Geology of the Edinburgh district

National programme

Open report OR/25/006

BRITISH GEOLOGICAL SURVEY

NATIONAL PROGRAMME
OPEN REPORT OR/25/006

Geology of the Edinburgh district

M A E Browne, D Gould, M C Akhurst, A Monaghan, T Reeves

Contributor/editor

I T Williamson, D Ball, H Johnson, J D Ritchie, C Woodward

Map

Sheet 32E, 1:50 000 scale, Edinburgh (Scotland)

Front cover

Edinburgh Castle (P001266).

Bibliographical reference

Browne, M A E, Gould, D, Akhurst, M C, Monaghan, A, Reeves, T. 2025. Geology of the Edinburgh district. *British Geological Survey Open Report*, OR/25/006. 138pp.

Keyworth, Nottingham British Geological Survey 2025

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from the BGS shop at Nottingham and Cardiff (Welsh publications only). Shop online at https://shop.bgs.ac.uk/

The London Information Office also maintains a reference collection of BGS publications, including fossils, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from the BGS shop.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of UK Research and Innovation.

British Geological Survey offices

Nicker Hill, Keyworth,
Nottingham NG12 5GG
Tel 0115 936 3100

BGS Central Enquiries Desk
Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales
Tel 0115 936 3241
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South,
Edinburgh EH14 4AP
Tel 0131 667 1000
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road,
London SW7 5BD
Tel 020 7589 4090
Tel 020 7942 5344/45
email bgslondonstaff@bgs.ac.uk

Cardiff University, Main Building, Park Place,
Cardiff CF10 3AT
Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford,
Wallingford OX10 8BB
Tel 01491 838800

Geological Survey of Northern Ireland, 7th Floor,
Adelaide House, 39-49 Adelaide Street, Belfast, BT2 8FD
Tel 0289 038 8462
www2.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House,
North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

UK Research and Innovation, Polaris House,
Swindon SN2 1FL
Tel 01793 444000
www.ukri.org

Website: https://www.bgs.ac.uk
Shop online: https://shop.bgs.ac.uk/

Foreword

This Open Report describes the geology of the Edinburgh district and surrounding area, and accompanies the BGS Sheet 32E (Edinburgh) sheets, with a Bedrock edition (2003) and a Bedrock and Superficial Deposits edition (2006). The report was originally intended as a Sheet Description, but this series was discontinued before revisions and editing of the manuscript were complete. Some authors retired from BGS, and the manuscript languished in the bottom drawer for a decade. With the new BGS strategy for Maps and Models for the 21st century (BGS 2023), it was decided that the manuscript still represented a valuable contribution to the knowledge of the geology of Edinburgh district. As a result, although published in 2025, the report represents the state of knowledge and understanding of the geology as reached in the early 2000s, and the reader needs to take into account the vintage of the report.

However, this report has been updated in two aspects. The first concerns the re-interpretation of the Devonian-Carboniferous boundary in the district, and indeed in the Midland Valley as a whole. This boundary was previously thought to occur within the Kinneswood formation, but work in the Scottish Borders (Marshall et al. 2018) has shown that the Devonian-Carboniferous boundary occurs at the boundary between the Kinneswood and Ballagan formations. The relevant strata can be reliably correlated to the Edinburgh district, so the chronostratigraphy of these formations has been updated in this report.

Secondly, changes in society and policy related to the green transition and decarbonisation of energy sources renders part of the Applied Geology section as out-of-date. Sections on fossil fuel sections are to a degree redundant, but have been retained for historic purposes. Comments in bold are added to provide more modern context and to reflect recent policy changes. The section on geothermal energy has been extensively updated by Alison Monaghan to match current interest and directions of research.

Alison Monaghan and Teddy Reeves have tracked revisions and corrections, and have extensively edited the manuscript, so that the outstanding work of the original authors Mike Browne, David Gould, Alison Monaghan and Maxine Akhurst can finally be published.

Maarten Krabbendam, Chief Geologist Scotland, 2025

Contents

FIGURES

PLATES

TABLES

Summary

The Edinburgh district, which lies towards the eastern end of the Midland Valley, incorporates parts of the counties of Fife and the Lothians. This sheet description for Edinburgh updates the account of the geology of the district that was published in 1962. The district includes most of the City of Edinburgh, the eastern half of the Pentland Hills (Pentland Hills Regional Park), almost all of the Midlothian Coalfield from Musselburgh to Penicuik, and the central portion of the Firth of Forth, including Inchkeith. The rocks present in the district record over 440 million years of geological history ranging from the Ordovician through to the most recent man-made deposits. The Devonian and Carboniferous rocks are placed in a recently updated lithostratigraphical framework. The oldest rocks were deposited in an ocean associated with a collision and subduction zone south of the 'Highlands' landmass. Later, in the Siluro-Devonian, rocks were deposited in a semi-arid continental fluviatile environment, into which mainly andesitic lavas erupted in Early Devonian times. These events were followed by regional uplift and erosion. Fluviatile conditions in a semi-arid environment returned in the early Carboniferous, succeeded by a hot tropical fluviodeltaic environment, which prevailed throughout most of the Carboniferous. The cyclical nature of Carboniferous sedimentary successions reflects the dynamic interaction of eustatic sea level changes, climate and tectonism in this environment. On two occasions, volcanism interrupted sedimentation and produced subaerial basaltic lava piles. Numerous small intrusions of Devonian and Carboniferous ages cut the sedimentary formations. Uplift and erosion in the latter part of the Carboniferous was followed by the establishment of an arid continental environment in the Permo-Triassic, but like the marine environments of the succeeding Jurassic and Cretaceous, the rock record in the district has been erased by substantial uplift and erosion since the beginning of the Cenozoic. The final moulding of the landscape occurred during the Quaternary over several glaciations, although most of the preserved deposits relate to the last main Late Devensian glaciation.

Social and economic pressures on present-day environments are continually increasing. In areas of population and industrial/commercial growth such as in the urban and peri-urban areas in and around Edinburgh, the need for a thorough understanding of the local natural resources, geodiversity, ground conditions and hazards is key to achieving sustainable development, maintaining and improving biodiversity, and encouraging lifelong learning. The district includes many classical geological sites, of which the igneous rocks of Arthur's Seat and Salisbury Crags are the most famous with links to James Hutton and the foundation of geology as a science. Of similar importance is Agassiz Rock with its links to the early interpretation of the work of glacial ice in fashioning Scotland's landscape. The district also contains a wide variety of mineral deposits that have been worked over the centuries, especially coal, oil shale and limestone. Building stone, ironstone, mudstone, sand and gravel have also been extracted. Sand and gravel quarrying is still continuing on a reduced scale. The legacy of old surface and underground workings, including subsidence risk, is a major factor in development planning, particularly within the Midlothian Coalfield, which encroaches on the south-eastern part of the City of Edinburgh. Within the rest of the City, the chief mineral workings are the large disused sandstone quarries, which produced famous sandstones for building such as Craigleith and Hailes. These have mostly been backfilled. The moderately hard groundwaters in parts of the city were of importance in the development of a large brewing industry. The Water of Leith and the North and South Esk rivers have been important in the development of mills of many kinds, in particular for papermaking.

Table 1 Superficial geological succession in the Edinburgh district BGS © UKRI

SUPERFICIAL DEPOSITS (DRIFT)
Quaternary
Holocene (11 500 years ago to present)
- Fluvial sand and gravel, including present-day river alluvium
- Lacustrine clay, silt and sand, including present-day lake deposits
- Peat, mostly basin peat with a little hill peat
- Marine and littoral sand and gravel, including post-glacial raised marine deposits and present day beach deposits

Devensian
Younger Dryas / Loch Lomond Stadial (12 900 to 11 700 years ago)
- Limited minerogenic deposits

Windermere Interstadial (14 700 to 12 900 years ago)
- Marine, littoral and deltaic sand, gravel, clay and silt
- Lacustrine and fluvial sand, gravel, clay and silt
- Glacioifluvial (ice-contact and terraced spreads) sand and gravel

Dimlington Stadial (30 000 to 14 700 years ago)
- Glacial till

Table 2 Bedrock geological succession in the Edinburgh district BGS © UKRI

SOLID ROCKS	Generalized thickness (m)
Carboniferous	
Pennsylvanian	
WESTPHALIAN	
Scottish Coal Measures Group	
Scottish Upper Coal Measures Formation: Sandstone, siltstone, mudstone and a few thin coal seams, mostly reddened	240
Scottish Middle Coal Measures Formation: Sandstone, siltstone, mudstone, ironstone, coal and seatearth	300
Scottish Lower Coal Measures Formation: Sandstone, siltstone, mudstone, ironstone, coal and seatearth	220
Mississippian – Pennsylvanian	
NAMURIAN	
Clackmannan Group	
Passage Formation: Mainly sandstone and seatearth, with thin coal seams	340
Upper Limestone Formation: Sandstone, siltstone, mudstone, marine limestone, coal and seatearth	320
Limestone Coal Formation: Sandstone, siltstone, mudstone, ironstone, coal and seatearth	410
Mississippian	
VISEAN	
Clackmannan Group	
Lower Limestone Formation: Sandstone, siltstone, mudstone, marine limestone, few thin coal seams	230
Bathgate Group *(Inchkeith and Firth of Forth)*	
Kinghorn Volcanic Formation: Basaltic lava flows	450
Strathclyde Group *(Lothians)*	
West Lothian Oil-shale Formation *(west of Midlothian Syncline)*	
Hopetoun Member: Sandstone, siltstone, mudstone, oil-shale, thin coal and limestone	410
Calders Member: Sandstone, siltstone, mudstone and oil-shale	380
Aberlady Formation *(east of Midlothian syncline)*: Mudstone, siltstone, few thin ironstone beds and limestone	>500
Gullane Formation: Sandstone, siltstone and mudstone, few thin coals	780
Arthur's Seat Volcanic Formation: Basaltic lava flows and volcaniclastic rocks	350
Strathclyde Group *(Firth of Forth)*	
Pathhead Formation: Sandstones, siltstones, mudstones, marine limestones, few thin coal seams and seatearths	110
Sandy Craig Formation: Sandstone, siltstone, mudstone, non-marine limestone, few thin coal seams	480
Pittenweem Formation: Siltstone, mudstone, sandstone, marine limestone, few thin ironstones and coals	250
Anstruther Formation: Siltstone, mudstone, sandstone, marine limestone, few thin ironstones and coals	400
Charles Hill Volcanic Member: Basaltic lavas and volcaniclastic rocks	40
Fife Ness Formation: Sandstone, siltstone, mudstone, non-marine limestone and seatearths	>20
TOURNAISIAN	
Inverclyde Group	
Ballagan Formation: Mudstone, siltstone, sandstone and thin dolostones (cementstones) and limestones	760
Devonian and Silurian	
LATE DEVONIAN	
Inverclyde Group	
Kinnesswood Formation: Sandstone and concretionary limestone and dolostone	310
EARLY DEVONIAN AND LATE SILURIAN	
Lanark Group	
Pentland Hills Volcanic Formation	2980
Greywacke Conglomerate Formation	60
WENLOCK	
North Esk Group	
Reservoir Formation: Grey-green and grey mudstone with thin siltstone interbeds	150
Ordovician	
CARADOC – ASHGILL	
Scaur Group	
Portpatrick Formation: Thick-bedded, coarse-grained pyroxenous wacke with laminated siltstone	1200
CARADOC	
Tappins Group	
March Burn Formation: Wackes, coarse-grained to conglomeratic, laminated siltstone and fine-grained sandstone	1100

1 Introduction

The Edinburgh district contains a selection of widely contrasting landscapes, ranging from the upland crags and moorlands of the Pentland Hills to the distinctive cityscape of Edinburgh and fertile agricultural lowlands. The underlying geology is responsible for the major landscape features, and the associated mineral deposits have been important in determining patterns of human settlement. In the extreme south of the district, the Ordovician wackes of the Southern Uplands form high barren ground (Kingside Edge [NT 243 556], 316 m OD; Ruther Law [NT 371 556], 383 m OD), while up-faulted Siluro-Devonian volcanic rocks form the Pentland Hills (Scald Law [NT 192 611], 579 m OD). Rough hills in the lower ground along the southern slope of the Firth of Forth, such as Arthur’s Seat [NT 275 730] (251 m OD), are the result of extrusive and intrusive igneous rocks of Carboniferous age. The courses of the main rivers, the Water of Leith, the North Esk and the South Esk, have been affected by overdeepening of valleys and incision of rocky gorges by glacial meltwater at the end of the Late Devensian glaciation. A broad platform covered by raised marine deposits of Late Devensian age is developed in northern Edinburgh, and reflects uplift of the land following melting of the thick ice sheets.

1.1 HISTORY OF RESEARCH AND RESURVEY

As the residence of James Hutton, the ‘Father of Geology’, during his most productive years, Edinburgh has a long association with geological research. On Salisbury Crags he demonstrated the nature of an intrusive contact (Hutton, 1795). James Hall (1805) conducted experiments on melting of basaltic rocks and Charles Maclaren (1839) wrote the first comprehensive description of the geology of the Lothians and Fife.

The Edinburgh district, covered by Sheet 32E of the geological map of Scotland, was originally surveyed by A Geikie and H H Howell between 1856 and 1857. The first edition of the Edinburgh Sheet (32, including the Edinburgh and Livingston districts) was published in 1859 at a scale of 1:63 360 with a descriptive memoir (Howell and Geikie, 1861). A revised map appeared in 1892. A more detailed survey resulted in a third edition of the map in 1910 and a second edition of the memoir (Peach et al., 1910). Some of this work also appeared in Geikie (1897). Carruthers et al. (1927) described the oil-shale deposits of the Lothians. The revised 4th edition of the map was published in 1965 (Solid) and 1967 (Drift), based on resurvey by J G S Anderson, J K Allan, J R Earp, J Knox, W Mykura, J E Richey, T Robertson, J B Simpson, W Tulloch, H S Walton and H E Wilson between 1938 and 1960. The results of this work are contained in the third edition of the memoir (Mitchell and Mykura, 1962) together with a coalfield memoir (Tulloch and Walton, 1958). A special 1:25 000 scale map of the City of Edinburgh was published in 1971. A 5th edition of the bedrock geology map was published at 1:50 000 scale without revision in 1977.

The latest editions of the bedrock map (BGS, 2003) and bedrock and superficial deposits map (BGS, 2006) are based on the following work: J I Chisholm and A D McAdam undertook the partial revision of the bedrock geology in the southern part of the City of Edinburgh from 1979 to 1985; H F Barron and D Gould resurveyed the Pentland Hills from 1994 to 1998; D H Land resurveyed the geology of Holyrood Park from 1994 to 1996, and P M Halpin revised the bedrock geology of the Prestonpans area from additional mining data in 1999. The bedrock geology of north-west Edinburgh was revised in 1999 in the light of P J Brand’s reinterpretation of the stratigraphy of the Gullane Formation. A D McAdam and D Gould resurveyed the superficial geology of the district from 1989 to 1999.

Work by Floyd (2001) on the modern stratigraphical framework of the Ordovician rocks was augmented by discussion of their structural setting (Smith et al., 2000) and provenance (Phillips et al., 2003) of the Southern Uplands. Barron (1998) summarised recent work on the Silurian rocks of the Loganlee Inlier.

The modern lithostratigraphical framework for the late Silurian to Early Devonian rocks (Lower Old Red Sandstone) was set out by Browne et al. (2002). After resurvey in the 1950s, Mykura (1960) published an account of the volcanic rocks of the Pentland Hills, updating the 1910 memoir. The Pentland Hills Volcanic Formation was not specifically included in the Caledonian Igneous Rocks GCR volume (Stephenson et al., 1999), as the Ochil Hills farther north-west were considered more nationally representative of this phase of late Silurian to Early Devonian volcanism.

Browne et al. (1999) established the modern lithostratigraphical framework for the Carboniferous rocks of the Midland Valley of Scotland. Chisholm and Brand (1994) have re-interpreted the lithostratigraphy of the Gullane and West Lothian Oil-shale formations in north-west Edinburgh. Briggs and Clarkson (1983) have described the arthropod fauna of the Granton Shrimp Bed, while Wood (1975) described the fossil fishes of the Wardie Shales. Marshall et al. (2018), working further east, revised the chronostratigraphy of the Devonian-Carboniferous boundary.

Clark (1956) and Black (1966) studied in detail the volcanic rocks of Arthur’s Seat, with more recent detailed petrological work summarised by Upton (2003). The Arthur’s Seat volcano has been included in the Carboniferous and Permian Igneous Rocks GCR (Upton, 2003). Joppa Shore is included in both the Upper Carboniferous (Cleal and Thomas, 1996) and Lower Carboniferous GCR volumes (Cossey et al., 2004) and Bilston Burn in the latter. Wardie Shore is a palaeobotanical GCR site (Cleal and Thomas, 1995).

The Lothians was a key area in Scotland for the elaboration of many of the concepts related to the recognition of ice-sheet glaciations and glacial sediments and landforms (Gordon and Sutherland, 1993). In particular, the earliest interpretations of glacial striae were made at Agassiz Rock [NT 254 702] near Blackford Hill, Edinburgh (Agassiz, 1841). Concepts of multiple glaciations were also advanced in the area although current thinking now assigns all known glacial sedimentary deposits (tills and meltwater deposits) to the advance and retreat of the last (Late Devensian) ice sheet. Multiple till sequences have been identified in the Edinburgh district that in part reflect the influence of two ice streams in the area. The main influence was ice advancing across the area from the west along the Forth valley and sourced in the southwest Highlands. The second was ice advancing generally north-eastwards from the Southern Uplands.

Kirby (1968) and Aitken et al. (1984) identified a basal till containing a characteristic, but minor proportion of, Highland erratic clast assemblage. An overlying till containing clasts of wacke and other rocks of Southern Uplands origin indicates subsequent expansion of ice from the south to the district except at the coastal fringe. The retreat phase of the Late Devensian resulted in deposition of glaciofluvial deposits and the cutting of meltwater channels formed as the Southern Uplands ice retreated south-westwards (Kirby, 1969c). A third till unit, the Roslin Till (Kirby, 1968; 1969c) was laid down on top of the outwash deposits south of Edinburgh City that has a Highlands erratic suite. Martin (1981) preferred to interpret this till as a debris flow deposit thus removing the need for Highlands-sourced ice to advance over the outwash deposits.

When glacial ice finally cleared from the district about 14 000 years ago, raised marine and raised beach deposits were laid down in the Edinburgh area. These are now at more than 35 m OD, whilst those formed at the Holocene maximum sea level (6000 years ago) transgression are now at 5–8 m OD. Ice-eroded hollows inland were occupied by lakes such as Corstorphine and Duddingston lochs. Although the arctic period of the Loch Lomond Stadial is not represented by glacial deposits, alluvial fan sediments are known from Corstorphine Loch (Bennie, 1894) and solifluction deposits occur in the former Holyrood Loch (Sissons, 1971).

The lengthy mining history of the district has been recorded in a wealth of mine plans and borehole logs. Memoirs on the Midlothian Coalfield (Tulloch and Walton, 1958), the oil shales of the Lothians (Carruthers et al., 1927), and the Limestones of Scotland (Robertson et al., 1949) have summarised much of the information available up to the 1950s.

The sand and gravel resources of the southern half of the district (the Esk valley and adjacent areas) were resurveyed and evaluated by J D Floyd, P M Halpin and J Smellie from 1982 to 1984 and resource maps were published at 1:25 000 scale by Aitken et al. (1984). Hard rock aggregate (Merritt et al., 1984), limestone (Robertson et al., 1949; MacPherson, 1986a), fireclay (Merritt, 1985), clay and mudstone for brickmaking (Elliot, 1985), special sand resources (Ridgway, 1982; MacPherson, 1986b), and dimension stone (McMillan et al., 1999) are not currently exploited in the district. The geothermal prospectivity of the Carboniferous and Late Devonian rocks of the Lothians was reported by Browne et al. (1985) but a more interesting recent development is the proposed use of ground source heat pumps at the former Monktonhall Colliery [NT 318 692] (Shawfair Village). The hydrogeology of the district was briefly described by Robins (1990), with particular reference to the use of groundwater for the now largely defunct Edinburgh brewing industry.

Numerous sites in the district have been declared Geological Conservation Review (GCR) sites and are described in the relevant volumes: Carboniferous and Permian Igneous Rocks GCR (Stephenson et al., 2003); Upper Carboniferous (Cleal and Thomas, 1996) and Lower Carboniferous GCR volumes (Cossey et al., 2004); and Quaternary in Scotland (Gordon and Sutherland, 1993). Other sites have been declared as Local Geodiversity Sites (formerly Regionally Important Geological and Geomorphological Sites, RIGS) including Craigleith Quarry, Torphin Quarry, Hermitage of Braid and Blackford Hill, Craigmillar Castle and The Pinnacle in the Pentlands.

The Edinburgh Geological Society's Excursion Guide (McAdam and Clarkson, 1986; 1996) contains descriptions of many geological localities in the district.

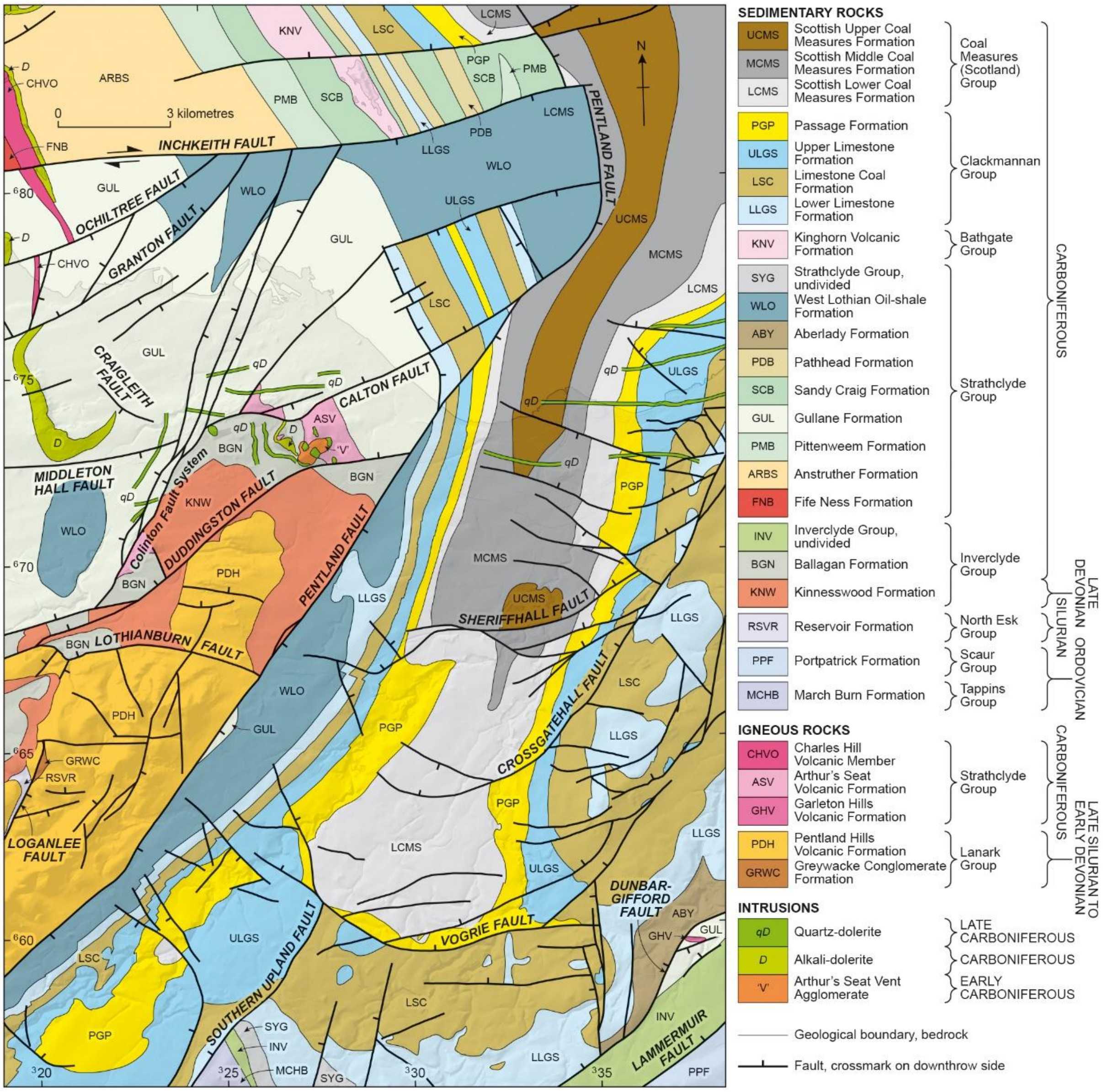


Figure 1 Bedrock map of the Edinburgh district. Contains NEXTMap Britain elevation data from Intermap Technologies^{TM}. BGS © UKRI

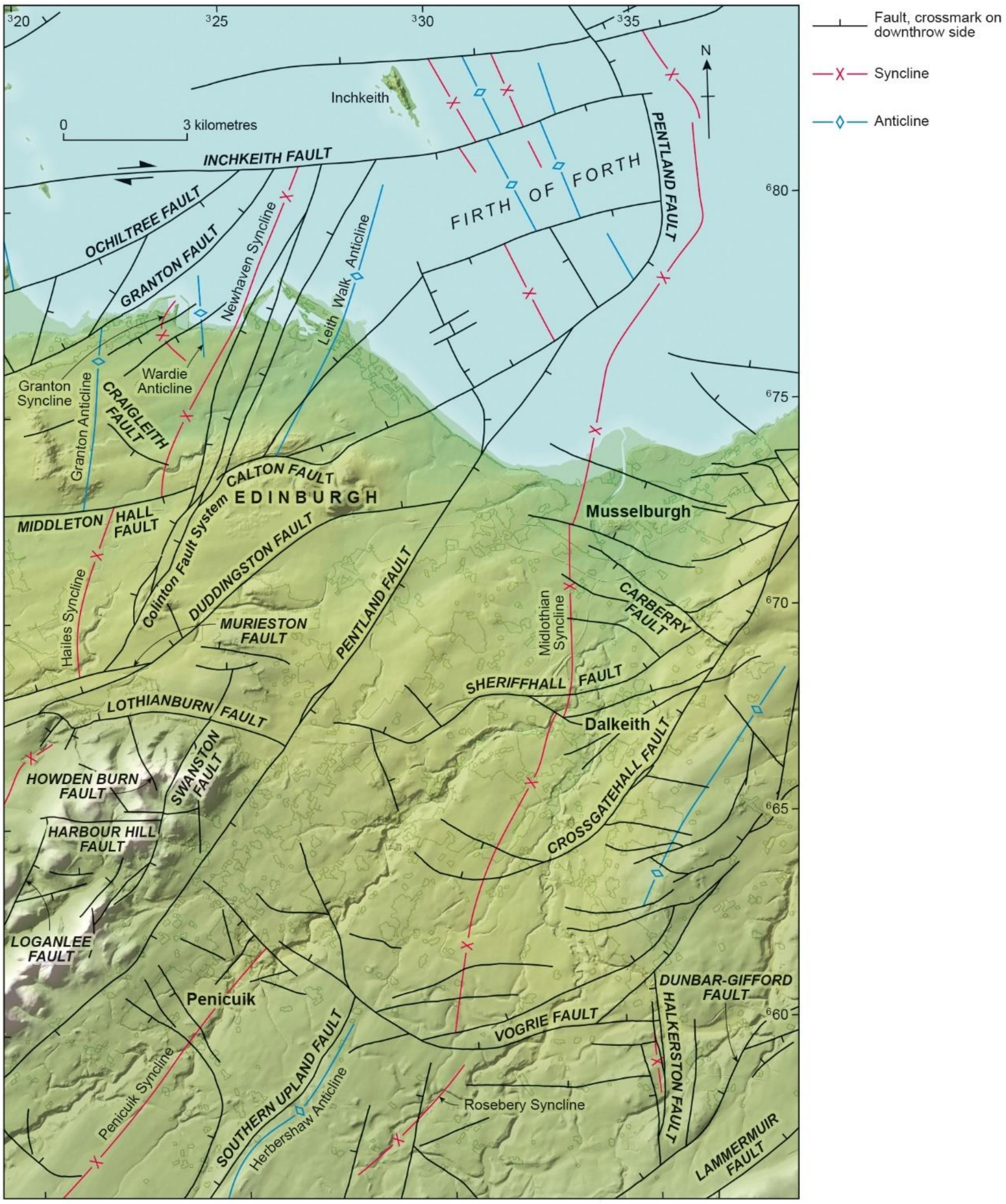


Figure 2 Main structural features of the Edinburgh district. Contains NEXTMap Britain elevation data from Intermap Technologies^{TM}. BGS © UKRI

1.2 GEOLOGICAL HISTORY OF THE EDINBURGH DISTRICT

The Edinburgh district lies predominantly within the Midland Valley of Scotland, a geological terrane consisting of a complex graben of north-east trend that contains several Siluro-Devonian and Carboniferous sedimentary basins and sub-basins (Figure 1; Chapter 7). The *en echelon* Southern Upland and Lammermuir faults (Figure 2) form the southern boundary of the Midland Valley in the district. Within the Midland Valley, the Pentland Fault, also north-east-trending, separates the upthrown block of the Pentland Hills from the downthrown basin of the Midlothian Coalfield. The Colinton Fault System and its splays to the north-west of the Pentland Hills form a major zone of disturbance. The displacements across these structures decrease northwards, and they are crosscut by a number of faults of westward trend, which formed conduits for the emplacement of quartz-dolerite dykes in Stephanian times. The axes of the principal folds in the Devonian and Carboniferous strata are orientated with NNE trend, with the steepest values of dip recorded immediately east of the Pentland and Colinton faults. A simplified bedrock geological map of the Edinburgh district is shown in Figure 1, the main structural features in Figure 2 and the geological succession is shown in Table 2.

