the D3 elements on a lower hemisphere equal area stereogram. The S3 cleavage generally dips moderately south-east, and L3C plunges gently to moderately east to south-south-east. F3 fold axes mainly plunge towards the south-east quadrant, but both they and the F3 axial planes show considerable local variation. The orientation of the D3 features largely reflects the dominant bedding and S2 cleavage orientations, with the later deformation features developed on the south-east dipping parts of the already folded succession. Good examples of L3 crenulations and F3 chevron folds are seen in thinly banded, finely cleaved, semipelitic units of the Findlater Flag Formation in the lower part of the Cross Burn section [NJ 4433 5276], east of Newmill, and in the Queans Stripe [NJ 4862 5755] near the northern margin of the district. At the first locality the semipelites are interbanded with psammitic units. A somewhat coarser S3 crenulation cleavage is well developed in the schistose, kyanite and staurolite-bearing graphitic pelite of the Fordyce Limestone Formation in the Burn of Braco between [NJ 5058 5373] and [NJ 5056 5361]. In thin section F3 microfolds are seen to postdate the porphyroblasts and fold the S2 biotite fabric. In these pelitic rocks minor recrystallised biotite locally defines the S3 cleavage. Minor open folds are best seen in the Burn of Tarnash and Birken Burn sections near their junction [NJ 4442 4893]. Their axial planes are very steep and no related cleavage is developed. More prominent F3 open to close folds are developed on the north flank of the Ardonald fold in thinly banded calcareous psammites, semipelites and calc-silicate rocks adjacent to the Den of Pitlurg [NJ 439 453]. F3 axes here plunge gently east (085° to 095°) commonly coaxial with the L2 intersection lineation. The related axial planes dip moderately north and commonly have a related weak S3 crenulation cleavage. D3 deformation is much more strongly developed farther west in the adjacent Glenfiddich district. Here, in the Burn of Davidston area [NJ 415 464] a moderately south-south-east-dipping S3 crenulation cleavage and related chevron folding are the dominant structures in the Mortlach Graphitic Schist Formation and abundant F3 minor folding is also seen in the Pitlurg Calcareous Flag Formation. A kilometre-scale synform is developed in the graphitic pelite unit and S2 is tightly folded by F3. Similar relationships continue south-westwards into Glen Rinnes. It is unclear whether this complementary structure to the antiformal Ardonald Fold is a D3 fold or whether D3 deformation has merely tightened a pre-existing F2 structure.

7.7 FAULTING

The present distribution of rock types in the Huntly and Turriff districts shows significant local fault control. In the Huntly district, the dominant faults are those associated with the PSZ, and those trending approximately north-west that offset the earlier mainly north-east and north-north-east structural trends. In Strathbogie northerly trending faults affect the parts of the Insch Pluton and control the northern end of the Devonian age Rhynie Outlier. In the Turriff district the generally northerly trending faults that bound the Devonian Turriff Outlier dominate the geology. north-north-west- to west-north-west-trending faults are present in the Insch Pluton and offset its northern boundary. Note that over much of the Huntly and Turriff districts the generally sparse bedrock exposure and broad nature of the lithostratigraphical units make it difficult to delineate faults. As a result the geological maps do not fully represent the fault population in the district. The fault history is undoubtedly complex, and the relative ages, periods of reactivation, and interaction of the differently orientated fault sets remain unclear. The more significant mapped faults are shown on Figure 10.

Faulting is known to have locally reactivated the PSZ, and evidence is seen at the margins of the Knock Pluton. The Drumnagorrach boreholes intersect broken and veined zones marked by chlorite, quartz, carbonate (commonly dolomite) and epidote, and in the Claymires boreholes, carbonate veining, zones of silicification, and brecciated carbonate-quartz-pyrite veining are common. Graphite and slickensided serpentinite are also locally present in these faulted zones.

The north-west- to west-north-west-trending faults are generally steep and both normal and reverse geometries are present. They cross-cut the PSZ but their age is unclear. The north-west-trending Cairnie and Isla fault systems may both have earlier histories, as there are distinct changes in the geology across them. The Cairnie Fault system marks the main northern limit of abundant metadolerite sheets and may possibly have reactivated an earlier lineament. Some gold is reported in stream sediment residues from parts of its trace. The Isla Fault also apparently exerts some control on the distribution of mafic-ultramafic elements of the Huntly and Knock plutons. Its trace now forms part of the north-north-east margin to the Huntly Pluton and it steps north-westwards through a complex mineralised zone between the Huntly and Knock plutons around Littlemill [NJ 518 474] and Auchincrieve [NJ 522 480] (Fletcher and Rice, 1989). Just south of Nethermills [NJ 506 506] its trace changes from north-west to just north of west, and follows the Isla valley until it intersects the north-east-trending Newmill Fault at the western edge of the district.

North-west-trending faults are common north of the River Isla and form prominent features, commonly marked by springs, on the mainly quartzite ridges of Sillyearn Hill [NJ 514 523] and Lurg Hill [NJ 508 573], and on Knock Hill [NJ 537 551]. Minor quartz-breccia float is present on the ridges and fracturing and quartz veining are observed locally, e.g. at [NJ 5295 5530], 300 m north-east of Knockbog Farm. Pyrite mineralisation is common in large metalimestone boulders (Fordyce Limestone Formation) by the Lime Burn east of Mains of Edingight, e.g. at [NJ 5203 5627], close to notable north-west-trending bench features. Similar trending faults in the Portsoy district to the north bound the Deskford Old Red Sandstone outlier, and hence must postdate the Mid Devonian.

North-east-trending faults are largely confined to the Keith area immediately west of the Huntly district. These form part of the Drummuir Fault system that extends from Keith south-west to Dufftown. An extension of this system cuts through the Dunnyduff area and a fault is exposed in a small quarry by the Burn of Tarnash at [NJ 4429 4925]. Here a 1 m to 1.5 m-wide subvertical breccia with some vein quartz cuts broken, closely jointed, and slightly weathered Corryhabbie quartzites. The bedding steepens immediately north-west of the fault breccia zone and becomes shallower again on the south-east side, implying that the fault downthrow is to the south-east.

South-east of Keith, small-scale, brittle, low to moderate angle faults and duplex structures are locally seen in Appin Group rocks. They are recorded from the Corryhabbie Quartzite Formation in the lower Tarnash Burn at [NJ 4426 4923], and from calcareous semipelites, micaceous psammites and calc-silicate rocks of the Tarnash Phyllite and Limestone Formation in the Herricks Burn' section at [NJ 4449 4913] and [NJ 4467 4910]. The fractures are marked by both green-black shiny chlorite-rich infill and by clay gouge. They generally dip gently to moderately south and south-south-east and are locally cut by small-scale steep faults. Their overall geometry suggests that they are mainly extensional and hence related to the uplift of the area following the Caledonian orogenic events. Such movements may in part be reactivating earlier small ductile to brittle north-north-west-directed thrust planes; such structures have been mapped at the base of the larger quartzite units in this area. Similar extensional structures are seen in the Glenfiddich district to the west, where they occur for several metres beneath the Old Red Sandstone unconformity, particularly in the vicinity of large faults.

A network of faults occurs in the western part of the Glens of Foudland. In the Den of Glennieston, immediately east of Glennieston Farm [NJ 5767 3464] and in the unnamed 'den' immediately west of Broomhall the semipelitic bedrock is fractured, iron- and manganese-stained, and strongly weathered. The dens form prominent north-west-trending features that link to the east-north-east-trending Glen Water, itself probably fault-controlled. In the upper part of this burn there are several springs, including Caird's Well. A little farther east, the Burn of Stodfold drains Stodfold Moss, flowing northwards to its confluence with Glen Water between Stodfold [NJ 5862 3427] and Clinkstone [NJ 5892 3435]. At [NJ 5871 3375], outcrops and large blocks of pebbly grit and conglomerate are fractured, with slickensides visible on fracture surfaces, and vein quartz locally present. Semipelite outcrops at [NJ 5876 3395] are similarly affected. The burn also marks a topographical feature with its eastern bank forming a scarp about 20 m high and lower ground lying to the west.

In the west of Strathbogie around Brown Hill [NJ 440 367], east-north-east-trending faults are present. Faults of this trend are commonly associated with emplacement of the end Carboniferous quartz-dolerite dyke-swarm and reflect north–south tension at this time. The east-north-east faults generally cross-cut the north-westerly trending set, implying that the latter lie within the Mid Ordovican to end Carboniferous age bracket. The north-west-trending faults are probably mainly Silurian–Devonian in age, linked to the widespread uplift and extensional faulting that took place in the Grampian Highlands at the end of the Caledonian Orogeny.

7.7.1 Turriff and Rhynie outliers

Faulting is conspicuously manifest in its control of the margins of the Old Red Sandstone outliers of Turriff and Rhynie (Strathbogie) in the Huntly–Turriff district. Two faults define the narrow (550 m to 2 km wide), north-trending western graben of the Turriff Outlier that extends from Wood of Wrae [NJ 730 525] in the north to Cushnie [NJ 700 410] in the south. This graben is separated from the main part of the outlier by a 1 to 2 km wide horst, upon which are preserved some 40 metres of conglomerates and breccias.

The main part of the Turriff Outlier is an east-facing, half graben that extends northwards to the Banffshire coast. It is 8 km wide at the northern margin of the district, but narrows southwards with Old Red Sandstone rocks cut out at Fyvie. The western bounding fault trends about 010° over much of its length, but in the south, beyond Sillerton [NJ 738 430] the fault trace swings gradually anticlockwise to trend south-east. Here, it delineates the southern margin of the Devonian outlier. In the Fyvie [NJ 765 380] area, the mapped andalusite and cordierite isograds, which here trend north-north-east, are displaced apparently dextrally by an average of four kilometres. Taking the downthrow on the normal fault here as about 1 km to the north-east, as estimated by Ashcroft and Wilson (1976) from detailed gravity and magnetic studies over the Turriff Outlier, this would imply that the metamorphic isograds dip at only around 15° to the west-north-west. Such dips would imply that the isograds lie close to the regional bedding and their dip relates to the geometry of the Turriff Syncline, whose profile is seen on the Banffshire coast section (see Stephenson and Gould, 1995, fig. 21).

On the basis of aligned topographical features, the fault which bounds the western graben of the Turriff Outlier is shown extending south-westwards through Glenmellan [NJ 654 383]. This fault may link up with the east-north-east- to west-south-west-trending fault, which is mapped in the Stodfold [NJ 586 342] to Whinbrae [NJ 595 347] area, at the western end of the Glens of Foudland (see above).

A north-trending fault in Strathbogie area bounds the western side of the Strathbogie Old Red Sandstone Outlier. The fault trace coincides with a marked break in slope at the eastern end of the Hill of Noth. A small excavation in the area at the time of survey at [NJ 5153 3072] revealed ‘thoroughly smashed’ semipelite and brecciated fragments of andesitic lava. A spring occurs some 70 m south of the excavation, but post diggings only 40 m to the south-south-east have unearthed abundant andesitic lava clasts. The evidence for continuation of the fault to the north along the break of slope at the eastern end of Hill of Kirkney is less obvious, but its trace can be gleaned from changes seen in soil colour and clast content. Red till with cobbles occurs beneath the soil in the fields due north of Boggs of Noth [NJ 5177 3131], but to the west the soil is grey brown with clasts of slaty semipelite.

Devonian lavas and volcaniclastic sediments (including Read’s ‘Cork rock’ – a markedly vesicular andesite) are exposed around Kirkney Bridge [NJ 5182 3361], just north of exposures of Macduff Slate. Although no clear break can be identified here at the boundary between the Dalradian and the Devonian sequence, the Macduff Slate is locally brecciated and the lavas are highly weathered; hence, a fault is inferred. South from the bridge to Boggs of Noth, the bedrock is obscured by till and other superficial deposits.

The northern limit to the outcrop of the Dryden Flags Formation is marked by an east-north-east-trending fault whose trace is mapped up the Glen of Cults [NJ 535314]. Most of the outcrops of both the Devonian and Dalradian rocks show intense brecciation and deep weathering here. Exposures just into the field immediately north of Roadside of Cults [NJ 5280 3108] show vertical, anastomosing 'fractures' with lozenge-shaped fragments of pelite 'smeared' around more competent gritty beds.

Read's mapping showed that the ORS inlier is displaced by an east-north-east-trending fault in the Burn of Raws, around the Raws of Noth [NJ 5175 3102]. Faulting in this area is indicated by fractured and weathered semipelite at around [NJ 510 308] in the Glen of Noth. These phenomena, together with the strong feature formed by the glen itself, are interpreted as indicating the presence of a significant fault that offsets the Devonian outcrop.

7.8 DETAILED STRUCTURE NOTES

7.8.1 Fyvie Gorge [NJ 780 369 to NJ 820 392]

Good exposure, way-up evidence and cleavage–bedding relationships all assist in the delineation of several major folds in the Fyvie Gorge section (see 1:50 000 Sheet 86E, Turriff). The abundant grading allows the way-up and structural facing to be determined throughout the section. The bedding strikes between 000º to 020º at the western end of the section, but swings clockwise to strike north-east near the Braes of Blairfowl [NJ 805 304] before swinging back to be more northerly again to the east. The rocks generally dip south-east, but at widely varying angles (10º to 90º); there are some westerly dips on the limbs of minor parasitic folds.

The folds, designated F2, are recumbent, upward-facing, close to tight, generally north-west vergent structures whose axial planes dip south-east at moderate to high angles. Upper limbs typically dip at 10º to 40º south-east, whereas the lower limbs dip more steeply (30º and 80º). Fold axes plunge gently north-east or south-west, as indicated by the minor folds. The related penetrative crenulation to continuous S2 cleavage wraps the cordierite and andalusite porphyroblasts, indicating fold development either during the later stages of the main metamorphic event or following the peak of metamorphism.

Minor late deformation is present in places. Although generally only giving rise to very open folds and warps, late deformation is more intense towards the east end of the section, notably around [NJ 820 387]. Monoformal folds with limbs dipping very gently west or subvertical deform the main cleavage, producing a strong crenulation. Quartz veins that elsewhere are near-parallel to the S2 cleavage, are also deformed here.

A prominent feature of rocks in the Fyvie Gorge section is development of a strong joint set that shows close and regularly spacing (about 2 cm in places). The joints generally trend at about 110º and dip between about 50 º and 70 º. These joints may relate to the main fault that bounds the Turriff Outlier (see below) as they show roughly the same trend.

7.8.2 The Slate Hills

Evidence for large-scale fold structures within the Slate Hills is ambiguous. On the Hill of Kirkney, to the west of Strathbogie, bedding dips in opposing directions on the north and south sides of the hill and high bedding–cleavage intersection angles are present on the ridge. In addition the rocks show minor folding and strong deformation at the eastern end of the ridge, all suggestive the presence of a syncline. However, east of Strathbogie, evidence for a syncline is much less clear. Cleavage is consistently steeper than bedding of the north side of the Hill of Corskie, Wishach Hill, Hill of Foudland, and on the Hill of Tillymorgan, but bedding–cleavage relationships are difficult to find on the south side of the hills. At two localities on the south side of Hill of Tillymorgan the cleavage dips at shallower angles than bedding, possibly indicating the presence on an overturned limb.

Smaller scale structures are present, but are difficult to see owing to the generally massive and fine-grained nature of the pelitic rocks. In two quarries on the western flank of the Hill of Foundland, at [NJ 5918 3330] and between [NJ 5963 3327] and [NJ 5957 3337], changes in strike of bedding indicate the presence of moderately steeply plunging recumbent folds. These open structures, to which the main cleavage appears to be axial-planar, plunge between 45 and 55º to the south-west. A similar structure is present on Hill of Tillymorgan [NJ 6557 3478]. Here, the fold is tighter, but it has a similar orientation and relationship to the main S2 cleavage. All these folds are asymmetrical and exhibit a Z-profile geometry, indicating an antiformal closure to the north-west.

Minor late deformation, seen in several outcrops (e.g. [NJ 5912 3338]), gives rise to large crenulations or flexures which plunge eastwards at about 50º to 60º with a very steep, but poorly developed, axial planar fracture cleavage.

A northerly dipping joint set is present in the Folla Rule area [NJ 731 330] along the northern margin of the Insch Mass. They may be associated with the shear/fault zones that are coincident with the northern boundary of the Insch Pluton in this area.

7.8.3 Strathbogie north of the Slate Hills

North of the Hill of Kirkney [NJ 502 315], turbiditic psammites (arenites) and semipelites are deformed by upright tight folds. Dips are generally steep and to the south-south-east or north-north-west. In places relatively intense minor folding occurs over a few metres of outcrop, indicating the presence of hinge zones. Upstream of Spence's Pot (Kirkney Water) at around [NJ 514 336], a series of small outcrops display irregular folding accompanied by a steeply dipping axial-planar cleavage; the structural data indicate the presence of an anticlinal closure.

In the valley of the Kirkney Water south from Tillyminnate, at around [NJ 498 318] and around [NJ 500 323], the psammitic and pelitic sequence shows small-scale grading and channelling that implies the rocks are the right way up. However, in the lower part of the Kirkney Water around [NJ 513 337], steeply north-dipping gritty and conglomerate beds are overturned to the south. Father north to the east of Hill of Collithie [NJ 5074 3428] dips are consistently to the north and the younging evidence from rippled bed bases at [NJ 5135 3432] shows the beds to be the right way up. Hence, there appears to be a large anticlinal closure partially defined by the gritty units, whose southern limb has been overturned, possibly by later deformation. The intense deformation in the pelitic rocks immediately south of the gritty/conglomeratic units is interpreted as a contact strain effect resulting from strain partitioning.

7.8.4 Glens of Foudland

Outcrops of the Macduff Slate Formation in the Glens of Foundland are characterised by steep dips, generally in excess of 60º, and by tight, generally upright folds. In a temporary exposure at Broomhill [NJ 5888 3455] grading shows that the rocks are inverted, at least locally. The main cleavage is steeper here than elsewhere, dipping to the north at about 85º. In the approximately 50 m-long road-cut adjacent to the A96, about 300 m west of Bainshole around [NJ 6064 3496], the nature of the folding is clearly seen. The folds are slightly recumbent, moderately tight to open F2 structures with axial planes dipping steeply to the north-west. Bedding–cleavage relationships reveal two antiform-synform fold pairs in the western part of the section, with a larger, more open hinge zone with parasitic minor folds exposed in its eastern part. The cleavage here is a strong, spaced S2 fabric.

7.8.5 Logg Wood, Inverkeithny

Logg Wood covers a steep hillside on the south-east side of the River Deveron around [NJ640 470]. There are several roadside quarries that provide good exposures of fine-grained arenites, semipelites, and pebbly grits with pelitic rip-up clasts. Further exposures also occur on the flanks of Logg Hill and on Logg Island in the River Deveron. The rocks here have been metamorphosed only under greenschist-facies conditions (chlorite to biotite grade). Bedding strike is roughly north–south, and dips are moderate, ranging from 35º to 78º E. The cleavage (S1), only poorly developed in parts, generally dips steeper than bedding, in places by up to 30º. Where way-up indicators are present the beds generally young to the east. At [NJ6395 4693] and [NJ6397 4698] the interbedded arenites and pelites show moderately tight, gently northward plunging folds with an S-profile geometry.

Joints are prominent in the Logg Wood sections. Although no single orientation is dominant, the joints mainly dip in excess of 45 º to the south-east or north-west quadrants.

7.8.6 Fabrics in the andalusite schists of the Whitehills Group

Schistose pelitic rocks in the upper part of the Whitehills Grit Formation crop out along the north side of the River Deveron near Kinnairdy Castle (around NJ 611 494). In thin section (S 93839, [NJ 6109 4951]; S93840, [NJ 6112 4937]), an S2 spaced cleavage is seen to crenulate an early penetrative fabric and to wrap the andalusite porphyroblasts. It is also axial planar to an open minor fold that possibly refolds an earlier isocline. The later cleavage is the dominant fabric in outcrop. It dips steeply east at the southern end of the section and at about 40º to the north-west, 150 m to the north.

Similarly schistose pelites and semipelites also crop out in the River Bogie at the northern end of Heugh of Bucharn [NJ 5192 3742]. In thin section the strong, spaced fabric is manifest as segregated quartz and mica-rich microlithons. This fabric has no clear precursor, but wraps the andalusite porphyroblasts in outcrop. A conjugate crenulation lineation is locally developed and relates to late-stage kink folds of the dominant S2 cleavage.

7.9 DISCUSSION

The most abundant folds observed in the Huntly and Turriff districts belong to the second D2 phase of deformation. The related S2 cleavage wraps andalusite and cordierite porphyroblasts in the Southern Highland Group rocks, showing that this deformation and folding event clearly postdated the peak of metamorphism. This secondary deformation, here termed D2, has been ascribed in the literature generally to a regional D3 event, e.g. see Fettes, 1970 and Strachan et al., 2002. An early cleavage (S1) that predates the growth of andalusite and cordierite is present in many samples, but few F1 folds have been recognised *per se*. This may be due to the generally poor exposure and more uniform semipelitic lithologies in the Southern Highland Group in the Huntly and Turriff districts. F1 folds are widely recognised in other well-exposed sections in the Southern Highland Group, notably where the metamorphic grade is low. F1 folds are upright on much of the Banffshire coast section, but at Fraserburgh (Kneller, 1987) and farther south at Collieston (Mendum, 1987) the early folds are generally recumbent. In the Huntly and Turriff districts F1 folds are largely upright, but locally are inclined. The apparently simple upright nature of most of the F1 folds may reflect either the absence of D2 deformation at shallow crustal levels, or the superimposition of D2 deformation and folding on D1 structures, resulting in tightening of the pre-existing folds and generation of a composite S1+S2 cleavage.

Thin-section studies commonly reveal at least two penetrative planar fabrics. In the finer-grained lithologies, a penetrative cleavage defined by micas is commonly deformed by a second fabric, S2. Characteristically, quartz veins and veinlets are also deformed by S2. The veins define ptygmatic folds, but are disrupted by the second fabric, which is typically axial planar. In some samples, both S1 and S2 fabrics are crenulated or kinked, indicating late-stage local deformation.

Two distinct planar fabrics (S1 and S2) can be distinguished in some outcrops, but in slaty semi-pelite and pelite outcrops, generally only a single fabric can be discerned in the field. In many instances this fabric has a spaced appearance and is clearly the S2 cleavage. However, the spaced or crenulated nature suggests the existence of a precursor S1 cleavage. Where the two cleavages are oblique, the slates lose their planar fissility and break into lozenge-shaped masses, becoming very tough where the two cleavages intersect at high angles.

8 Metamorphism

8.1 REGIONAL SETTING

Dalradian sedimentary and volcanic rocks in north-east Scotland underwent regional and contact metamorphism during the Ordovician Grampian Orogeny. The Huntly and Turriff districts includes a major part of the type area for the 'Buchan' metamorphic facies series, characterised by low to intermediate pressures and relatively high temperatures (Read, 1952; Stephenson and Gould, 1995). It also includes the 'transition' to the Barrovian facies series in its western part. The regional metamorphic pattern is disrupted or strongly modified both by the Portsoy Shear Zone and by the presence of the various mafic-ultramafic plutons, notably Insch, Huntly and Knock (Figure 11). Peak metamorphic conditions were attained approximately coeval with emplacement of these plutons, which is dated at about 472 Ma ago, based on U-Pb zircon ages (Dempster et al., 2002; Condon and Martin, cited in Oliver et al., 2008 as a personal communication, Carty et al., 2012).

The Buchan facies series is defined by the successive appearance in pelitic rocks of biotite, cordierite, andalusite and sillimanite with increasing grade (Spear, 1993). Metamorphic grade increases from lower greenschist facies (chlorite zone) in the Turriff area to middle amphibolite facies (andalusite- and sillimanite-bearing zones) in the extreme south-east part of the district. Locally, it reaches upper amphibolite facies (sillimanite–potash feldspar zone) within and adjacent to the Huntly and Knock Gabbro-peridotite plutons and the Portsoy Gabbro-serpentinite Intrusion-swarm. These intrusions lie within and immediately east of the Portsoy Shear Zone (PSZ) (Ashworth, 1975). Here there is a convergence of metamorphic grade between the regional and contact metamorphic events, particularly adjacent to the larger mafic-ultramafic plutons.

West of the PSZ, a higher pressure Barrovian metamorphic event is superimposed on the earlier Buchan metamorphic assemblage, and, farther west still, on an early Barrovian mineral assemblage, resulting in secondary garnet, staurolite and kyanite. In the western parts of the district, kyanite commonly occurs as pseudomorphs after andalusite in the more pelitic lithologies (Beddoe-Stephens, 1990; Chinner, 1980; Chinner and Heseltine, 1979).

8.2 REGIONAL METAMORPHIC PATTERN

8.2.1 Temperature and pressure conditions of the regional metamorphism

On the Banffshire coast, regional metamorphic temperatures of less than 500°C are recorded from assemblages in the axial parts of the Turriff Syncline, reflecting their shallower crustal levels (Hudson, 1985). To the west, south and east of this area metamorphic assemblages show that temperatures increased systematically, as demonstrated by the trace of the andalusite isograd (Harte and Hudson, 1979; Baker, 1985). South of the Aberchirder Granite, temperatures reached about 530°C within the andalusite zone (Hudson, 1985). In the south-west of the district, temperatures locally exceeded 600°C in the Portsoy Shear Zone (Beddoe-Stephens, 1990). Hornfels assemblages lying marginal to the large mafic-ultramafic intrusions locally record temperatures between 600°C and 950°C (Ashworth and Chinner, 1978; Droop and Charnley, 1985; Droop et al., 2003). Droop and Charnley (1985) estimated that emplacement of these synmetamorphic mafic-ultramafic intrusions occurred at crustal depths of between 15 to 18.5 km (P = 4-5 kb). The subsequent work of Droop et al. (2003) confirmed this estimated emplacement depth at 16 ± 3 km (P = 4.5 kb).

Pressures increase outwards from the Turriff Syncline reaching a maximum of 4 to 4.5 kb immediately east of the PSZ. However, to the west of the PSZ, Beddoe-Stephens (1990, 1992) documented a distinct later pressure increase of at least 2 kb. Garnet zoning profiles and metamorphic mineral equilibria in this area are consistent with the local replacement of andalusite by kyanite, and appear to be coeval with the S2 fabric. The sharp westward pressure increase has been attributed to west- or west-north-west-directed overthrusting across the PSZ during D2.

8.2.2 Features of the regional metamorphic pattern

Mineral assemblages characteristic of the lowest chlorite zone occur in a north–south tract immediately west of the Devonian Turriff outlier, extending as far south as Auchterless [NJ 69 39] (Figure 11). In the Glens of Foundland, small clots of biotite overgrow and replace primary chlorite in slaty pelitic rocks.

Chloritoid occurs in low-grade rocks in the Hill of Foudland Slate Member (Leslie, 1988). Although stable over a relatively wide P-T range in low grade rocks, the chloritoid-chlorite-muscovite assemblages found here are limited to pressures of less than 3 kb. In thin section, pressure shadows and tails at the ends of obliquely orientated chloritoid laths indicate that these porphyroblasts predate the S2 fabric. The appearance of chloritoid is a function of the bulk composition, only occurring in oxidised, relatively aluminous, iron-rich rocks with >20% Al^2O^3 and $Fe^{3+} >> Fe^{2+}$.

Chlorite-zone rocks are succeeded successively by biotite-, cordierite- and andalusite-zone rocks to the east, south and west. The transition from biotite-zone rocks, via the cordierite-zone, into andalusite-zone rocks can be seen in the Fyvie Gorge section, between Ardlogie [NJ 7804 3725] and the Ords [NJ 7890 3658], and in Clashindarroch Forest in the south-west of the District. In the Fyvie Gorge, chlorite- and biotite-bearing pelitic rocks become progressively more spotted until they take on a 'knotted' appearance as the cordierite and andalusite porphyroblasts grow in size and abundance. The porphyroblasts are wrapped by the S2 cleavage. In Clashindarroch Forest, the rocks are less schistose as those in the Fyvie Gorge and cordierite and andalusite are less-well developed, imparting a spotted, rather than strongly porphyroblastic appearance.

Higher grade rocks occur in Strathbogie to the north-west of the Ness Bogie, between Bridgend [NJ 5160 3580] and Bucharn [NJ 5210 3691]. They are characterised by andalusite-bearing schistose pelites and garnet-biotite-hornblende-plagioclase-bearing calc-silicate rocks. Good examples of the andalusite-bearing pelites are also exposed in the Burn of Auchintoul section by Kinnairdy Castle [NJ 609 498]. Evidence of transition from Buchan to Barrovian P-T conditions was recorded by Read (1923), who noted that the andalusites are well formed, and that scarce staurolite and small garnets are also present here. The grey subhedral andalusite porphyroblasts contain abundant inclusions of quartz, biotite and minor graphite or magnetite. Droop et al. (2003) carried out a detailed mineralogical study of the rocks within and adjacent to the Huntly Gabbro-peridotite Pluton. In schistose pelites from Clashmach Hill [NJ 498 385] they reported the assemblage muscovite-biotite-quartz-plagioclase±andalusite±staurolite±garnet±ilmenite. The andalusite forms subrectangular poikiloblasts up to 6 mm long with quartz inclusions, and staurolite forms micropoikiloblasts up to 3 mm long. In contrast the garnets are rare, tiny (about 150 µm diameter) and subhedral. Droop et al. (2003) used version 2.75 of THERMOCALC (Holland and Powell, 1998) to obtain P-T values of 2.7 ± 1.2 kb and 537 ± 42°C respectively, from the Clashmach pelites, values consistent with those obtained by Hudson (1985) from andalusite-zone rocks on the Banffshire coast.

Metamorphic assemblages within and adjacent to the Portsoy Shear Zone generally lie in the lower to middle amphibolite facies. Beddoe Stephens (1990) used several reaction-based geothermometers and geobarometers, and garnet zoning patterns, to define P-T values in three Argyll Group pelite samples from the western side of the Huntly Pluton that lie within the Portsoy Shear Zone. Calculated P-T values ranged between 4 kb and 4.5 kb and between 580°C and 610°C, respectively. Droop et al. (2003) applied more sophisticated methods (see above) to medium-grained plagioclase- and quartz-rich garnet-biotite gneisses containing minor staurolite and fibrolitic sillimanite. These are associated with finer-grained muscovite-bearing schistose garnet-biotite pelites and crop out by Cairnie at [NJ 482 446]. P-T values of 6.5 ± 1.3 kb and 637 ±

31 °C were obtained from the finer-grained pelite. These Barrovian assemblages and P-T values are compatible with middle amphibolite-facies metamorphism.

To the west of the PSZ the metamorphic assemblages are of lower amphibolite grade. Pelitic units in the Mortlach Graphitic Schist and Fordyce Limestone formations contain kyanite, staurolite and garnet. Euhedral kyanite occurs in graphitic pelite in the Ardonald limestone quarries [NJ 4617 4434], and Read (1923) recorded staurolite, kyanite and garnet from the Ardonald Burn section just to the north. Staurolite and andalusite (var. chiastolite) occur in abundant graphitic pelite float of the same unit immediately west of the district on the eastern slope of Cairds Hill around [NJ 4314 4648]; the andalusite is probably pseudomorphed by kyanite. Calc-silicate bearing lithologies in the Pitlurg Calcareous Flags Formation are dominated by tremolite and phlogopite; hornblende is present locally. The generally flaggy psammitic and minor semipelitic units of the Findlater Flag Formation contain no metamorphic index minerals.

Staurolite, kyanite and garnet are common in schistose pelites within the Fordyce Limestone Formation in the Paithnic–Grange–Edingight area, north of the River Isla. Notable exposures occur in the Burn of Paithnick [NJ 4811 5402], Burn of Braco [NJ 5088 5373]. Similar metamorphic assemblages are also found south of the River Isla, where the pelites crop out on the northmost flank of Balloch Hill [NJ 472 496] and in the Mill of Wood Burn.

In thin section, staurolites typically consist of a pale yellow pleochroic core with abundant inclusions that define an earlier fabric, surrounded by a deeper yellow pleochroic and inclusion-poor rim. Many garnet porphyroblasts show evidence for two or even three distinct growth phases, again with inclusion-rich cores and inclusion-poor rims; some show a distinct rim zone representing re-equilibration under later lower grade conditions. Kyanites are commonly lath-shaped and show varying degrees of alteration to white mica. In some examples they exhibit similar inclusion patterns to the staurolites.

The fabrics and mineralogy indicate that primary metamorphic mineral growth followed D1 deformation, with the second phase of growth coeval with D2 deformation. In the western part of the Huntly district, both events occurred under middle amphibolite facies conditions within the kyanite zone.

8.3 HORNFELSED AND MIGMATITIC ROCKS

8.3.1 Rocks associated with the Huntly and Knock plutons

Associated with the large mafic-ultramafic plutons and related intrusions are contaminated mafic rocks, and migmatitic and xenolithic rocks that include numerous hornfelsed metasedimentary enclaves. Ashworth (1975, 1976) ascribed these high grade rocks that lie within and immediately east of the Huntly, Knock and Portsoy intrusions, and the nearby migmatitic gneisses of the Cowhythe Psammite Formation, to the sillimanite-potash feldspar zone (upper amphibolite grade). Peak metamorphic temperatures estimated for these rocks range between 700° and 950°C, with pressures ranging from 4 to 5 kb (Ashworth and Chinner, 1978; Droop and Charnley, 1985; Droop et al., 2003). Many of the rocks are migmatites and it can be difficult to separate migmatitic and partially melted metasedimentary rocks from contaminated mafic igneous rocks, both in the field and petrographically. Indeed, the distinction between hybrid igneous rocks and partially melted pelitic rocks may be gradational in some areas. The rocks are generally 'noritic' and contain upper-amphibolite facies mineral assemblages that typically include cordierite, hypersthene, sillimanite, garnet, biotite, K-feldspar and hercynite (spinel) (Read, 1923; Ashworth, 1976; Droop and Charnley, 1985; Droop et al., 2003; see also discussion of the Huntly and Knock plutons, sections 5.3.6 to 5.3.8).

Droop et al. (2003) also used THERMOCALC in combination with garnet-biotite, garnet-cordierite and garnet-orthopyroxene Fe, Mg exchange geothermometers, the orthopyroxene-garnet geothermometer, and the garnet-orthopyroxene-plagioclase-quartz geobarometer to obtain

P-T values on both nonmigmatitic and migmatitic hornfelsed rocks that occur within and marginal to the Huntly pluton. A nonmigmatitic cordierite-sillimanite-bearing hornfelsed pelite, was sampled from a large loose block on the east side of the River Deveron, north of Dunbennan Hill at [NJ 499 422]. It contains scattered subhedral garnet porphyroblasts up to 3 mm across, and randomly orientated 'bundles' of prismatic sillimanite, typically about 8 x 2 x 2 mm, interpreted as pseudomorphs after andalusite. The porphyroblasts lie in a fine-grained granoblastic matrix of biotite, cordierite, plagioclase, quartz and ilmenite. The cordierites are locally replaced by chlorite + andalusite. P-T values calculated for this rock were 5.1 ± 0.8 kb and 628 ± 75°C respectively, taking an arbitrary aH_2O value of 1.0. Droop and Charnley (1985) describe hybrid mineral assemblages from the western side of the Huntly intrusion at Cuttle Hill [NJ 494 474]; in thin section, sector-twinned cordierites, 0.5 to 1 cm across, are surrounded by staurolite and gedrite clusters, set in a matrix of biotite, plagioclase, cordierite and quartz with minor garnet and sillimanite.

The migmatitic rocks correspond mainly to the 'cordierite-bearing migmatites' of Ashworth (1976). They include stromatic metatexites that are abundant around Cumrie and Cormalet Hill [NJ 523 448] in the northern part of the Huntly Pluton. These hornfels rocks comprise blue-grey fine-grained cordierite-plagioclase-K-feldspar-ilmenite melanosomes with veins of granitic leucosomes, mostly < 1 cm thick, and commonly in subparallel arrays. The leucosomes are garnetiferous and make up some 20 to 40 per cent of the rock type. They also form branching, anastomosing and discordant veins indicating the presence of a melt phase. Droop et al. (2003) also recognise garnet-bearing tonalites and cordierite-norites that they term schollen diatexites. These rock types, which consist of about 70 to 95 per cent of mobilised igneous textured mobilised material, are common and form a significant component part of the Huntly and Knock plutons. Most of the schollen are pelitic but quartzite and calc-silicate rocks also occur. In the Cormalet–Cumrie area garnet-bearing tonalites contain euhedral inclusion-free garnets up to 1 cm across and sporadic blocky cordierites in a medium- to coarse-grained matrix of biotite, quartz and euhedral plagioclase. Small patches of fibrolite were also recorded. The orthopyroxene-bearing varieties, termed cordierite norites by Read (1923), and 'noritoids' by Ashworth (1976) crop out at Battlehill Quarry [NJ 539 395], in the River Deveron at Castle Bridge [NJ 533 409] and north of Dunbennan Hill at [NJ 499 422]. Droop et al. (2003) noted that at Battlehill Quarry the cordierite norites have a mafic igneous appearance and form discordant bodies with sharp contacts against gabbros and high-grade hornfels. The rocks are medium-grained and consist essentially of randomly orientated cordierite, orthopyroxene, garnet and plagioclase. The cordierites are fresh and form subhedral prisms with simple or sector twinning and the orthopyroxenes are markedly pleochroic and form elongated subhedral prisms with rounded plagioclase inclusions. Garnets are generally less abundant than cordierite and orthopyroxene; they form subhedral grains that are either inclusion-free or contain scattered ilmenite and biotite inclusions. Plagioclase crystals show marked normal zoning with An-rich cores (labradorite to bytownite) and upper andesine rims. In parts they also exhibit oscillatory zoning. Biotites form thick books up to 1.5 mm across in the Castle Bridge samples, but are mainly interstitial in other examples. Quartz is present in only minor amounts, commonly as small cuspate interstitial grains. K feldspar is also only rarely present, mainly as interstitial microperthite. Dark green hercynite is a more abundant component. In the Battlehill samples it is a minor phase, mostly forming inclusions within cordierite, but it is modally abundant in samples from Castle Bridge and Dunbennan Hill where it forms oblong clusters up to 5 x 2 x 2 mm of 0.01 to 1 mm granules intergrown with fine-grained cordierite. The clusters have square cross-sections and Droop et al. (2003) recorded that they are locally cored by aggregates of prismatic sillimanite, indicating that they are pseudomorphs after that mineral. Retrograde textures include biotite-quartz intergrowths replacing orthopyroxene and fine-grained biotite rims on garnets. Droop et al. (2003) interpret the mineralogy and texture of these diatexites as indicating the presence of a significant melt phase and hence that the cordierite norites represent cumulates. They favour a process of partial melting with the main mineralogy generated as solid products of incongruent melting reactions.