The earliest recognised event is the deposition of turbiditic wackes of the Marchburn Formation (Tappins Group) at the accretionary margin on the northern side of the Iapetus Ocean in Late Ordovician (Caradoc) times. Sequences of these marine sedimentary rocks, including the wackes of the slightly younger Portpatrick Formation (Caradoc–Ashgill) are part of the Southern Uplands Terrane, but only small parts of the succession are exposed in the Edinburgh district. Shortly after deposition, these rocks were steeply tilted and stacked in fault-bounded blocks.

North of the Southern Upland Fault, early Silurian marine siltstones of the Reservoir Formation (Llandovery) are preserved in the Loganlee Inlier in the Pentland Hills.

Younger rocks of various ages unconformably overlie the Ordovician and Silurian rocks. In the Pentland Hills, these mainly belong to the late Silurian to Early Devonian Lanark Group, previously known as part of the Lower Old Red Sandstone. The Lanark Group in the Edinburgh district is dominated by the Pentland Hills Volcanic Formation, with minor interbeds of the Greywacke Conglomerate Formation.

The Pentland Hills Volcanic Formation is the local expression of the extensive calc-alkaline magmatism in Scotland that followed the final closure of the Iapetus Ocean (Thirlwall, 1981). Intermittent eruption of calc-alkaline magma interspersed with deposition of sandstone and conglomerate red beds was interrupted by periods of tilting and erosion, with several intraformational unconformities. The volcanic rocks are mostly olivine basalts and pyroxene andesites, but trachytes, dacites, rhyolites and volcaniclastic rocks also occur.

Folding and uplift during Mid Devonian times (Acadian Orogeny) was followed by erosion in later Devonian times. As a result no Mid Devonian and few late Devonian rocks occur in the district. The late Devonian Kinneswood Formation (Inverclyde Group) thus rests unconformably upon rocks of the Lanark Group.

During deposition of the Inverclyde Group sedimentary rocks, the environments of deposition gradually changed from fluviatile (Kinnesswood Formation; Late Devonian) to coastal alluvial and marginal marine/lagoonal (Ballagan Formation; Tournaisian; Early Carboniferous). The intermittent aridity of the environment is shown by the development of pedogenic calcrete horizons (formerly known as cornstones) within the Kinnesswood Formation, and additionally with ferroan dolostones (cementstones) within the Ballagan Formation.

The Strathclyde Group (Visean) sedimentary rocks were deposited in fluviatile, deltaic, lacustrine and sometimes marine conditions, with cyclical patterns of sedimentation becoming widely established. Browne et al. (2003) suggests that the change of sedimentation of the Inverclyde and Strathclyde groups, marked by an intra-Carboniferous unconformity in the Midland Valley, broadly coincides with a change in tectonic setting from extensional rifting to dextral strike/oblique-slip. This latter regime produced NNE-trending growth synclines such as the Midlothian–Leven Syncline. This regime persisted until Westphalian times. Thick sandstone beds are developed locally in the Gullane Formation, while oil-shale beds, recording algal-rich, eutrophic lacustrine conditions, occur in the West Lothian Oil-Shale Formation. Sandstone and oil shale are much less common in the Aberlady Formation, the equivalent unit south-east of the Midlothian Coalfield. A local volcanic centre was active in the Edinburgh area in earliest Strathclyde Group times. Several vents, of which Lion's Head, Lion's Haunch and Edinburgh Castle Rock were the most important, erupted transitional to mildly alkaline basalt lavas and tuffs of the Arthur's Seat Volcanic Formation; several types can be identified on phenocryst content. At about the same time, eruptive activity in west Fife produced the Charles Hill Volcanic Member, whose deposits extend southwards under the Firth of Forth to the Edinburgh coast at Silverknowes. An eruptive centre developed in the Burntisland area of Fife contemporaneous with the upper part of the West Lothian Oil-shale Formation. Alkali basalt lavas and tuffs of the Kinghorn Volcanic Formation crop out on Inchkeith and are inferred to extend about halfway across the Firth of Forth. The Strathclyde Group rocks north of the Inchkeith Fault are referred to formations defined onshore in Fife (Table 2).

The overlying Clackmannan Group sedimentary rocks were laid down in latest Visean and Namurian times. The cyclical pattern of sedimentation continued, but the relative proportions of marine and deltaic sediment varied during the period. The Lower Limestone Formation contains several marine limestone units, which have faunas that enable correlation across the Midland Valley. Thick limestone developments are particularly common in the south-eastern part of the Midlothian Coalfield, where the Blackhall Limestone (previously known locally as the North Greens Limestone) reaches 20 m in thickness. In the Limestone Coal Formation limestone beds are rare to absent, but many of the cyclothems culminate in coal seams indicating an increased frequency of deltaic conditions. The Upper Limestone Formation resembles the Lower Limestone Formation, but the limestone beds are thinner, though very persistent. Local uplift and erosion has removed the upper part of this formation (above the Calmy Limestone) in the southern half of the Midlothian Basin. The overlying Passage Formation consists largely of fluviatile sandstone with some siltstone and rare coals, indicating a decreasing influence of coastal conditions during this period although marine incursions were still a feature.

A number of alkali dolerite sills were intruded into Strathclyde Group and earlier rocks. They may be coeval with the Visean Kinghorn Volcanic Formation or with the Namurian Passage Formation lavas present in the western Midland Valley.

During Westphalian times, the Coal Measures were deposited. They are cyclothemic deposits dominated by sandstone and siltstone with seatearths and coal seams. Marine deposits are confined to six mudstone beds, two with distinctive faunas; the Vanderbeckei (or Queenslie), and Aegiranum (or Skipsey's) marine bands. These two horizons are recognised throughout the Midland Valley and are used to divide the Coal Measures into Lower, Middle and Upper Coal Measures formations.

The onset of Variscan compression in later Carboniferous times is shown by tightening of NNE trending folds folding axes and displacement along NNE to NE trending faults; further north this led to dextral reactivation of major Caledonides strike slip faults bounding the Midland Valley. The major Midlothian and Leven synclines were accentuated by the formation of rising anticlines such as the Burntisland Arch and Cousland–D'Arcy Anticline as part of a series of major fold structures spanning the Forth valley and Firth of Forth (Browne et al., 2003; Underhill et al., 2008). Initially, the Variscan compression also produced intraformational unconformities in the Upper Coal Measures offshore before terminating Carboniferous sedimentation in Bolsovian (Westphalian C) times. The Pentland and Colinton fault systems further developed at this time. Continuing compression tilted the rocks on the western limb of the Midlothian Syncline so that they are vertical or even overturned. The Pentland Fault that earlier in the Carboniferous functioned as a normal fault reactivated as a reverse fault.

The Variscan contractional phase was followed by a extensional phase, during which east to west-trending fractures were created and tholeiitic basalt magma was intruded, forming quartz-dolerite dykes. The magmatically related Midland Valley Sill-complex is exposed to the west and north of the district, and it may underlie the north-western third of the Edinburgh sheet. Intrusion is dated to about 307 million years (Monaghan and Parrish, 2006).

There is no evidence for the deposition of Stephanian, Permian or Mesozoic sedimentary rocks in the district. Reddening of the Upper Coal Measures may indicate a period of uplift and exposure. There is no conclusive evidence of Permian igneous activity in the district. Any deposits of Permian to Cretaceous age which may have been deposited have since been eroded. Uplift of Scotland prior to the opening of the North Atlantic during the Mesozoic Era culminated in the Paleocene Epoch, and the district was part of a landmass sloping from west to east throughout the Palaeogene Period (Underhill et al., 2008).

During the Pleistocene Epoch (2.4 to 0.01 Ma), Scotland was subjected to a series of glaciations separated by interglacials. During the Main Late Devensian glaciation (Dimlington Stadial) about 30 000 to 14 700 years ago, glacial ice 0.5–2 km thick is believed to have covered the Edinburgh district. Extensive spreads of glacial till were deposited by the ice sheet and during ice decay some of this was reworked by meltwaters to produce glaciofluvial deposits. Areas of hummocky morainic drift represent locations where stagnant ice decayed in situ. Meltwaters were released, commonly suddenly when an ice or gravel barrier was breached, and the high flow rates caused the erosion of several narrow, deep meltwater channels, such as Colinton Dell and the Hermitage of Braid, into which the postglacial rivers have been diverted. The superficial geological succession is shown in Table 1.

Large flat basins such as Corstorphine Loch represent hollows scoured out by ice streams diverted around nearby upstanding masses of hard igneous rock and later infilled by glaciofluvial and postglacial deposits (Cadell 1893).

Immediately after deglaciation the land surface remained isostatically depressed due to the weight of ice that had just been removed, and as a result sea level was about 40 m above present OD in the Edinburgh district. Marine deposits, including glaciomarine mud and beach and deltaic sand and gravel, covered the coastal area for 0.5–2 km inland, and infilled some over-deepened river valleys (e.g. the buried channel of the Water of Leith at Inverleith). During the renewed arctic period of the Loch Lomond (Younger Dryas) Stadial sea level fell to below that of the present day, whilst during the early Holocene, sea level rose to stand at approximately 8 m above OD. A rock platform with thin, raised littoral deposits is developed intermittently at this level, e.g. between Granton and Newhaven.

2 Ordovician and early Silurian

Ordovician rocks crop out in two separate areas on the southern edge of the Edinburgh district (Figure 1). Both areas are part of the Southern Uplands Terrane, formed within an accretionary prism margin setting that developed during the closure of the Iapetus Ocean in Late Ordovician to early Silurian times (Stone, 1995; Phillips et al., 2003). Early Palaeozoic rocks within the Edinburgh district comprise parts of the Ordovician Tappins and Scaur groups. Within the Midland Valley Terrane, the Silurian is represented by the outcrop of the North Esk Group in the Loganlee Inlier in the Pentland Hills (Figure 1).

2.1 TAPPINS GROUP

2.1.1 Marchburn Formation

A small area east and NE of Leadburn Station [NT 250 565] is underlain by rocks of the Marchburn Formation of the Tappins Group (Floyd, 1996) of Caradoc age. The formation's outcrop is bounded to the NW by the Southern Upland (Leadburn) Fault, and to the NE by an unconformable boundary with strata of the Inverclyde Group. It comprises the oldest wacke sandstone formation within the Southern Uplands Terrane and is considered to have formed a basement high because the overlying Inverclyde Group sedimentary rocks are unusually thin. One exposure, now covered over, was recorded on the ridge 1.3 km ENE of the disused Leadburn Station [NT 246 559]. In the district, the Marchburn Formation rocks are wackes with conglomeratic layers (known colloquially as 'Haggis Rock') and are interpreted to be turbiditic deposits. For further details see description of the Peebles district (Hughes and Boland, 1995).

2.2 SCAUR GROUP

2.2.1 Portpatrick Formation

Thick-bedded, coarse-grained pyroxenous wackes of the Portpatrick Formation (Caradoc to Ashgill) of the Scaur Group (Floyd, 1996) crop out in the extreme SE corner of the district, SE of the Lammermuir Fault [NT 380 560].

Only two exposures of Portpatrick Formation rocks occur in the Edinburgh district: beside the B7007 road [NT 362 557], and at the edge of a disused and partly infilled quarry near Falahill [NT 382 560]. However, numerous exposures of the same rocks occur along the A7 road in the Haddington and Galashiels districts.

2.3 NORTH ESK GROUP

2.3.1 Reservoir Formation

Strata of the North Esk Group (Llandovery–Wenlock) occur at the western margin of the Edinburgh district, and are part of a well-known sequence in the Silurian succession forming the Pentland Hills Inlier (Tipper, 1976; Robertson, 1989; Clarkson et al., 2000). Rocks of Llandovery age belonging to the Reservoir Formation (Tipper, 1976; Robertson, 1989; Bull and Loydell, 1995) crop out in a narrow strip, forming the eastern part of the Loganlee Inlier, extending within the district from north of Loganlee Reservoir [NT 192 628] to Green Cleugh [NT 197 644]. The inlier is bounded on the west by the Black Hill Felsite, and on the east it is faulted against rocks of the Pentland Hills Volcanic Formation. The strata are steeply inclined and the strike is approximately NNE.

The best exposures are on the SE slope of Black Hill [NT 187 619], where steeply dipping to vertical green-grey and purple mudstones, buff to greenish grey siltstone and rare fine-grained sandstone beds young to the WNW (Robertson, 1985, 1989). Load and flute casts show that depositional currents flowed to the east-southeast (Mykura and Smith, 1962).

Robertson (1989) considered the Reservoir Formation to be part of a turbidite sequence deposited in an offshore, deep water submarine canyon complex. However, Bull and Loydell (1995) reinterpreted the depositional setting of the formation as a shelf environment influenced by storm processes. Study of acritarch assemblages from the formation (Molyneux et al., 2008), including the Loganlee Inlier, supports the shallow water interpretation of Bull and Loydell (1995).

Sparse, poorly preserved graptolites have been recorded from the Loganlee Inlier (Mykura and Smith, 1962). A detailed study of graptolites of the North Esk Group by Bull and Loydell (1995) was undertaken on material collected mostly from the Reservoir Formation. Graptolites from this formation were assigned to the *spiralis* Biozone and demonstrate deposition during late Llandovery times (Bull and Loydell, 1995). Samples from the Logan Burn [NT 1886 6199] have yielded low diversity acritarch and spore assemblages similar to those in the lower part of the Reservoir Formation in the North Esk Inlier (Barron, 1998; Molyneux et al., 2008). This correlation places the rocks of the Loganlee Inlier in the late Llandovery (Telychian), rather than the Wenlock, as also noted by the graptolite study (Bull and Loydell, 1995).

3 Late Silurian to Early Devonian

Latest Silurian and Devonian sedimentary and volcanic rocks, previously referred to as the Old Red Sandstone (ORS), were deposited over the Midland Valley of Scotland as a terrestrial sequence at the margin of the Caledonian mountain belt, in a terrane accretion setting within a strike-slip regime (Phillips et al., 1997). The Siluro-Devonian was also a period of volcanism; sequences of basaltic, andesitic and trachytic lavas occur across Scotland (Thirlwall, 1988; Stephenson, 1999, Trewin and Thirlwall, 2002) and occur in the Edinburgh district as the Pentland Hills Volcanic Formation. The southern margin of the Midland Valley is faulted, but a few outliers show that at least the upper part of the Siluro-Devonian sedimentary sequence transgressed on to rocks of the Southern Uplands Terrane. The succession on the southern margin of the Midland Valley constitutes the Lanark Group (Browne et al., 2002). The exposures of Lanark Group rocks in the Edinburgh district occur in an up-faulted block bounded on its south-eastern margin by the Pentland Fault, and include the Greywacke Conglomerate and Pentland Hills Volcanic formations (Figures 1 and 3).

3.1 LANARK GROUP

3.1.1 Greywacke Conglomerate Formation

Rocks of the Greywacke Conglomerate Formation occur in a faulted inlier on the western slopes of Harbour Hill [NT 202 645]. The outcrop lies between rocks of the Pentland Hills Volcanic Formation; the Bonaly Member to the west and the Bell’s Hill Member to the east. Farther to the south-west the Greywacke Conglomerate Formation is in contact with rocks of the Reservoir Formation (early Silurian). The evidence suggests that the outcrop of the Greywacke Conglomerate Formation in the Edinburgh district is an interdigitation between the Bonaly and Bell’s Hill members. This is consistent with the absence of the lower members of the volcanic formation in the Livingston district to the west, where the Greywacke Conglomerate and overlying Swanshaw formations intervene between the North Esk Group and Pentland Hills Volcanic Formation.

The Formation comprises grey-green and purple, massive to coarsely bedded, clast-supported conglomerate with sandstone interbeds. The clasts are predominantly arenaceous wackes with subordinate radiolarian chert and jasperised basic lava. The matrix is lithic arenite. The clasts are derived largely from a cryptic greywacke source within the Midland Valley (Syba, 1989), with some input of lithologies typical of the northern belt of the Southern Uplands. However, Mykura and Smith (in Mitchell and Mykura, 1962) noted that pebbles of North Esk Group and Pentland Volcanic Formation rocks occur in the upper part of the sequence in the vicinity of Loganlee. This is consistent with the Greywacke Conglomerate Formation being deposited in the Loganlee–North Esk area coaeval with and after the deposition of the Bonaly Member in the Bonaly area, but before the Bell’s Hill and Allermuir members of the Pentland Hills Volcanic Formation.

3.1.2 Pentland Hills Volcanic Formation

Rocks of the Pentland Hills Volcanic Formation form most of the Pentland Hills lying within the Edinburgh district. The volcanic succession is unusually thick for the southern margin of the Midland Valley, possibly reaching a total of 2000 m at the north end of the outcrop (Browne et al., 2002), though thicker sequences occur in the central and northern parts of the Midland Valley (Francis et al., 1970).

The volcanic rocks have been described in detail by Mykura (1960), providing the basis for the twelve volcanic members of Browne et al. (2002). The formation is notable for the wide variety of magmas compared with the rest of the Siluro-Devonian calc-alkaline province (Trewin and Thirlwall, 2002). Several intraformational unconformities are recognised and there is no continuous succession through all the many members (Figure 3). The location of the vents or fissures from which the lavas and tuffs were erupted has not been established, although a location under the Carboniferous rocks near Colinton has been suggested (Peach et al., 1910). Small vents occur in the Pentland Hills but they are too small to account for major outpourings of lava. A microgranite dome, the Black Hill Felsite, forms the effective base of the Pentland Hills Volcanic Formation overlying Silurian strata.

Figure 3. Lithostratigraphy of the Pentland Hills Volcanic and Greywacke Conglomerate formations BGS © UKRI

Succession south of the Lothianburn Fault

3.1.2.1 Black Hill Felsite

Only the NE extremity of the Black Hill Felsite dome [NT 193 640] extends into the Edinburgh district. The Black Hill Felsite (Plate 1) is a microgranite, with abundant phenocrysts and crystal aggregates of alkali feldspar, and rarer microphenocrysts of quartz, orthoclase and biotite set in a microcrystalline quartz-feldspar matrix. Within some of the phenocrysts are specular areas that resemble micropegmatitic intergrowths of quartz and feldspar that are difficult to explain (Flett, 1899).

Peach et al. (1910) described it as a laccolith intruded close to the surface. Mykura (1960) reinterpreted it as an extrusive flow of highly viscous lava, in physical contact with its feeder pipe or fissure at the SW end of the body. It was considered to be extruded onto rocks of the Reservoir Formation (Silurian), and it is unconformably overlain by the Greywacke Conglomerate Formation, which contains clasts of a similar felsite considered by Barron (1998) to have been derived by erosion of this Black Hill Felsite body. Mykura (1960) considered the felsite to be roughly contemporaneous with the trachyte of the Torduff Hill Member.

Plate 1 Aerial view north-west of Loganlee Reservoir [NT 1910 6210] at the Pinnacle; Black Hill Felsite and Reservoir Formation to left; Castlelaw Hill [NT 2247 6479], composed of rhyolite and trachyte flows in distance, centre (P001115) BGS © UKRI

3.1.2.2 TORDUFF HILL VOLCANIC MEMBER

The rocks of the Torduff Hill Volcanic Member are fault-bounded to the east and west, and faulted against or unconformably overlain to the north and south by Carboniferous rocks, so that their stratigraphical position is conjectural. The rocks crop out over an area of about 0.25 km^2 on Torduff Hill [NT 205 672] and comprise pale grey, aphanitic, fine-grained trachyte and trachyandesite, rarely biotite- and partly feldspar-phyric and partly kaolinised. They resemble the rocks of the Braid Hills Member more closely than any other part of the Pentland Hills Volcanic Formation (Mykura, 1960). In places they display contorted flow banding, and elsewhere are conspicuously brecciated. As a result, the exposed thickness is difficult to calculate, but is estimated to be 140 m.

3.1.2.3 WARKLAW HILL VOLCANIC MEMBER

Several flows of olivine basalt are exposed on Warklaw Hill and in Torphin Quarry [NT 205 678]. They are separated by a fault from trachyte of the Torduff Hill Member. Mykura (1960) described the succession in detail as the Warklaw Hill 'Group'. The base of the succession is not seen, due to faulting across the Lothianburn Fault along the northern margin. The lowest unit, best exposed in the Kinleith Burn in the Livingston district [NT 190 670], consists of six flows of olivine basalt with micro- to macrophenocrysts of olivine and ilmenite, with a total exposed thickness of 32 m. The overlying unit, exposed in the lower part of Torphin Quarry, consists of 85–90 m of highly altered olivine-microphyric basalt. The thickest flow in this unit is 27 m, and pebbly beds of lava debris up to 2 m thick occur between flows. The third unit consists of 33 m of olivine-plagioclase-macrophyric basalt in several flows, which typically have vesicular tops. The highest unit, exposed on the southern slopes of Warklaw Hill and in a roadside cut on the west side of Torduff Reservoir [NT 206 677], consists of olivine basalt with phenocrysts of kaolinised plagioclase up to 50 mm long, and smaller phenocrysts of olivine pseudomorphed by iddingsite. The flows are up to 4 m thick and contain rafts of siltstone and mudstone.

3.1.2.4 BONALY VOLCANIC MEMBER

Rocks of the Bonaly Volcanic Member crop out to the east of the fault bounding the eastern extent of the Torduff Hill Member. The base of the member is not seen in the main outcrop. A 325 m thick succession is well exposed in the gorge of the Dean Burn, 200 m south of Bonaly Tower [NT 211 674–NT 213 665], and on the north slope of White Hill [NT 214 673]. Individual flows of pyroxene andesite, olivine basalt, and trachybasalt are exposed in the Dean Burn section, forming the lowest exposed part of the member. Above these rocks, the remainder of the member consists of poorly exposed undivided andesitic, trachybasaltic and basaltic rocks. However, a thin unit of red-brown, volcaniclastic pebbly sandstone with conglomerate beds near the top is exposed in Bonaly Reservoir when empty (D I Jackson, written comm. and specimen, 1998), and a thin rhyolite flow occurs near the top of the member.

South of the west-trending Harbour Hill Fault [NT 202 653], only a small outcrop of undivided basaltic, trachybasaltic and andesitic rocks occur, and the member is absent south of Green Cleugh [NT 196 644], where the contact with the Silurian Reservoir Formation rocks, previously mapped as a fault, is interpreted as an unconformity.

3.1.2.5 BELL'S HILL VOLCANIC MEMBER

The Bell's Hill Volcanic Member, previously described by Mykura (1960) as the Bell's Hill and Howden Burn 'Group', lies unconformably on the rocks of the Bonaly Volcanic Member. The unconformity is exposed on the east side of White Hill [NT 216 673], where about 3 m of conglomerate are poorly exposed at the base. The Member mainly comprises aphanitic rhyolite with flow banding. There are two main outcrops, north and south of the Harbour Hill Fault. Within the dominant rhyolite north of the Harbour Hill Fault, there is a 30 m thick bed of conglomerate with sandstone interbeds, well exposed in the Howden Burn [NT 224 674]. The exposed thickness of the member decreases southwards from 220 m to 20 m, due to overstepping by the Capelaw Volcanic Member. The outcrop south of the Harbour Hill Fault extends as far as the gully south of Green Cleugh [NT 196 635], where it is cut off by faults to the south and west. The boundary with the Greywacke Conglomerate Formation on the west slopes of Harbour Hill [NT 202 644] is also interpreted as faulted. The thickness of the member in the southern outcrop is unknown, due to the massive nature of the rhyolite. Mykura (1960) recorded several flows of pink, flow-banded, nonporphyritic rhyolite of flinty appearance. The interbedded sedimentary rocks consist mostly of conglomerate containing rounded clasts of wacke sandstone, siltstone, microgranite and quartzite, and angular pebbles of rhyolite, felsite, basalt and andesite with thin interbeds of coarse, grey-green or purple lithic arenite.

3.1.2.6 CAPELAW VOLCANIC MEMBER

The Capelaw Volcanic Member was previously divided into a lower basic 'group' and an upper acid 'group' (Mykura, 1960), and is only recognised north of the Harbour Hill Fault. Three or four andesite and basalt flows lie unconformably on the Bell's Hill rhyolites, the unconformity being marked locally by a 0 to 5 m thick conglomerate, exposed beside the Howden Glen track [NT 232 669]. The pyroxene andesite and olivine basalt flows are 120 m thick in the Swanston area, but southward the thickness is reduced to 30 m in the footwall block of the Harbour Hill Fault. On Swanston Golf Course [NT 233 673], two thin rhyolite flows are intercalated within the more basic flows. The andesite and basalt flows are overlain by a thick flow of feldspar-biotite-phyric dacite that is typically silicified and kaolinised. This flow reaches 100 m in thickness, and forms the summit of Capelaw Hill [NT 217 660] and crops out at a lower elevation between the Howden Burn and Swanston faults.

3.1.2.7 ALLERMUIR VOLCANIC MEMBER

The Allermuir Volcanic Member (Allermuir 'Group' of Mykura, 1960) unconformably overlies the Capelaw Volcanic Member to the north of the Harbour Hill Fault; to the south, where the Capelaw Member is absent, it directly overlies the Bell's Hill Volcanic Member. It is generally the lowest member of the Pentland Hills Volcanic Formation present within the Edinburgh district, south of Glencorse Reservoir [NT 210 633]. In the Livingston district to the west, the member lies on sedimentary rocks. The Allermuir Member is at least 420 m thick north of the Harbour Hill Fault, and 550 m thick south of it. North of the Harbour Hill Fault, the succession consists of a 200 m thick stack of undivided microporphyritic pyroxene andesite and olivine basalt lavas, overlain by a 15 m thick flow of distinctive feldspar-phyric olivine basalt, in turn overlain by pyroxene andesite lavas 60 to 100 m thick, including at least one flow of hornblende andesite. Trap featuring is better developed on the northern slopes of Allermuir Hill [NT 226 664] (Plate 2) than anywhere else in the Pentland Hills.

South of the Harbour Hill Fault, a basal bed of grey-green lithic arenite, 10 to 20 m thick, is well exposed at [NT 211 644]. Above this, there is a thick succession of pyroxene andesites and olivine basalts in 4 to 5 m-thick flows, interrupted by two volcaniclastic beds. A thin bed of tuff and volcaniclastic sandstone crops out on the north side of Loganlee Reservoir [NT 1942 6248–NT 1966 6258] (Barron, 1998) and on the south side of the valley [NT 2005 6270]. Approximately 200 m above the base of the member, a 2 to 3 m-thick bed of volcaniclastic sandstone is exposed along the shore of Glencorse Reservoir [NT 213 636] and in the Kirk Burn [NT 216 644]. Near the top of the member, coarse-grained lapilli-tuff containing angular fragments of olivine basalt and pyroxene andesite, interbedded with tuffaceous sandstone, crops out on the shores of Glencorse Reservoir [NT 2175 6380 and NT 2185 6395] and is overstepped by tuffs of the Caerketton Member on the south-western slopes of Castlelaw Hill [218 642].

Plate 2 Northern Pentland Hills viewed south-east from the City Bypass, Juniper Green, showing trap featuring in andesite flows of Allermuir Volcanic Member; Caerketton [NT 2365 6625] and Allermuir [NT 2270 6618] left and right centre horizon. (P001193) BGS © UKRI

3.1.2.8 CAERKETTON VOLCANIC MEMBER

The distinctive Caerketton Volcanic Member (Caerketton 'Group' of Mykura, 1960) can be traced from Caerketton Hill [NT 236 663] south-westwards to the western boundary of the district and beyond. Rhyolitic tuff with rounded clasts of rhyolite in a silicified matrix, overlies flow-banded and brecciated rhyolite on Caerketton Hill [NT 238 662] although the top of the member is not exposed. The member reaches its maximum development on Castlelaw Hill [NT 225 648] (Mykura, 1960) where rhyolitic tuff, 20 m thick, is overlain by 160 m of tuff intercalated with flow-banded rhyolite and silicified biotite-phyric trachyte (similar to the Woodhouselee Volcanic Member). Farther south-west, the Caerketton Volcanic Member consists of a 20 m-thick bed of highly altered and silicified tuff, and a localised flow of olivine basalt between Carnethy and Scald Law [NT 196 615] is assigned to this member.