Droop et al. (2003) also recognised orthopyroxene-cordierite-bearing pelitic hornfels that form schollen and xenoliths within the cordierite norites and occur as screens and xenoliths in the gabbros in the southern and western parts of the Huntly Pluton. These are dark blue-grey, fine-grained, cordierite-rich rocks commonly containing small (1 to 2 mm) garnet porphyroblasts. Their matrices typically consist of small equant grains of orthopyroxene, plagioclase and twinned cordierite, with abundant granules of ilmenite and, in many samples, of hercynite. In some examples cordierite makes up >60 per cent of the mode. Quartz and K-feldspar are normally absent, and biotite rare to absent, except in some of the more leucocratic layers, which possibly represent leucosomes.

Examples of high-grade hornfelsed rocks are also found within and adjacent to the Knock Pluton. About 1 km south of Knock Hill summit at [NJ 537 542] cordierite and sillimanite occur in a plagioclase (andesine)-hypersthene-biotite-magnetite rock. Garnets are common in these rocks, particularly in the hybrid basic-metasedimentary rocks, where locally they attain several centimetres in diameter, e.g. on the west flank of Barry Hill [NJ 558 545], and on Wether Hill [NJ 567 542].

Cores from the Drumnagorrach and Claymires boreholes (drilled adjacent to the western and eastern margins of the Knock intrusion respectively) contain hornfelsed, amphibolite grade, semipelitic and calcareous metasedimentary rocks interlayered with foliated metabasic rocks. The calc-silicate rocks contain large pods of diopside, and in the semipelites biotite-magnetite-?cordierite and garnet-biotite-sillimanite assemblages are present.

Droop et al. (2003) obtained a range of P-T values for the cordierite norites and high-grade hornfelses related to the Huntly Pluton based on the various geothermometers and geobarometers and THERMOCALC. Best-fit results gave pressures in the range 4 to 5 kb and temperatures between 900 and 950°C with aH_20 values being constrained to lie between 0.1 and 0.4. They also used the whole-rock chemistry of 72 metasedimentary and mafic igneous rocks to show that the orthopyroxene-cordierite hornfelses and the cordierite norites were relatively depleted in 'granitophile' components compared to their probable pelitic protoliths. The hornfelses and migmatites showed chemistries compatible with being restites. Mass balance calculations and modelling suggested that the amount of melt produced and subsequently migrated from the hornfelses and cordierite norites was about 57 per cent and 53 per cent respectively. If the fugitive melts were granitoid (72–75% SiO2), as seems likely on petrographical grounds, they argued that, as most of the orthopyroxene-cordierite hornfelses were completely drained of melt during their formation, the degree of partial melting attained about 60 per cent. Droop et al. (2003) also carried partial melt experiments using two samples of schistose pelite (Clashindarroch Formation) from Clashmach Hill [NJ 498 385], one containing andalusite and minor garnet and the other being free of these minerals. The rock powders were heated to 900°C for 150 hours under a pressure of 5 kb, with $\log fH_2$ set at -1 and an aH_2O of 0.35. The resulting melt was quenched and studied under an SEM. The assemblage obtained from the andalusite-bearing pelite consisted of orthopyroxene, cordierite, hercynite, ilmenite and minor biotite in a matrix of glass. The pelitic sample lacking andalusite produced cordierite, hercynite and ilmenite in the glass matrix. Melt proportions were about 60 and 65 per cent respectively and melt compositions were reasonably uniform and corresponded to peraluminous potassic granite. Similar results have been obtained by other authors from pelitic systems (Carrington and Harley, 1995; Stevens, 1995). Droop et al. (2003) suggest that the granitoid melts underwent little or no in situ fractional crystallisation and contributed to the Early Ordovician peraluminous two-mica granites that are characteristic of north-east Scotland. These intrusions range in size from small pods or dykes up to large plutons (e.g. Strichen, Aberchirder). They show isotopic signatures implying an upper crustal source and similar emplacement ages (about 470 Ma) to the mafic-ultramafic intrusions. They also noted that the prograde P-T path of the contact metamorphosed rocks in the south-west part of the Huntly Pluton had a low positive dP/dT slope, implying an increased lithostatic load at the time of gabbro intrusion. They suggested that the gabbro itself may have been responsible for this increased load.

8.3.2 Other contact metamorphic rocks

Rocks in the Macduff Slate Formation are contact-metamorphosed along the northern margin of the Insch Intrusion (Leslie, 1988). The aureole north of the Boganclogh Sector, is well seen on the northern flanks of Hill of Noth [NJ 4984 3008] and on the watershed between Glen of Noth and Kirkney Water. It contains progressively more spotted pelitic rocks which become tough, fine-grained, cordierite and andalusite hornfelses immediately adjacent to the intrusion. The incoming of cordierite-hornfelses takes place generally over a few tens of metres. Although pelites in the Macduff Slate Formation are spotted over a wide area north of the cordierite-hornfelses, much of this is probably due to the regional metamorphism. However, a 500 m-wide spotted zone extending from south of Quarry Hill [NJ 4673 3173], eastwards into Glen of Noth is part of the contact aureole of the Insch intrusion. The limit of cordierite-hornfelses runs approximately south-east across the summit ridge of Hill of Noth. The lower half of the east ridge of Hill of Noth is comprised of very dark grey, indurated gritty arenites.

In thin section, the regional chlorite+quartz-dominated matrix in the hornfelses is seen to have recrystallised to fine-grained more equant biotite and quartz in psammitic and semipelitic units. A well developed, but faint, penetrative fabric is present in the groundmass of hornfelses, clearly wrapping porphyroblasts, but overgrown by late chlorite. This is probably the regional, S2 fabric that forms the second cleavage immediately outwith the aureole (Fettes, 1970). Where developed, porphyroblasts of cordierite and andalusite occur in a very fine-grained groundmass consisting largely of sericite with abundant olive brown clots of biotite and large grains of magnetite. The cordierite porphyroblasts are rounded with diffuse margins. Abundant inclusions preserve an S1 internal fabric at a high angle to the groundmass fabric. Cordierite rims are generally altered to yellow pinite, particularly adjacent to late chlorite porphyroblasts. Andalusite (var. chiastolite) forms rectangular laths, or square to rhomboid sections. Inclusions are common. In some sections the andalusite is still fresh, but generally it has been altered to white mica aggregates.

As described above, the most extreme hornfelsing occurs in metasedimentary enclaves within and adjacent to the Huntly–Knock intrusion. These hornfelses include sillimanite, spinel and corundum in addition to andalusite and cordierite. In places, temperatures have been sufficiently high (c. 900°C) for sedimentary lithologies to be assimilated into the basic magmas, giving rise to hybrid rocks which contain highly aluminous phases together with igneous minerals (Read, 1923; Ashworth and Chinner, 1978; Droop and Charnley, 1985; Droop et al., 2003).

Hornfelses are developed in gritty arenites and slaty pelites of the Macduff Slate Formation adjacent to the eastern margin of the Aberchirder Granite. The transition from pelites into the hornfelses occurs around Skeibhill [NJ 635 522], about 400 m east of the granite contact (Read, 1923). Massive 'speckled grey hornfels' from a quarry 460 m east of Quarryhill at [NJ 6332 5152] contains colourless to pink, clear, andalusite prisms with sparse inclusions in a fine-grained granular matrix of quartz, muscovite, biotite, iron oxides and minor cordierite (Read, 1923). The marginal veined contact zone at the south-east edge of Cleanhill Wood is described in the section on the Aberchirder Granite.

8.4 RETROGRADE METAMORPHISM

The whole district has been subject to a late retrogressive metamorphic event of variable intensity. It is characterised by new chlorite growth and less commonly, white mica. New chlorite porphyroblasts several millimetres across overgrow existing fabrics, particularly in semipelite and micaceous psammite lithologies. Chlorite partly replaces earlier ferromagnesian minerals in the more pelitic rocks; in calc-silicate assemblages, it commonly replaces hornblende. Large, late-stage chlorite porphyroblasts form prominent green spots in micaceous psammites in the Den of Pitlurg at [NJ 4497 4534]. Cordierite is altered to pinite, andalusite is replaced by muscovite sheaves and sericite, and plagioclase is partly altered to sericite.

Retrograde metamorphic effects occur in the PSZ (see above) and in individual shear zones in the basic intrusions. Kyanite shows marginal alteration to white mica aggregates. Although the retrogression is the last regional metamorphic event in the district, late chlorite is commonly kinked, indicating localised later deformation or movements.

9 Applied geology

In order for local and national government authorities to make appropriate strategic decisions with regard to exploitation of mineral and water resources, conservation and management of the natural environment, assessment of hazardous ground conditions, waste management and pollution control, etc., an understanding of the bedrock and superficial geology of a particular region is necessary. The following sections provide a summary of the geological resources and hydrogeology of the Huntly–Turriff district. Both hard rock and sand and gravel resources have been quarried until relatively recently, but currently there is no such activity.

9.1 RESOURCES

9.1.1 Aggregate (hard rock)

Resources of hard rock for crushed rock aggregate are abundant in the Huntly–Turriff district. They include the fine- and coarse-grained mafic rocks of the North-east Grampian Basic Subsuite, quartzitic and psammitic rocks of the Grampian, Appin and Argyll Group and wacke sandstones of the Southern Highland Group. Metamorphosed limestones have also been quarried for this purpose (see below). Large former workings include the quarries in the Huntly Pluton in the Bin Forest [NJ 498 431] and at Battle Hill [NJ 539 395].

9.1.2 Building stone

Granites and other hard rock lithologies have been used locally as building stone in the past, but resources are limited and they have not been used extensively. There is no current commercial extraction of rock within the district for this purpose. Disused granite quarries are present at Carvichen [NJ 542 389] and Avochie [NJ 542 470].

9.1.3 Limestone and dolostone

Although limestone is not currently quarried, it has been worked for decades for the production of lime, building and road stone, commonly in a piecemeal fashion, especially for lime. Abandoned quarries are restricted to the north-west part of the district, where the bulk of the Dalradian metamorphosed limestone outcrops occur. Most of the disused quarries are small, but some of the more recent operations have resulted in considerably larger quarries, notably those of Limehillock [NJ 515 518] and Blackhillock [NJ 450 483]. The quarries and pits are located within the crop of Appin and Argyll Group rocks and mostly exploited calcite-rich metalimestones. The metalimestones are generally hard and fresh, particularly where thickly bedded; intercalated pelitic laminae are only rarely present. Their lithostratigraphy is discussed in Chapter 2. Metamorphosed dolostones are uncommon, the main occurrence being thin units interbedded with siliciclastic rocks within the Tarnash Phyllite and Limestone.

The major oxide and trace element geochemistry of fifty-seven samples from several of the more important limestone- and dolostone-bearing units is summarised in Table 5. The majority of the limestones are reasonably pure. The main impurity is silica (SiO_2), median values for which are less than 15 per cent. Strontium (Sr) is the most abundant trace element, reaching several thousand parts per million (ppm) in most samples. The metadolostones show greater amounts of impurities, characterised by higher SiO_2, Al_2O_3, Na_2O and K_2O contents and, with the exception of Sr, higher trace element concentrations than the metalimestones. More detailed information on the geochemistry of Dalradian metacarbonate rocks in the district is available from BGS, as listed in the section on Sources of Information at the end of this explanation.

Table 5 Summary of the geochemistry of major Dalradian limestones within the Huntly and Turriff districts (major elements are shown as oxides (weight %) and trace elements as ppm).

Lithostratigraphy	Dufftown Limestone	Tarnash Phyllite and Limestone	Fordyce Limestone, Keith Limestone	Argyll Group, unassigned
n =	6	4	43	4
SiO_2	4.33	18.70	14.46	6.95
Al_2O_3	0.71	4.22	2.93	1.53
TiO_2	0.03	0.17	0.11	0.07
Fe_2O_3	0.34	2.07	1.04	0.72
MgO	1.33	8.44	0.59	3.83
CaO	50.91	32.90	44.41	46.73
Na_2O	0.09	0.38	0.33	0.02
K_2O	0.10	0.20	0.61	0.95
MnO	0.04	0.09	0.03	0.08
P_2O_5	0.04	0.05	0.06	0.04
LOI	41.42	30.74	35.49	38.84
Ba	37	59	64	82
Ce	10	37	24	13
Cr	12	23	30	16
Ga	2	10	6	3
La	9	32	19	7
Nb	2	5	3	3
Ni	11	11	6	b.d
Pb	7	10	9	7.5
Rb	7	8	22	19
Sr	1574	336	1485	679
V	8	16	14	24
Y	3	11	6	2
Zn	10	27	14	17
Zr	30	58	41	26

9.1.4 Slate

Quarrying of Dalradian Southern Highland Group pelitic rocks for roofing slate was once a major activity in the 'Slate Hills' along the southern margin of the district. The resultant slates were heavy and variable in quality, due mainly to the presence of silty and sandy laminae, but also due to local minor folding. In addition, in many places the slates were quarried in an uncoordinated and somewhat haphazard manner. However, Read noted that the local people considered Foudland slates to 'withstand the somewhat boisterous Aberdeenshire climate better than do modern Welsh slates' (Read 1923, page 216). Quarrying was most extensive on the Hill of Foudland [NJ 603 332], where workings and waste tips occur over about 3 km^2. Quarries are also present on the hills of Kirkney, Corskie, Wishach, Skares and Tillymorgan. The quarries are all sited on the northern side of the hills, to avoid the main effects of the contact metamorphism caused by the Insch Pluton and Kennethmont diorite and granite intrusion. Within their contact metamorphic aureoles, the slates lose their fissility and become more massive and recrystallised, with the growth of andalusite and cordierite. Quarrying commenced on the Hill of Corskie in 1700, followed by the Hill of Tillymorgan in 1750 and Foudland in 1754 (Blaikie, 1834). Slate production peaked in the early part of the 19th century coincident with the spread of turnpike roads, but declined with the coming of the railway in the 1840s and 1850s (Walsh, 2000). The railways allowed the import of Welsh slate and Ballachulish and Easdale slates, resulting in the demise of local slate quarrying. An assessment of the quality and extent of the slates on the Hill of Foudland was made by Walsh (2008) who found that they were unsuitable for redevelopment as a source material for remedial roofing work on historic buildings.

9.1.5 Sand and gravel

Sand and gravel resources are restricted largely to the Deveron and Ythan river valleys and their tributaries (Figure 15). They are concentrated mainly in the northern part of the Turriff district. The deposits are principally glaciofluvial and alluvial in origin, although limited ice-contact sand and gravel deposits do occur as hummocks, kames and eskers. Several deposits have been worked in the past, but there is no known commercial exploitation at present. Several of the larger deposits reach 7 to 10 m in thickness, but most are rather less. Notable deposits underlie glaciofluvial terraces in the Ruthven area [NJ 510 470], in the course of the Burn of King Edward in the north-east of the district, in ground extending south-east from Turriff, and within the area of an isolated glaciofluvial terrace at Tippercowan [NJ 815 551]. Sand and gravel underlies terraces upon which the southern half of Turriff has been built, effectively sterilising these resources. The deposits shown around Huntly occur in raised alluvial terraces. Formerly, they have been worked locally in pits but their thickness and resource potential is now likely to be very limited. Available information indicates that the sand and gravel deposits in the Huntly and Turriff districts contain a greater proportion of gravel rather than sand, but proportions are variable, even within individual deposits (Peacock et al., 1977).

Sand and gravel have also been worked from the Buchan Gravels Formation at Windy Hills [NJ 809 399]. This deposit reaches over 10 m in thickness and lies on schistose pelite thoroughly decomposed to silty clay (Merritt, 1981). It comprises well-rounded vein quartz and quartzite gravel, bound locally by white, kaolinitic, sandy clay. Similar deposits also occur at Delgaty, north-east of Turriff [NJ 745 508] and at Dalgatty Forest [NJ 736 459] to the south of Turriff; the latter containing brown sandstone clasts in addition to the vein quartz and quartzite. Weathered, disaggregated conglomerates of the Gardenstown Conglomerate Formation (Inverness Sandstone Group) form clayey bouldery gravel and constitute a minor resource within the crop of the Devonian Turriff Outlier in the Turriff–Fyvie area.

More detailed information on the character of the deposits and their economic potential is given in Peacock et al., 1977, Merritt, 1981, and in Merritt et al., 2003 (see section on Sources of Information).

9.1.6 Brick clay

Eyles and Anderson (1946) undertook a comprehensive survey of brick clay deposits in north-east Scotland, including physical testing. Two sources of brick clay were identified within the district, one at Plaidy [NJ 730 550] and the other at Parkseat [NJ 561 246], north-east of Huntly (Parkseat was formerly shown as Kinnoir Brickworks on the 1954 Ordnance Survey 1-inch topographical map).

At Plaidy, an erratic of Jurassic clay was discovered in the railway cutting immediately north of the station. It was used for the local manufacture of bricks and tiles, but was considered worked out by 1946 (Eyles and Anderson, 1946). The brick clay worked at Kinnoir is part of an extensive area of glaciolacustrine deposits underlying flat-lying ground extending from north from grid line 39 to ground around Parkseat. Examination of the worked pits and subsequent, more recent investigation by BGS indicates that although the deposit is up to 2.5 m thick or more in places, the clay thins laterally and becomes more impure, containing sand and stones. The clay is brown, plastic and laminated, with silty and micaceous laminae. Firing tests revealed it yielded poor quality products of low strength (Eyles and Anderson, 1946). The clay was used to manufacture tiles, bricks and drainpipes.