A pit dug into this member on Scald Law [NT 1938 6130] revealed laminated/bedded pyroclastic rock almost entirely composed of angular to sporadically cuspate volcanic lithic clasts up to 3 mm across. These clasts include fragments of devitrified glass and flow-banded felsites and ragged 'fiamme' aligned parallel to sedimentary lamination (Barron, 1998). Crystal clasts are absent. The rock is highly altered, with much devitrification of glassy clasts and local recrystallisation of the matrix and clasts. The rhyolite forming the upper part of the member is locally spherulitic and contains small phenocrysts of sodic plagioclase or sanidine, set in cryptocrystalline matrix with much silicification (Mykura, 1960).

3.1.2.9 WOODHOUSELEE VOLCANIC MEMBER

The Woodhouselee Volcanic Member is preserved south of the Harbour Hill Fault [NT 237 656] south-west to the western margin of the district at Eight Mile Burn [NT 191 595]. In the Castlelaw Hill [NT 225 648] to Woodhouselee area [NT 233 645] 220 m of biotite- and feldspar-phyric trachyte overlie and interdigitate with rhyolite of the Caerketton Volcanic

Member. Farther to the south-west, trachytes of the Woodhouselee Volcanic Member form the summits of Turnhouse [NT 212 626] and Carnethy [NT 203 619] hills and Scald Law [NT 192 611]. The rocks are typically pale pink to pale lilac trachyte and minor andesite, both with phenocrysts of biotite and alkali feldspar, principally sanidine, in a matrix of laths of sanidine (or sodic plagioclase in the case of the andesites) with patches of haematite (Mykura, 1960). They are typically highly kaolinised and some are strongly silicified.

3.1.2.10 CARNETHY HILL VOLCANIC MEMBER

The Carnethy Hill Volcanic Member, previously referred to as the Carnethy and Hillend 'Group' (Mykura, 1960), extends continuously from the Lothianburn Fault [NT 250 674] to the vicinity of Silverburn [NT 203 603] and reaches 400 m in thickness. On Caerketton Hill [NT 235 660] it is in faulted contact with rocks of the Allermuir and Caerketton volcanic members. The rocks are principally olivine basalts with a few interbedded flows of pyroxene andesite. Trap features are generally poorly developed.

A distinctive flow of andesite tending to trachyandesite occurs at the base of the exposed succession on Lothianburn Golf Course [NT 224 673]. On the eastern slopes of Carnethy Hill [NT 206 613], a 10 m-thick flow of olivine basalt is exposed in old workings, previously reffered to as the 'Carnethy Porphyry'. It has labradorite phenocrysts up to 30 mm long, augite microphenocrysts and pseudomorphs after olivine set in a fine-grained dark-green matrix (Mykura, 1960). A thin bed of basaltic tuff occurs on Fala Knowe [NT 212 615].

This completes the succession displayed to the south of the major east–west Lothianburn Fault (Figure 2). To the north of this fault, a separate succession is developed. Attempts were made to correlate the succession with that of the northeastern Pentland Hills (Mykura, 1960). However, they came to the conclusion that the majority of the rocks north of the Lothianburn Fault likely represent units stratigraphically above the Carnethy Hill Volcanic Member.

3.1.3 Succession north of the Lothianburn Fault

3.1.3.1 FAIRMILEHEAD VOLCANIC MEMBER

The Fairmilehead Volcanic Member comprises a varied succession of rhyolite, biotite trachyte, olivine basalt and pyroxene andesite, forming thin flows and thin beds of rhyolitic tuff, with a total thickness of at least 420 m. It is very poorly exposed. Mykura (1960) described sections within the member and pointed out that it could be a much-attenuated combined equivalent of what are defined currently as the Allermuir, Caerketton and Carnethy Hill volcanic members. The outcrop is now largely built over.

3.1.3.2 BRAID HILLS VOLCANIC MEMBER

The Braid Hills Volcanic Member consists of a thin basal tuff overlain by a 100 m thick sequence of biotite trachyte and biotite andesite (Flett, 1910). Trachytes and andesites of the Braid Hills Volcanic Member are predominantly composed of feldspar, commonly replaced by kaolinite, muscovite, and secondary quartz. Biotite and feldspar phenocrysts, a common characteristic of these rocks, might be preserved unaltered (Flett in Peach et al., 1910). Petrographically, rocks of this member resemble the trachytes of the Torduff Hill rather than the Woodhouselee Volcanic Member.

3.1.3.3 BLACKFORD HILL VOLCANIC MEMBER

A 5 m-thick basal tuff with some trachytic clasts is overlain by a 60 m-thick andesite flow, showing columnar jointing in places, which forms the mass of Blackford Hill [NT 254 705] (Mykura, 1960). Fine-grained pyroxene andesite, characteristically feldspar-phyric, was formerly quarried for road stone (Flett in Peach et al., 1910). It is overlain, on the King's Buildings campus [NT 265 706], by flows of feldspar-phyric olivine basalt resembling the 'Carnethy Porphyry' (Carnethy Hill Volcanic Member) with an interbedded 5 m-thick bed of basic tuff (Cockburn, 1956). This is the highest exposed unit in the Pentland Hills Volcanic Formation.

3.2 AGE AND GEOCHEMISTRY

The volcanic rocks of the Pentland Hills form part of a calcalkaline differentiation trend (Thirlwall, 1981), relating to a north-westerly subducted slab of oceanic Plate after the final closure of the Iapetus Ocean. The geochemistry is very similar to that of the Ochil Volcanic Formation (Browne et al., 2002) and other volcanic units of Siluro-Devonian age on the northern side of the Midland Valley. Thirlwall (1988) obtained an age of 412.6 ± 5.7 Ma (Rb/Sr on biotite; Pridoli to Pragian on the timescale of Gradstein et al., 2004) for a rhyodacite lava from the Capelaw Volcanic Member on the northern slopes of Allermuir Hill [NT 235 670].

3.3 SEDIMENTOLOGY AND DEPOSITIONAL ENVIRONMENT

The sedimentary rocks of latest Silurian to Early Devonian age in the Edinburgh district are all fluviatile, either siliciclastic or volcaniclastic, ranging from lithic arenite to conglomerate. They were laid down on the surface of recently erupted lava flows, in many cases after earth movements had tilted, folded and eroded the underlying volcanic rocks. They contain a high proportion of igneous material, but with a contribution from locally available sedimentary rocks. It is unclear whether the volcanic rocks originally formed classic cones and craters, or fissure-related low-profile lava fields with the silicic flows forming localised ‘buns’. The spatial extent is not understood but the volcanic rocks may have been located towards the southern edge of a NE trending sedimentary basin the location of which was controlled by sinistral strike-slip movement.

Barron (1998) interpreted the tuff at the base of the Caerketton Volcanic Member as a primary bedded ash, possibly formed during phreatomagmatic explosions. Local winnowing of the deposit with removal of fine matrix is also indicated (Beddoe-Stephens, 1998).

4 Late Devonian and early Carboniferous

In the Edinburgh district, Late Devonian-Carboniferous rocks occur largely beneath a cover of Quaternary deposits (Chapter 9). In this account these rocks comprise sedimentary strata of the Inverclyde Group overlain by Strathclyde Group volcanic and sedimentary sequences, as well as the volcanic strata of the Bathgate Group underlying the Firth of Forth and Inchkeith. The Lower Limestone Formation, currently regarded as part of the early Carboniferous succession, is the basal unit of the Clackmannan Group and is more conveniently described in the following late Carboniferous chapter. The palaeontology of the early Carboniferous rocks has been summarised by Dean (2000).

4.1 INVERCLYDE GROUP

The Inverclyde Group consists of the Kinnesswood, Ballagan, and Clyde Sandstone formations. Although initially the Kinnesswood was considered to be Tournaisian, it is now understood to belong to the latest Devonian (Marshall et al., 2018). The transition from the Kinnesswood to the Ballagan Formation marks the Devonian-Carboniferous boundary. The Clyde Sandstone Formation has not been definitively recognised within the Edinburgh district.

The Kinnesswood and Ballagan formations are characterised by sandstone with pedogenic carbonate concretions (‘cornstones’) and silty mudstone containing thin beds and nodules of dolostone (‘cementstone’), evaporates (mainly gypsum) and limestone, respectively. Carbonaceous rocks, especially coal seams and oil shales, are absent. The group was laid down whilst Scotland lay in low latitudes south of the equator (Trewin, 2002). At this time, the climate was generally considered to be semi-arid and seasonally wet.

Nationally the base of the Inverclyde Group is taken where the sandstone-dominated aeolian and fluvial lithologies of the underlying Late Devonian Stratheden Group is succeeded by carbonate-bearing strata in a gradational sequence. The group forms the topmost part of the regional onlapping sequence of the Devonian ‘Old Red Sandstone’ lithofacies from the marine Central North Sea Basin on to mainland Scotland. Locally, the base of the group is taken at an unconformity on Early Devonian volcanic and Ordovician sedimentary strata in the district.

The distribution of the oldest Inverclyde Group strata in the Midland Valley of Scotland appears to be controlled by sinistral strike-slip movement on pre-existing Caledonian faults (Bluck, 1978 and 2001) and by residual palaeogeographical highs such as the extensive Salsburgh Block to the west of the Edinburgh district (Read et al., 2002). The similarity of the Inverclyde Group succession in the Midland Valley, with similar aged strata in the Southern Uplands Terrane and on the northern fringes of the Northumberland and Solway basins suggests that extensional (and possibly rift-related) faulting may have operated contemporaneously with sedimentation across these areas. Subsequently, following intra-Carboniferous uplift and erosion, the sedimentary and volcanic history of the Midland Valley is distinct from that in basins to the south. Thus, following deposition of the Clyde Sandstone Formation there appears to have been a defining change in the tectonic style from extension to dextral strike slip, and a change in palaeoenvironment, to terrestrial rather than the continuing mainly marine paralic setting south of the Southern Uplands (Trewin, 2002).

4.2 KINNESSWOOD FORMATION

The Kinnesswood Formation consists predominantly of white, pink to red-brown, moderate- to well-sorted, medium-grained quartzose sandstone (Barron, 1998), that is mostly tabular and trough cross-bedded and arranged in upward-fining units. Fine-grained, planar or poorly bedded sandstone, red-brown and pale green mudstone/siltstone and nodules and thin beds of concretionary carbonate (calcrete or ‘cornstone’) also occur. Rip-up clasts of mudstone and carbonate are also found, especially at the bases of sandstone beds. Lithic, matrix-supported conglomerate and coarse pebbly sandstone occur at the base of the formation where it rests unconformably on older strata, usually the Pentland Hills Volcanic Formation but also the North Esk Group. The clasts, usually no more than 10 cm across, consist mostly of lavas and also vein quartz, quartzite, jasper, chert and wacke sandstone. The cross-bedded sandstones were deposited in channels and banks of rivers apparently flowing mainly from the south-east. The fine-grained sandstones and mudstones represent overbank deposits formed on the associated floodplains.

The carbonate nodules and beds that characterise the Kinnesswood Formation are calcrete horizons; they developed in soil profiles on stable alluvial plains under the influence of a fluctuating water table in a semi-arid and seasonally wet climate. The calcretes are best developed towards the base of the formation, as in the Livingston district (Sheet 32W) where the formation is best exposed (Barron, 1998). Borehole records for former brewery wells such as that at Blackford Avenue No. 1, Edinburgh (Tait, 1925a) for Younger’s Brewery (NT 27 SE/ 111) [NT 2580 7144], show the basal 12 m of the formation above the unconformable contact with the underlying Pentland Hills Volcanic Formation to consist of over 30 % calcrete.

Plate 3 Sandstones with thin greenish grey mudstone beds, Kinnesswood Formation, Dreghorn Spur road cutting [NT 2315 6840], view of east wall during construction iii (P219745) BGS © UKRI

The Kinnesswood Formation occurs at surface in the western part of this district in and around the Pentland Hills, from Craigentarrie [NT 195 647] to Dreghorn [NT 231 685] and Swanston [NT 237 683], and underlies southern Edinburgh around Blackford Hill [NT 260 714] and the Braid Hills [NT 240 695]. It is reasonably well exposed in former building stone quarries, such as in the Craigmillar Castle Local Geodiversity Site (LGS) [NT 285 708] where calcrete clasts are a common minor component. About 46 m of strata near the top of the formation are well exposed at the Dreghorn Link Road LGS section [NT 231 685] where the dominant lithology (90 %) is sandstone. This section (Plate 3) reveals some typical features of the Kinnesswood Formation, since it is mostly sandstone without calcrete, and contains beds of grey mudstone and fragments of fossilised trees typical of the Ballagan Formation, but lacking ferroan dolostone (cementstone). A conglomeratic top to the formation has been mapped locally at Colinton [NT 200 680] just north of Torphin Quarry.

The maximum thickness of the Kinneswood Formation in the Midland Valley of Scotland (about 640 m) is attained in the Edinburgh area (Mitchell and Mykura, 1962, p. 31), but is estimated to be 300 m in west Edinburgh and 100 m to 400 m in the Pentland Hills (Barron, 1998; Table 2).

4.3 THE BALLAGAN FORMATION

The Ballagan Formation is characterised by generally grey mudstone and siltstone with nodules and beds of ferroan dolomite ('cementstone'), in beds generally less than 0.3 m thick. Gypsum, and to a much lesser extent anhydrite, and pseudomorphs after halite occur. Desiccation cracks are common and the rocks commonly show evidence of brecciation during early diagenesis. Both these features are associated with reddening of the strata, especially in the Edinburgh district compared to the classical grey-coloured Ballagan Formation outcrops such as at Ballagan Glen, Stirlingshire. Thin sandstone beds are commonly present, and thick localised sandstones are also now included in the Ballagan Formation (as developed in the Edinburgh and Livingston districts) so that the unit now encompasses strata that were earlier called the Tyninghame Formation in the Lothians (Chisholm et al., 1989).

The macrofauna, where present, is restricted to a few species and is characterised by the bivalve *Modiolus latus*, but ostracods are more abundant along with *estheriid crustaceaus* and *spirorbids* worms. The base of the formation, although gradational, is taken at the lithological boundary between strata characterised by a mudstone–dolostone association and the underlying calcrete limestone and sandstone of the Kinnesswood Formation. The formation top is drawn at the top of the highest unit of mudstone and dolostone in any particular area.

Andrews et al. (1991) and Turner (1991) interpreted the Ballagan Formation as being deposited in coastal alluvial plains, lakes and marginal marine flats. These were subject to periodic desiccation with fluctuating salinity, partly as a result of sea-water being introduced by storm flooding events. The open sea lay to the east initially (Cope et al., 1992, maps C2, C3); later it is more evident with more marine faunas in the dolostone beds ('cementstones') being found in the Solway Basin. Andrews et al. (1991) explained the lack of sulphide in the mudstones, and the sourcing of the magnesium and calcium ions in the dolostone, by marine flooding events of limited extent or duration into the alluvial plains and their lakes. Muddy limestone accumulated where lake waters were sufficiently deep to prevent development of conditions suitable for diagenetic dolomitisation. The inundations in general left no marine faunal record but provided a strong geochemical signal in the sulphate evaporite minerals, ferroan dolostone and strontium isotope geochemistry. Because of the dominance of siliciclastic deposition over evaporite precipitation, Andrews et al. (1991) concluded that the formation was laid down in a humid environment subject to drier periods of evaporation rather than a generally arid one.

The Ballagan Formation crops out on the western side of the Pentland Hills between Clubbiedean Reservoir [NT 200 666] and Craiglockhart [NT 230 700]. It also underlies much of central Edinburgh east of the Colinton Fault System including parts of Princes Street Gardens [NT 255 737], around the Royal Mile (Plate 4) and the western end of Holyrood Park [NT 270 735] (Figures 1 and 2). The Inverclyde Group (undivided) is present on the southern margin of the district south-east of Howgate [NT 254 570] and in a broad belt in the south-east corner at Middleton Hall [NT 370 580]. In general, the formation is poorly exposed but is still reasonably well seen in a road cutting east of the bridge over the Water of Leith [NT 208 682 to NT 213 680]. Here about 78 m of strata are still partially exposed, with sandstone forming c. 67 % of the section. Exposures of the Ballagan Formation can be seen in Holyrood Park at the classic Hutton sites at Salisbury Crags [NT 270 730] and the Camstone Quarries [NT 273 737], showing desiccation cracks, ripple-marks and lithic conglomerates containing both carbonate and quartz clasts. In the Scottish Parliament Water Borehole, NT27SE/449 [NT 2670 7380], only 29 % of the succession of over 91 m thickness is sandstone; the remainder is mudstone and siltstone with carbonate ('cementstone') nodules, the latter partly distributed in pedogenic profiles and also as two thin limestone beds of ‘cementstone’. Nearby temporary sections at Moray House [NT 2640 7350] and the Pleasance [NT 2630 7350] (Plate 4) had only 11 % and 13 % sandstone in 15 to 17 m of strata.

The maximum thickness of the formation is about 900 m in the West Lothian area (Mitchell and Mykura, 1962, p. 38), but is estimated to be 750 m thick in west Edinburgh. The detailed sequence of informal members reported by these authors is, in ascending succession, Lower Shale (100 m thick according to Barron, 1998), Middle Sandstone (180 to 400 m thick in NT16SE), Upper Shale (400 m thick in NT16SE) and Upper Sandstone, although this is difficult to verify in the Edinburgh district. The ‘Upper Sandstone’ of the Pentland Hills (Mitchell and Mykura, 1962, p. 38) may actually belong to the Clyde Sandstone Formation, which elsewhere consists predominantly of fine- to coarse-grained sandstone, commonly pebbly, with beds of red brown or grey mudstone. Pedogenic limestone, as nodules or beds, and calcite cemented concretionary sandstones are also present. The pebble clasts are largely of intrabasinal limestone or mudstone origin. These strata were laid down in a wide variety of fluviatile environments, ranging from braided stream to river floodplain with well-developed overbank deposits. The only known marine band is that of the Scotsman Office Beds (Mitchell and Mykura, 1962; fig. 8 and p.38), recognised on the presence of marine ostracods (Peach et al. 1910, p.56). Distinguishing the Ballagan and Clyde Sandstone formations is difficult in the Edinburgh district; although calcretes are characteristic of both the Kinnesswood and Clyde Sandstone formations, pedogenic limestone is also developed in the Ballagan Formation, that in this district is also distinctly richer in sandstone and poorer in dolostone than is the norm.

Plate 4 Ballagan Formation in excavation on former brewery site at St John’s Hill, The Pleasance [NT 2630 7350], viewed from the north (P733304) BGS © UKRI

A few intervals of volcanic rock occur within the Ballagan Formation. Near the base, drilling in The Meadows [NT 254 727] has proved two thin basalt flows and a bed of lapilli-tuff. About two-thirds of the way up the formation, a thin flow of olivine-clinopyroxene-feldspar-macrophyric basalt occurs at St Mary’s Street [NT 263 737], where it is overlain by a thin lapilli-tuff bed, and possibly the same flow also occurs at the Wells o'Wearie [NT 273 725] in Holyrood Park.

4.4 STRATHCLYDE GROUP

The **Strathclyde Group** is a varied sequence of sedimentary and volcanic rocks (Table 2), characterised by the presence of carbonaceous beds, including coal and oil shale. They were laid down between 345 Ma and 326 Ma (Visean; earliest Asbian to Brigantian) (Cope et al., 1992; Browne and Monro, 1989) in largely fluviatile and lacustrine environments, with periodic marine incursions and abundant volcanics. The base of the group is taken at the base of the Clyde Plateau Volcanic Formation (dated as 335 Ma; Monaghan and Parrish, 2006) in the central and western Midland Valley of Scotland, at the base of volcanic formations in the Lothians (dated as 342 Ma; Monaghan and Pringle, 2004), and at the base of the Fife Ness Formation in Fife.

Strathclyde Group strata consist of interbedded sandstone, siltstone and mudstone with common seatearth, coal seams and sideritic ironstone. Deposition of the Strathclyde Group marks a lithological change from concretionary limestone and dolostone-bearing strata typical of the Inverclyde Group to a coal-bearing sequence in which volcanic rocks are locally common. Two differing sequences of Strathclyde Group rocks are present in the district, bounded by the Inchkeith Fault (Figure 2. Immediately to the north of the fault, the formations recognised, defined and mapped are the Fife Ness, Anstruther, Pittenweem, Sandy Craig, Kinghorn Volcanic and Pathhead formations (Table 2). Formations defined in the Edinburgh and adjacent districts, and mapped south of the fault, show lateral variation with differing formations in the western and eastern parts of the district (Table 2). Strathclyde Group strata in the city of Edinburgh and on the western limb of the Midlothian Syncline are the Arthur's Seat, Gullane and West Lothian Oil-shale formations. The Garleton Hills Volcanic, Gullane and Aberlady formations are recognised on the eastern limb of the Midlothian Syncline (Table 2). Chisholm et al. (1989) named the formations by revising the earlier terminology of Mitchell and Mykura (1962).

Oil shale and freshwater limestone (Loftus, 1985; Loftus and Greensmith, 1988; Raymond, 1991) are minor but important components of the group. These reflect the development of substantial lakes ('Lake Cadell', 2000– 3000 km^2) in a humid climate. These particular lake sediments are characterised by the accumulation of abundant remains of filamentous, mat-forming, benthonic cyanophyte (blue-green) microbes/algae (Raymond, 1991, p.366). This is contrary to the view of Loftus and Greensmith (1988), who regarded the filaments as flocculent oozes of the nonfilamentous planktonic *Botryococcus brauni*. The latter appears to be a minor constituent of the oil shale and limestone. Maddox and Andrews (1987) recognised the value of cryptalgally laminated dolostones in regional correlation and as time markers of basin-wide 'regression'. Guirdham (1998), like Raymond (1991), interpreted the carbonate deposition in a hydrologically closed, shallow, playa-type lake setting. In contrast, the oil shales formed in hydrologically open, thermally stratified deep lakes, where shore levels and water levels were stable over long periods. Switches between the two systems were caused either by climate change (increased aridity and seasonality within an overall humid, subtropical environment) or by local tectonism and vulcanicity. Guirdham (1998) also recognised a second category of closed lake in which microbial tufa carbonates accreted in shallow, nutrient-rich sub-basins with a significant volcaniclastic input.

The palaeoclimate during deposition of the Strathclyde Group was mainly humid as inferred by the presence of coal, oil shale and sideritic mud-grade palaeosol. However, the presence of calcretes and calcareous mudstones ('marls') in the West Lothian Oil-shale, Aberlady and Sandy Craig formations (Andrews and Nabi, 1998) point to periods of semi-arid climatic conditions during Asbian times. Wright and Vanstone (2001) noted that regular orbitally forced glacioeustatic sea-level oscillations with an apparent 100 ka periodicity started abruptly around 330 Ma (early Asbian) and that these characterised the Late Palaeozoic from Asbian onwards. Prior to this, pre-Asbian climates were relatively stable with infrequent changes. Fluctuations in climate occurred during glacial lowstands of sea level. It is only during the Brigantian (Raeburn Shale and younger marine beds) that any marine cycles are seen in the Strathclyde Group strata that might be associated with such a systematic mechanism.

A northerly trending structural feature referred to as the ‘Bo’ness Line’ (see Rippon et al., 1996, fig. 1; Read et al., 2002, fig. 9.13) may have influenced the lithostratigraphical and sedimentological contrasts between the western and eastern halves of the Midland Valley. Underhill et al. (2008) inferred the development of several major syn-sedimentary folds of northerly trend that controlled deposition during the early to late Carboniferous. However, the distribution of the West Lothian Oil-shale Formation may partly be due to the control exercised by volcanic outpouring represented by the Garleton Hills, Arthur’s Seat, Kinghorn and Clyde Plateau volcanic formations. Such upstanding deposits may have functioned as residual topographical barriers to ingress of the sea from the east. The Southern Uplands Terrane to the south and the Salsburgh High to the west of the district were also topographically influential. The Midlothian–Fife Syncline was an active growth fold from the mid Visean, with volcanism occurring on its flanks. Fault control is explained in terms of dextral strike slip throughout the Visean associated with vulcanicity in areas of transtension (Ritchie et al., 2003).

Palaeocurrent flow is generally from the north throughout accumulation of the Strathclyde Group, and Stuart et al. (2001) have determined ^{40}Ar/^{39}Ar ages on detrital muscovite that suggest a source for the detritus in Scandinavia. They recognised that this source area remained a major topographical high and supplied sediment to Scotland for over 100 Ma because of post-orogenic uplift and exhumation events.

4.4.1 City of Edinburgh and western Midlothian Syncline, south of the Inchkeith Fault

The Visean extrusive igneous rocks of the Edinburgh district belong to a suite of transitional to mildly alkaline basaltic to rhyolitic rocks which is recognised across the Midland Valley (Stephenson et al., 2003; Upton et al., 2004), and is chemically distinct from the Siluro-Devonian igneous rocks of the district. To aid description and assist correlation of flows with the vents and plugs from which they originated, the Tournaisian and Visean olivine basalts and hawaiites of the Midland Valley, and their coarser-grained equivalents, have previously been classified on the basis of the nature and size of the phenocryst phases (Table 3).

Table 3 Nomenclature of basic igneous rocks of Carboniferous and Permian age in the Midland Valley of Scotland. On the BGS Digital Geological Map of Great Britain, these are referred to based only on their abundant phenocryst assemblage (e.g. “Jedburgh-type basalt” is referred to as feldspar-microphyric basalt).

Basalt type of MacGregor (1928)	Phenocrysts		Chemical classification of Macdonald (1976)	Type locality
	Abundant	Subordinate		
Macroporphyritic (phenocrysts > 2mm)				
Markle	*Pl*	± *ol*, Fe	*pl* ± *ol* ± Fe-phyric basalts, basaltic hawaiites or hawaiites	Markle Quarry, East Lothian
Dunsapie	*pl* + *ol* + *cpx*	± Fe	*ol* + *cpx* + *pl* ± Fe-phyric basaltic hawaiites or *ol* + *cpx* + *pl*-phyric basalts	Dunsapie Hill, Edinburgh (vent intrusion)

Craiglockhart	*ol* + *cpx*		Ankaramite	Craiglockhart Hill, Edinburgh (flow)
Microporphyritic (phenocrysts < 2mm)				
Jedburgh	*Pl*	± *ol,* Fe	*pl* ± *ol* ± Fe-phyric basaltic hawaiites, hawaiites and in some cases basalt	Little Caldon, Stirlingshire (plug). Also in Jedburgh area
Dalmeny	*Ol*	± *cpx, pl*	*ol* ± *cpx*-phyric basalt	Dalmeny Church, West Lothian (flow)
Hillhouse	*ol* + *cpx*		*ol* ± *cpx*-phyric basalt (locally basanites)	Hillhouse Quarry, West Lothian (sill)

4.4.2 Arthur's Seat Volcanic Formation

Rocks of the Arthur's Seat Volcanic Formation (Figure 4 and 5) were erupted during Visean time (Monaghan and Pringle, 2004; Monaghan et al., 2014) from a few vents in the vicinity of Edinburgh Castle [NT 252 735] and Holyrood Park [NT 275 727]. The thickest development is on Whinny Hill [NT 278 734] in Holyrood Park, where 13 to 15lava flows with some intercalated volcaniclastic rocks form a pile 350 m thick (Black, 1966; Land, 1996; Land and Cheney, 2000), thinning to 300 m at Duddingston [NT 280 720] on the south side of the Park. At nearby Calton Hill (NT 263 742) the succession totals 190 m (Figure 4). The volcanic rocks of the Craiglockhart Hills [NT 227 701], where about 60 m are present, now correlate with this formation following the reinterpretation of the Visean strata in the district by Chisholm and Brand (1994). All of the developments within the City of Edinburgh were described in Day (1933), and in great detail by Black (1966), and were included in popular guides to the rocks of the Arthur's Seat Volcanic Formation (Land, 1996; McAdam and Clarkson, 1986; Land and Cheney, 2000). Holyrood Park and Calton Hill were described in the Geological Conservation Review by Upton (2003). Clarkson and Upton (2006, pp.118–120) also provided a popular account of these igneous rocks with a description of Edinburgh's Visean volcanic scenery. The Castle Rock vent is envisaged as being associated with an original cone about 2 km across and that of Arthur's Seat 3 to 5 km across on lushly vegetated wetlands, although the latter is open to debate.