9.1.7 Peat

Peat commonly occurs throughout the Huntly and Turriff districts on hills and in basins and its distribution is discussed in Chapter 4. Basin peat is economically more important as it is generally thicker than hill peat, but deposits are less extensive and commonly waterlogged. The main peat mosses have been worked extensively in the past, but there is no current exploitation beyond local piecemeal cutting. Formerly, peat was cut widely for fuel (both for domestic use and commercially for the fish curing industry) and for agricultural and horticultural purposes. Small quantities are still used in the whisky industry. Estimates of current resources are difficult to determine, there being no more recent account of the extent, thickness and worked state of peat in the district since the assessment and wartime pamphlet of Fraser (1948).

The main peat mosses, worked or unworked, are shown in Figure 16. The most extensive mosses occur in the north-west part of the district, with some recorded in 1948 as covering about100 ha. Abandoned worked mosses have commonly reverted to poorly drained, low-grade pasture.

Fraser (1948) noted that true basin peat in the districts generally consists of lower layers of sedge and reedgrass (*Phragmites*) peat, with upper layers of cottongrass and sphagnum moss peat forming the raised moss. Many basin peat mosses have an intermediate transitional layer of peat ('grenze') derived from pine and birch debris, commonly containing stumps and branches of *Pinus sylvestris* (Scots pine). Although dominantly occurring in topographical depressions on low-lying ground, basin peat may also occur in concave depressions on hill slopes. In contrast, hill peat is more consistent across the district, with little or no variation in structure or composition, though there is local hagging and erosion.

9.1.8 Metalliferous minerals

There is a long history of mineral exploration and related geological investigations in the mafic-ultramafic intrusions of the Huntly district (Gunn, 1997). Commercial exploration for copper-nickel (Cu-Ni) has been carried out intermittently since the late 1960s, while investigations by BGS in the 1980s concentrated on the evaluation of the potential of these bodies as sources of economic platinum-group element (PGE) mineralisation.

The largest exploration programme for copper-nickel was conducted by Exploration Ventures Limited (EVL), a joint venture between Rio Tinto Zinc and Consolidated Goldfields, between 1969 and 1973. Work undertaken included extensive mapping, geochemical and geophysical surveys, and diamond drilling. Attention was focused on the Littlemill–Auchencrieve area in the south-eastern part of the Knock intrusion. Drilling in this sector outlined a 'geological reserve' of 3 million tonnes grading 0.52% Ni and 0.27% Cu in two subparallel zones dipping towards the north-west. Copper and nickel occur in massive discontinuous lenticular sulphide bodies in a structurally complex contact zone at the edge of the Knock intrusion (Fletcher and Rice, 1989). The sulphide zone, up to 20 m thick at Littlemill, is roughly conformable with the banding in the enclosing olivine cumulates interlayered with modified, contaminated and granular gabbroic and noritic rocks and metasediments (Figure 17). Pyrrhotite, chalcopyrite and pentlandite form the main primary assemblage that displays some magmatic textures, although intense deformation and hydrothermal reworking are commonly evident. Fletcher and Rice (1989) reported elevated precious metal concentrations in these ores, up to a maximum of 574 ppb Au + Pt + Pd (gold + platinum + palladium).

Disseminated sulphide mineralisation of primary magmatic origin is widespread in the cumulate lithologies of the Knock and Huntly intrusions at concentrations of 0.5 to 1 vol%, but locally up to about 15% in olivine-bearing units (Gunn and Shaw, 1992). No significant enrichments in Cu, Ni or PGE have been reported in association with this style of mineralisation. However, some irregular discordant bodies of graphite- and sulphide-bearing orthopyroxene-rich pegmatites in the West Huntly cumulate body contain elevated precious metal contents, up to about 700 ppb Au + Pt + Pd (Fletcher and Rice, 1989). Two such occurrences have been located in the Bin

Quarry [NJ 498 431], but drilling by BGS failed to establish any significant continuity between the bodies at depth.

BGS also conducted exploration for PGE in the deformed mafic-ultramafic intrusions along the Portsoy Lineament in the upper Deveron valley south-west of Huntly (Gunn et al., 1990). Elevated PGE contents occur in the clinopyroxene-bearing ultramafic rocks of the Succoth–Brown Hill intrusion and drilling in one zone revealed Pt + Pd values up to about 270 ppb. Local enrichment of Pd relative to Pt, accompanied by elevated Au (up to 370 ppb), indicate the possible importance of late hydrothermal processes in producing the precious metal enrichments.

Following identification in 1979 of the world-class barium-zinc-lead (Ba-Zn-Pb) deposits at Aberfeldy in Perthshire, systematic exploration for stratabound mineralisation of this type was undertaken by BGS elsewhere in the Argyll Group, including the north-east Grampian area. In the Huntly district geochemical and geophysical surveys were conducted in the Wellheads and Succoth–Gouls areas to the west and south-west of Huntly respectively (Chacksfield et al., 1997). Results were most encouraging from the Wellheads area, but the further drilling of six boreholes by BGS in 1986 encountered no significant bedrock mineralisation (Coats et al., 1987).

The potential for the discovery of additional mineralisation in the Huntly district remains, although thick superficial deposits make exploration difficult, especially over the Knock Pluton. Further Cu-Ni ± PGE may be present in zones of deformation within the Huntly and Knock bodies, while the pretectonic intrusions within the Portsoy Shear Zone are also prospective for PGE mineralisation. There is also potential for the occurrence of stratabound mineralisation in Argyll Group rocks within and adjacent to the Portsoy Shear Zone in the Huntly district, for example, Chacksfield et al. (1997) identified further targets for investigation in the Wellheads and Succoth–Gouls area.

9.2 HYDROGEOLOGY

9.2.1 Bedrock

Although the Dalradian Supergroup is lithologically variable, the rocks within it have been grouped into one hydrogeological unit because of their negligible intergranular porosity. Movement of groundwater in these rocks depends on interconnected fractures and fissures, resulting in widely varying and complex flowpaths influenced not only by the direction of the hydraulic gradient, but by structural features such as faults, joints and fracture zones. The steeply dipping attitude of Dalradian rocks precludes flow along secondary voids on bedding planes remnants, a common feature within gentler-dipping rocks of negligible porosity.

The hydraulic conductivity of Dalradian rocks is very low (~0.05 m/day), with transmissivity values normally <10 m^2/day. Zones of higher permeability are common within 10 m of the surface where weathering processes have increased the amount of interconnected void space available for groundwater storage. Where overlain by granular superficial deposits such as sand and gravel, a useful, although localised, resource may be present because of the increased availability of recharge from infiltrating rainwater. The presence of a large number of springs across the Huntly and Turriff districts is evidence of shallow, active groundwater movement in bedrock. Over 80 springs have been used as sources of water across the district, including 14 that have been developed for public supply. Threats to water quality such as bacterial contamination have reduced the number in use over the years, but many are still relied upon for local usage. The full implementation of the Deveron Water Supply Scheme has also resulted in abandonment of ground water sources, at least for domestic and industrial use.

Groundwater from deeper boreholes drilled into Dalradian rocks number around 20 in the district. Individual yields range from 0.2 to 2 litres/second (l/s). Most boreholes are no deeper than 30 m and supply domestic water to individual houses. Water-bearing voids can exist in hard rocks at great depths, but experience in other parts of Scotland suggests that most groundwater circulation occurs within 60 m of the surface, with much reduced flow below. Water quality is generally very high from borehole sources. The water is weakly mineralised with a carbonate concentration around 10 mg/l (Robins, 1990), reflecting the low carbonate content of the country rock.

On the western margins of the area, the Pitlurg Calcareous Flag Formation and other minor limestone units are thought to have the same aquifer characteristics as the remainder of the Dalradian. However, in limestone and carbonate-rich rocks in other parts of the Highlands carbonate concentrations in groundwater are raised to around 50 mg/l (Robins, 1990). The presence of a shallow, weathered zone increases the possibility of localised pollution of near-surface groundwater, especially where bedrock is exposed. Within recharge areas the transmission of contaminants from the surface can occur rapidly in fissured hard rocks, and springs, in particular, can be vulnerable.

Around Huntly, almost 20 springs and one borehole are present in areas underlain by Ordovician mafic and ultramafic rocks, although some of the springs originate from river alluvium around the town. A single borehole to the north of Huntly provides a good supply of high quality water to a farm, and indicates that aquifer characteristics are similar to those found in areas underlain by the Dalradian rocks, with yields of less than 1 l/s on average.

The shaly mudstones of the Devonian Dryden Flags Formation in the extreme south of the area have been studied and assessed hydrogeologically in the Rhynie area, 4 km south of the district. Drilling investigations revealed that fissure flow was dominant, with groundwater inflow largely restricted to a small number of points. A promising yield from one of the 2 trial boreholes of 15 to 20 l/s was tempered by the chemistry of the water, which showed very high concentrations of iron and manganese associated with low oxygen contents (Robins, 1990). This borehole was rejected for use as a public supply source. The second borehole contained lower amounts of these substances, indicating significant variation in the aquifer. The outcrop of the Dryden Flags Formation within the Huntly district in Strath Bogie likely has a moderate to good permeability of 1 m/d and reasonable water quality. As such it represents a presently untapped but potential water resource.

Near Turriff, the Devonian Gardenstown Conglomerate Formation forms a relatively large aquifer. Investigations in two deep boreholes north-east of Turriff [NJ 757 509] (Robins, 1989) show groundwater flow to be fissure-controlled. Porosity and permeability tests on core samples of sandstone gave results of 8 to 12% and 10^{-4} m^2/day respectively. Pumping tests indicate that the difference between the proportion of flow via fissures and that in pore spaces is four orders of magnitude.

One of the boreholes has been in use for public supply for over 10 years and has performed reliably and consistently. The two boreholes indicate long-term borehole yields in this aquifer between 10 and 15 l/s. Water quality tests show the groundwater to be moderately mineralised and similar to that found in Devonian aquifers in other parts of Scotland (Robins, 1989). Only one other borehole is recorded as being in use in the Devonian aquifer, so there is potential for further development (Ball, 1999).

Hydrograph data from one of the Turriff boreholes shows the groundwater level to be largely unresponsive to rainfall events, with consistent levels of water storage throughout the year (Robins, 1989). This suggests a relatively high rate of infiltration and throughflow in the mainly fissured aquifer, particularly where only patchy till cover is present. The likelihood of surface pollution entering the unsaturated zone and reaching the water table in a relatively short space of time is possible across the aquifer, particularly at the numerous localities where rock is close to surface.

9.2.2 Superficial deposits

Superficial deposits contain only small amounts of groundwater and form localised, discontinuous aquifers where granular material is present. Shallow groundwater flow within layers of gravelly drift results in many small springs and seepages. Thin gravel layers in alluvial deposits within the main river valleys, such as the Deveron valley around Huntly, provide the main storage in the area. River gravel permeability can be very high, although the thickness of these deposits is normally restricted to a few metres. Consequently, the overall volume of groundwater moving through the gravels is quite low. An important function of valley gravels is to provide temporary storage for groundwater prior to entering rivers as baseflow and help to maintain river flow during periods of dry weather. These deposits provide a significant element of the total river flows in the district during the summer months.

10 Sources of information

Further geological information held by the British Geological Survey relevant to the Huntly and Turriff districts is listed below. It includes published material in the form of maps, memoirs and reports and unpublished maps and reports. Also included are other sources of data held by BGS in a number of collections, including borehole records, mine plans, fossils, rock samples, thin sections, hydrogeological data and photographs.

Searches of indexes to many of the collections can be made on the GeoIndex system at http://www.bgs.ac.uk.

This computer-based system undertakes searches of indexes to collections, digital databases and to digital versions of the geology and geophysics of the UK at various scales. Searches can be specified for particular geographical areas. The results of the searches are displayed as on-screen maps. At the present time (2014) the following themes are available:

- Borehole records
- Water wells
- Site investigation reports
- Drillcore
- Samples, including registered petrographical, palaeontological and geochemical samples
- Stream sediment geochemistry
- Geophysical logs
- Topography
- Outlines of BGS maps at 1:50 000 and 1:10 000 scale and 1:10 560 scale County Series Aeromagnetic and gravity data recording stations
- Various land survey records

Details of geological information available from the British Geological Survey can be accessed via the BGS Web Home Page at http://www.bgs.ac.uk.

BGS MAPS

Geology maps

1:625 000

United Kingdom (North Sheet) Bedrock Geology, 2007

Quaternary Geology, 1977

1:250 000

Moray Buchan (Sheet 57N 04W) Solid geology, 1977

1: 63 360

Sheet 86 (Huntly) Solid and Drift Editions, 1923

1: 50 000

Sheet 86W (Huntly) Solid Edition, 2000

Sheet 86E (Turriff) Solid and Drift Edition, 1995

1:10 000 and 1:10 560

Details of the original geological surveys are listed on editions of the 1:63 360 geological sheets. Copies of the fair-drawn maps of these earlier surveys may be consulted at the BGS Library, Edinburgh.

The maps at six-inch or 1:10 000 scale covering wholly or in part in the 1:50 000 scale Sheet 86 are listed below, together with the surveyors' initials and the dates of the survey. The surveyors were: M J Brown (MJB), T P Fletcher (TPF), D Gould (DG), A G Gunn (AGG), J R Mendum (JRM), S D Redwood (SDR), D Stephenson (DS) and C W Thomas (CWT). Only partial revision of the Huntly and Turriff districts was undertaken during the recent mapping programme, work being concentrated on Sheet 86W (Huntly), particularly the mafic and ultramafic igneous intrusions. The Huntly and Knock intrusions were mapped by S J Redwood, A G Gunn and M J Brown. They also undertook a detailed geochemical and petrological study together with M T Styles. S J Redwood also mapped the Dalradian rocks around the southern end of the Huntly intrusion, whereas D J Fettes and C W Thomas undertook mapping in Clashindarroch Forest in the south-west corner of the sheet. The Dalradian rocks to the west and south-west of the Huntly intrusion were mapped by J R Mendum and D Stephenson. C W Thomas undertook mainly reconnaissance mapping of the Southern Highland Group in the Turriff district (Sheet 86E) and mapped along the northern margin of the Insch intrusion in Strathbogie and in the Slate Hills. The Fyvie Gorge was mapped in greater detail, as were some other small areas where bedrock exposure is above average.

The maps are not published but scanned images and paper copies are available for consultation in the Libraries at BGS Edinburgh, and BGS Keyworth, and at the BGS London Information Office in the Natural History Museum in South Kensington. Paper copies can be printed on demand and purchased from the Sales Desk. As only local reconnaissance traverses were carried out in the Turriff district (Sheet 86E), except for the Fyvie Gorge, the bulk of the geology is based on the original surveys by H H Read and others.

Map	**Geologist**	**Map name**	**Date**
NJ43NW	DS	Glass	1993
NJ43NE	AGG	Wellheads	1996
NJ43SW	DS	Grumack Hill	1993
NJ43SE	CWT	Clashindarroch Forest	1993
NJ44NW	DS	Cairds Hill	1994
NJ44NE	MJB	The Balloch	1996
NJ44SW	DS	Davidston	1993
NJ44SE	MJB, AGG	Drumdelgie	1996
NJ45NW	FM		1961
NJ45NE	DG	Aultmore	1998
NJ45SW	DS	Keith	1993
NJ45SE	DS	Grange	1996
NJ53NW	SDR, CWT	Huntly South	1996
NJ53NE	SDR	Thomastown	1996
NJ53SW	CWT	Gartly	1993
NJ53SE	CWT	Gartly Moor	1993
NJ54NW	AGG, SDR	Ruthven–Milltown	1996
NJ54NE	SDR	Fourman Hill	1996
NJ54SW	AGG, SDR	Huntly North	1996
NJ54SE	SDR	Lessendrum	1996

NJ55NW	JRM	Edingight	1996 (solid), 1998 (drift)
NJ55NE	JRM	Ordiquhill	1996 (solid), 1998 (drift)
NJ55SW	SDR, JRM	Knock	1996
NJ55SE	SDR	Crombie	1996
NJ63SW	CWT	Hill of Foudland	1993
NJ65NW	DG, TPF	Hill of Ord	1997
NJ65NE	TPF	Stonieley	1997
NJ73NE	CWT	Fyvie	1992

Geophysical maps

1:1 500 000

Colour shaded relief gravity anomaly map of Britain, Ireland and adjacent areas, 1997

Colour shaded relief magnetic anomaly map of Britain, Ireland, 1998

1:625 000

United Kingdom (North Sheet) Aeromagnetic anomaly, 1972; Bouguer anomaly, 2007; Regional gravity, 1981

1:250 000

Moray Buchan (Sheet 57N 04W) Aeromagnetic anomaly, 1978; Bouguer gravity anomaly, 1977

1:50 000

Geophysical information maps; these are plot-on-demand maps which summarise graphically the publicly available geophysical information held for the sheet in the BGS databases. Features include:

- Regional gravity data: Bouguer anomaly contours and location of observations.
- Regional aeromagnetic data: total field anomaly contours and location of digitised data points along flight lines.
- Gravity and magnetic fields plotted on the same base map at 1:50 000 scale to show correlation between anomalies.
- Separate colour contour plots of gravity and magnetic fields at 1:125 000 scale for easy visualisation of important anomalies.
- Location of local geophysical surveys.
- Location of public domain seismic reflection and refraction surveys.
- Location of deep boreholes and those with geophysical logs.

Geochemical atlases

1:250 000

In the Huntly and Turriff districts steam sediment and water samples were collected from first and second order streams in the late 1970s, coverage averaging 1 sample per 1.6 km^2. Stream sediment samples were analysed for 30 elements and the water samples for acidity, conductivity, bicarbonate, fluoride and uranium content. Point-source geochemical data processed to generate a smooth continuous surface presented as an atlas of small-scale colour-classified digital maps. The data from the Huntly and Turriff districts are included within the Regional Geochemistry of the East Grampians area, published by the Geological Survey in 1991.

Data from the Geochemical Baseline Survey of the Environment (G-BASE), formerly the Geochemical Survey Programme, are also available in other forms including hard copy and digital data.

Hydrogeological maps

1:625 000

Sheet 18 (Scotland) 1988.

Groundwater vulnerability (Scotland) 1995.

BGS BOOKS AND ONSHORE TECHINICAL AND SCIENTIFIC REPORTS

Memoirs, reports and papers relevant to the Huntly and Turriff districts are arranged by topic. Some may be out of print or not widely available, but may be consulted at BGS and other libraries.