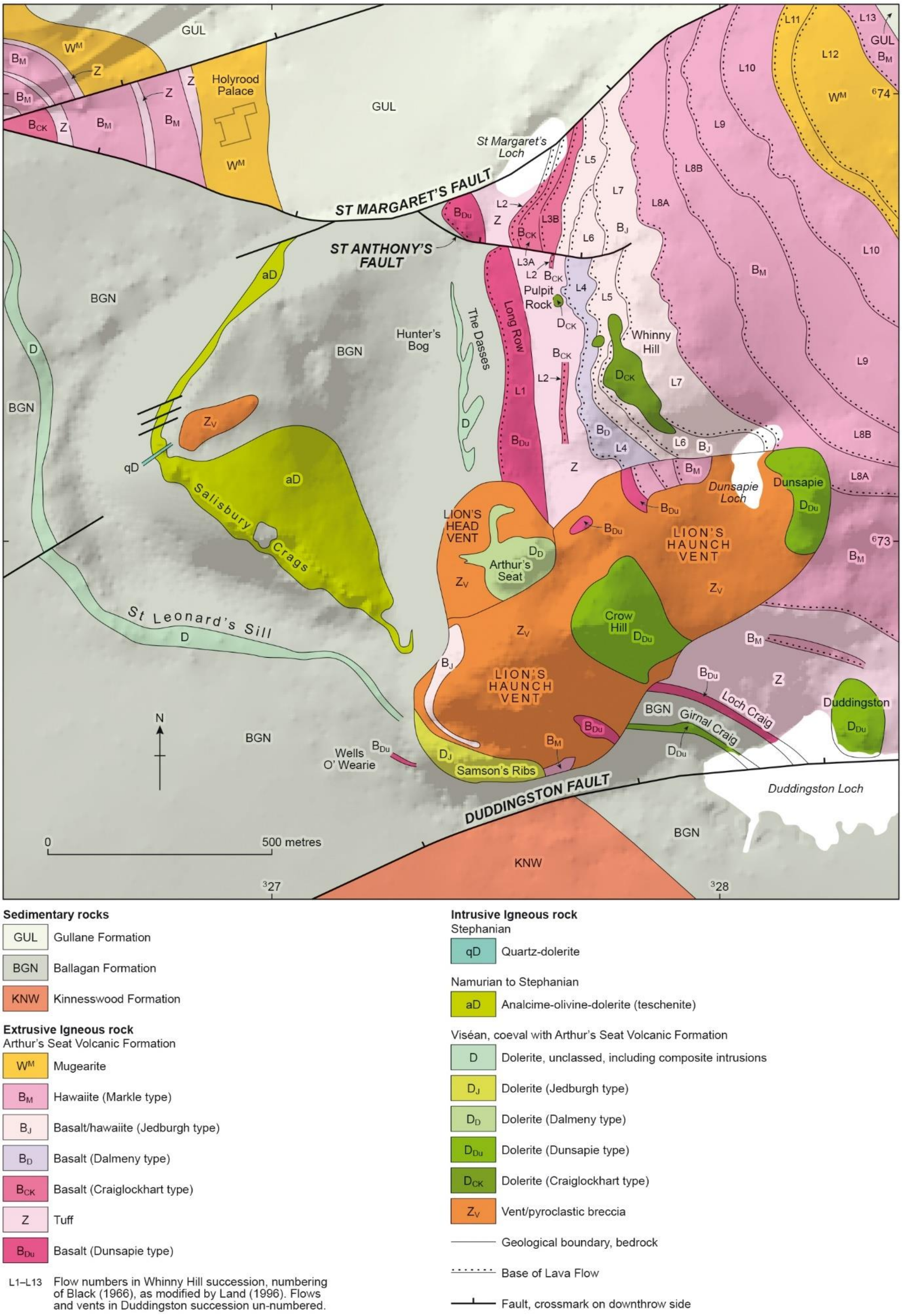


Figure 4 Geology of Holyrood Park BGS. Contains NEXTMap Britain elevation data from Intermap Technologies$^{\text{TM}}$. © UKRI

Holyrood Park Sequence

The numbered flows in the following description are from Black (1966) and Land (1996). The basal units of the succession were interpreted by Land and Cheney (2000) to have been erupted from the Castle Rock Vent [NT 252 735]; however geochemical analyses indicate Lava 1 flows were sourced from local volcanism, though not necessarily the Arthur's Seat volcano (Monaghan et al., 2014). This is based on the compositional similarity between the vent rocks and the lowermost Flow 1 and the common presence of quartz xenocrysts with augite reaction rims, which are otherwise rare in rocks of this formation (Black, 1966; Upton, 2003). After producing thin beds of tuff and lava intercalated in the upper part of the underlying Ballagan Formation, this vent produced a major flow of olivine-clinopyroxene-plagioclase-macrophyric basalt (Dunsapie-type); this is the basal Flow 1 (Long Row) on Whinny Hill and at Duddingston (Loch Craig), but does not occur on Calton Hill (Figure 4). On Whinny Hill, the Long Row (Plate 5) is overlain by 30 m of tuff and fissile mudstone with a 1 m thick bed of cherty limestone containing fossilised plant rootlets.

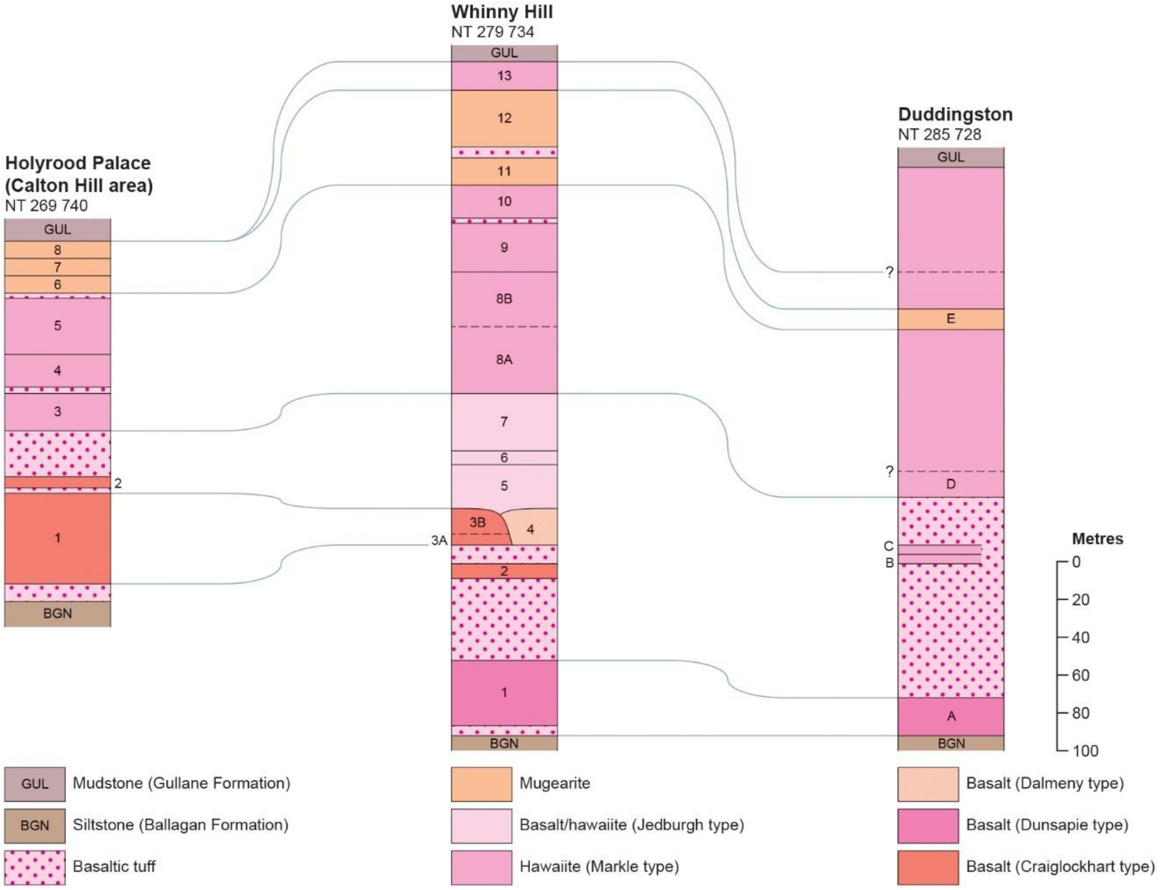


Figure 5 Correlation of lava flows within the Arthur's Seat Volcanic Formation; numbering system after Black (1966) and Land (1996) BGS © UKRI

Flow 2 on Whinny Hill, a clinopyroxene-olivine-macrophyric basalt (Craiglockhart type), might have been erupted from the Lion's Head Vent or nearby (Black, 1966), but subsequent activity has removed any evidence for this. Seven metres of tuff containing plant and fish fossils intervene between this lava and Flow 3A (Upton, 2003). Flows 3A and 3B are also of clinopyroxene-olivine-macrophyric basalt (Craiglockhart type). They might have been erupted from the Pulpit Rock (Clark, 1952 and 1956; Black, 1966), a small parasitic vent [NT 7355 2775] on the north side of Arthur's Seat (Figure 4).

Flow 4 is of olivine-microphyric basalt (Dalmeny type), the only flow in the lava pile with this composition (Figures 4 and 5). Petrographically, it is similar to a large intrusion within the Lion's Head Vent, which therefore may be assumed to be the source of this lava. This flow is absent north of St Anthony's Fault (Figure 4), due to the positive feature formed by flows 2, 3A and 3B in this area.

The Lion's Haunch Vent cross-cuts the Lion's Head Vent (Figure 4), and is regarded as the source for flows 5, 6 and 7. These flows are plagioclase-microphyric basaltic or hawaiitic rocks (Jedburgh type), of similar lithology to a sheet within the Lion's Haunch Vent (Black, 1966). Several minor intrusions of plagioclase-macrophyric hawaiite (Markle type) also occur within the vent, and are considered to be a possible source of hawaiite flows 8A, 8B, 9, 10 and 13 (Black, 1966). Flows 11 and 12 are mugearites, the most evolved rocks preserved on Whinny Hill, which Black (1966) also considered to have been erupted from this vent. Thin basal beds of volcaniclastic conglomerate occur locally at the base of flows 8A and 10.

To the south-east of the Lion's Haunch Vent, the Duddingston succession differs considerably from that at Whinny Hill (Figure 5). The basal flow (Loch Craig) can be correlated with Flow 1 (Long Row) on Whinny Hill, but is followed by a thick pyroclastic sequence with two thin hawaiite (Markle type) flows near the top. The thicker sequence of pyroclastic deposits preserved at Duddingston, compared to Whinny Hill, was considered by Black (1966) to reflect a northerly wind direction during eruption and preferential accumulation of ash on the leeward side of the volcanic cone. Flows 2 to 7 are not represented (Figure 4). The succeeding hawaiite flows, with one mugearite, include the equivalents of flows 8 to 13 on Whinny Hill, but the topmost flows are later than Flow 13 (Figure 5).

Plate 5 Holyrood Park, view southwards from Haggis Knowe, with Lion's Head Vent (distance) [NT 2750 7295], Long Row lava (left), Dasses Sill [NT2740 7360] (centre right, middle ground) (P002869) BGS © UKRI

There are several flows that do not correlate with the main lava sequence in the Lion's Haunch Vent (Figure 4), and probably postdate the flows outside the vent. These include hawaiite (Markle type) flows similar to the later flows on Whinny Hill (Figure 5), but also include flows of olivine-clinopyroxene-plagioclase-macrophyric basalt (Dunsapie type), indicating a return to more primitive magma, which is of similar lithology to intrusions within the vent.

Calton Hill Sequence

The Arthur's Seat Volcanic Formation exposed at Calton Hill [NT 260 740] comprises a basal unit of lapilli-tuff about 50 m thick (Figure 5). This is succeeded by two flows of clinopyroxene-olivine-macrophyric basalt (Craiglockhart type) with a total thickness of 90 m, correlated with flows 3A and 3B on Whinny Hill (Figures 4 and 5). These lavas are succeeded by 15 m of tuff with fragments of hawaiite (Markle type) and three plagioclase-macrophyric basalt (Markle type) lava flows with thin tuff interbeds that are correlated with flows 8 to 10 on Whinny Hill (Figure 5). Above a thin prominent tuff bed, traceable across the hill, the upper part of the volcanic formation comprises three thin mugearite flows. These are 22 m thick in total, with tuff interbeds that are considered equivalent to mugearite flows 11 to 12 on Whinny Hill (Black, 1966). The Calton Hill succession is an attenuated equivalent of that on Whinny Hill, but lacks Flow 1 (equivalent to the Long Row) and the basalt and hawaiite lavas of Dalmeny and Jedburgh type of flows 4 to 7 on Whinny Hill.

Craiglockhart Hill Sequence

Strata on Craiglockhart Hill [NT 228 702] consist of well-bedded tuff, about 30 m thick with lithic and crystal clasts, overlain by a 30 m thick flow of clinopyroxene-olivine-macrophyric basalt (the type example of Craiglockhart type). The basalt flow is prominently columnar-jointed in the centre, although with a slaggy texture at the base and top. In the southern part of the outcrop, an additional thin basaltic flow may be present within the tuffs. There is no evidence to indicate from which vent the Craiglockhart lavas and tuffs erupted. The strata are regarded as the stratigraphically younger levels of the Arthur's Seat Volcanic Formation.

Evolution of the Arthur's Seat Volcano and other Tournaisian to Visean volcanic rocks

The geochemistry of the volcanic rocks of the Arthur's Seat Volcanic Formation, like that of other Tournaisian to Visean volcanic rocks of the Midland Valley of Scotland, is consistent with within-Plate basic magmatism (Macdonald, 1980; Smedley 1986a, b). Stephenson et al. (2003) and Upton et al. (2004) considered that magma generation was likely to be due to the melting of the upper mantle during crustal extension related to subduction processes hundreds of kilometres farther south. The Arthur's Seat volcano is estimated to have been approximately 1000 m high and 5 km in diameter (Upton, in Stephenson et al, 2003). It was fed from a magma chamber that at first supplied relatively undifferentiated basaltic magma (Dunsapie type). This was followed by little-differentiated basaltic magma with enrichment in cumulate crystals, seen as olivine-pyroxene-phyric basalt (Craiglockhart type); more differentiated magmas erupted later as basaltic and hawaiitic lavas (Dalmeny, Jedburgh, Markle types) and then mugearite.

The increasingly fractionated composition suggests that magma ascent rates had decreased allowing time for fractionation to occur. However, after eruption of the extrusive rocks of the cone, there was a change to more primitive magma, as evidenced by the basaltic lava flow within the Lion's Haunch Vent, the intrusions within and adjacent to the Lion's Haunch Vent, and the Whinny Hill Intrusion (Figure 4).

4.5 GULLANE FORMATION

The Gullane Formation consists of a 'cyclical' sequence predominantly of pale coloured, fine- to coarse-grained sandstone, interbedded with grey mudstone and siltstone. Subordinate lithologies are coal, seatearth, ostracod-rich limestone and dolostone, sideritic ironstone and, rarely, marine beds with low diversity faunas lacking, for example, corals. The depositional environment was predominantly fluviodeltaic, with rivers disgorging into paralic lake waters that very occasionally became marine. Desiccation cracks, soft-sediment deformation structures and bioturbation are typical of this formation. The type section is in the adjacent Haddington district (BGS Map Scotland 33W) in the Spilmersford Borehole [NT 4570 6902] (NT 46 NE/73), from 155.44 to 287.27 m depth.

Onshore, the Gullane Formation crops out under much of the city of Edinburgh in the hanging-wall block of the Murieston, Calton and Duddingston faults and the Colinton Fault system (Figures 1 and 2). The pattern of outcrop is complicated by folding along NNW trending axes, such as the Drylaw Anticline and Newhaven Syncline (Figure 2). A narrow outcrop of the Gullane Formation is present in the footwall block of the Pentland Fault, near Pentland Mains [NT 251 654], on the western limb of the Midlothian Syncline (Figure 1). The formation is inferred to underlie the syncline and also be present (but thin) within the undivided Strathclyde Group strata on the southern margin of the syncline at [NT 256 570] and [NT 280 560].

A small outcrop of pyroclastic rocks within the Gullane Formation on the western limb of the Granton Anticline at Silverknowes [NT 204 771] has been assigned to the Charles Hill Volcanic Member as seen on the coast by Braefoot Bay [NT 186 838], Fife in the Kirkcaldy district (Browne and Woodhall, 1999).

The Gullane Formation in the Edinburgh district is locally well known from its members. These are in ascending stratigraphical order, the Abbeyhill Shales, Granton Sandstones (which include the Craigleith Sandstone and the Ravelston Sandstone) and Wardie Shales (Mitchell and Mykura, 1962). The Abbeyhill Shales, overlying the Arthur's Seat Volcanic Formation, are grey and green mudstone and siltstone, about 100 m thick, that are locally bituminous and include thin ostracod-bearing limestones deposited in an overall nonmarine environment.

The overlying Granton Sandstones are off-white, sandstones, at least 175 m to 225 m thick, that are quite well exposed in Edinburgh city, particularly at Craigleith Quarry [NT 226 745], around Ravelston [NT 217 742] and on the shore at Silverknowes [NT 202 771] (McMillan et al., 1999). The Granton Sandstones include thick beds of fluvial and lacustrine-deltaic sandstones, with the distinctive and highly siliceous, fine-grained quartz-arenite of the Craigleith Sandstone (Plate 6) at the base. This sandstone is up to 105 m thick, and has impressive remains of petrified trees (Pitys withami) still to be seen in the Royal Botanic Gardens and at other gardens in the city. The Craigleith Sandstone is overlain by at least 13 m of claystones containing a thin marine limestone (Craigleith Marine Band) near the base, as seen in the conserved section in Craigleith Quarry. Up to 80 m of largely argillaceous strata intervene between the Craigleith Sandstone and overlying Ravelston Sandstone. The latter is up to 40 m thick and is well exposed at the Dean Bridge [NT 243 740]. Above this, the Wardie Shales are an argillaceous succession that includes the Ravelston Marine Band near the base and other individually mapped beds, such as the General's Rock and marine Muirhouse Shrimp Bed (Tait, 1925b) from which the first conodont animal discoveries were made (Aldridge et al., 1986; Briggs et al., 1991; Cater, 1987; Cater et al., 1989). The Wardie Shales are up to 530 m thick and comprise mudstone, siltstone and thin sandstone beds with oil shale, dolostone and ironstone. The BGS Leith Docks Geothermal Borehole NT27NE/290 [NT 28479 75934] penetrated about 120 m of the Wardie Shale with about 19 % of sandstone in this part of the succession. The thin nonmarine dolostones contain ostracods and algal bodies. The Wardie Sandstone, about 25 m thick, forms Birnie Rocks and the Long Craig on west Granton shore. The Wardie Shales include the formerly mined Wardie Coal (Tait, 1925c) that has a marine band in its roof, but recent site investigation drilling has also revealed two other seams up to 1 m thick in this part of the succession. The Dalmahoy Shale occurs locally at the top of the Wardie Shales. Further named marine bands in the Gullane Formation include the Woodhall (Tait, 1916), Campbell Park, West Mills (Lower and Upper) and Redhall/Humbie marine bands (Chisholm and Brand, 1994). The base of the last mentioned now forms the top of the Wardie Shales rather than the base of the Hailes Sandstone as previously thought (cf. Mitchell and Mykura, 1962). The Hailes Sandstone now lies wholly within the Calders Member of the West Lothian Oil-shale Formation.

Plate 6 Craigleith Sandstone, a sandstone bed within Gullane Formation, with well-formed cross-bedding. From Craigleith Quarry RIGS BGS © UKRI

4.6 WEST LOTHIAN OIL-SHALE FORMATION

The West Lothian Oil-shale Formation is characterised by distinctive seams of oil shale within a 'cyclical' sequence dominated by pale-coloured sandstones interbedded with grey siltstones and mudstones. Subordinate lithologies are coal, ostracod-rich limestone and dolostone, sideritic ironstone and beds of fossiliferous mudstone deposited in a marine environment, including bioclastic limestones with rich and relatively diverse faunas. Thick, pale green-grey or grey, argillaceous, calcareous beds, some containing volcaniclastic detritus (Jones, 2007) and described as 'marl', are also present and may have formed on extensive semi-arid plains. The 'marl' can rest directly on the mud-cracked top of an oil shale (the Broxburn Shale) as was seen in a temporary section on the Edinburgh Bypass at Burdiehouse [NT 2750 6690 to NT 2805 6690]. The environment of deposition was of fluviolacustrine deltas, subject to periodic inundation by marine water, with large freshwater lagoons rich in algae and other organic matter in which oil shale accumulated. The type area is West Lothian, where a composite section of the formation has been built up from numerous boreholes drilled to prove the oil shale seams. The base is well exposed in the Water of Leith near Redhall [NT 218 702] in Edinburgh (Chisholm and Brand, 1994, p.100), and partly exposed sections in most parts of the formation can be seen on the coast from South Queensferry [NT 13 78] to Blackness [NT 05 80] in the Livingston district (BGS Sheet 32W). The base of the formation is taken at the base of the Redhall (Humbie) Marine Band, the local equivalent of the lowest of the Macgregor Marine Bands (Wilson, 1974). The formation is laterally equivalent to the Aberlady Formation in the east of the district, and to part of the Bathgate Hills and Kinghorn volcanic formations in districts to the west and north. The top is drawn at the base of the Hurlet Limestone of the Lower Limestone Formation. The maximum thickness of the formation exceeds 450 m within the Edinburgh district, increasing to more than 1120 m in West Lothian (Chisholm et al., 1989, section 4.5). The formation is divided into two mappable members: the lower Calders Member and the upper Hopetoun Member.

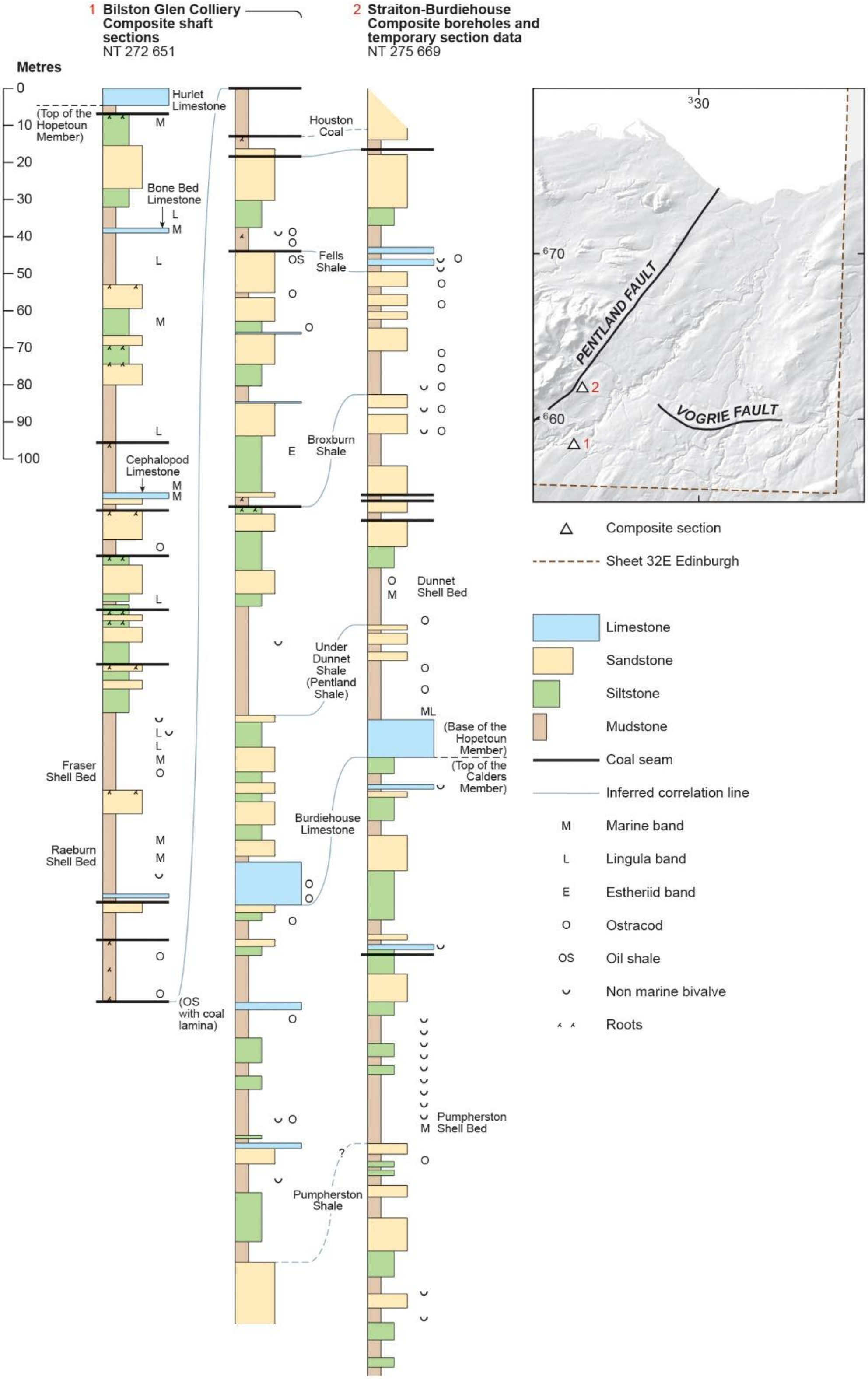


Figure 6 Composite lithological sections through the upper part of the West Lothian Oil-shale Formation in the Loanhead-Straiton area. Contains NEXTMap Britain elevation data from Intermap Technologies^{TM}. BGS © UKRI

Calders Member

The lower part of the West Lothian Oil Shale Formation, the Calders Member, crops out within the city of Edinburgh, preserved as the youngest strata within the Hailes Syncline [NT 215 710] (Figure 1). A complete sequence of the Calders Member, overlying the Gullane

Formation and overlain by the Hopetoun Member, is present on the western side of the Midlothian Syncline near Pentland Grove [NT 254 648]. The Calders Member comprises a succession of mudstone, siltstone and sandstone with thin beds of argillaceous limestone and dolostone, and oil shale. The member is about 290 m thick (Cameron and McAdam, 1978, fig. 2), but is estimated at 350 m in west Edinburgh. The Redhall (Humbie) Marine Band defines the base of the member within the district. The overlying sequence of strata, which is about 50 m thick, includes the Dalmahoy Shale. The overlying Hailes Sandstone, with a maximum thickness of about 57 m, was much worked in the past for dimension building stone and is described as blue in the lowest quarter and white and pink above (McMillan et al., 1999). Strata in the upper part of the member include the Pumpherston Shell Bed, a fossiliferous mudstone with a rich marine fauna (Figure 6). However, the overlying Pumpherston Shale, which is a well-known oil-shale deposit within the Calders Member in the adjacent Livingston district, is poorly developed in the Edinburgh district and unworked.

Hopetoun Member

The Hopetoun Member is on average about 830 m thick in the Lothians (Cameron and McAdam, 1978, fig. 2). It consists of a sequence of mudstone, siltstone, sandstone and calcareous mudstone ('marl') with thin beds of oil shale, coal, limestone and dolostone comprising the upper part of the West Lothian Oil-Shale Formation (Figure 6). The lower boundary of the Hopetoun Member is defined at the base of the Burdiehouse Limestone (Figure 6). The limestone (Plate 7) is a lacustrine deposit, 6–9 m thick, containing abundant fossilised ostracod, plant and fish remains. In the central area of the district, it was much quarried at Burdiehouse [NT 272 671] and Straiton [NT 273 667] and was extracted in the same area by underground workings at the Clippens Mine. The Burdiehouse Limestone is only tentatively correlated in the Strathclyde Group strata on the eastern side of the Midlothian Coalfield (see Aberlady Formation). The immediately overlying Camps Shale has not been formally recognised but the mudstones near the top contain *Lingula* and a poor marine fauna in the Burdiehouse and Straiton area (and at Hopetoun House). At Straiton the Under Dunnet Shale was formerly mined as the 'Pentland Shale', and is a little higher in a generally argillaceous succession with the Dunnet Shell Bed marine band at its top (Figure 6). The main parts of the Dunnet Shales known in the adjacent Livingston district (Cameron and McAdam, 1978) have not been recognised, but the Broxburn, Fells and possibly Raeburn ('Paper Shale') shales are present, and the first two have been mined at Straiton. The marine mudstones of the Raeburn Shell Bed (the Pleurotomaria Beds in Midlothian) and Fraser Shell Bed have been recognised in sections at the former Bilston Glen Colliery (Main Intake Supplies Road Section; NT26NE/88). Above, the Cephalopod (Cotcastle) Limestone and Bone Bed (Under) Limestone are developed near the top of the Hopetoun Member. Interbedded with the argillaceous succession are thin dolostone beds such as the Fells Limestone, bedded to massive, pale greenish grey limestone, or calcareous mudstone (marl) such as the Broxburn and Houston Marls. In the Halls Farm Borehole (NT25NW 16) [NT 2118 5558] just to the south of the Edinburgh district, a thin succession has been assigned tentatively to the Hopetoun Member, from the Raeburn Shell Bed (including the Fraser Shale) to the locally closely spaced Gilmerton Cephalopod and Bone Bed limestones. Interestingly, the 70 m of strata in the Halls Farm Borehole include concretionary limestone ('cornstone'), calcareous mudstone ('marl') and greenish grey sandstone with conglomerate. These last two lithologies, particularly the conglomerate, are characteristic of the footwall block strata of the Vogrie Fault (Figure 2) seen in the Shiells Borehole (NT26SE 157 [NT 2789 6092]), whose stratigraphical position of which can only be surmised. The base of the Hurlet Limestone, which defines the top of the Hopetoun Member, is correlated across the Midland Valley of Scotland (Browne et al., 2002).