General geology

British Regional Geology: The Grampian Highlands, 4th Edition, 1995

Geology of the country around Banff, Huntly and Turriff 1923 Memoir.

The history of geological investigations in the Huntly and Knock mafic-ultramafic intrusions, Grampian Region. BGS Technical Report WA/97/6.

Geochemistry

British Geological Survey. 1991. Regional geochemistry of the East Grampian area. (Keyworth, Nottingham: British Geological Survey.) ISBN 0 85272 198 6

Petrology and geochemistry

A new approach to map production and petrogenetic interpretation using petrological databases: an example from the Huntly–Knock intrusions of Aberdeenshire. *BGS Technical Report,* WG/94/14

A petrological study of ultramafic rocks from the East Grampian region between Ballater and Huntly. *BGS Technical Report,* WG/94/10

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DOCUMENTARY COLLECTIONS

Borehole record collection

BGS holds collections of records of boreholes, which can be consulted at BGS, Edinburgh, where copies of most records may be purchased. For the Huntly district there are records of the sites and logs of about 270 boreholes and for the Turriff district for some 41 boreholes. Index information, which includes site references, for these bores has been digitised. The logs have been digitised but original hand-written or typed paper copies are archived. Note that many of the older borehole records are drillers' logs.

Site exploration reports

This collection consists of site exploration reports carried out mainly to investigate foundation conditions prior to construction. There is a digital index and the reports themselves are held on microfiche. For the Huntly and Turriff districts there are about 18 reports.

Mineral exploration data

Numerous maps and plans relating to mineral exploration activities over the Huntly and Knock intrusions are held at BGS, Edinburgh

Hydrogeological data

Records of water boreholes are held at BGS, Edinburgh. In total there are records of 46 boreholes linked to water supplies in the Huntly and Turriff districts.

Geochemical data

Records of stream-sediment and other analyses are held at BGS, Keyworth.

Gravity and magnetic data

Records are held at BGS, Edinburgh. These include regional survey data and digitised records of the aeromagnetic survey flown by EVL in 1970.

Seismic data

Records of earthquakes are held at BGS, Edinburgh.

MATERIAL COLLECTIONS

Geological survey photographs

Photographs illustrating aspects of the geology of the Huntly and Turriff districts are deposited for reference in the archives mainly at BGS, Edinburgh with some at BGS Keyworth. The photographs depict details of the various rocks exposed either naturally or in excavations and also some general views.

Petrological collections

The petrological collections for the Huntly and Turriff districts consist of over 2100 samples. Most samples are of the mafic-ultramafic intrusive rocks in the district: there are 1635 thin sections from the Huntly district, mostly from the mafic-ultramafic rocks. In contrast only 29 rocks have been thin-sectioned from the Turriff district. Information on databases of thin sections can be obtained from the Mineralogy and Petrology Section, BGS, Edinburgh. Numerous reference hand specimens from the East Grampian Project and the Mineral Reconnaissance Programme are also held at BGS in Edinburgh and Keyworth.

Bore core collection

Samples have been collected from core taken from boreholes. Continuous core is available from 21 boreholes drilled by BGS during the East Grampian Project and Mineral Reconnaissance Project, and from four boreholes drilled by Exploration Ventures Limited.

Palaeontological collections

There are about 60 specimens containing fossil material from the Huntly and Turriff districts in the BGS palaeontological collections. These include specimens from the Old Red Sandstone outliers and the Jurassic erratics in the Banffshire Coast Drift Group at Plaidy, and of ?Cretaceous chalk flints from the Buchan Gravels Formation.

COLLECTIONS HELD OUTWITH BGS

Sites of Special Scientific Interest are the responsibility of Scottish Natural Heritage, Great Glen House, Leachkin Road, Inverness, IV3 8NW.

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BGS web site: http://www.bgs.ac.uk

Appendix 1 Geochemical analyses of the Keith–Portsoy Granite

Major element analyses (Values shown as oxides in weight percent)

Sample No. (GX)	1713	1714	1715	1716	1717	1718	1719	1720
SiO_2	70.43	70.37	70.25	70.50	67.87	71.68	70.99	71.40
TiO_2	0.61	0.63	0.65	0.67	0.81	0.48	0.54	0.56
Al_2O_3	13.90	14.11	13.96	13.88	15.00	13.78	14.01	13.82
Fe_2O_3	3.60	3.72	3.67	4.01	4.46	2.96	3.17	3.43
Mn_3O_4	0.04	0.05	0.04	0.07	0.05	0.03	0.02	0.03
MgO	0.96	0.96	1.04	1.01	2.03	1.27	1.51	0.84
CaO	1.09	1.21	1.47	1.26	1.87	1.65	0.78	1.01
Na_2O	2.70	2.65	3.06	2.78	4.37	2.64	2.63	2.57
K_2O	4.92	5.15	4.43	4.73	1.97	4.68	5.23	5.00
P_2O_5	0.17	0.18	0.18	0.18	0.05	0.12	0.12	0.17
BaO	0.07	0.07	0.07	0.07	0.13	0.22	0.24	0.07
LOI	0.86	0.82	0.73	0.77	0.93	0.57	0.70	0.92
Total	99.35	99.92	99.55	99.93	99.54	100.08	99.94	99.82

Analyses by BGS using X-Ray Fluorescence Spectrometry on fused glass beads.

Trace element analyses (Values shown as parts per million (ppm)).

Sample No. (GX)	1713	1714	1715	1716	1717	1718	1719	1720
Rb	217	222	138	224	48	144	137	211
Sr	143	142	188	148	379	188	215	135
Y	44	30	31	41	23	30	32	21
Zr	276	281	290	289	397	233	265	262
Nb	20	20	20	21	22	18	18	18
Th	17	17	16	17	17	17	19	16
Pb	23	23	20	20	22	19	12	21
Zn	59	59	31	62	57	32	16	51
Cu	8	9	1	8	19	3	1	10
Ni	10	9	9	11	17	9	12	8
Hf	6	6	7	8	10	6	6	6
U	2	4	3	5	<1	3	2	2

Analyses by BGS using X-Ray Fluorescence Spectrometry on pressed powder pellets.

Sample localities

GX 1713: Lurgbrae [NJ 5001 5719]. Massive boulder of granite showing very weak foliation.

GX 1714: Hillockhead of Muldearie [NJ 3936 5106]. Large boulder of foliated granite.

GX 1715: Market Hill, Glass [NJ 4171 3965]. Large boulder of foliated granite.

GX 1716: NE end of Hill of Bellyhack [NJ 3978 4314]. Boulder of foliated granite.

GX 1717: Intertidal outcrop, 390m north-north-west from Westerwards Croft [NJ 5792 6668]. Steeply dipping sheet of foliated augen granite cross cuts amphibolitic mafic sheet.

GX 1718: Boggierow Quarries [NJ 5747 6518]. Approximately 4m-thick foliated granite sheet concordant with semipelite sequence.

GX 1719: Boggierow Quarries [NJ 5748 6516]. Approximately 1m-thick foliated granite sheet concordant with semipelite sequence.

GX 1720: Borehole 92, E4 (145.76 m above OD) – Keith Bypass site Investigations. Outskirts of Fife Keith. [NJ 4214 5001]. Highly foliated and lineated augen granite. Sample from 7 m depth.

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FIGURES

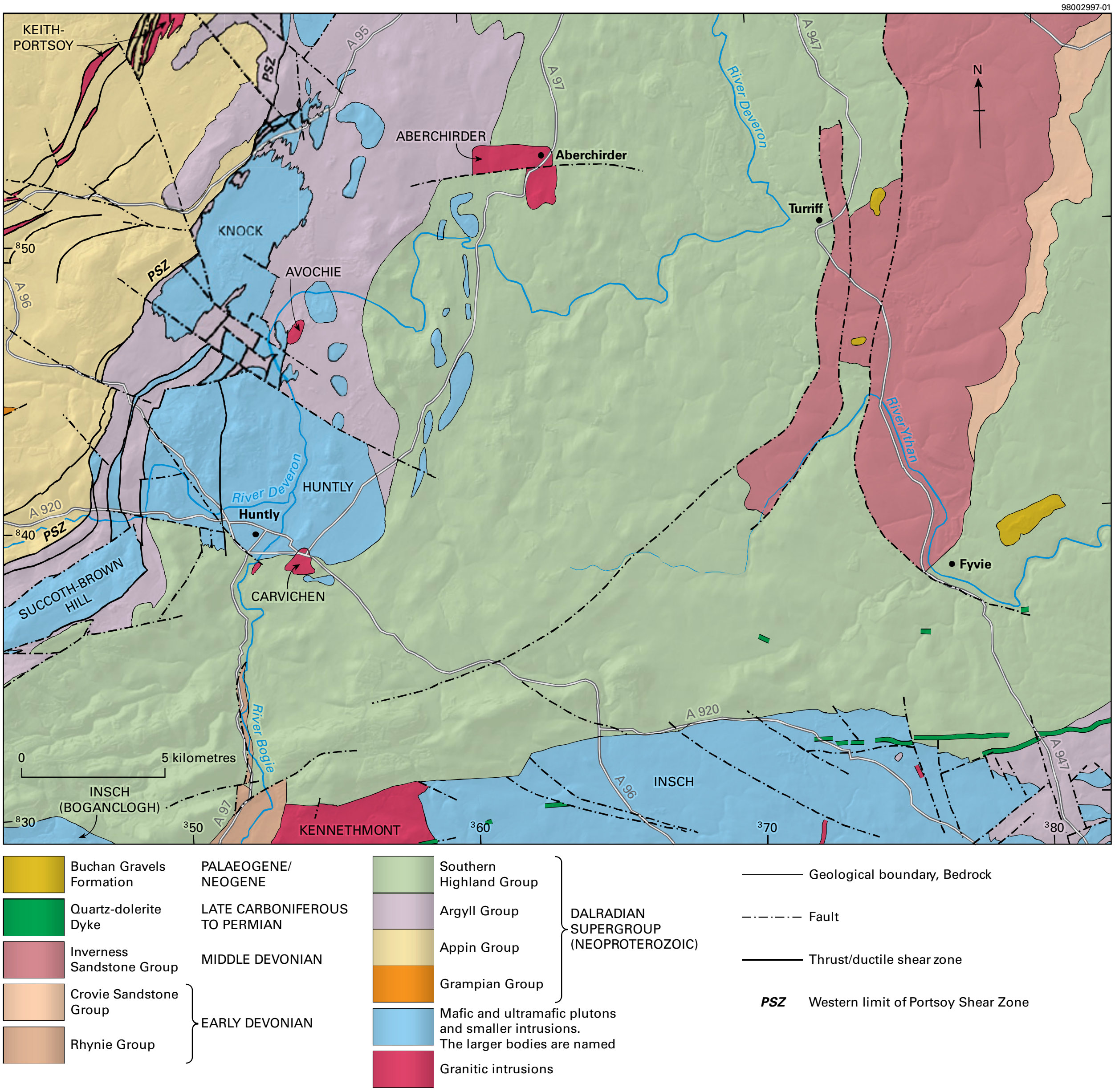

Figure 1 Simplified bedrock geology map of the Huntly and Turriff districts.

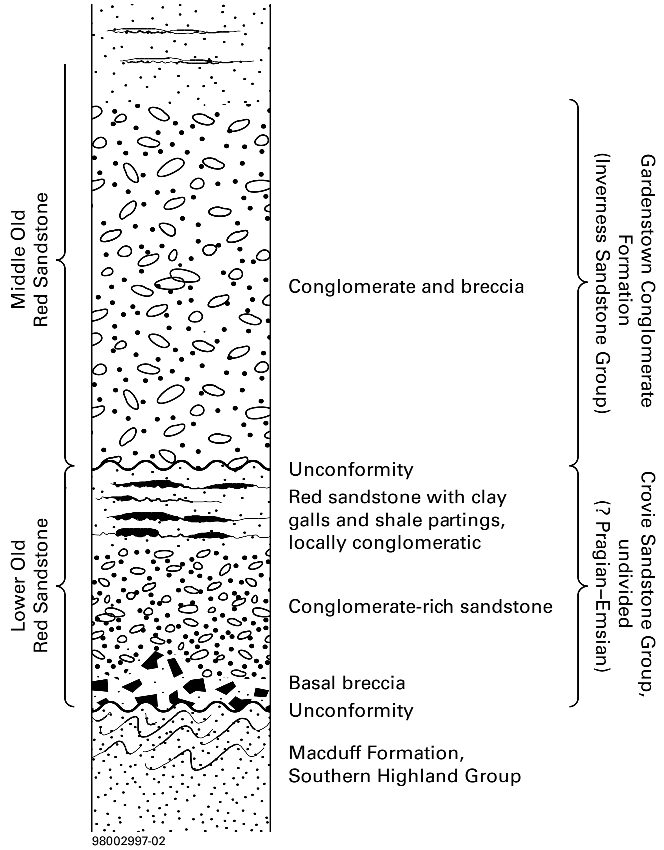

Figure 2 Schematic generalised vertical section through the Old Red Sandstone rocks of the Turriff Outlier. Relative thicknesses are notional and based on descriptions in Read (1923). The Gardenstown Conglomerate is locally unconformable on the Macduff Formation in the southern part of the Turriff Outlier.

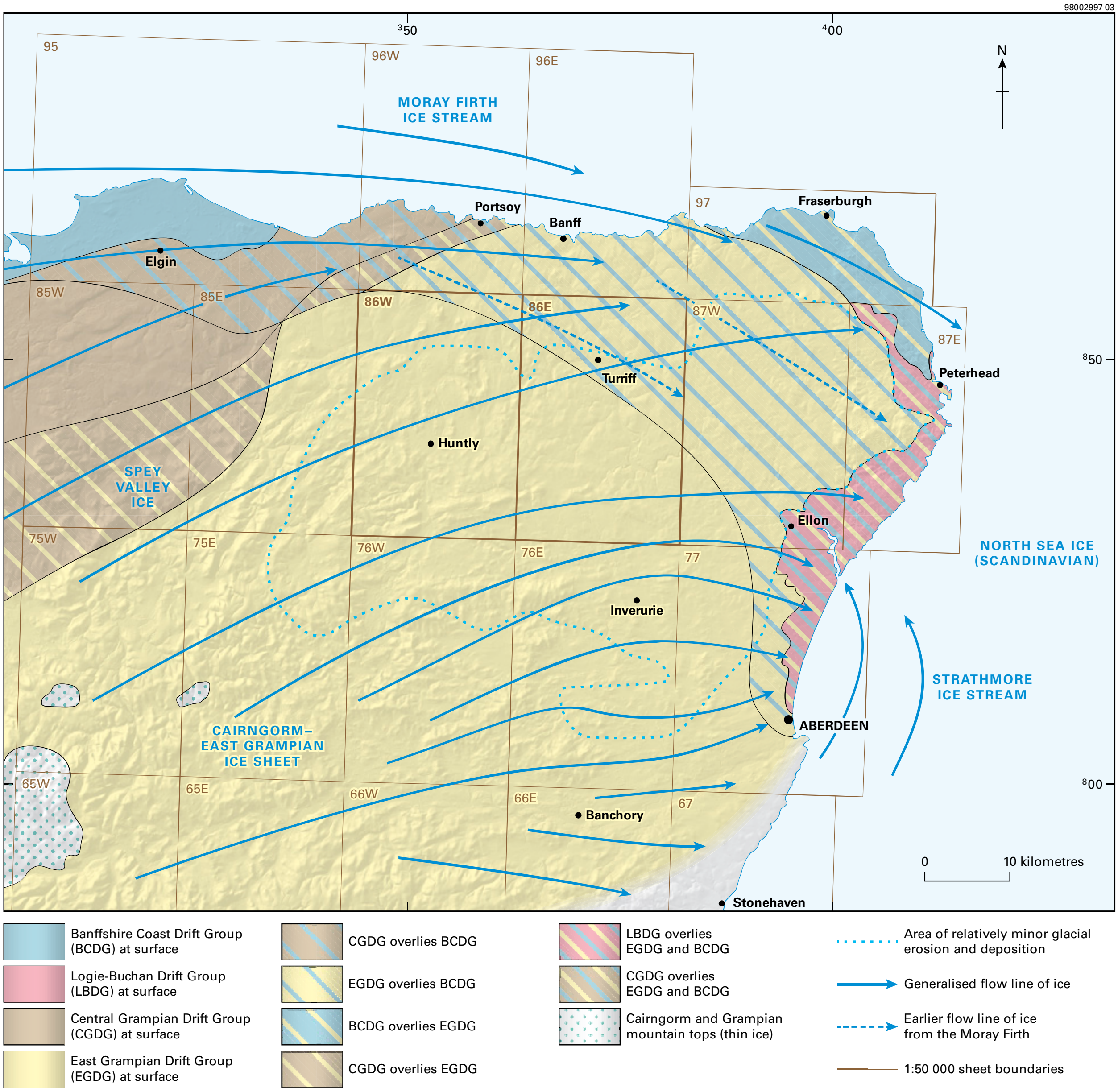

Figure 3 Distribution of the glacigenic drift groups in north-east Scotland showing their relationships. Arrows show the directions of movement of the different ice streams (after Merritt et al., 2003).

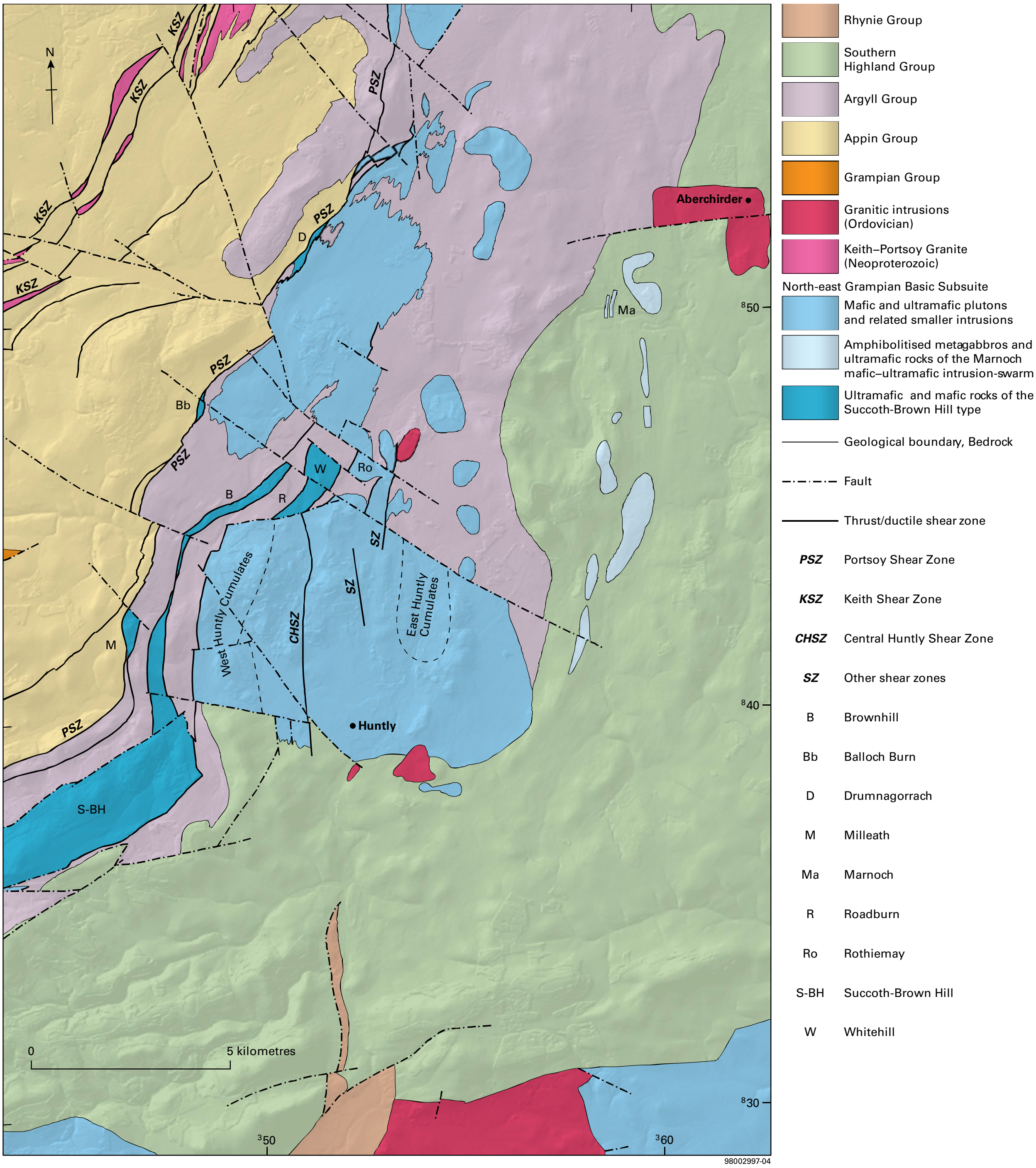

Figure 4 Distribution of pre-tectonic and syntectonic mafic-ultramafic intrusive rocks in the Huntly district.

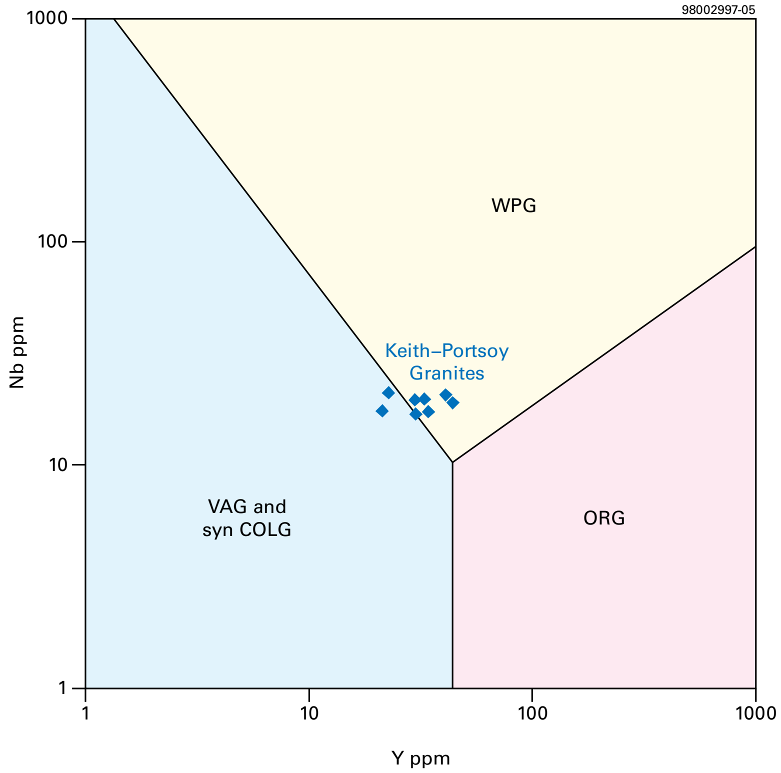

Figure 5 Niobium (Nb) v. Yttrium (Y) plot showing the Keith–Portsoy granite samples in relation to the fields of within-plate granites (WPG), volcanic arc and syn-collisional granites (VAG and syn COLG) and ocean-ridge granites (ORG).

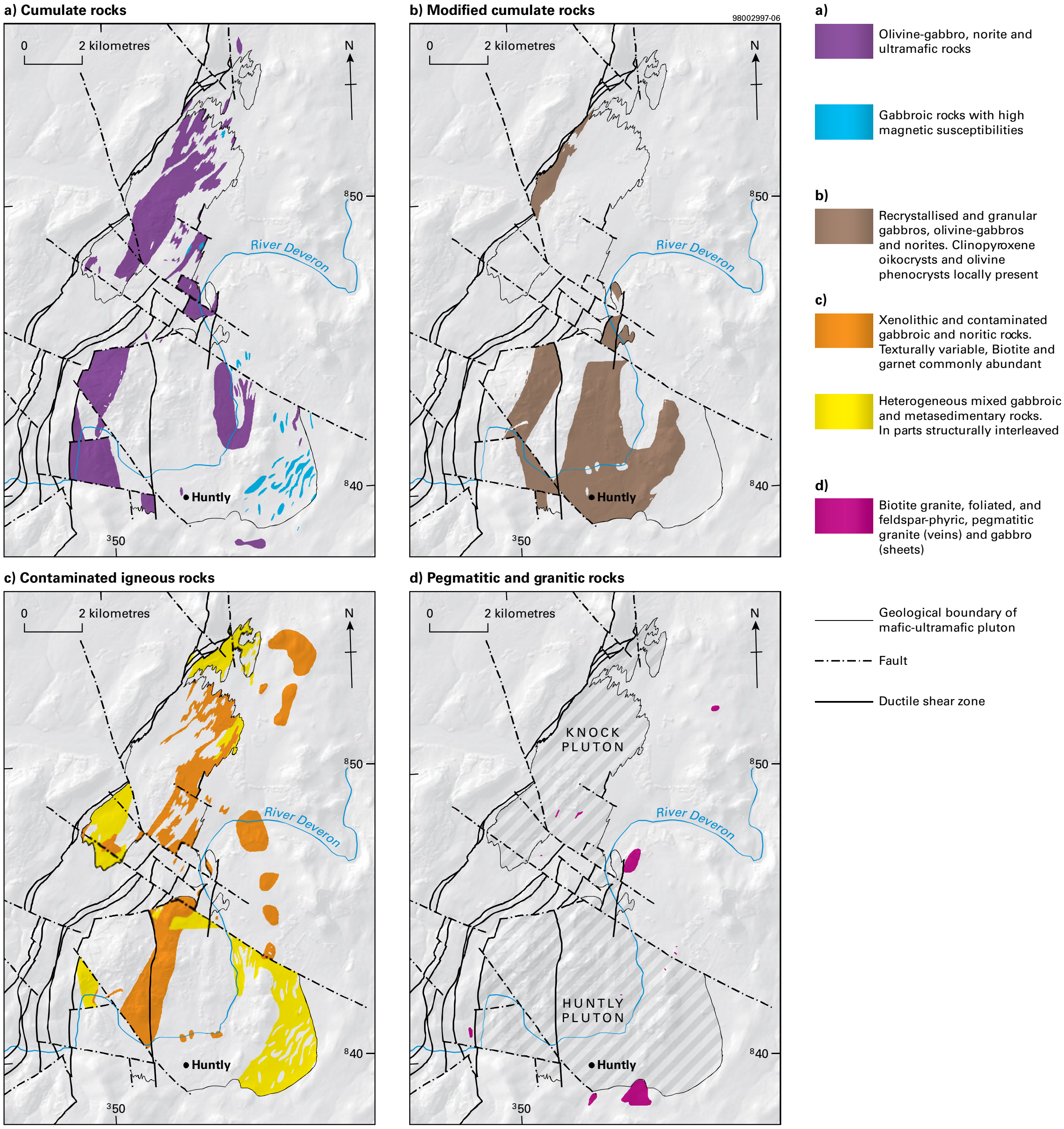

Figure 6 Maps showing the distribution of the main component lithologies in the Huntly and Knock gabbro-peridotite plutons. a) Cumulate rocks ; b) Modified cumulate rocks; c) Contaminated igneous rocks; d) Pegmatitic and granitic rocks.

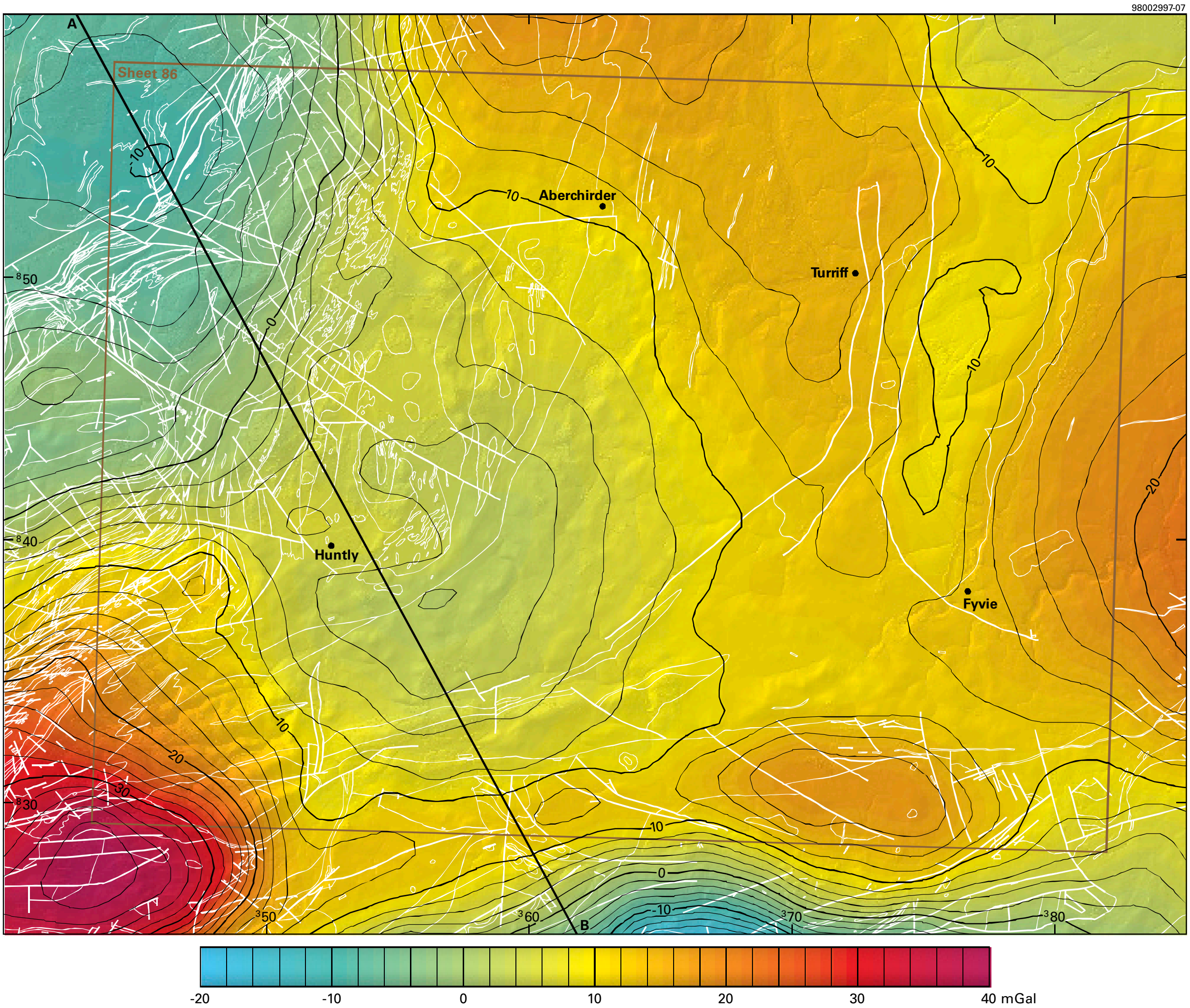

Figure 7 Bouguer gravity anomalies in the Huntly and Turriff districts. Values based on a reduction density of 2.75 Mgm^{-3}. The underlying white lines relate to the generalised bedrock geology, based on the 1:250 000 geological map.

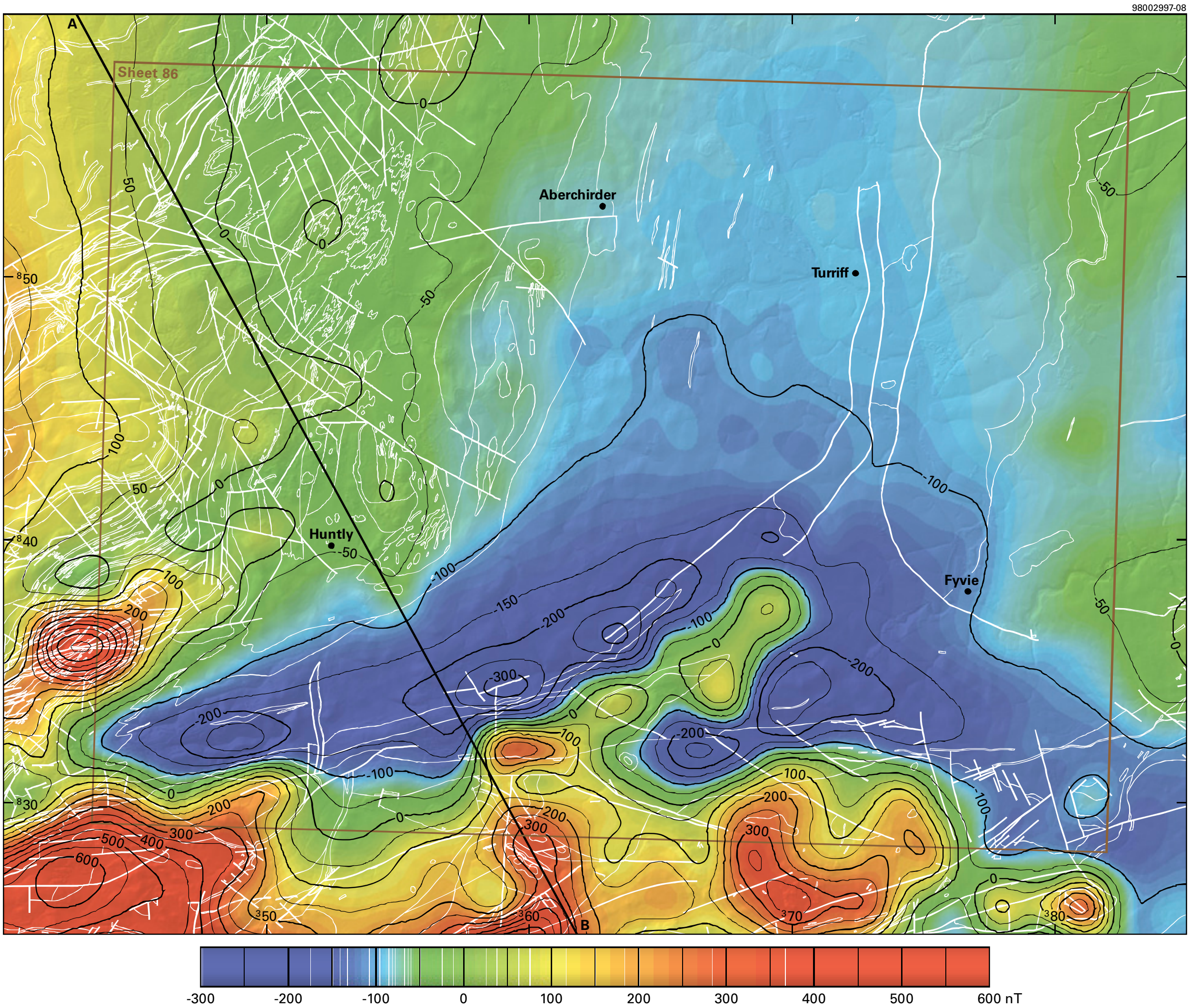

Figure 8 Total field magnetic anomaly in the Huntly and Turriff districts. Contours based on data collected at 305 m above ground level on east–west flight lines 2 km apart. The underlying white lines relate to the generalised bedrock geology, based on the 1:250 000 geological map.

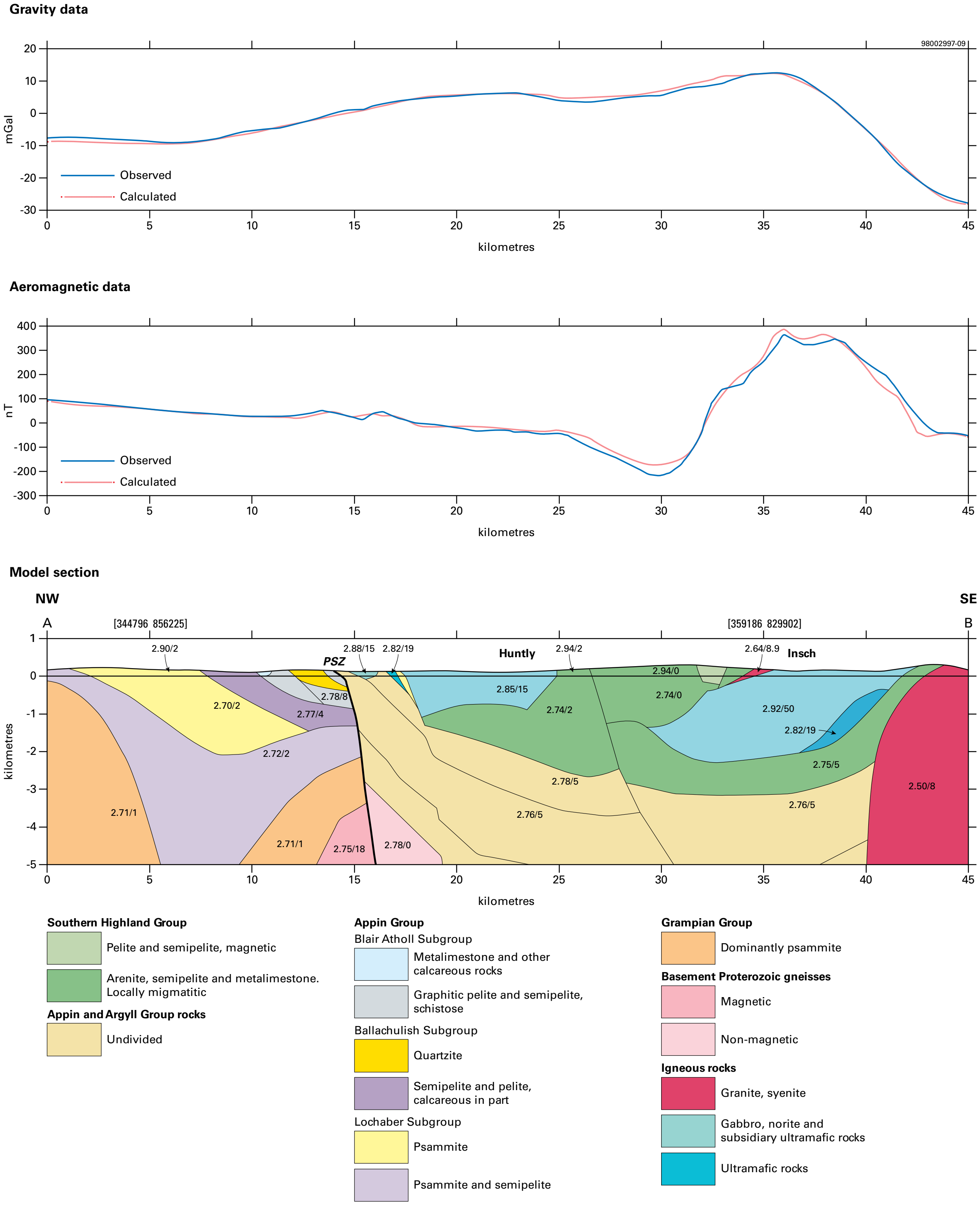

Figure 9 Part of a full-crust modelled section across the Huntly and Insch plutons. Location shown in Figure 7. The numbers cited inside the polygons indicate the bedrock density and magnetic susceptibility values used in the model.