Plate 7 Burdiehouse Limestone; stoop and room mineworkings in excavations for the Edinburgh City Bypass [NT 2750 6690]; detail of roof and support pillars with overlying mudstone strata, void space partly filled with glacial till from collapsed crown holes nearby. (P220286) BGS © UKRI

4.7 EASTERN MIDLOTHIAN SYNCLINE, SOUTH OF THE INCHKEITH FAULT

Strathclyde Group strata, exposed on the eastern limb of the Midlothian Syncline within the district, consist of the Garleton Hills Volcanic, Gullane and Aberlady formations (Table 2).

4.8 GARLETON HILLS VOLCANIC FORMATION

The Garleton Hills Volcanic Formation is the basal unit of the Strathclyde Group in the eastern part of the Edinburgh district. Fine-grained basaltic tuff and basalt lavas, up to 9 m thick, conformably overlie or are faulted against Inverclyde Group strata in the south-eastern corner of the district near Borthwick [NT 375 595]. A faulted inlier in Currie Glen [NT 373 594–NT 378 593] exposes the top of a basalt lava flow and is overlain by red mudstone and tuff 3 m thick. The formation conformably underlies strata of the Gullane Formation. Although the correlation of these rocks with the Garleton Hills Volcanic Formation in its type area of East Lothian is slightly tenuous, it is made on the basis that both sets of rocks are on the eastern flank of the dextral strike-slip controlled Midlothian Syncline sedimentary basin. Correlation with the Arthur’s Seat Volcanic Formation is no longer tenable (see Upton, 2003) given the postulated extent of this volcano complex. Volcanic rocks found in the Midlothian No. 1 Borehole at D’Arcy [NT 3625 6473] at 954.6 m to 1028 m depths, which have also been correlated with the Arthur’s Seat Volcanic Formation, probably also belong to the Garleton Hills Volcanic Formation.

The formation is well known farther east in the adjacent Haddington district where many of the volcanic rocks have a more evolved trachytic composition indicative of crystal fractionation prior to eruption (Williamson, 2003). The formation has been dated using $^{40}Ar/^{39}Ar$ at 342.1 ± 1.3 Ma, which places extrusion at approximately the Tournaisian–Visean boundary (Monaghan and Pringle, 2004).

4.9 GULLANE FORMATION (EASTERN LIMB OF MIDLOTHIAN SYNCLINE)

The Gullane Formation conformably overlies the Garleton Hills Volcanic Formation in the Borthwick area of the district [NT 373 592], and is about 140 m thick (Chisholm et al., 1989). It comprises mainly mudstone and siltstone, with subordinate sandstone and thin limestone bands and coal seams (Figure 7). The top of the formation is not seen in this area as it is faulted against the Aberlady Formation across the Dunbar–Gifford Fault (Figure 2).

Under the Midlothian Syncline, the Carrington Oil Well [NT 3122 6103] proved the Gullane Formation to be at least 400 m thick, but the true thickness may need adjustment for steep dips. About 30 % of the succession appeared to be sandstone. At Straiton [NT 270 670], in a series of oil wells, the formation appears to be more than 700 m thick but the poorly constrained dip may greatly affect the real thickness value. In the D’Arcy and Cousland gas field on the eastern side of the Midlothian Basin, the records of about a dozen wells provide data about the development of the Strathclyde Group. At D’Arcy (Figure 7), in the Midlothian No. 1 Well [NT 3624 6473], the Gullane Formation is at least 450 m thick (with about 29 % sandstones), and is underlain by volcanic rocks about 75 m thick that are likely to belong to the Garleton Hills Volcanic Formation. Sandstone (>148 m thick) beneath the volcanic rocks may be equivalent to the Fife Ness Formation north of the Inchkeith Fault. These rocks are known to be of Asbian (TC) age. At Cousland [NT 370 680] the formation is more than 530 m thick with about 33 % of the succession comprising sandstones, represented by the Midlothian No. 1 Well.

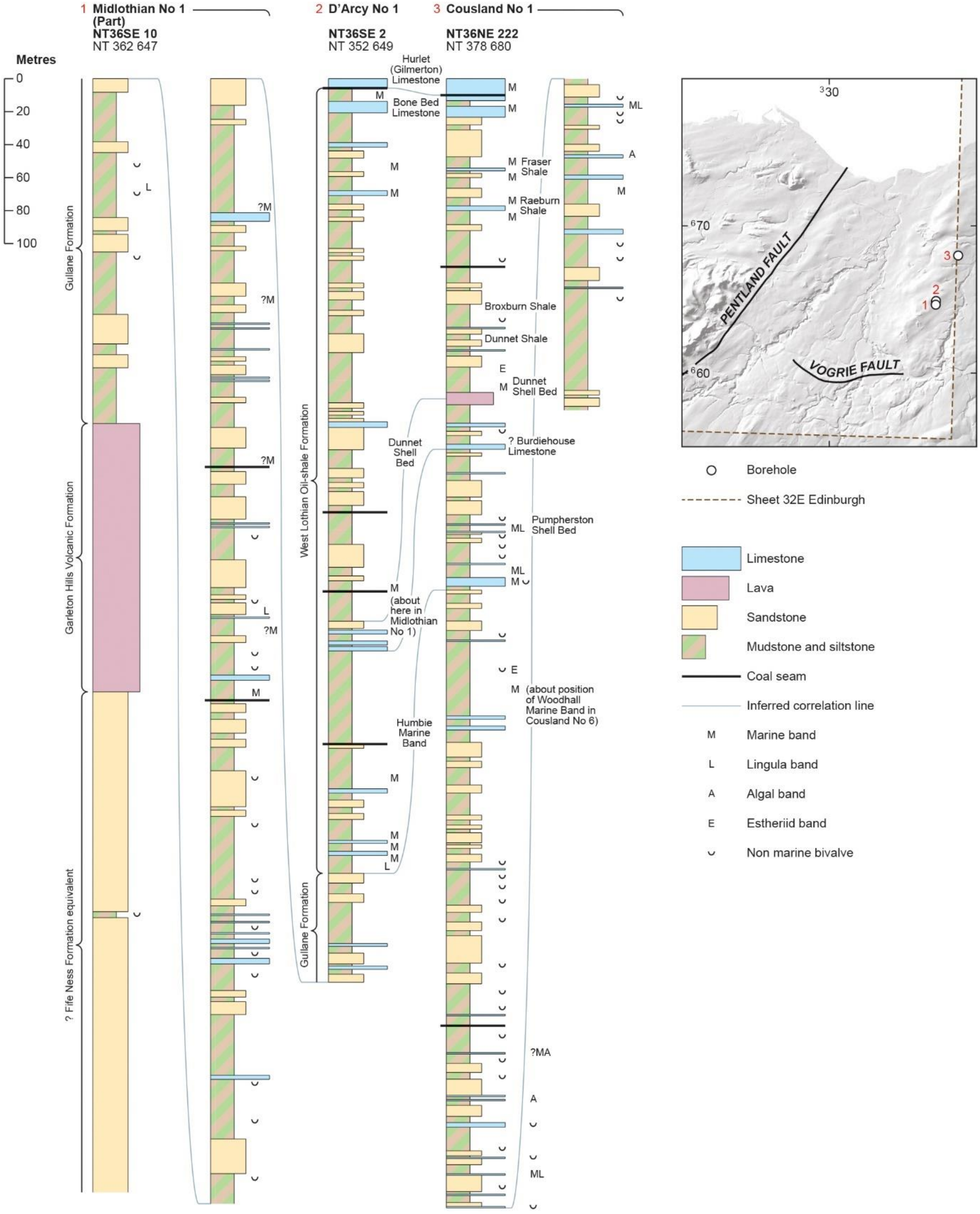


Figure 7 Generalised vertical sections for the Strathclyde Group in the Cousland–D'Arcy Anticline. Contains NEXTMap Britain elevation data from Intermap Technologies^{TM}. BGS © UKRI

4.10 ABERLADY FORMATION

The Aberlady Formation is known at surface only in the south-eastern corner of the district around Borthwick Castle [NT 370 600] north of the Dunbar–Gifford Fault. The formation consists of a 'cyclical' sequence predominantly of pale-coloured sandstone interbedded with grey siltstone and grey mudstone, and is up to 140 m thick (Chisholm et al., 1989). Subordinate but common lithologies are coal, seatearth, ostracod-rich limestone, dolostone and sideritic ironstone, and also mudstone with characteristic marine faunas (marine bands) or bioclastic limestones with relatively rich and diverse faunas. The last-named feature distinguishes the Aberlady from the Gullane formation. The depositional environment was fluviodeltaic, with rivers draining into lakes and marine embayments. The type section of the Aberlady Formation is from depths of 21.64 to 155.44 m in the Spilmersford Borehole [NT 4570 6902] (NT 46 NE/73) in the adjacent Haddington district (BGS Sheet 33W). The formation has a laterally gradational boundary with the correlative West Lothian Oil-shale Formation to the west, being distinguished from it chiefly by the rarity of oil-shale beds. Distinct limestone beds are correlated between these formations. The Burdiehouse Limestone is tentatively recognised within the Aberlady Formation and is correlated with the base of the Hopetoun Member of the West Lothian Oil-shale Formation, and with the base of the Sandy Craig Formation north of the Inchkeith Fault (Table 2). The Burdiehouse Limestone is up to 11 m thick in the Lothians but only a few metres have been tentatively identified in the Cousland–D'Arcy area. The Lower Crichton Limestone, toward the top of the Aberlady Formation on the eastern limb of the Midlothian Syncline, is correlated with the Bone Bed Limestone in the West Lothian Oil-shale Formation. Finally, the top of the Aberlady Formation is defined at the base of the overlying, conformable Hurlet Limestone that is recognised across the Midland Valley (Browne et al., 2002).

4.11 WEST LOTHIAN OIL-SHALE FORMATION (MIDLOTHIAN)

The West Lothian Oil-shale succession under the Midlothian Syncline is generally poorly known. In the Carrington Oil Well [NT 3122 6103], the Hopetoun Member succession above the Raeburn Shale is probably faulted and no more than 33 m is preserved. The underlying strata are at least 280 m thick down to the Burdiehouse Limestone (tentative correlation), and comprise about 36 % sandstone. The Calders Member, including interpreted correlatives of the Macgregor Marine Bands, is a minimum of 135 m thick (base not reached) and comprises about 41 % sandstone. In the D'Arcy and Cousland gas field (Figure 7), on the eastern side of the Midlothian Basin, the records of about a dozen wells provide data about the Strathclyde Group stratal thicknesses. In the D'Arcy area, the Hopetoun Member above the Raeburn Shale is 60 to 70 m thick and about 235 to 260 m below, both with about 32 % sandstone in the succession. The underlying Calders Member is about 130 m thick. At Cousland, the Hopetoun Member above the Raeburn Shale is 70 m thick, reducing to about 132 m below the Shale, with the Calders Member only about 82 m thick. The marine bands of the Fraser, Raeburn and Under Dunnet shell beds were recognised in the Cousland No. 1 Well (NT36NE/222) [NT 37810 68020], and the Under Dunnet in the D'Arcy No. 1 Well (NT36SE/9) [NT 336241 664796]. The Pumpherston Shell Bed and Humbie Marine Band were also identified in the Cousland Well, along with at least three other marine bands in the Gullane Formation beneath. In the D'Arcy Well, four poorly developed marine bands and two *Lingula* bands were identified. Correlation of these bands within the Gullane Formation is not possible with currently available information.

4.11.1 Fife coastal zone, north of the Inchkeith Fault

Strathclyde Group strata have been mapped in the northern part of the Edinburgh district from interpretation of seismic, gravity and magnetic potential field data, borehole geophysical logs and biostratigraphical data. Seismic surveys span the offshore area of the Edinburgh district, and extend to within approximately 3 km of the southern coastline of the Firth of Forth. The seismic profiles are calibrated using an acoustic velocity log from the Conoco Firth of Forth No. 1 Well [NT 4298 9212], within the Firth of Forth and 11 km NE of the district. The formations present are interpreted from a suite of geophysical logs and biostratigraphical data from the Firth of Forth No. 1 Well (Ritchie et al., 2003; Figure 8). There are two distinctive reflectors recognised in the well, at the top of the Kinghorn Volcanic Formation and the top of the Lower Limestone Formation (top Visean), and these are mapped to the surrounding area assisted by modelling of Bouger gravity anomaly and total magnetic field data, to define the extent of volcanic rocks. Picking of formation boundaries from geophysical logs of the well was guided using known stratigraphical thicknesses (Forsyth and Chisholm, 1977; Browne, 1986. fig. 2).

North of the Inchkeith Fault, the Strathclyde Group comprises the Fife Ness, Anstruther, Pittenweem, Sandy Craig, Kinghorn Volcanic and Pathhead formations. The range of depositional environments is similar throughout, with alternating fluviatile, deltaic, and lacustrine facies, with some thin intercalated marine, mainly argillaceous beds. An indication of the lithologies within each formation is based on onshore occurrences in Fife (Forsyth and Chisholm, 1977).

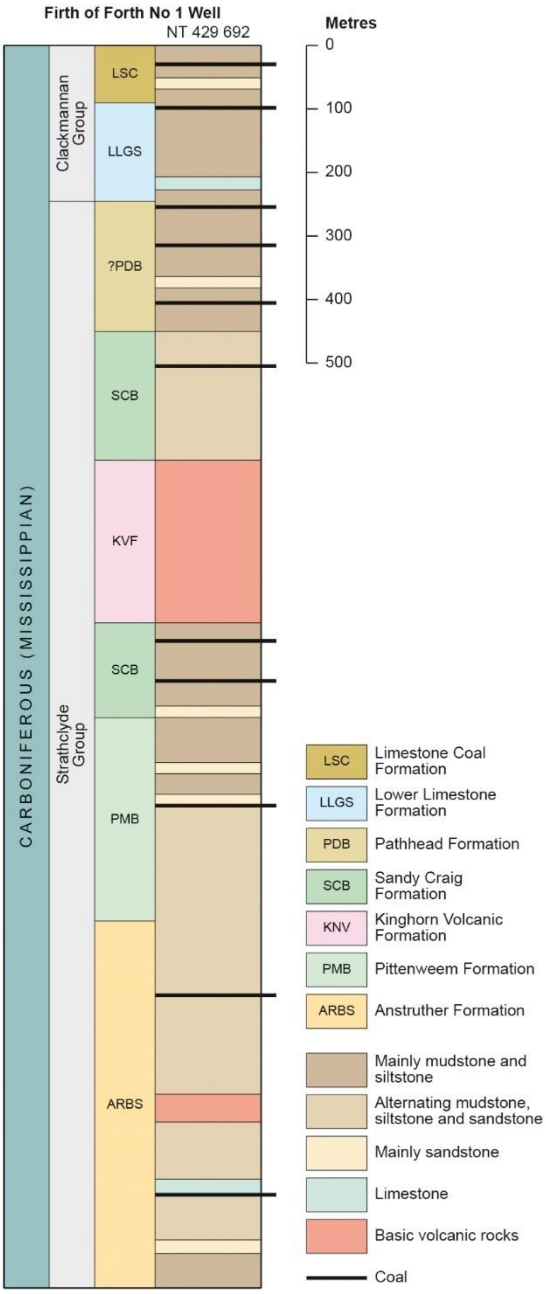


Figure 8 Generalised lithostratigraphy and lithologies in the Firth of Forth No.1 Well BGS © UKRI

4.12 STRATHCLYDE GROUP (FIRTH OF FORTH)

A different sequence of units comprises the Strathclyde Group in the north of the Edinburgh district, in the Firth of Forth and exposed locally on the Fife coast (Figure 1, Table 2).

4.13 FIFE NESS FORMATION

The Fife Ness Formation is present at the western margin of the district, mapped from its outcrop on Inchcolm just in the adjacent Livingston district (Sheet 32W). It is inferred to underlie the strata of the Anstruther Formation that are exposed on the island of Car Craig [NT 199 830], on the western margin of the district. The Fife Ness Formation is known in east Fife to consist predominantly of off-white and reddish brown or purplish grey sandstone arranged in upward fining cycles. Argillaceous beds within the formation are commonly poorly bedded; seatearths occur but no coal seams are present. Dolostone beds are developed but rare, and the associated nonmarine faunas comprise ostracods, spirorbids and algal nodules. Strata inferred to have been deposited in a marine environment are absent and the formation is essentially fluvial and lacustrine in origin. The maximum thickness of the formation exceeds 230 m in east Fife (Forsyth and Chisholm, 1977) but little is known about the formation in the Edinburgh district.

4.14 ANSTRUTHER FORMATION

The Anstruther Formation, which crops out on Car Craig [NT 199 830], overlies the Fife Ness and underlies the Pittenweem Formation north of the Inchkeith Fault (Figure 1). The base of the formation is marked by basaltic lavas and interbedded basaltic tuffs of the **Charles Hill Volcanic Member** on Car Craig, and also where seen 1.4 km to the west on Meadulse [NT 190 831] and Inchcolm [NT 193 826] islands, and the Fife coast at Braefoot Bay [NT 184 835] just in the Livingston district. Lavas and pyroclastic rocks within the member are correlated with an outcrop of basaltic tuffs once quarried at Lauriston Cottage [NT 204 771] on the coastline in the north of Edinburgh, extending the volcanic member across the Inchkeith Fault and intercalating it with the basal Gullane Formation within the Abbeyhill Shales Member. The Anstruther Formation is picked in the Firth of Forth No. 1 Well from 1420.4 to 2009.5 m (total depth) below sea bed (Figure 8).

Lithologies within this part of the formation, interpreted from geophysical logs, are mostly mudstone, siltstone, and sandstone with beds of coal, limestone and basaltic lava and/or tuff. Exposures in Fife demonstrate the limestone beds to be of nonmarine character, and also dolostone beds that may contain oncolites and stromatolites. Minor components include marine mudstone and siltstone and a few algal rich oil shale beds. Sandstone is generally off-white in colour, fine- to medium- grained and subordinate to the argillaceous rocks. Thick, upward-fining, multistorey channel sandstone beds are developed locally. The overall pattern of sedimentation is of upward coarsening lake delta cycles, capped by erosively based thinner upward-fining fluvial units. The marine faunas are usually impoverished, lacking corals and rich assemblages of brachiopods. The abundant nonmarine faunas are dominated by *Naiadites obesus*, with *Paracarbonicola* in the lower part of the formation. The maximum thickness of the formation exceeds 810 m (Forsyth and Chisholm, 1977).

4.15 PITTENWEEM FORMATION

The Pittenweem Formation overlies the Anstruther and underlies the Sandy Craig formations north of the Inchkeith Fault (Figure 1). It crops out at the sea bed in the hanging-wall block of the Pentland Fault, east of Inchkeith, where Strathclyde Group strata are folded along NNW trending axes (Figure 2). In the Firth of Forth No. 1 Well the Pittenweem Formation is picked between 1105.8 and 1420.4 m below sea bed where it is composed predominately of argillaceous sedimentary rocks with sandstone, coal and limestone beds (Figure 8). The top of the formation is identified from the last occurrence of a palynological assemblage that includes *Perotrilites tesellatus* and is assigned to the mid Asbian NM Biozone as defined by Neves et al. (1973). This last occurrence is at about the horizon of the Pittenweem Marine Band of east Fife (Forsyth and Chisholm, 1977). The thickness of the formation is over 260 m, as noted from partial sections onshore in east Fife (Forsyth and Chisholm, 1977; Browne, 1986). Onshore in Fife, the formation consists dominantly of mudstone and siltstone, with subordinate fine to medium grained sandstone; beds of nonmarine limestone and dolostone are less common than in the underlying Anstruther Formation. Marine mudstone, siltstone and limestone occur as minor, but important, components. A few algal-rich oil-shale beds and thin beds of coal and ironstone also occur. Like the Anstruther Formation, sedimentation comprises upward coarsening deltaic cycles, capped by erosively based thinner upward fining fluvial units. The marine faunas in the 'marine bands' are usually diverse and locally abundant. The rich but low diversity nonmarine faunas are dominated by the bivalve *Naiadites obesus*. The Pittenweem Formation is distinguished by the comparatively high diversity of the marine faunas in beds that are assigned to the Macgregor Marine Bands. These beds of mudstone and siltstone were named by Wilson (1974) in the Lothians, but they appear to be best developed in east Fife where they are probably all found within the Pittenweem Formation. At least five marine beds exist in the partial type sections of this formation, and comprise approximately 6 % of its thickness. They represent the first fully marine incursions to affect east central Scotland in Carboniferous times (Wilson, 1987, fig. 7). Whilst the faunas are largely facies controlled (Chisholm et al., 1989; Wilson, 1974, fig. 3), all the major fossil groups except trilobites are represented, although corals are scarce. The Macgregor Marine Bands are recognisable as a group, but no single marine bed as yet has been correlated with confidence over an appreciable distance (Wilson, 1974).

4.16 SANDY CRAIG FORMATION

The Sandy Craig Formation is exposed on Inchkeith, crops out on the sea bed in the Firth of Forth and is present in the Firth of Forth No. 1 Well (Figure 8). It is interbedded with rocks of the Kinghorn Volcanic Formation both at surface and in the subsurface. In the Firth of Forth No. 1 Well the top of the Sandy Craig Formation is picked at 498.4 m and the base at 1105.8 m below sea bed but this interval includes the volcanic formation. The base of the Sandy Craig Formation is taken at the last occurrence of the NM Biozone in the Firth of Forth No. 1 Well (see Pittenweem Formation). Interpretation of geophysical logs indicates the lower part of the formation is of siltstone and mudstone with beds of coal and limestone (Figure 8). That part of the formation above the volcanic strata is of similar lithology but more sand-rich. Onshore, the argillaceous strata typically include a minor percentage of algal-rich oil-shale. The limestone was deposited in a nonmarine, lacustrine environment. Both limestone and dolostone beds may contain oncolites and stromatolites. Multicoloured, mainly fine- to medium-grained sandstone is subordinate to the argillaceous rocks, but thick, upward-fining, multistorey sandstones are developed locally. Greenish grey claystone and calcareous marl occur, also thin beds of coal and ironstone. Nodular beds of pedogenic limestone and dolostone ('cornstone') are also present. The overall pattern of sedimentation within the formation is of upward-coarsening deltaic cycles capped by thinner upward-fining fluvial units with an erosive base. Marine faunas are very rare, and are usually of low-diversity, consisting in some cases only of the brachiopod *Lingula*. The abundant but low diversity nonmarine faunas are dominated by the bivalve *Curvirimula*. The maximum thickness of the formation, as now defined, is about 670 m in east Fife (Browne, 1986; fig. 2).

4.17 KINGHORN VOLCANIC FORMATION

The Kinghorn Volcanic Formation (Bathgate Group) is interbedded with the Sandy Craig Formation north of the Inchkeith Fault (Figure 1). The top of the volcanic formation is a locally distinct, well-resolved reflector on seismic reflection profiles (Ritchie et al., 2003, figs. 3 and 8). Basalts and tuffs of the Kinghorn Volcanic Formation are distinguished from logs of the Firth of Forth No. 1 Well between 762 m and 1020 m depths below seabed (Figure 8). Basalt lava and basaltic tuff within the formation are exposed on Inchkeith [NT 295 827]. The 'noisy' character of the aeromagnetic anomaly (Figure 19) in the vicinity of the island indicates that the volcanic formation underpins the Inchkeith High, a structural element within the Firth of Forth (Ritchie et al., 2003), in the hanging-wall block of the Pentland Fault (Figure 2). The formation is also exposed on the Fife coast at Kinghorn Ness [NT 270 860] 1.2 km north of the district, where it consists of basaltic lava flows mainly of subaerial origin, but locally subaqueous with pillow and hyaloclastic textures (Browne and Woodhall, 1999; Woodhall, 2003). The lavas are dominantly olivine- and olivine-clinopyroxene-phyric basalt, and rarely, olivine-clinopyroxene-plagioclase-phyric basalts. They are mostly microporphyritic but some macroporphyritic varieties also occur. Pyroclastic, volcaniclastic and siliciclastic sedimentary rocks are also typical of the formation, which is also well known for the preservation of early Carboniferous floral assemblages (Cleal and Thomas, 1995; Woodhall, 2003). The type section is on the Fife coast between Kinghorn and Kirkcaldy [NT 254 863 to NT 278 882]. In this area, the Kinghorn Volcanic Formation is known to interdigitate with sedimentary strata of the Pathhead and Sandy Craig formations. Its distribution is otherwise entirely under the Firth of Forth and is shown in Figure 1. The maximum thickness of the formation is over 422 m in the Seafield No. 1 Shaft [NT 2769 8953] (BGS Reg. No. NT28NE/35) in the Kirkcaldy district (Sheet 40E).

The southern continuation of the Kinghorn Volcanic Formation outcrop rises above the sea at Inchkeith. Davies (1936) recognised six lava units, with intervening sedimentary units (here referred to the Sandy Craig Formation) and several sills, some of which were previously interpreted as lavas. A total thickness of 153 m of volcanic rocks and 96 m of intrusions was recognised out of a total exposed thickness of 352 m. A limestone between the second and third lava units is considered to be the Rosyth Algal Dolostone (Guirdham et al., 2003), although it was previously correlated with the Burdiehouse Limestone which is slightly lower in the succession. No volcanic rocks of this age are recognised in the Edinburgh district south of the Firth of Forth Fault, but thin tuffs occur at this horizon in the Livingston district (e.g. Port Edgar Ash). A good fauna of 13 fossil fish and tetrapod bones has been found on Inchkeith, justifying the locality's inclusion in the Geological Conservation Review by Dineley and Metcalf (1999, pp. 98–99).

The lowest lava unit, the Cawcans Lavas, consists of three flows totalling 45 m. The lowest flow is a 30 m thick olivine-microphyric basalt (Dalmeny type), the others are clinopyroxene-olivine-microphyric basalt (Hillhouse type). These are separated by 9 m of sedimentary rock from the Kinghorn Lavas, a unit of four clinopyroxene-olivine-microphyric basalt lavas (Hillhouse type) totalling 20 m. This is succeeded by about 90 m of sedimentary rock, intruded by several sills.

The Lighthouse Lavas comprise a 15 m thick flow of olivine-microphyric basalt (Dalmeny type), followed by a 35 to 45 m thick composite flow with olivine-microphyric basalt (Dalmeny type) forming the lower part, and is clinopyroxene-olivine-microphyric basalt (Hillhouse type) forming the upper part. Above this is a flow of olivine-microphyric basalt (Dalmeny type), present only in the southern part of the island where it increases southwards from 8 to 20 m. These lavas are separated by 4 m of sedimentary rock from the Kirkcaldy Lava, a clinopyroxene-olivine-microphyric basalt (Hillhouse type) about 8 m thick.

After another 18 to 22 m of sedimentary rock, the Skerries Lavas consist of a 10 m-thick, extensively lateritised olivine-microphyric basalt (Dalmeny type), overlain by an analcime-bearing clinopyroxene-olivine-microphyric basalt ('star' basalt), 11 to 15 m thick. This flow underlies a thick basalt sill, above which is the youngest exposed flow of clinopyroxene-olivine-microphyric basalt (Hillhouse type), 15 m thick.

4.18 PATHHEAD FORMATION

The Pathhead Formation is the youngest of the Strathclyde Group formations north of the Inchkeith Fault (Figure 1). It is not exposed within the district but crops out at the seabed, within the Inchkeith Fault Zone, north and east of Inchkeith (Figures 1 and 2). Onshore, 2.5 km to the north in the Kirkcaldy district, the formation consists predominantly of mudstone and siltstone with beds of limestone and dolostone and subordinate pale-coloured, fine- to medium-grained sandstone. Thin beds of coal and ironstone also occur. The overall pattern of sedimentation within the formation is of upward coarsening deltaic cycles, erosively overlain by thinner upward-fining units deposited in fluvial environments. Beds mainly of mudstone and siltstone containing fossils characteristic of a marine environment are more common than in the underlying formations, and their faunas are usually diverse and abundant. The bivalve *Curvirimula* dominates the nonmarine faunas that are found in mudstone, dolostone and limestone, but ostracods and plant fossils are also common with algal stromatolites in some bedded lacustrine carbonates. The maximum thickness of the formation, as now defined, is about 220 m in east Fife (Browne, 1986, fig. 2).

5 Late Carboniferous

Rocks deposited in the later part of the Carboniferous are present at subcrop over most of the Edinburgh district. Strata within the Clackmannan and Scottish Coal Measures groups are present within the Midlothian Coalfield onshore and the Leven Syncline offshore (Figure 1). The distinction of late Carboniferous is informal; strata of the Clackmannan Group and the Coal Measures Group were deposited from mid Brigantian to Bolsovian times.

5.1 CLACKMANNAN GROUP

In contrast to the older Carboniferous succession, the sedimentary rocks of the Clackmannan Group form laterally extensive formations which can be mapped across the Midland Valley of Scotland; they conformably overlie the varied sedimentary and volcanic formations of the Strathclyde Group (Browne et al., 1999). The Clackmannan Group is mostly Namurian in age but the oldest formation within the group, the Lower Limestone Formation, was deposited during the latest Visean (Browne et al., 1999), whilst the youngest Passage Formation continues into the Westphalian. The Clackmannan Group comprises the Lower Limestone, Limestone Coal, Upper Limestone and Passage formations. These units are characterised by strongly cyclical sequences of sandstone, siltstone, mudstone, limestone, coal and seatearth. The presence or absence of lithologies, especially limestone, and differing proportions of the rock types characterises each formation. Thus, beds of limestone are more conspicuous in the Lower and Upper Limestone formations than elsewhere, coals are most common in the Limestone Coal Formation, and sandstones and seatearths are the most prominent constituents of the Passage Formation. Depositional environments for all four formations were largely tropical. The style of sedimentation is related to the repeated advance and retreat of fluviodeltaic systems into an embayment of varying salinity. The Lower and Upper Limestone formations contain the highest proportion of marine deposits, while alluvial deposits dominate the Passage Formation; the Limestone Coal Formation is transitionary.

The base of the Clackmannan Group is taken at the base of the Lower Limestone Formation, where a cyclical sequence of marine limestone-bearing strata rests conformably on various formations of the early Carboniferous Strathclyde Group (West Lothian Oil-shale, Aberlady and Pathhead formations).

The outcrop patterns of the Clackmannan Group and its constituent formations is largely controlled by the Midlothian and Penicuik synclines in the west central part of the district, and the D'Arcy–Cousland Anticline on the eastern side. The asymmetric nature of the Midlothian and Penicuik synclines (Figure 2) imposes shallow dips on their eastern limbs and steep dips on their western limbs, with overturned beds against the Pentland Fault. Thus broad outcrops are typical of most of the area, but these are narrow on the west side of the synclines between Joppa [NT 320 733] at the coast and Penicuik [NT 235 600] in the south-west corner of the area influenced by high dips.

The NE trending Midlothian sedimentary basin into which the Clackmannan Group sediments were deposited is thought to have been generated by strike-slip faulting on the major bounding faults of the Midland Valley terrane (Browne et al., 2003; Monaghan and Pringle, 2004) causing varying rates of subsidence and, therefore, sediment accommodation. Synsedimentary folding (dextral strike/ oblique slip) is known to have controlled the thicknesses of sedimentary rocks under the Firth of Forth and northwards in onshore Fife, including the Westfield (Bowhill) Basin [NT 200 980] and in the Kincardine

(Clackmannan) Basin [NS 970 922] (Underhill et al., 2008; Hooper 2003). The isopachyte maps of formation thicknesses demonstrate this fundamental control for these areas (Browne, 1986). In Midlothian, sufficient data are available for the Limestone Coal and Upper Limestone formations to construct isopachyte maps (Figures 9 and 10) which illustrate similar controls. Data for the Passage Formation are less abundant, but also suggest similar fault-controlled basin development (Figure 10). The presence and movement history of the Pentland Fault (with reversal of throw during the late Carboniferous) on the western, steep limb of the Midlothian Syncline, has resulted in the loss of much of the western side of the sedimentary basin by tectonically induced erosion. The total preserved thickness of the Clackmannan Group is more than 1100 m in the basin centre and less than 500 m on the southern and eastern margins. The late Carboniferous fold axes, imposed as a distant response to Variscan tectonism in southern Britain, are geographically distinct from the axis of the sedimentary basin which is farther west near the position of the Pentland Fault (Figures 9 and 10).

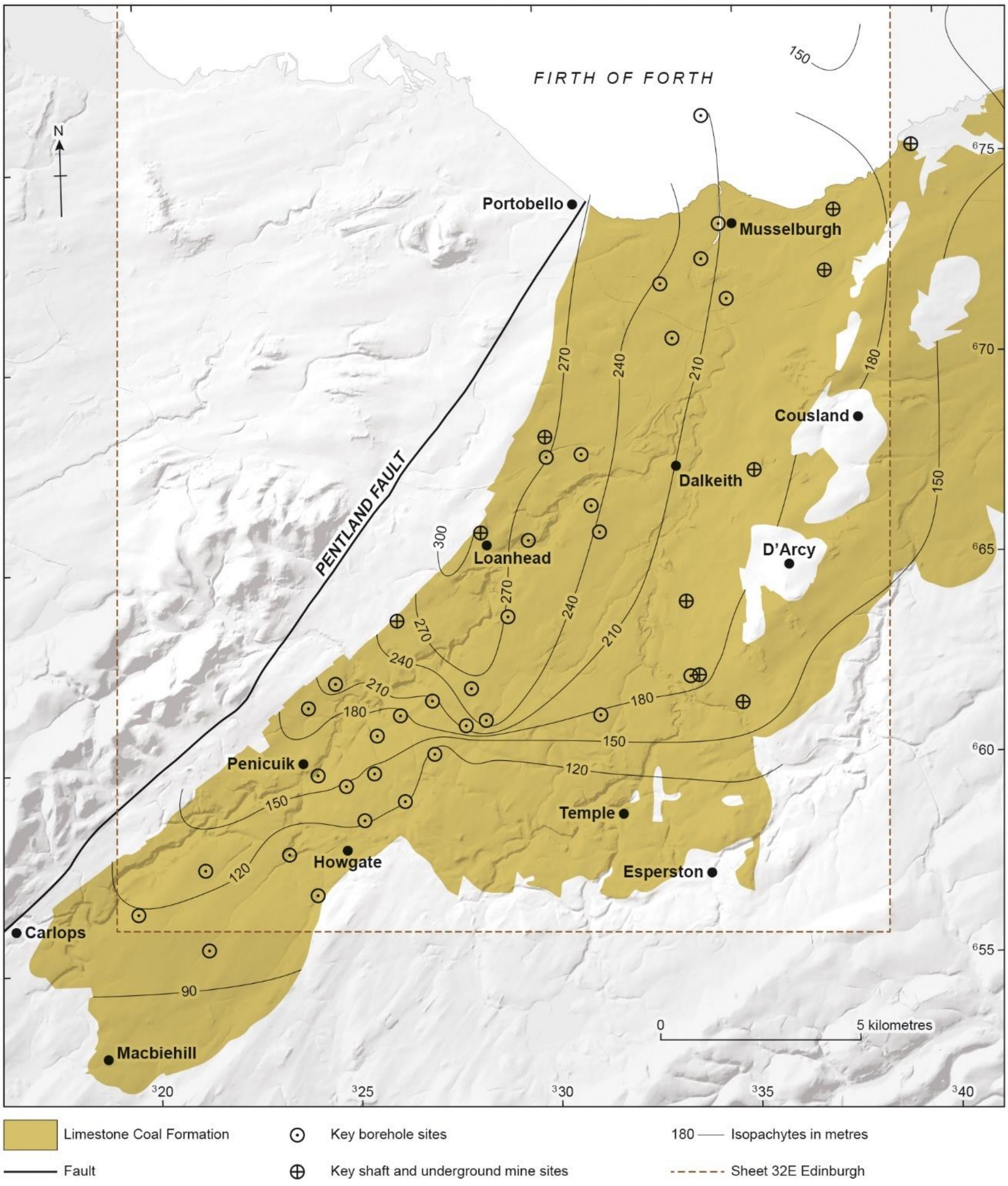


Figure 9 Isopachyte map for the Limestone Coal Formation. Contains NEXTMap Britain elevation data from Intermap Technologies^{TM}. BGS © UKRI

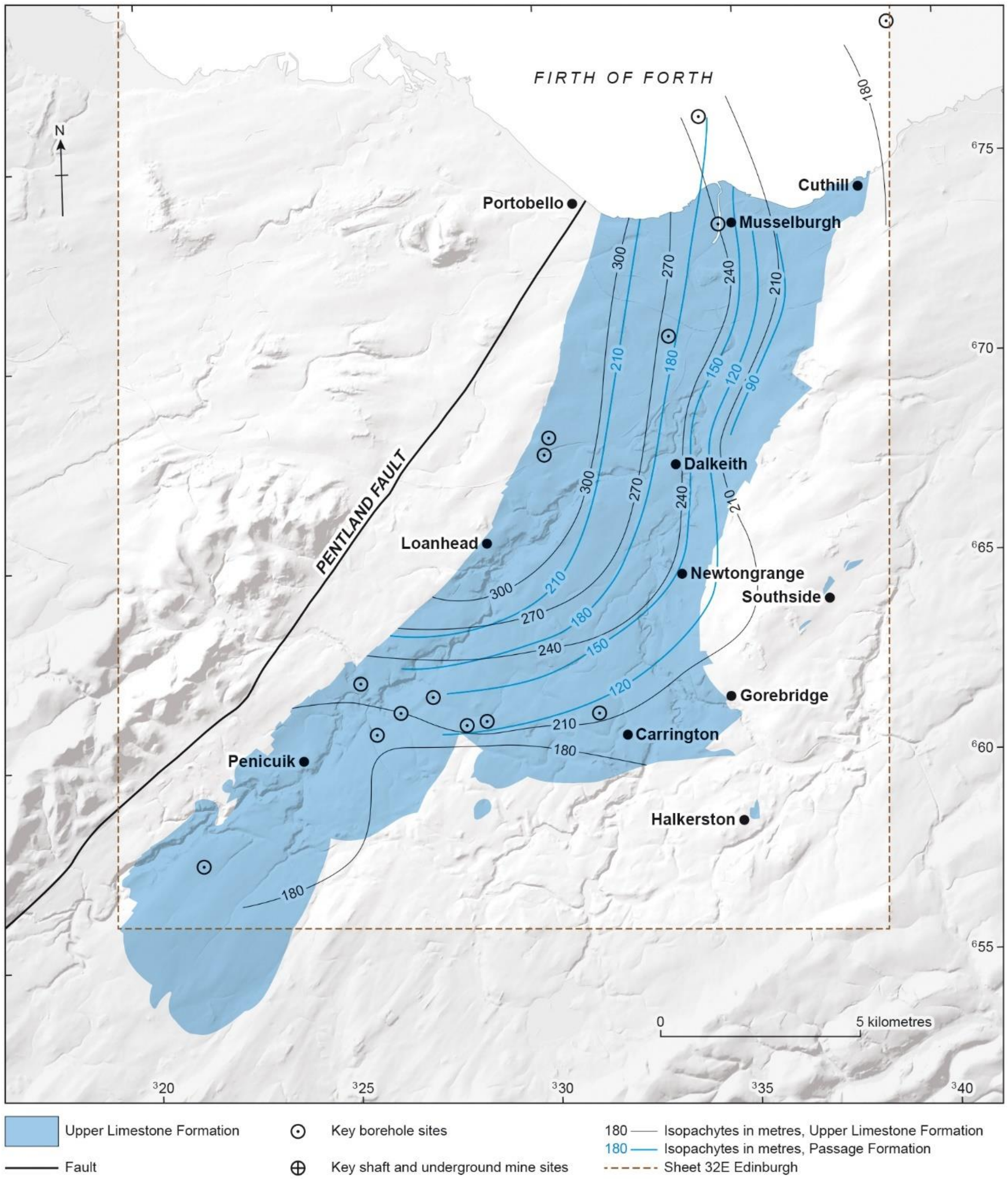


Figure 10 Isopachyte map for the Upper Limestone and Passage formations. Contains NEXTMap Britain elevation data from Intermap Technologies™. BGS © UKRI

5.2 LOWER LIMESTONE FORMATION

The Lower Limestone Formation, of Brigantian (latest Visean) age, occurs at crop within the district around the Midlothian Syncline (Figure 1). The formation comprises repeated upward-coarsening cycles of limestone, mudstone, siltstone and sandstone. Thin beds of seatearth and coal may cap the cycles. Sandstones amount to 26 to 49 % of the total succession in the formation. Limestone and hard calcareous mudstone represent as much as 21 to 30 % of the total lithology, reflecting lower siliciclastic input and perhaps a stable-shelf depositional setting. The pale to dark grey limestone is commonly a bioclastic lime mudstone or, rarely, bioclastic wackestone (Dunham, 1962), containing marine faunas and is usually notably argillaceous. The mudstone (which may also contain marine fossils) and siltstone are predominantly grey to black. A few nonmarine faunal beds are also known.

Nodular clayband ironstone and limestone are well developed in the mudstone sequences. The sandstone is usually fine- to medium-grained and generally off-white to grey in colour. Other minor lithologies in the formation include cannel coal and blackband ironstone (interleaved mud ironstone and coal). The sedimentary cyclicity recognised in the Lower Limestone Formation (and subjacent strata) reflects some control by eustatic sea level changes that can be interpreted in terms of sequence stratigraphy. However, autocyclic processes, particularly basin subsidence in a strike-slip-controlled developing sedimentary basin, were probably dominant (Kassi et al., 2004).

The base of the Hurlet Limestone defines the base of the formation, and the top of the Top Hosie Limestone defines the top. These limestones together with the Inchinnan, Blackhall, and Main, Mid and Second Hosie limestones (see table 4 in Browne et al., 1999 for former regional/local names) are correlated across the Midland Valley. The Lower Limestone Formation (Figure 11) in the Edinburgh district has a much higher percentage of limestone and calcareous mudstone than in the formation farther to the north and west (Browne et al., 1999). In the Edinburgh district, three thick limestones (Plate 8) occur within the formation (former local names and general thickness range in brackets), namely the Second Hosie (Bilston Burn; 2–14 m), Blackhall (North Greens; 9–25 m) and Hurlet (Gilmerton; 3–18 m). Thinner limestones include the Top Hosie (0–1 m), Mid Hosie (Upper Vexhim; 0.25–1.88 m), Main Hosie (Lower Vexhim; 0.7–2.2 m) and Inchinnan (Dryden; 0.7–1.76 m). The Blackhall Limestone is the only Midlothian example for which there is a recent petrographical study. Pickard (1994) recognised that there were basically three lithofacies in the limestone in the following stratigraphical order: bioclastic wackestone overlain by lime mudstone and mottled limestone. Pickard (1994, fig. 10) related the lithofacies to marine transgression (wackestone), deepening water acme (thin black mudstone), and regression leading to subaerial exposure (argillaceous and mottled facies).

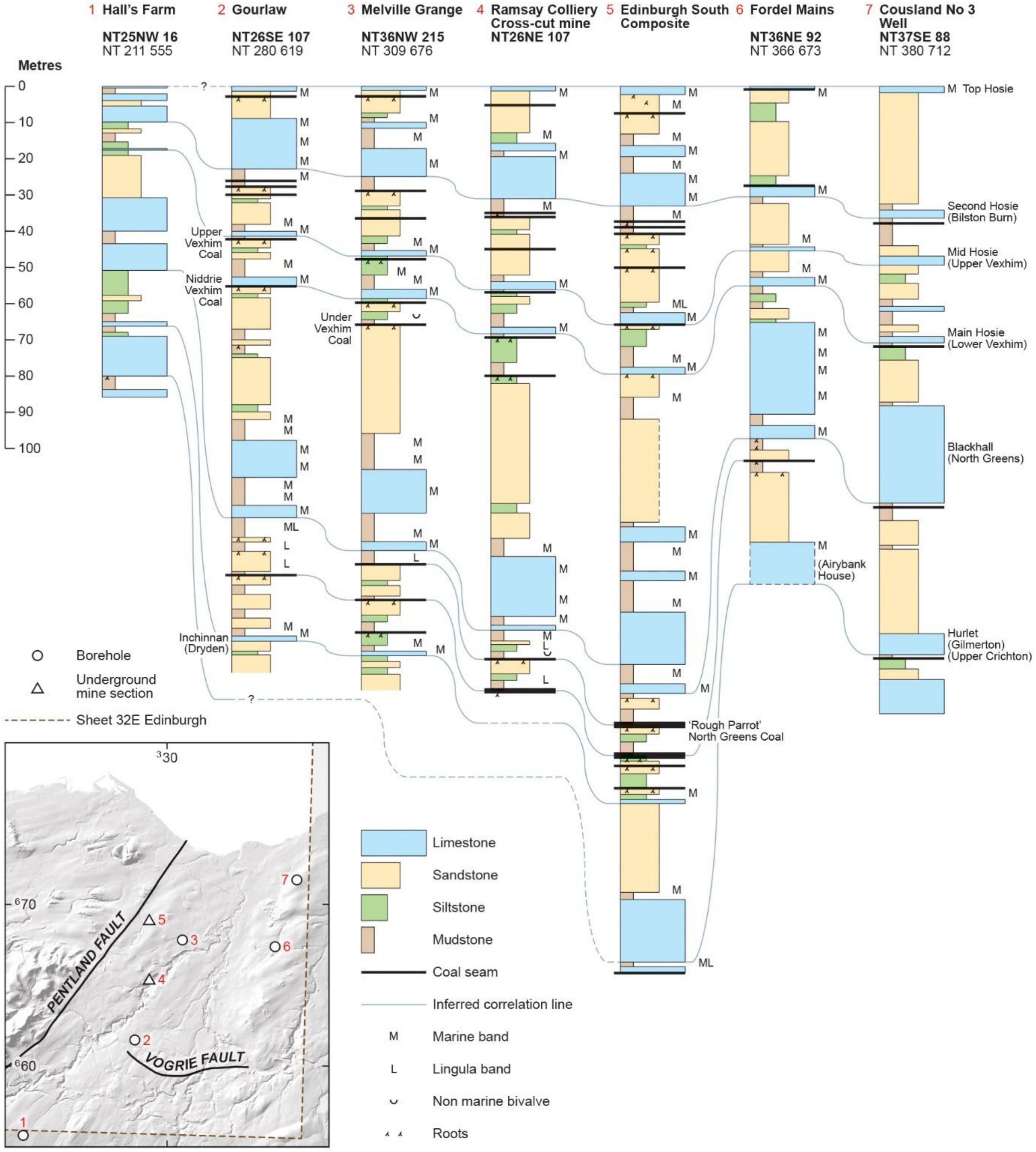


Figure 11 Generalised vertical sections for the Lower Limestone Formation. Contains NEXTMap Britain elevation data from Intermap Technologies^{TM}. BGS © UKRI

Coal seams within the Lower Limestone Formation are usually thin (less than 0.3 m) and few in number. Locally, thicker seams occur within that part of the formation underlying the Blackhall Limestone, such as the North Greens Coal that is over 1.3 m thick, and the canneloid Rough Parrot Coal which is up to 1 m thick and passes laterally into the Gilmerton Ironstone. Coals within the Lower Limestone Formation that are over 0.6 m thick and have been mined include the Under Vexhim, Lower (Niddrie) Vexhim coals, and locally the 'Lillie's Shale' Coal below the Second Hosie Limestone.

On the western limb of the Midlothian Syncline the formation occupies a narrow tract of land that extends south-west from Joppa [NT 312 679] at the coast to the Penicuik Syncline (Figures 1 and 2) south of Penicuik [NT 191 580]; at Gilmerton [NT 290 690] folding expands the outcrop width. South of the Vogrie Fault (Figure 2), the formation crops out in a broad stretch of land around the southern margin of the Midlothian Syncline eastwards from

Wellington School [NT 242 565] to Chester Hill [NT 341 562]; ground that includes the Herbershaw Anticline and the Rosebery and Halkerston synclines. The formation lies along the eastern limb of the Midlothian Syncline from Chester Hill to Crichton [NT 387 620] on the eastern edge of the district. From Gorebridge [NT 350 610] northwards to Dolphingstone [NT 384 728], four separate inliers of the Lower Limestone Formation mark the trace of the D'Arcy–Cousland Anticline (Figure 1 and 2). The two southern inliers at D'Arcy [NT 360 650] and Cousland [NT 376 684] are the largest and most structurally complex (Hallett et al., 1985, fig. 3).

The formation may be as much as 220 m thick around Gilmerton [NT 292 687] and Niddrie [NT 303 717] near the basin depocentre adjacent to the Pentland Fault, but thins southwards to less than 90 m south-west of Penicuik, and as little as 66 m on the eastern side of the Midlothian Syncline from Mount Lothian to Borthwick [NT 366 603] (Tulloch and Walton, 1958). In the Hall's Farm Borehole (NT25NW/16) [NT 2111 5558] just south of the district, the formation is 76 m thick. In the Auchendinny Borehole [NT 2496 6125], in the footwall block of the Vogrie Fault, it is more than 100 m thick with the North Greens Coal (0.66 m thick) near the base of the bore. Just north of the Vogrie Fault, the formation is more than 160 m thick, where the Gourlaw Borehole (NT26SE/107) [NT 2801 6191] in the centre of the Midlothian Syncline, terminated at the Inchinnan (Dryden) Limestone. The section in the Roslin Colliery Crosscut Mine [NT 2628 6358 to NT 2707 6283] is similar to the former with the North Greens Coal being 1.16 m thick. South of the Sheriffhall Fault (footwall), the formation was proved to the levels of the Inchinnan (Dryden) Limestone in the Melville Grange Borehole (NT36NW/215) [NT 3091 6770] and the North Greens Coal in the Bilston Glen Underground (NT36NW/216) [NT 3113 6637] Boreholes, where the thickness is greater than 166 m and 142 m, respectively. In the Ramsay Colliery [NT 276 659] the unit was at least 160 m thick (proved to level of the North Greens Coal).

Plate 8 Blackhall Limestone, Lower Limestone Formation; Middleton Quarry [NT 3530 5750]; underground view showing dimensions of stoops and rooms, lowest 6 m of 15 m thick seam extracted (P001518) BGS © UKRI

5.2.1 Fife coastal zone, north of the Inchkeith Fault

Lower Limestone Formation strata are mapped from seismic reflection and geophysical data sets to the north of the Inchkeith Fault (Figures 1 and 2), conformably overlying strata of the Strathclyde Group. The Top Hosie (Upper Kinniny) Limestone at the top of the formation, associated with a good seismic reflector, has been interpreted from geophysical log data in the Firth of Forth No.1 well (and is mapped in the vicinity of the Inchkeith Fault Zone by Ritchie et al., 2003). The formation is picked between 283.2 m and 133.8 m below sea bed (149.8 m thick). Lithologies, interpreted from geophysical logs, are mostly siltstones and mudstones with a thick limestone bed above the base and a coal seam at the top of the formation.

5.3 LIMESTONE COAL FORMATION

The Limestone Coal Formation, of Pendleian (early Namurian) age, comprises sandstone, siltstone, and mudstone in repeated cycles; the majority coarsen upwards, but others fine upwards. The cycles are usually capped by seatearth and coal. The siltstone and mudstone are usually grey to black, while the sandstone is usually off-white to grey and fine-to-medium grained. Sandstone accounts for 58 m to 135 m of the Limestone Coal Formation or 38 to 74 %, but averaging about 51 %. The highest percentages of sandstone are found in the footwall of the Vogrie Fault within the Penicuik Syncline. Coal seams are common, and many exceed 0.3 m in thickness (Plate 9); some 15 coal seams exceed 1 to 1.3 m thickness. The cumulative thickness of coal is 3 to 28 m, or 3 to 10 % of the formation. Minor lithologies include cannel coal and ‘blackband’ carbonaceous clay ironstone and ‘clayband’ clay ironstone, the latter nodular as well as bedded. Beds containing large numbers of shells (coquinas) of *Lingula* or of the nonmarine bivalves *Naiadites* and *Curvirimula* occur in the fine-grained rocks, including the ironstones and cannel coal; their preservation, mainly as squashed moulds, means that these shells usually do not form conspicuous musselbands like those of the Coal Measures. Marine shelly faunas are present in some fine-grained strata, but shelly marine limestones are not a common feature, being present only locally as thin beds towards the base of the formation as part of the Johnstone Shell Bed. Upward-fining parts of the succession, dominated by fine- to locally coarse-grained sandstone, are widely developed, and thicker multistorey channel sandstone beds are present. Locally, successions may be particularly sandy or muddy. The Johnstone Shell Bed and marine bands in the Black Metals Member can be correlated throughout the Midland Valley, but the coal seams are not so easily correlated and retain their local names (Figure 12). Details of these seams are given in the Midlothian Coalfield Memoir (Tulloch and Walton; 1958, pp. 27–60). The Johnstone Shell Bed, a shelly argillaceous marine band in 2 to 3 beds towards the base of the formation, locally contains one to two discontinuous beds of thin limestone (0.2–1.0 m thick; equivalent to the Slingstane Limestone of southern Lanarkshire and West Lothian) but the limestones occur almost exclusively in the southern part of the Edinburgh district.

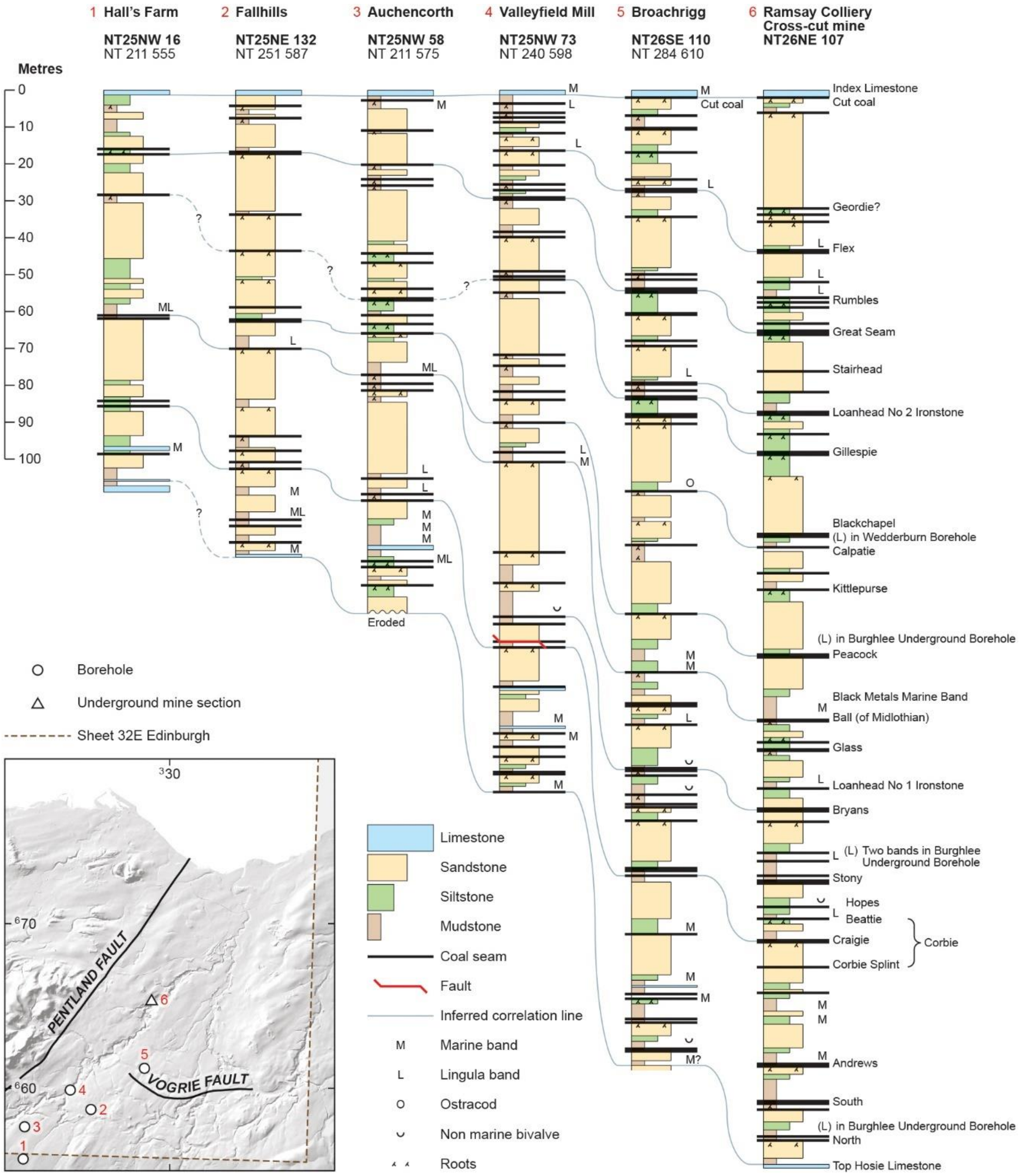


Figure 12 Generalised vertical sections for the Limestone Coal Formation. Contains NEXTMap Britain elevation data from Intermap Technologies^{TM}. BGS © UKRI

The outcrop of the Limestone Coal Formation is narrow on the steeply dipping western limbs of the Midlothian and Penicuik synclines. East of the Leadburn Fault by Howgate [NT 250 590], the outcrop is broad to Temple [NT 320 590] and Halkerston [NT 350 580] in the area of the Rosebery Syncline. From just south of Gorebridge [NT 350 610] northwards to the coast at Prestonpans [NT 380 740], the outcrop on the eastern limb of the Midlothian Syncline is broad where it includes the inliers of Lower Limestone Formation on the D'Arcy–Cousland Anticline [NT 360 640 and NT 380 680].