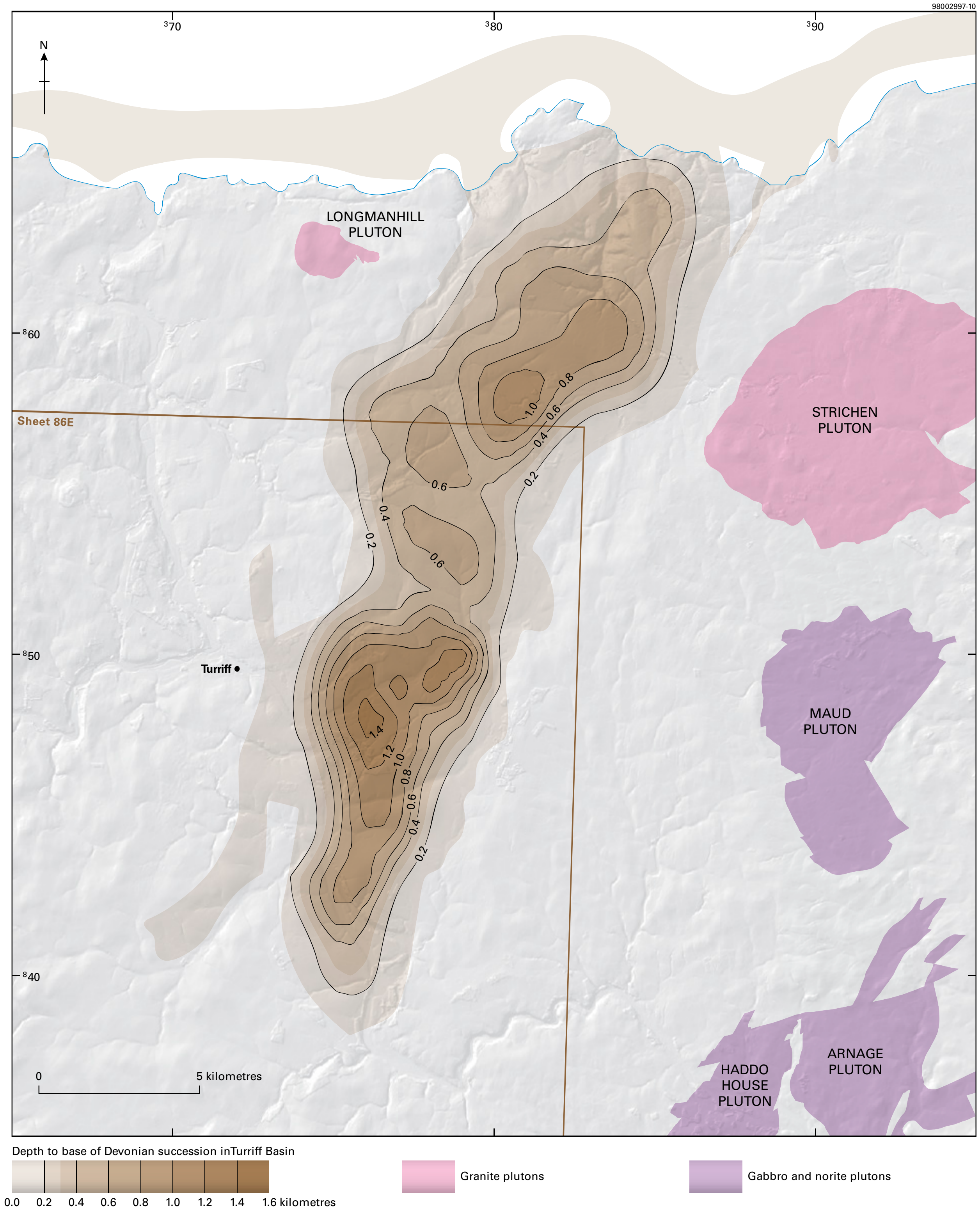

Figure 10 A geophysical model showing the depths to the base of the Devonian succession in the Turriff Basin.

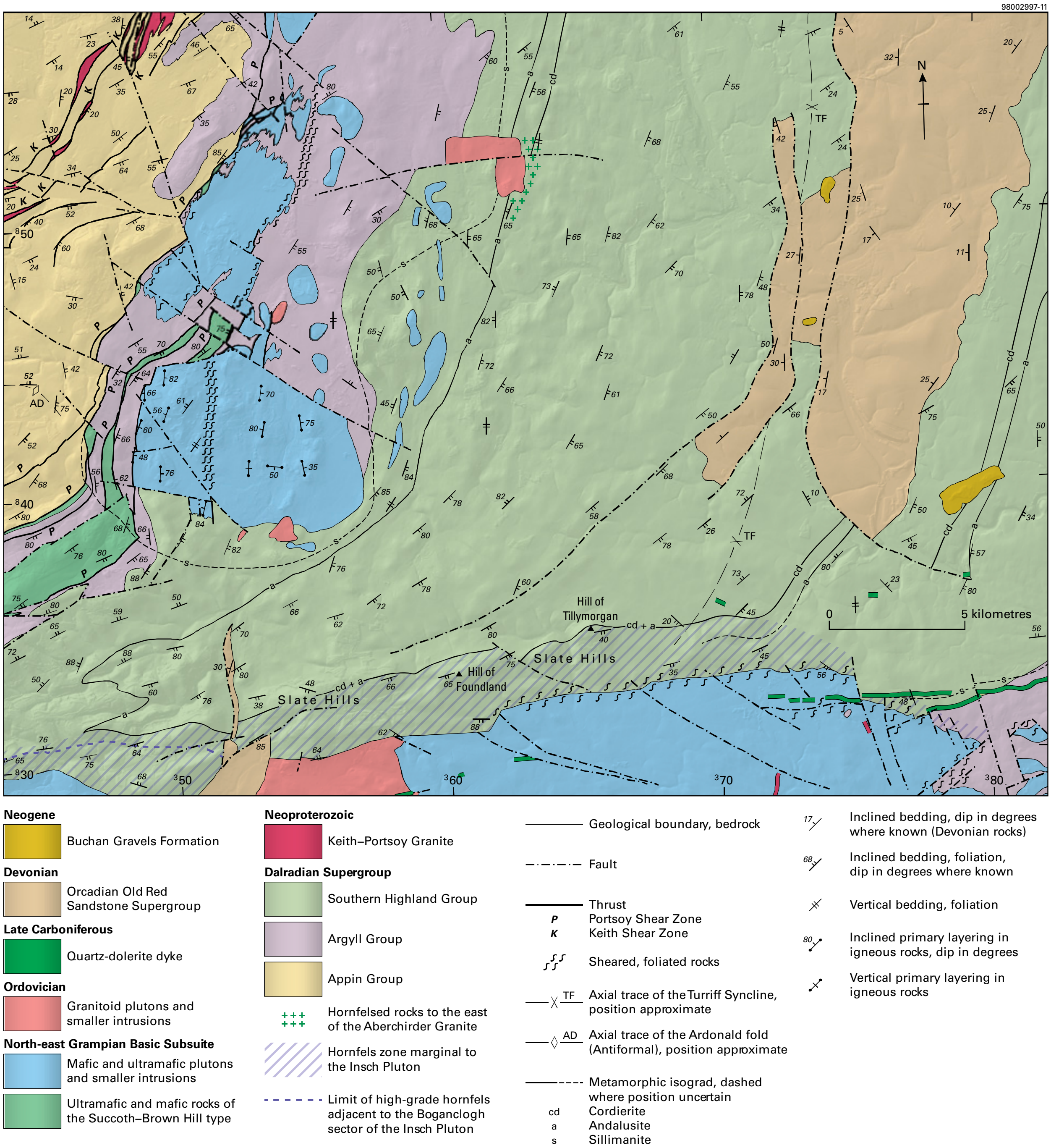

Figure 11 Structural and metamorphic features of the Huntly and Turriff districts.

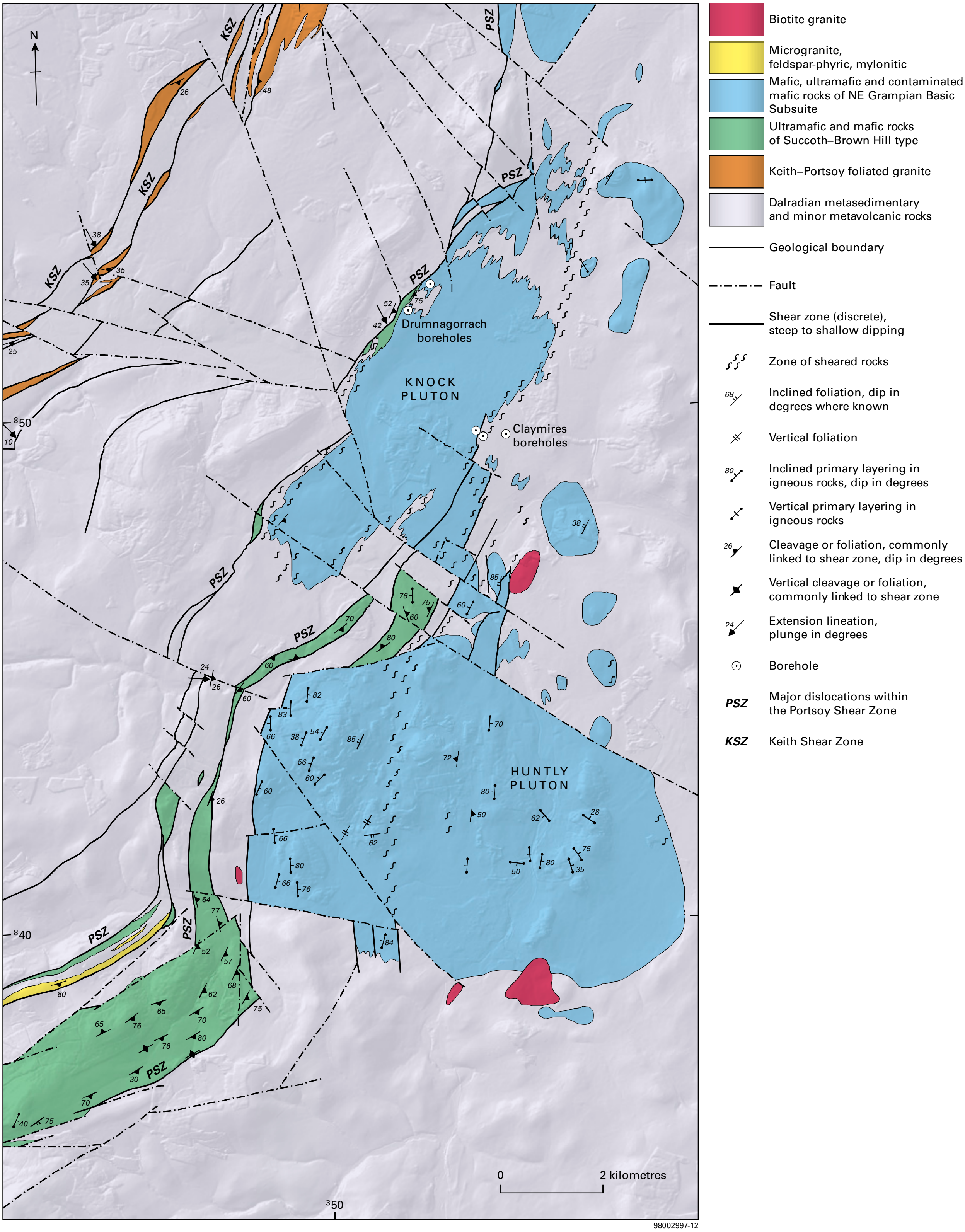

Figure 12 Structural features associated with the Keith and Portsoy shear zones.

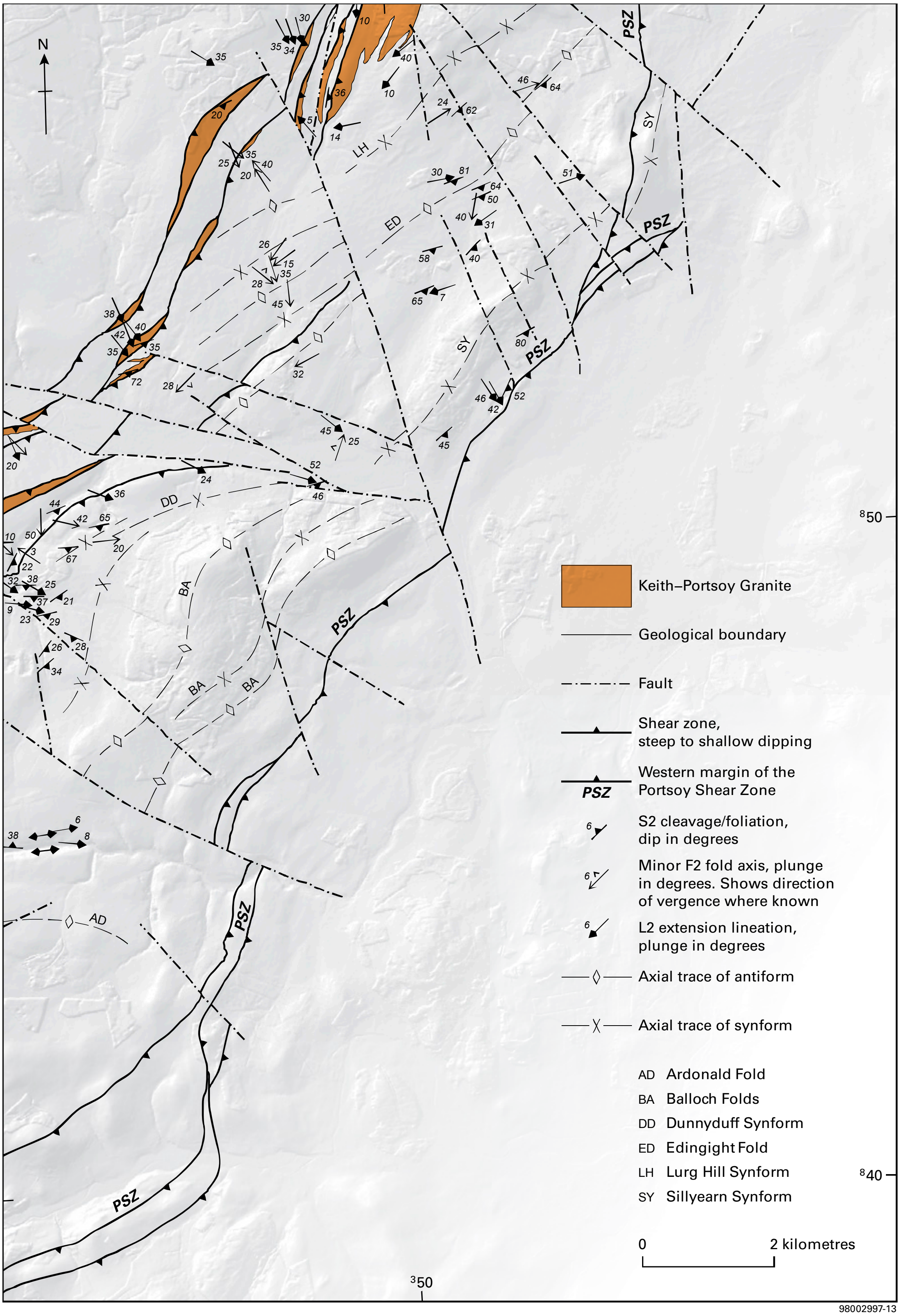

Figure 13 D2 structural features in the area west of the Portsoy Shear Zone.

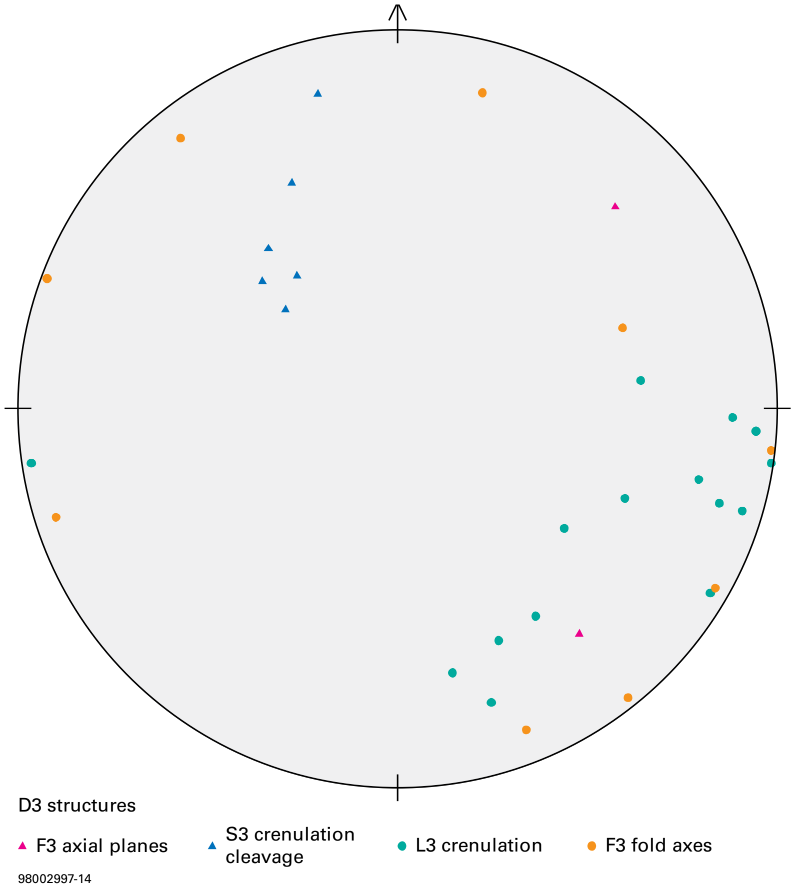

Figure 14 Stereogram showing the orientation of the D3 structural features in the area west of the Portsoy Shear Zone (Huntly district). (Lower hemisphere, equal area projection).