The formation varies in thickness (Tables 4, 5, and 6) from approximately 300 m at Bilston Burn [NT 2800 6475 to NT 2865 6490] and 276 m in the Ramsay Pit 156 Fathom Level [NT 2828 6573], near the basin depocentre on the western side of the Midlothian Syncline (Tulloch and Walton; 1958; fig. 10), to as little as 100 m west of Carlops (Hall's Farm Borehole [NT 2118 5558]), just off the southern margin of the sheet in the Penicuik Syncline.

At Penicuik it has an apparent 229 m vertical thickness at Valleyfield Mill Borehole [NT 2405 5982], but this reduces to 180 m true thickness using an average dip value of 36º. Just south of the Vogrie Fault, the formation is 119 m thick in the Auchendinny No. 3/79 Borehole [NT 2707 6025]. Just north of the Vogrie Fault, the formation is 236 m thick in the Esklee Borehole [NT 2728 6204] and 272 m in the Gourlaw Borehole [NT 2801 6191]. The formation is about 180 m thick on the eastern basin margin at Prestongrange [NT 370 740]. In the Monkton House Borehole [NT 3325 7044] a value of 240 m (completed at the Upper Johnstone Shell Bed) is suggested for the centre of the basin north of the Sherrifhall Fault, in contrast to Prestonlinks Colliery [NT 393 750] on the eastern flank. Here, underground bores suggest a little more than 145 m, with nine coal seams exceeding 0.6 m in the Monkton House Borehole but only three in one of the Prestonlinks Colliery boreholes. There are at least 23 seams of coal or ‘blackband’ carbonaceous clay ironstone (Figure 12) that have been worked on a significant basis, both by mining and opencast. The thickest is the Great Seam Coal that is up to 2.8 m thick, the origin of the name reflecting the large blocks produced in cutting the coal.

Table 4 Interval thickness data for the Limestone Coal Formation, south of the Vogrie Fault

Area	Position relative to the axis of the Midlothian Syncline	Name of borehole or section	British National Grid Reference (NT)	BGS Borehole Registered Number	Limestone Coal Formation (LSC) m	Interval thicknesses within the Limestone Coal Formation in metres				
						Top Hosie Limestone to Johnstone Shell Bed (TOHO-JSB)	Johnstone Shell Bed to Corbie Coals (JSB-COCG)	Corbie Coals to Black Metals Member (COCG-BKME)	Black Metals Member to Great Seam Coal (BKME-GSC)	Great Seam Coal to Index Limestone (GSC-ILS)
South of the Vogrie Fault	West limb of syncline	Auchencorth No 1/79 Borehole	2119 5754	NT25NW/58	147	up to 22	16	35	51	24
	Axis of syncline	Penicuik No 96 Borehole	2353 5953	NT25NW/11						33
	East limb of syncline	Hall's Farm Borehole	2118 5558	NT25NW/16	100	8	8	26	30?	26
		Valleyfield Mill Borehole	2405 5982	NT25NW/73	180†	19	27	62	86	34
		Auchendinny 2/79 Borehole	2475 5950	NT25NW/57	145	12	16	39	56	22
		Howgate (section)	250 580		120					
		Fallhills Borehole	2519 5877	NT25NE/132	124	9	15	31	52	15
		Auchendinny Wood Borehole	2564 6073	NT26SE/145		ft	18	39	73	30
		Upper Firth Borehole	2622 5909	NT25NE/133	122	11	16	33	47	15
		Auchindinny 4/79 Borehole	2622 6124	NT26SE/126	177	14	18	38	73	34
		Auchendinny 3/79 Borehole	2707 6025	NT26SE/128	119	10	15	22	44	24
		Temple (section)	320 590		120					
		Fushiebridge (section)	350 610						30	

Table 5 Interval thickness data for the Limestone Coal Formation, south of the Crossgatehall Fault, and south of the Sheriffhall Fault

Area	Position relative to the axis of the Midlothian Syncline	Name of borehole or section	British National Grid Reference (NT)	BGS Borehole Registered Number	Limestone Coal Formation (LSC) m	Interval thicknesses within the Limestone Coal Formation in metres				
						Top Hosie Limestone to Johnstone Shell Bed (TOHO-JSB)	Johnstone Shell Bed to Corbie Coals (JSB-COCG)	Corbie Coals to Black Metals Member (COCG-BKME)	Black Metals Member to Great Seam Coal (BKME-GSC)	Great Seam Coal to Index Limestone (GSC-ILS)
South of the Crossgatehall Fault	West limb of syncline	Roslin Colliery Crosscut (section)	2628 6358 to 2707 6283	NT26SE/32					106	42
		Esklee Borehole	2728 6204	NT26 SE/ 177	236	20		55	95	38
		Bilston Burn (section)	2800 6475 to 2865 6490 647	NT26SE/1	300					
		Burghlee Colliery No 1/54 (Underground) Borehole	2912 6401	NT26SE/48				71	100	
		Easthouses Colliery Underground Borehole	3135 6568	NT36NW/62		21	23	67	73	
	Axis of syncline	Gourlaw Borehole	2801 6191	NT26SE/107	272	25	31	60	102	53
		Broachrigg Borehole	2840 6106	NT26 SE/ 110	261	20	31	56	101	54
	East limb of syncline	Lady Victoria Pit (borehole)	3330 6374	NS36SW/45	198					
		Emily Pit (borehole)	3355 6202	NT36SW/71	177					
		Engine Pit Shaft, Lingerwood Colliery (borehole)	3365 6354	NT36SW/55			24?	62	60	45
		Vogrie (section)	360 630		150					
South of the Sheriffhall Fault	West limb of syncline	Ramsay Pit 156 FM Level (section)	2828 6573	NT26NE/107b	276	28	24	65	98	62
		Burghlee Underground Borehole	2949 6558	NT26NE/148		22	24	58	80	
		Melville Grange Borehole	3091 6770	NT36NW/215	212	32	25	50	65	38
		Bilston Glen Underground Borehole	3113 6637	NT36NW/216		35	23	50	>80	

Table 6 Interval thickness data for the Limestone Coal Formation, north of the Sheriffhall Fault

Area	Position relative to the axis of the Midlothian Syncline	Name of borehole or section	British National Grid Reference (NT)	BGS Borehole Registered Number	Limestone Coal Formation (LSC) m	Interval thicknesses within the Limestone Coal Formation in metres				
						Top Hosie Limestone to Johnstone Shell Bed (TOHO-JSB)	Johnstone Shell Bed to Corbie Coals (JSB-COCG)	Corbie Coals to Black Metals Member (COCG-BKME)	Black Metals Member to Great Seam Coal (BKME-GSC)	Great Seam Coal to Index Limestone (GSC-ILS)
North of the Sheriffhall Fault	West limb of syncline	Gilmerton-Melville Diamond Borehole	3007 6765	NT36NW/11	260	26	29	55	93	47
		Gilmerton Colliery (borehole)	3004 6864	NT36NW/40	277	32				55
		Stoneyhill Borehole	3299 7188	NT37SW/53				>55	81	35
	Axis of syncline	Monktonhall Colliery No 1 Shaft (borehole)	3224 7016	NT37SW/62					>70	49
		Monkton House Borehole	3325 7044	NT37SW/43	Approx 225		>15	71	68	49
		Musselburgh Sea Borehole No 1	3405 7606	NT 37NW/ 2	238			38	72	38
	East limb of syncline	Musselburgh Station Borehole	3401 7245	NT37SW/254					60	33
		Esk Mouth Borehole	3453 7332	NT37SW/ 31	215	35	15	55	74	37
		Wedderburn Borehole	3466 7147	NT37SW/ 178			>17	47	67	31
		Cowden Colliery (borehole)	3600 6706	NT36NE/40	192					
		Carberry Colliery (borehole)	3633 7007	NT37SE/73	210					
		Wallyford No 2 Pit (borehole)	3705 7217	NT37SE/37	204					
		Prestongrange No 1 Pit (borehole)	3730 7366	NT37SE	180					
		Prestonlinks Colliery No 36 Underground Borehole	3882 7843	NT37NE/20				30	59	40
		Prestonlinks Colliery (borehole)	3938 7503	NT37NE/3	145					36
					† Calculated thickness in dipping strata					

The vertical interval data from the Top Hosie Limestone to the base of the Johnstone Shell Bed marine bands (and other intervals in the Limestone Coal Formation) are summarised in Tables 4, 5, and 6. The interval varies from 35 m in the Bilston Glen Undergound Borehole [NT 3113 6637] to as little as 8 m in the south of the district near Auchencorth (less than 22 m; Top Hosie Limestone eroded in the Auchencorth No. 1/79 Borehole [NT 2119 5754]), and includes the North, South and Andrews coal seams (Figure 12). An eastwards traverse south of the Vogrie Fault (Figure 9) shows this interval is about 14 m in the Auchendinny No. 4/79 Borehole [NT 2622 6124], 10 m in the Auchendinny No. 3/79 Borehole [NT 2707 6025] and by the Leadburn Fault farther south, 9 m in the Fallhills Borehole [NT 2519 5867] and 11 m in the Upper Firth Borehole [NT 2622 5909]. North of the Vogrie Fault, this interval is 20 m at the Esklee Borehole [NT 2728 6204]), and near the depocentre, 28 m in the Ramsay Pit 156 Fathom Level [NT 2828 6573].

The Johnstone Shell Bed, in two leaves, occurs in an interval from 9 m to 27 m thick, capped by the Corbie Coals (Corbie Splint, Craigie and Beattie).

Above the Corbie Coals are the Stony, Bryans, Loanhead No. 1, Glass and Ball coal seams. The Ball seam is at the base of the Black Metals Member (which is present as one or two leaves). The interval between the Corbie Splint Coal and the base of the Black Metals Member varies in thickness from over 71 m at Burghlee Colliery No. 1/54 (Underground) Borehole [NT 2912 6401], near the depocentre, to 35 m in the south near Auchencorth No. 1/79 Borehole [NT 2119 5754] by Penicuik, and 30 m in the east in Prestonlinks Colliery No. 36 Underground Borehole [NT 3882 7843]. The interval is only 22 m thick in the Auchendinny Borehole No. 3/79 [NT 2707 6025]). There are at least two Lingula bands in this part of the succession above the Stony Coal and the Loanhead No.1 Ironstone.

The interval between the base of the Black Metals Member and the Great Seam Coal varies from about 100 m at Loanhead (Burghlee Colliery Underground Borehole No. 1/54 [NT 2912 6401]), near the depocentre in the west, to 60 m at Newtongrange in the Engine Pit Shaft, Lingerwood Colliery [NT 3365 6354] in the east, and 30 m at Fushiebridge [NT 350 610] at the south-east end of the coalfield. It is 51 m thick in the Auchencorth No. 1/79 Borehole [NT 2119 5754]. The interval contains the Peacock, Kittlepurse, Calpatie, Blackchapel, Gillespie, Loanhead No. 2, Stairhead and other lesser coal seams. There are at least three Lingula bands in this part of the succession above the Peacock and Calpatie Coals and the Loanhead No. 2 Ironstone. This last is probably the SubHartley Lingula Band of the Central and Fife coalfields (Francis et al., 1970).

The interval above the Great Seam to the base of the Index Limestone at the bottom of the Upper Limestone Formation is less well constrained, but is 62 m in the Ramsay Colliery [NT 276 659] near the depocentre, less than 55 m in the Gilmerton Colliery Crosscut Mine [NT 3004 6864], and 36 m at Preston Links [NT 395 755] in the east. At Auchencorth No. 1/79 Borehole [NT 2119 5754] it is 24 m and only 15 m by the Leadburn Fault (Fallhills Borehole [NT 2519 5867]). There are at least three Lingula bands in this part of the succession above the Rumbles (commonly *Orbiculoidea* is present), Flex and Geordie Coals. A thin mudstone rich in marine fossils forms the floor to the Index Limestone.

Plate 9 Limestone Coal Formation; Blinkbonny Coal Opencast Site, Gorebridge [NT 3485 6240] (P735466). Excavation of several thick coal seams, including the Bryans Splint Coal. (Westerly dipping strata.) Taken July 2000. BGS © UKRI

5.4 UPPER LIMESTONE FORMATION

The Upper Limestone Formation, of Pendleian to Arnsbergian (early Namurian) age, is characterised by repeated upward-coarsening cycles comprising grey limestone overlain by grey to black mudstone and calcareous mudstone, siltstone and paler sandstone capped by seatearth and coal. The cycles are typically 5 to 20 m thick. The limestones are commonly bioclastic lime mudstones or, rarely, bioclastic wackestones (Dunham, 1962), containing marine faunas and are usually notably argillaceous. The sandstone is generally off-white and fine to medium grained and varies from 90 to 130 m or 41 to 64 % of the total, averaging about 47 %. Limestone and hard calcareous mudstone represent only 1 to 3 % of the formation (in contrast to 25–30 % limestone in the Lower Limestone Formation), reflecting a higher siliciclastic sediment input and perhaps a less-stable marine shelf depositional setting during accumulation of the later Upper Limestone Formation. Coal seams are usually less than 0.6 m thick, and range from less than 1 % to no more than 2 % of the succession (1.3 m–4.88 m total). Minor lithologies include ironstone and cannel coal. Upward fining sequences of coarse- to fine-grained sandstone passing up into more fine-grained rocks, are also present.

The base of the formation is taken at the base of the Index Limestone, and the top is drawn at the top of the Castlecary Limestone (Plate 10) where this is not removed by erosion. The main limestones are the Pendleian Index (0.6–2.4 m) and Arnsbergian Orchard (0.8–4.0 m), Calmy (1.0–1.3 m) and Castlecary (0–3.0 m) limestones.

Plate 10 Castlecary Limestone, the two approximately 1 m thick easterly dipping units in foreground, and overlying Passage Formation strata; Joppa Shore SSSI [NT 3188 7343] (P734787) BGS © UKRI

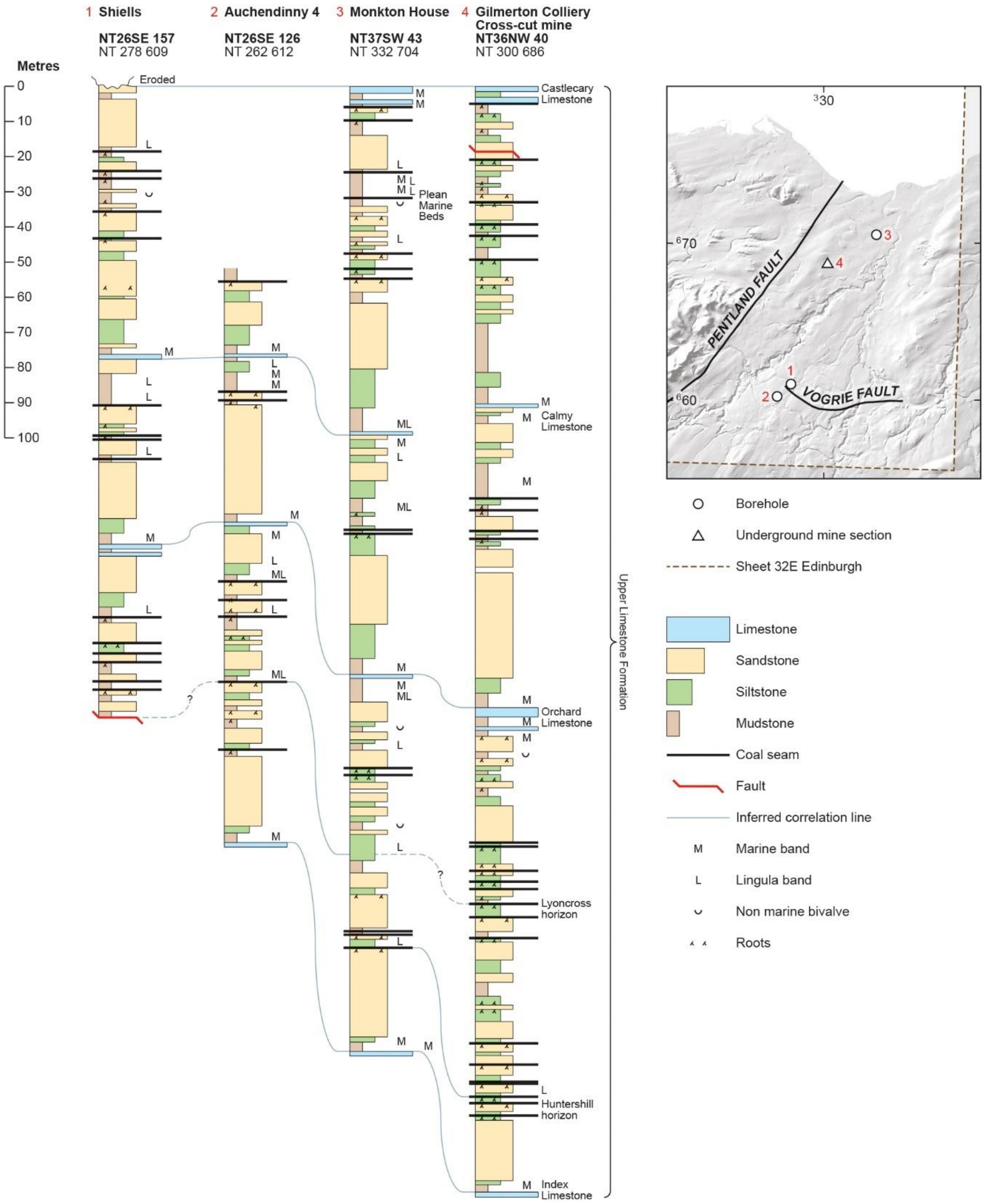


Figure 13 Generalised vertical sections for the Upper Limestone Formation. Contains NEXTMap Britain elevation data from Intermap Technologies™. BGS © UKRI

On the western limb of the Midlothian Syncline, the Upper Limestone Formation occupies a narrow tract of land from the coast at Joppa [NT 317 735] southwards to Roslin/Auchendinny [NT 265 635]. South of the Vogrie Fault, the outcrop remains narrow on the steeply dipping limb of the Penicuik Syncline, but widens considerably on the eastern flank from Wellington School [NT 235 565] to Rosslynlee Hospital [NT 265 605]. On the eastern side of the Midlothian Syncline, the formation also occupies a narrow belt from Arniston [NT 335 620] in the south to Prestonpans [NT 370 730] at the coast, reflecting the presence of the D'Arcy–Cousland Anticline to the east of its outcrop. Outliers preserved because of synclinal folding are present south of the Vogrie Fault at Edgelaw [NT 285 595] and Cauldhall [NT 282 588] moors, and at Halkerston [NT 350 585]. On the eastern side of the D'Arcy–Cousland Anticline four small faulted outliers occur between Mayfield [NT 365 633] and Vogrie [NT 376 646].

The formation (Figures 10 and 13, Tables 7 and 8) is up to 330 m thick at Bilston Burn [NT 2800 6475 to NT 2865 6490] (Tulloch and Walton; 1958, fig.13) and in the Gilmerton–Melville Diamond Borehole [NT 3007 6765], and 307 m (faulted) at Gilmerton Colliery Crosscut Mine [NT 3004 6864] and northwards to Joppa [NT 317 735] along the basin depocentre to the east of the Pentland Fault. It is over 210 m thick in the east of the basin by Newtongrange [NT 335 635] and Musselburgh [NT 360 730] and about 180 m in the south of the area by Carrington [NT 325 625]. East of Musselburgh at Cuthill [NT 380 740] it is also about 180 m thick.

The Index, Orchard, Calmy and Castlecary are the main limestone beds of the Upper Limestone Formation that occur in the Edinburgh district and, locally, the Pendleian Huntershill Cement and Lyoncross limestones and equivalents of the Arnsbergian Plean limestones are also recognised. The Index Limestone, never more than 2.4 m thick, occurs widely throughout the area, but the Huntershill Cement Limestone in the overlying sequence does not, being occasionally identified as an interval of mudstone containing only *Lingula* sp and sometimes a marine fauna. The South Parrot Coal overlies these strata and underlies the Lyoncross Limestone; this limestone is up to 0.4 m thick but only locally developed, and usually mudstone with a marine fauna or *Lingula* mark the horizon.

The interval between the Index and Lyoncross limestones varies from 55 m at Gilmerton near the depocentre, to 62 m in the Monkton House Borehole No. 37 [NT 3325 7044], to less than 50 m south of the Vogrie Fault at Penicuik (e.g. 35 m in the Auchencorth No. 1/79 Borehole [NT 2119 5754]; it is 50 m at Preston Links in the east of the basin (Tulloch and Walton; 1958, Plate iv)).

Table 7 Interval thickness data for the Upper Limestone and Passage formations, south of the Vogrie Fault, south of the Crossgatehall Fault, and south of the Sheriffhall Fault

Area	Position relative to the axis of the Midlothian Syncline	Name of borehole or section	British National Grid Reference (NT)	BGS Borehole Registered Number	Interval thicknessess in the Upper Limestone Formation in metres					Passage Formation (PGP) m
					Upper Limestone Formation (ULGS)	Index Limestone to Lyoncross Limestone (ILS-LLS)	Lyoncross Limestone to Orchard Limestone (LLS-OLS)	Orchard Limestone to Calmy Limestone (OLS-CAL)	Calmy Limestone to Castlecary Limestone (CAL-CAS)	
South of the Vogrie Fault	West limb of syncline	Auchencorth No 1/79 Borehole	2119 5754	NT25NW/58		35	19			
	Axis of syncline	Penicuik No 96 Borehole	2353 5953	NT25NW/11			15	57	55	150
	East limb of syncline	Auchendinny Wood Borehole	2564 6073	NT26SE/145		47	44			
		Auchindinny 4/79 Borehole	2622 6124	NT26SE/126		47	44	48		
South of the Crossgatehall Fault	West limb of syncline	Roslin Colliery Crosscut (section)	2628 6358 to 2707 6283	NT26SE/32		64	36			
		Bilston Burn (section)	2800 6475 to 2865 6490 647	NT26SE/1	330				120	
	Axis of syncline	Shiells 1/82 Borehole	2789 6092	NT26SE/157				56	77*	133
		Broachrigg Borehole	2840 6106	NT26 SE/110		Approx 92				
	East limb of syncline	Carrington (section)	325 625		180				55	
		Newtongrange (section)	335 635		210					
		Arniston Mains No 2 Borehole	3398 6037	NT36SW/95				45		
South of the Sheriffhall Fault	West limb of syncline	Melville Grange Borehole	3091 6770	NT36NW/215		Approx 82				

Table 8 Interval thickness data for the Upper Limestone and Passage formations, north of the Sheriffhall Fault

Area	Position relative to the axis of the Midlothian Syncline	Name of borehole or section	British National Grid Reference (NT)	BGS Borehole Registered Number	Interval thicknessess in the Upper Limestone Formation in metres					Passage Formation (PGP) m
					Upper Limestone Formation (ULGS)	Index Limestone to Lyoncross Limestone (ILS-LLS)	Lyoncross Limestone to Orchard Limestone (LLS-OLS)	Orchard Limestone to Calmy Limestone (OLS-CAL)	Calmy Limestone to Castlecary Limestone (CAL-CAS)	
North of the Sheriffhall Fault	West limb of syncline	Gilmerton Colliery (section)	3004 6864	NT36NW/40	>307	55	73	86	ft90	240
		Gilmerton-Melville Diamond Borehole	3007 6676	NT36NW/11	330			82	113	
		Niddrie Railway Cutting (section)	3132 7267 to 3152 7220	NT37SW/16	320	76	42	95	109	
		Joppa Shore (section)	3174 7349 to 3230 7345	NT37SW/1						210
	Axis of syncline	Monktonhall Colliery No 1 Shaft (borehole)	3224 7016	NT37SW/62	290	42	66	80	102	204
		Monkton House Borehole	3325 7044	NT37SW/43	272	62	42	73	95	185
		Musselburgh No.1 Offshore Borehole	3405 7606	NT37NW/2	>245	>55	46	63	>78	187
	East limb of syncline	Musselburgh Station Borehole	3401 7245	NT37SW/254		>60				
		Esk Mouth Borehole	3453 7332	NT37SW/ 31	249			66	99	166
		Wedderburn Borehole	3466 7147	NT37SW/ 178		>50				
		Levenhall No 71 Borehole	3581 7310	NT37SE/6						108
		Musselburgh (section)	360 730		210					
		Cuthill (section)	380 740		180					
	East limb of syncline	Prestonlinks Colliery No 36 Underground Borehole	3882 7843	NT37NE/20		55	29			
									*Eroded top to the Castlecary Limestone	

The interval between the Lyoncross and the base of the Orchard Beds varies from 73 m at Gilmerton and Monktonhall to only 15 m in south-west Penicuik (Penicuik No.96 Borehole [NT 2353 5953]). It is 46 m in the Musselburgh Sea Bore No. 1 [NT 3405 7606] and 30 m at Preston Links. This interval includes a number of thin coal seams.

The Orchard Limestone may be distinguished from other Scottish Carboniferous limestones because of its slightly increased abundance of shelly fossils, but is commonly unrecorded or in thin inconstant beds of only 0.3 to 2 m thickness in the Edinburgh district. Near Penicuik and generally at the southern end of the area the limestone can be up to 4 m thick, but not always as one leaf. The limestone occurs near the base of the Orchard Beds comprising marine mudstone and siltstone, which in total can be 22 m thick.

The interval from the base of the Orchard Beds to the Calmy Limestone (Tulloch and Walton; 1958, Plate iv) is up to 90 m thick at Niddrie Railway Cutting section [NT 314 724], near the depocentre, but at Penicuik in the south it is 48 m in the Auchendinny No. 4/79 Borehole [NT 2622 6124]), and 45 m at Arniston Mains No. 2 Borehole [NT 3398 6037] on the east side of the basin. Thin and inconstant coal seams occur in this interval with the Wood Coal, the local equivalent of the Upper Hirst Seam of the Central Coalfield. Where the Wood Coal is developed in the northern part of the basin, it is up to 0.75 m thick, for example at Niddrie [NT 314 724], Gilmerton [NT 301 676] and Bilston Glen [NT 282 648] and about 0.5 m in Cowden Colliery, Dalkeith [NT 3600 6706].

The Calmy Limestone is a pale to dark grey, fine-grained, crinoidal bioclastic limestone and usually only 1.3 m thick or less within the Edinburgh district, except in the southern part of the area around Penicuik where up to 2.5 m has been recorded. The Calmy Limestone is overlain by strata that include lateral equivalents of the Plean limestones and related marine bands of the Central Coalfield, and the Castlecary Limestone at the top of the formation. Four marine or Lingula bands have been recorded with one or two inconstant limestone beds. The Castlecary Limestone is also pale to dark grey, fine-grained, crinoidal bioclastic limestone but may be locally dolomitic and contain distinctive oncolitic algal nodules. The Upper Limestone Formation overlying the Calmy Limestone to the Castlecary Limestone (Tulloch and Walton; 1958, Plate iv) varies from over 120 m at Bilston Glen [NT 282 648], near the depocentre, to as little as 55 m in south-west Penicuik (Penicuik No. 96 Borehole [NT 2353 5953]) and in the River South Esk near Carrington Barns [NT 332 615], in the south of the basin. Here the Castlecary Limestone was eroded by down-cutting of subsequently sandstone-filled channels of the overlying Passage Formation. In the Monkton House Borehole [NT 3325 7044] it is 95 m. A number of thin coal seams are developed but rarely reach 40 cm in thickness. The Castlecary Limestone is usually developed in two beds up to 1.5 m thick separated by mudstone 1.3 m thick, but the limestone is missing through penecontemporaneous erosion in the southern part of the district to the south of Bilston Glen.

5.5 PASSAGE FORMATION

The Passage Formation is Arnsbergian to Langsettian (Namurian to early Westphalian) in age and characterised by an alternation of fine- to coarse-grained sandstone (with some conglomerate) and structureless claystone (including some high-alumina seatclay and fireclay). Sandstones form 62 to 128 m thickness or 47 to 64 % of the total succession (Figure 14). The claystone is commonly mottled reddish brown and greenish grey. Upward-fining cycles, ranging from 3 m to 20 m thickness, or noncyclic sediments predominate over upward-coarsening cycles. Bedded grey and black siltstone and mudstone are also present, as well as beds of limestone, ironstone, cannel coal and coal. Coal seams form 0.35 to 5.64 m total thickness or up to 4 % the total succession, almost all accounted for by the Eskmouth Extra Coal near the top of the formation. The depositional environment was predominantly alluvial and deltaic but with periodic evidence of marine conditions. Periods of greater marine influence are indicated by ‘Marine Bands’ and discontinuous limestone and ironstone beds. The ‘Marine Bands’ are to be found in the lower half of the unit; five have been identified at Joppa Shore [NT 321 734] and four in Gilmerton Colliery (NT36NW/40) [NT 3000 6865 to NT 3062 6851]. These intervals of mudstone with marine fossils are considered equivalent to the No. 0 to No. 3 Marine Band ‘groups’ of the Central Coalfield to the west of the district (Francis et al., 1970, fig.20). Whether the uppermost bands recognised within the Edinburgh district are equivalent to the No. 5 or No.