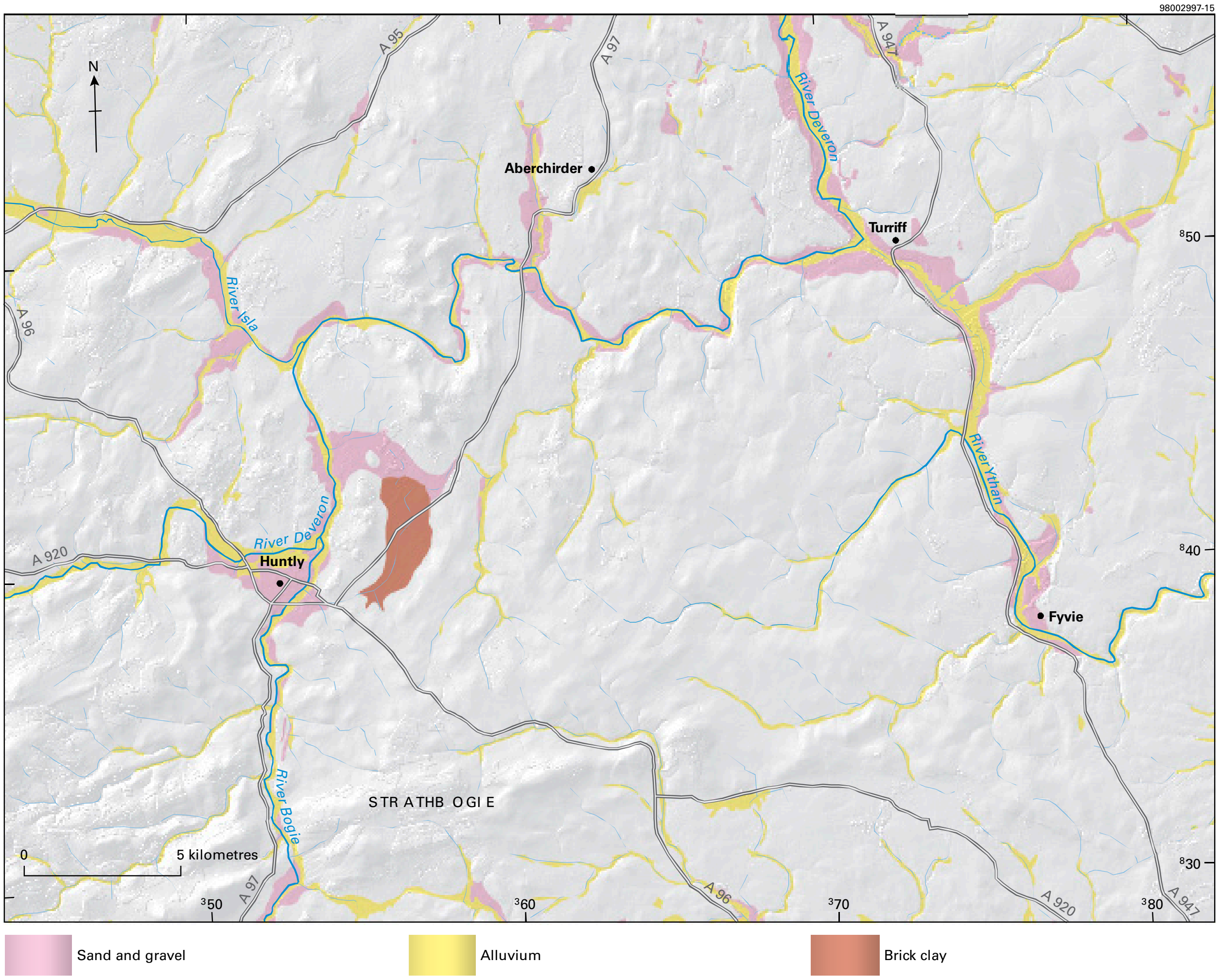

Figure 15 Generalised distribution of sand and gravel resources within the Huntly and Turriff districts (modified after Peacock et al., 1977).

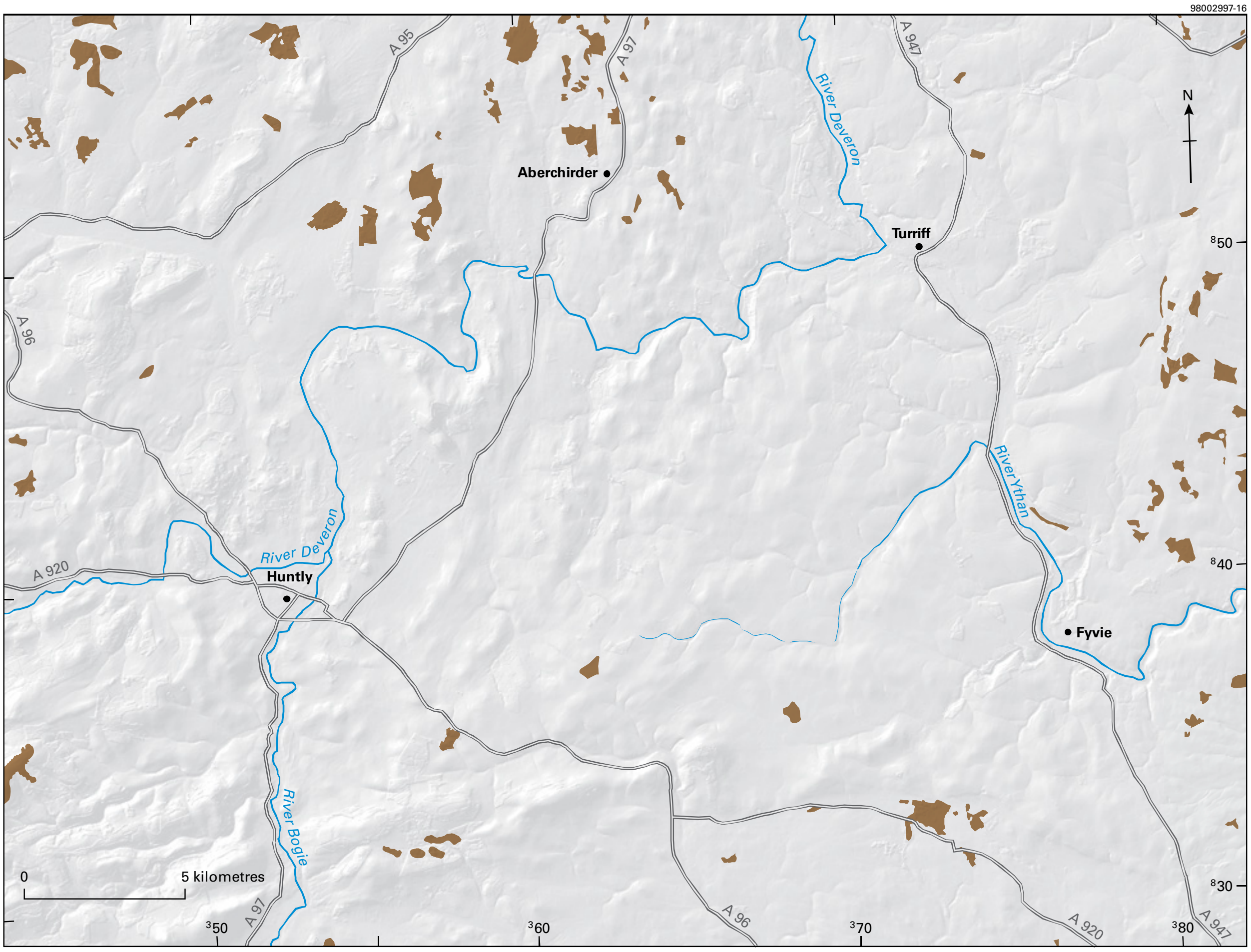

Figure 16 The distribution of significant peat mosses within the Huntly and Turriff districts (after Fraser, 1948).

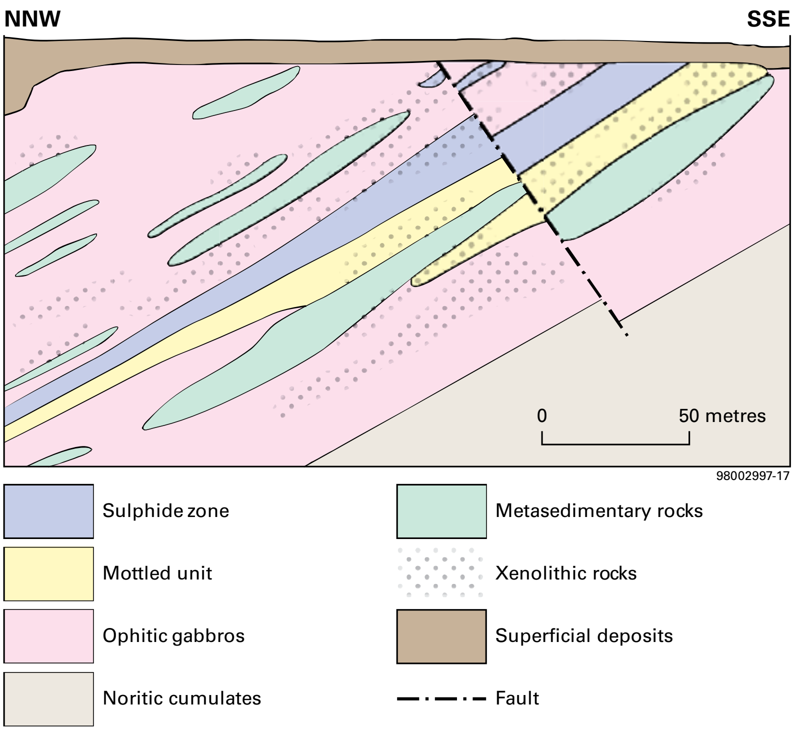

Figure 17 Cross-section through the ore zone at Littlemill, Knock.

PLATES

Plate 1 Complex banding in metagabbroic rocks in the Succoth–Brown Hill pluton (P808816)

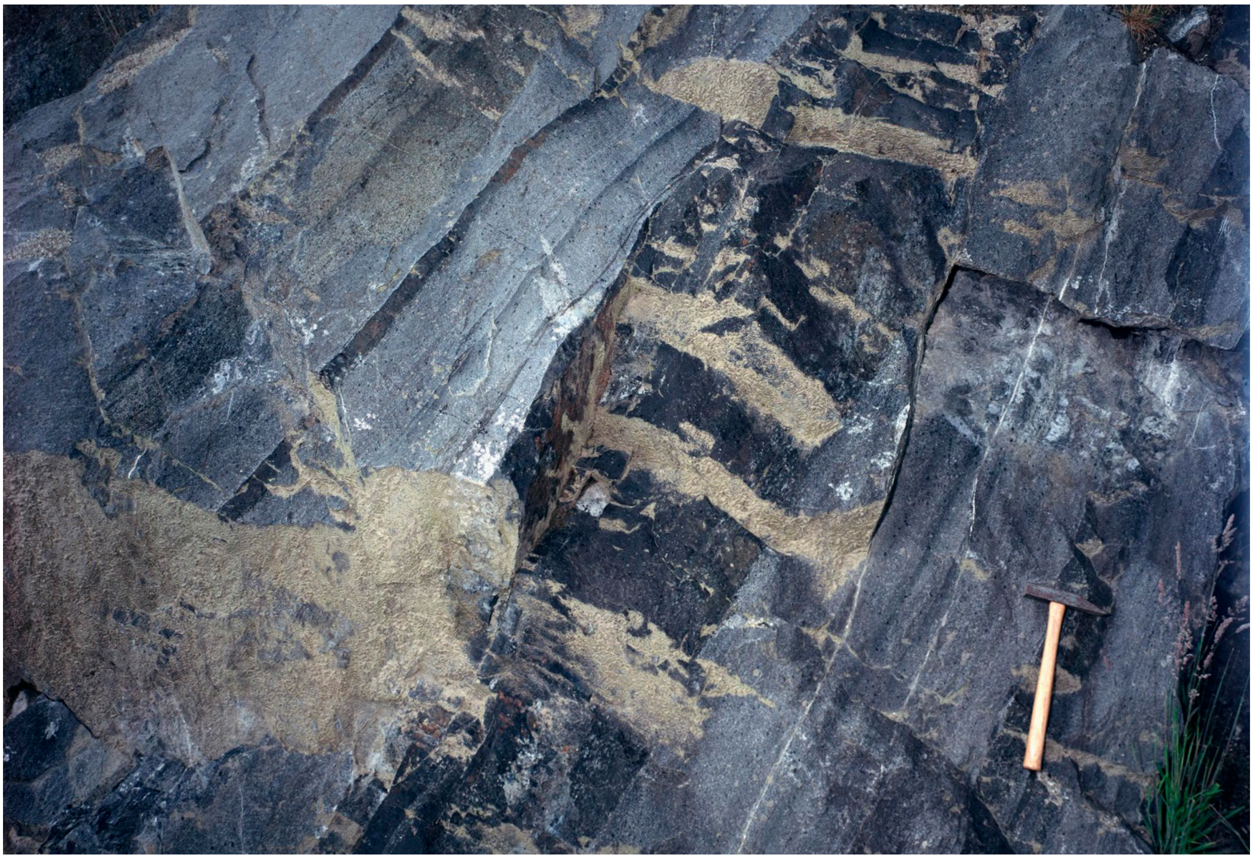

Plate 2 Magmatic layering in olivine-gabbro cumulates, Bin Quarry, Huntly Pluton (P008624)

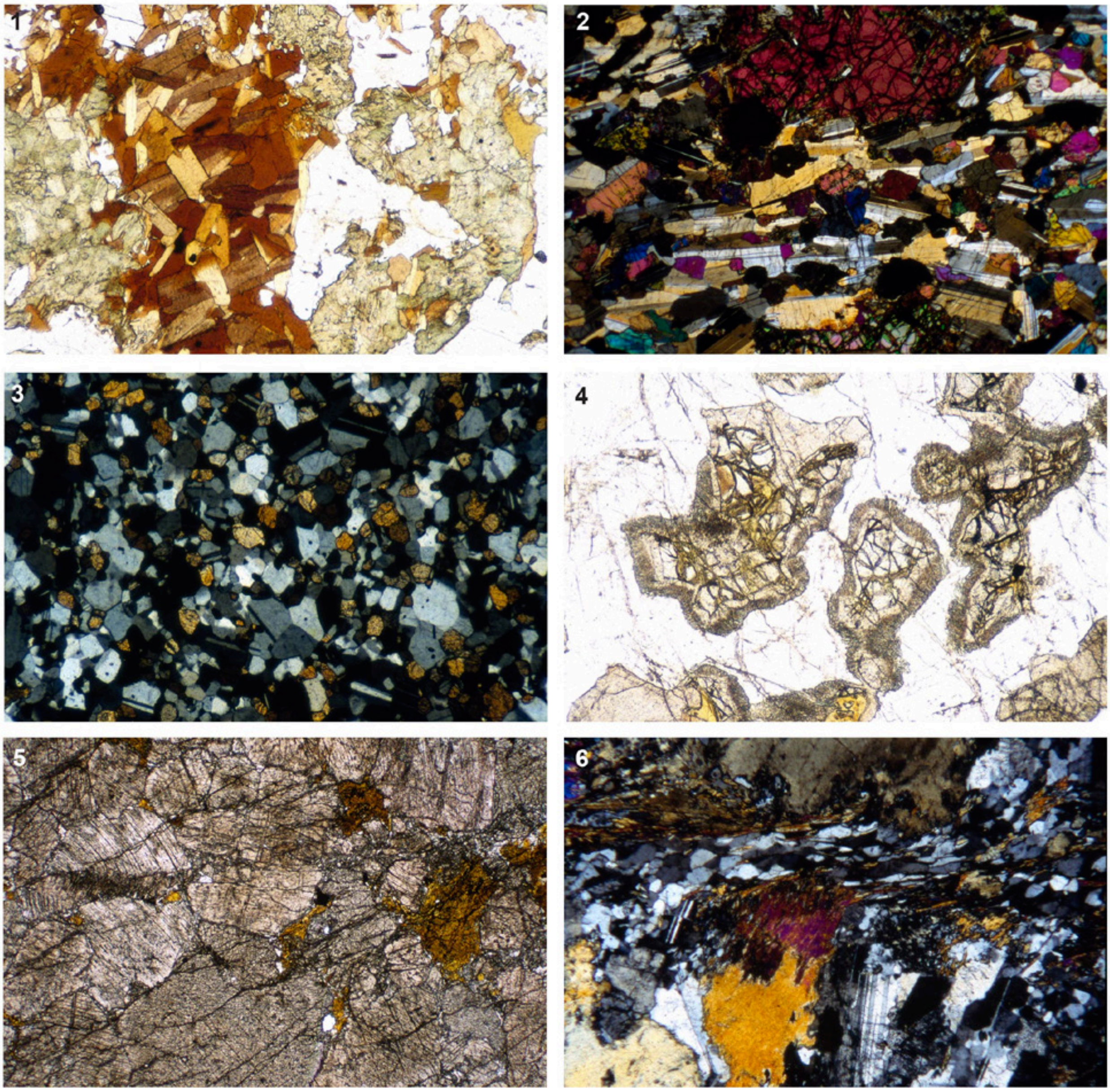

Plate 3 Photomicrographs of rocks from pre- and syntectonic mafic–ultramafic intrusions in the Huntly district.

1. Cumulate, West Huntly (P808811)
2. Glomeroporphyritic olivine-gabbro, west Huntly (P808813)
3. Granular/schistose gabbro, central Huntly (P808812)
4. Contaminated gabbro, central Huntly (P808814)
5. Clinopyroxenite/wehrlite, Succoth–Brown Hill (P808815)
6. Sheared metagabbro, Succoth–Brown Hill (P808810)