6 Marine Bands of the Central Coalfield is doubtful. Marine Bands are poorly developed in the southern part of the Edinburgh district and the marine faunas of these horizons become progressively impoverished upwards.

The Passage Formation forms a narrow outcrop on the steeply dipping western limb of the Midlothian Syncline (Figure 1) from Joppa [NT 320 735] southwards to the Sheriffhall Fault [NT 300 670], where it widens because of shallower dipping strata as far south as Roslin [NT 275 630], just north of the Vogrie Fault. The formation also occupies a north-east-trending elongate zone 1 to 2 km wide in the middle of the Penicuik Syncline [NT 255 620 to NT 210 565]. The outcrop of the Passage Formation in the centre of the Midlothian Syncline is truncated to the north of the Vogrie Fault and here [NT 270 630 to NT 320 600] only occupies a narrow, curved easterly trending tract. On the eastern limb of this fold the outcrop is generally narrow from Carrington [NT 325 605] northwards to Musselburgh [NT 360 730].

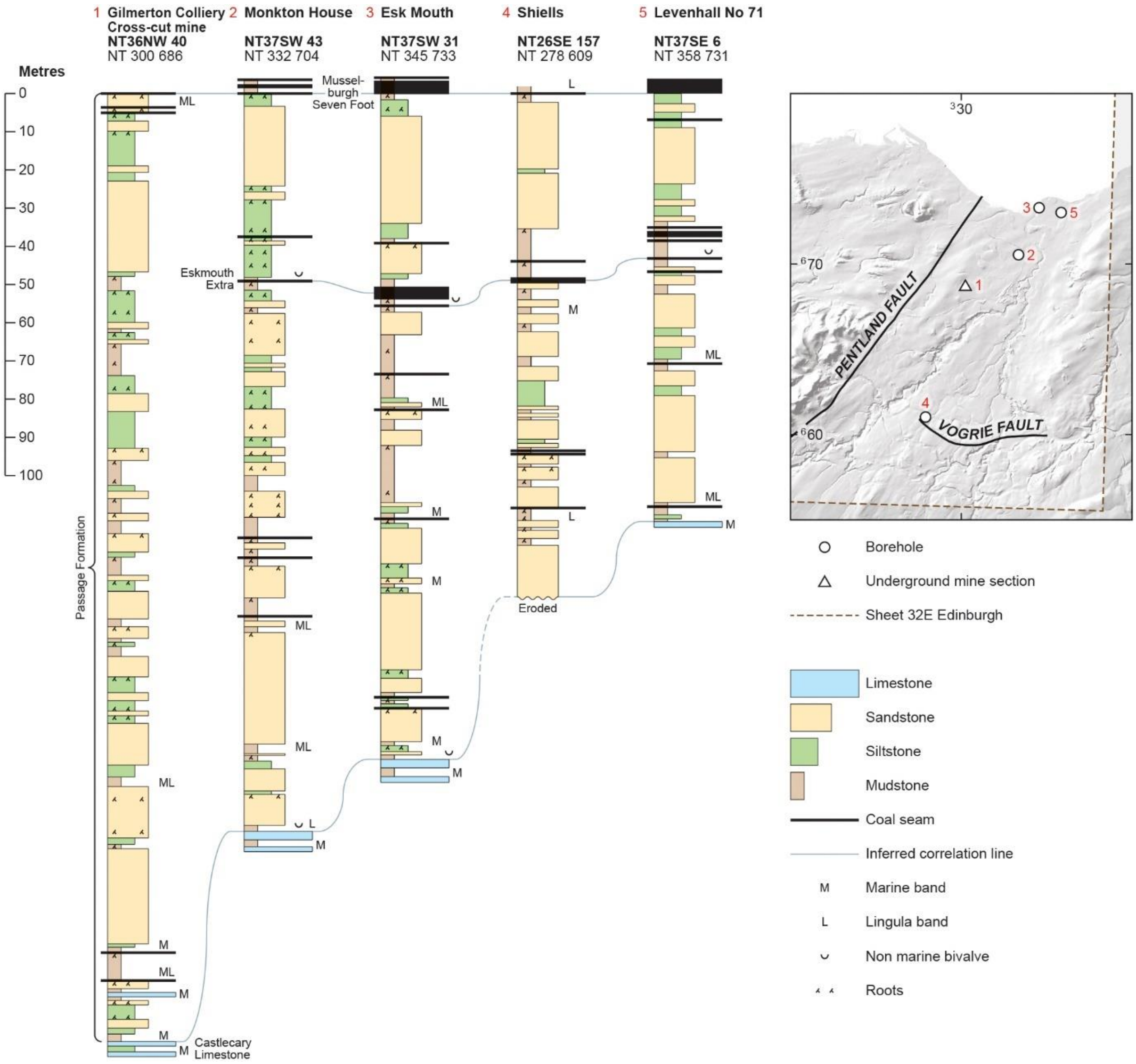


Figure 14 Generalised vertical sections for the Passage Formation. Contains NEXTMap Britain elevation data from Intermap Technologies^{TM}. BGS © UKRI

The thickness of the formation Is poorly known (Tulloch and Walton; 1958, fig.14) but is 210 m at Joppa and 240 m near the depocentre, at Gilmerton and 150 m in the Penicuik No. 96 Borehole [NT 2353 5953] in the south. In the Musselburgh Sea Bore No. 1 [NT 3405 7606] the formation is 187 m thick with the multi-leaved, approximately 6 m-thick Eskmouth Extra Coal up to 55 m below the top with sandstone dominating the succession above the coal. Just 2 km south of the Musselburgh Station Borehole [NT 3401 7245] in which the Eskmouth Extra Coal is about 2 m thick, the Monkton House Borehole only shows a few centimetres of cannel coal and coal at this horizon. In the hanging wall of the Vogrie Fault (Figure 2) the Passage Formation appears to be 133 m thick in the Shiels Borehole 1/82 [NT 2789 6092], with an erosive base that cuts out the underlying Castlecary Limestone. Here the top occurs just below a coal seam (Melville 'group') with a *Lingula* band in its roof. In the east at Levenhall No. 71 Borehole [NT 3581 7310] the formation is about 108 m thick, including the Eskmouth Extra Coal (about 3.4 m thick) and the Castlecary Limestone at the top of the sea.

5.6 SCOTTISH COAL MEASURES GROUP

The Scottish Coal Measures Group (Westphalian in age) comprises repeated cycles of sandstone, siltstone and mudstone with coal and seatearth, arranged in both upward-fining and upward-coarsening units. The strata are generally grey in colour but extensively reddened towards the top. A wide range of alluvial and lacustrine depositional environments are represented. These include wetland forest and soils (coal and seatearth), floodplain (planty or rooted siltstone and mudstone), river and delta distributary channel (thick sandstone beds), prograding deltas (upward coarsening sequences) and shallow lakes (mudstone intervals with nonmarine macrofossil faunas). Marine Bands are rare but provide important stratigraphical markers.

In Scotland, the base of the Coal Measures Group is now taken at the base of the Lowstone Marine Band or its local correlative, or at a surface of disconformity. Present practice therefore differs in detail from that adopted by MacGregor (1960), but the base of the group is still drawn at a slightly higher stratigraphical level than in England and Wales, where it lies at the base of the Subcrenatum Marine Band, and so at the base of the Langsettian (Westphalian A) Stage. This horizon has not been recognised in Scotland, though it may correlate with one of the higher marine bands of the Passage Formation (No. 6 Marine Band of the Central Coalfield; Browne et al., 1999. p.18). The boundary between the Scottish Lower and Middle Coal Measures formations is drawn at the Vanderbeckei Marine Band, and that between the Scottish Middle and Upper Coal Measures formations at the Aegiranum Marine Band. The latter boundary thus lies at a lower level in the sequence than the Middle/Upper Coal Measures boundary in England and Wales.

Onshore within the Edinburgh district, the Scottish Coal Measures Group occurs along the main axis of the Midlothian Syncline (Figure 1), from the north side of the Vogrie Fault just south of Rosewell [NT 280 610] to the coast at Joppa [NT 325 735] and Musselburgh [NT 353 735]. The Scottish Lower Coal Measures Formation forms a broad outcrop southward from Eskbank [NT 325 670] to Rosewell [NT 280 610] but also occurs in a small faulted outlier farther south-westwards under southern Penicuik [NT 235 595] in the rather narrower Penicuik Syncline south of the Vogrie Fault. The Scottish Middle Coal Measures Formation forms a broad outcrop north of the Sheriffhall Fault just north-west of the Eskbank–Dalkeith area [NT 330 680] to just south of the coast [NT 335 720]. They also have a limited crop just to the south of this fault. The Scottish Upper Coal Measures Formation is limited to two occurrences onshore, with one outcrop comprising a syncline in the hanging-wall of the Sheriffhall Fault at Dalkeith Palace [NT 330 680], and the other exposed on the shore at Musselburgh Harbour [NT 335 735].

5.7 SCOTTISH LOWER COAL MEASURES FORMATION

The Scottish Lower Coal Measures Formation (Figure 15) comprises sandstone, siltstone and mudstone, with minor coal, in repeated cycles which most commonly coarsen upwards, but also fine upwards, with seatearth and coal at the top. The mudstone and siltstone are usually grey to black, while the sandstone is fine to medium grained and off-white to grey in colour. Coal seams are common (15–24) and many (11–12) exceed 0.3 m in thickness, amounting cumulatively to between 8 and 15 m or 5–8 % of the total succession. Minor lithologies include cannel coal and 'blackband' carbonaceous clay ironstone and 'clayband' clay ironstone, the latter nodular as well as bedded. Fossiliferous intervals, composed mainly of nonmarine bivalves, are termed 'mussel bands', and usually occur in mudstone or ironstone beds. Upward fining parts of the succession, dominated by fine- to coarse-grained sandstone, are widely developed and thick multistorey sandstone beds are a feature of the formation. Cumulatively these sandstone intervals amount to between 61 and 143 m or 45 to 64 % averaging 53 % of the formation.

There are more than 10 coal seams that have been mined within the Scottish Lower Coal Measures in the Edinburgh district. The thickest of these are in the lower third of the unit. The main coal seams are the Little Splint (Midlothian), Cowpits Five Foot, Quarry (Midlothian), Salters, Musselburgh Nine Foot, Musselburgh Fifteen Foot, Four Foot (Midlothian) and Musselburgh Seven Foot. Details of these seams are given in the relevant Coalfield Memoir (Tulloch and Walton; 1958, pp.93–116). Although it has long been recognised that the nonmarine bivalve faunas of the Midlothian Coalfield are poor, these ‘mussels’ have been recorded above most of the above-named seams except the Salters and Quarry. One to two intervals bearing marine fossil faunas (Marine Bands) have also been described above the Seven Foot Coal and below the Four Foot (Tulloch and Walton; 1958, fig.15) where these seams thin and split into the Melville ‘group’, for example in the Edinburgh City Bypass temporary section near Gilmerton (NT36NW/417) [NT 3004 6769] (Browne, 1998a).

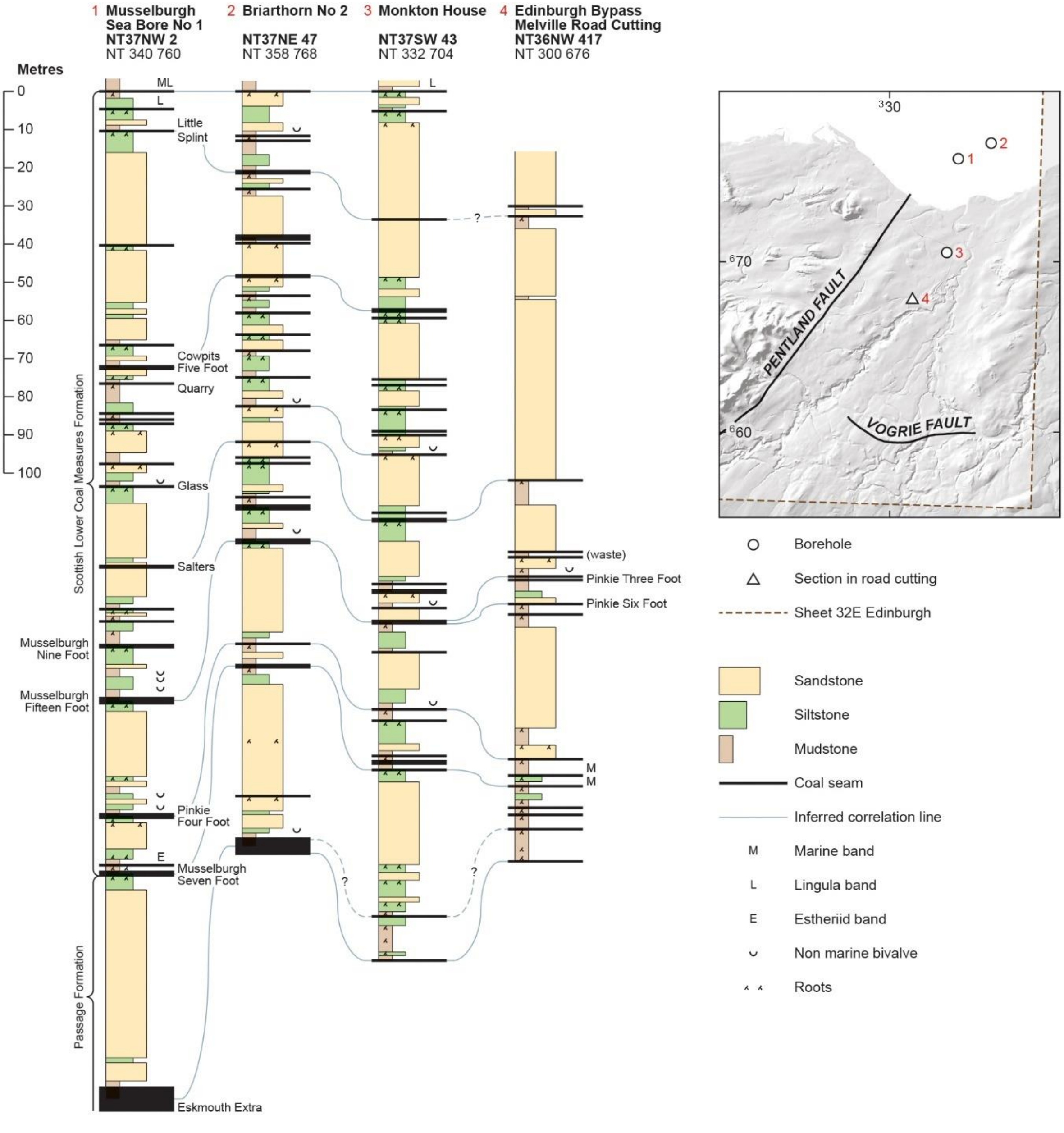


Figure 15 Generalised vertical sections for the Scottish Lower Coal Measures and upper part of Passage Formation. Contains NEXTMap Britain elevation data from Intermap Technologies™. BGS © UKRI

The maximum thickness of the formation is about 220 m to 240 m in the Sealab No. 2 Borehole [NT 3272 8449] (BGS Reg. No. NT38SW/1) under the Firth of Forth, located on the northern edge of the Edinburgh district. The variation in thickness is a function of correction for a stratal dip ranging between 35 and 40° (uncorrected thickness about 288 m). Onshore in Midlothian, it is less than 180 m thick at Monktonhall Colliery (Tulloch and Walton; 1958, Plate v), but elsewhere is probably thinner. Offshore in the Briarthorn boreholes, the thicknesses are 128 m (No. 3 (NT37NE/48) [NT 3740 7845]), 151 m (No. 2 (NT37NE/47) [NT 3587 7680]), 160 m (No. 1 (NT37NE/46) [NT 3543 7543]) and about 185 m (No. 5 (NT37NE/50) [NT 3506 7648]); this variation reflecting location nearer the depocentre of the sedimentary basin on a westerly thickening trend. Farther west in the Musselburgh Sea Tower No. 3 Borehole (Musselburgh No. 3 Offshore Bore NT37NW/1) [NT 3341 7509], it is 224 m thick near the centre of the Midlothian basin and 205 m in Sea Bore No. 1 (NT37NW/2) [NT 3405 7606]).

5.8 SCOTTISH MIDDLE COAL MEASURES FORMATION

The Scottish Middle Coal Measures Formation (Figure 16) is made up of similar lithologies to the Lower Coal Measures; sandstone, siltstone and mudstone in repeated cycles which most commonly coarsen upwards, but also fine upwards, with seatearth and coal at the top. The mudstone and siltstone are usually grey to black, while the sandstone is fine to medium grained and off-white to grey in colour. Sandstone accounts for 60 m to more than 126 m or 44 to 65 % of the formation. Few coals have been mined extensively in the Middle Coal Measures, with the thickest seams in the Edinburgh and adjacent districts being the McLachlan, Clayknowes, Musselburgh Splint, Musselburgh Rough, Beefie, Musselburgh Diamond, Musselburgh Jewel, and Golden coal seams (Figure 16). Details of these seams are given in the relevant Coalfield Memoir (Tulloch and Walton; 1958). There are 7 to 18 coal seams in the formation of which at least 9 to 11 are over 0.3 m thick. Cumulative thickness of coal varies from at least 6.3 m to more than 10 m or 4 to 5 % of the total succession. Although nonmarine bivalve faunas or ‘mussels’ of the Midlothian Coalfield are not abundant, they have been recorded above most of the above-named seams except the Clayknowes, Rough and Golden coals. Tulloch and Walton (1958, fig.15) described a distinctive mudstone with marine fossils, the ‘Skipsey’s Marine Band’. However, it is now known that there are three thin intervals of marine strata in the upper part and top of the formation; the basal pair were formerly associated with the Aegiranum Marine Band (“Skipsey’s”) and the third, uppermost one is considered to define the base of the Scottish Upper Coal Measures Formation (Browne; 1998b, fig.1). The lower pair are now called the Wellesley and Chemiss Den marine bands. In the Briarthorn No. 4 Borehole (Briarthorn No. 4 Seabore, NT37NE/49) [NT 3570 7821], the 1.7 m thick McLachlan Coal lies above the lower two marine bands. The Vanderbeckei (Queenslie) Marine Band is developed at the base of the formation.

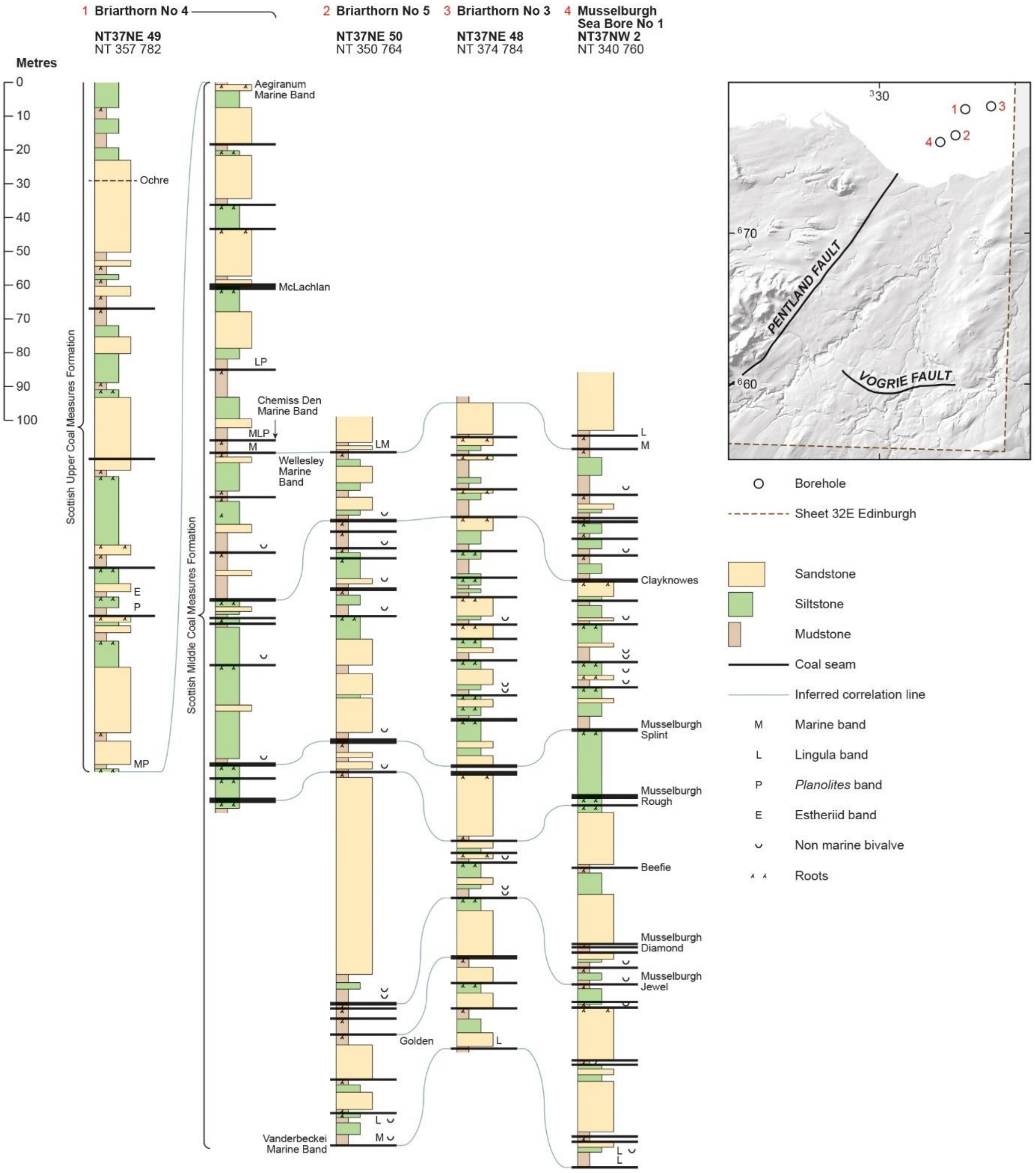


Figure 16 Generalised vertical sections for the Scottish Upper and Middle Coal Measures. Contains NEXTMap Britain elevation data from Intermap Technologies^{TM}. BGS © UKRI

The maximum thickness of the Scottish Middle Coal Measures Formation is about 350 m based on the dip-corrected section of the Sealab No. 1A Borehole [NT 3230 8568] (BGS Reg. No. NT38NW/31) in the Firth of Forth, located just to the north of the Edinburgh district boundary. Onshore in Midlothian, the formation is over 240 m thick under Musselburgh Harbour [NT 335 730], but the thickness is generally not well constrained. Offshore, from the overlapping records (at the levels of the Splint and Rough coals) of the Briarthorn No. 4 Seabore (NT37NE/49) [NT 3570 7821] and Briarthorn No. 5 Seabore (NT37NE/50) [NT 3506 7648], the Middle Coal Measures are assessed to be about 320 to 325 m thick. A similar thickness is implied in the Musselburgh Sea Bore No. 1 (NT37NW/2) [NT 3405 7606]) but the interval is only partly cored and similarly may be as much as 350 m in the Musselburgh No. 3 Offshore Borehole (NT37NW/1) [NT 3341 7509] nearer the centre of the basin.

5.9 SCOTTISH UPPER COAL MEASURES FORMATION

The Scottish Upper Coal Measures Formation (Figure 16) comprises sandstone, siltstone and mudstone in repeated cycles which most commonly fine upwards. The mudstone occurs most commonly as structureless beds and seatearth. The sequences are usually reddish brown and purplish grey in colour due to oxidation of originally grey strata beneath the sub-Permian unconformity, but some reddening may be primary, related to periods of lowered water table during deposition. Coal seams are not common (five are known), are normally less than 0.3 m thick and may be replaced, totally or in part, by red (haematitic) and dark grey carbonaceous diagenetic limestone. Brecciation textures may occur and nodular pedogenic carbonate is present in some claystone/siltstone rocks as noted to the north of the Edinburgh district in Fife. Sandstones appear to form about 46 % of the formation but data are scarce and incomplete.

The fossiliferous mudstone that defines the base of the formation in the Edinburgh district, the ‘Aegiranum Marine Band’, has recently been tentatively re-correlated with the ‘Buckhaven Planolites Band’ in Fife (Browne; 1998b, fig.1) and the Montague Bridge Marine Band in the grounds of Dalkeith Palace (referred to by Tulloch and Walton; 1958, pp.114–115). One mudstone bed, about 45 m above the base of the formation with *Planolites opthalmoides* in the Briarthorn No. 4 Seabore (NT37NE/49) [NT 3570 7821], represents a period of poorly developed marine conditions. The top of the formation is eroded, at an unconformity of regional extent beneath inferred Permian strata.

The maximum thickness of the formation probably exceeds 1200 m under the Firth of Forth based on the interpretation of commercial seismic data. In the Briarthorn No. 4 Borehole (Briarthorn No. 4 Seabore, NT37NE/49) [NT 3570 7821] about 200 m of Upper Coal Measures were proved in detail; coal seams up to 0.38 m are present and an ochre bed 0.28 m. The lithologically varied strata, including variegated ‘marl’, seatearth and sandstone, are generally red in colour and without any obvious pattern of cyclical deposition. Some of the oxidation of these strata was probably penecontemporaneous with their deposition in a drier, more seasonally wet climate. Post depositional folding, faulting, uplift and erosion/weathering also contributed to the oxidation.

6 Intrusions

6.1 EARLY DEVONIAN

A few minor intrusions (Ordovician to Devonian Caledonian Igneous Supersuite) cut the Siluro-Devonian Pentland Hills Volcanic Formation, to which they are petrologically and genetically related.

Dykes of pre-Carboniferous age are rare in the Edinburgh district, and occurrences of the North Britain Siluro-Devonian Calc-Alkaline Dyke Suite are confined to the Pentland Hills. They have been described by Cockburn (1952). A microdiorite dyke cuts the Siluro-Devonian Greywacke Conglomerate Formation on the west side of Harbour Hill [NT 201 644], and another cuts rhyolitic ash of the Caerketton Member of the Pentland Hills Volcanic Formation on Caerketton Hill [NT 239 663]. A sill of microdiorite intrudes trachyte on Woodhouselee Hill [NT 232 643]. A dyke of pyroclastic breccia occurs on the northern slope of Allermuir Hill, 300 m south of the most southerly vent [NT 228 668]. The Black Hill Felsite (Chapter 3 and Plate 1) emanates from a feeder dyke at its south-western extremity, in the Livingston district.

A plug or boss of microgranite, belonging to the North Britain Siluro-Devonian Felsic Intrusion Suite, intrudes rhyolite of the Bell's Hill Member of the Pentland Hills Volcanic Formation on Harbour Hill [NT 205 650]. It is petrographically similar to the Black Hill Felsite (Chapter 3), except for the absence of phenocrysts and the locally spherulitic matrix. It might have formed the feeder for some of the Bell's Hill rhyolites, or possibly for some later extrusive unit.

A few small vents occur in the Pentland Hills. The largest concentration occurs on the northern slopes of Allermuir Hill [NT 231 673] at Swanston (Geikie, 1897; Peach et al., 1910), where the vents are filled with pyroclastic breccia containing clasts of either rhyolite or andesite and basalt. However, one vent contains both rhyolitic and andesitic clasts. Five small occurrences of vent rocks, from Mortonhall Quarry [NT 246 693] westward toward Liberton [NT 259 692], are possibly along the line of a former fissure in the underlying Siluro-Devonian lavas of the Fairmilehead Volcanic Member (Mykura, 1960). Angular fragments of varied volcanic rocks are enclosed in a rhyolitic matrix. A small vent filled with basaltic pyroclastic breccia occurs on the eastern slopes of Caerketton Hill [NT 245 664].

6.2 CARBONIFEROUS

The Carboniferous bedrock succession in the Edinburgh district is cut by many intrusions, mostly forming basaltic sills, of Mississippian and possibly later age. Early Carboniferous plugs, vents, dykes and sills that are clearly related to the Arthur's Seat Volcanic Formation are spectacularly exposed in Edinburgh's Holyrood Park [NT 27 73]. A later phase of intrusions cuts rocks younger than the Arthur's Seat Volcanic Formation, and shares geochemical characteristics with the Kinghorn Volcanic Formation. Some of these are probably coeval with the Kinghorn rocks, but others may be as young as Namurian or Westphalian. These sills are in turn cut by dykes of the Stephanian quartz-dolerite suite.

6.2.1 Intrusions related to the Arthur's Seat Volcanic Formation

6.2.1.1 SILLS

A group of sills intruding the Ballagan Formation in or near Holyrood Park, and the Arthur's Seat Volcanic Formation (Black, 1966; Upton, 2003), are part of the Midland Valley Carboniferous to early Permian Alkaline Basic Sill Suite (Monaghan and Parrish, 2006). The petrology varies slightly but all represent types of basalt that occur in the lava pile. They are regarded as sourced from the same magma chamber from which the Arthur's Seat Volcanic Formation rocks were erupted (Upton, 2003).

6.2.1.2 ST LEONARD'S SILL

The St Leonard's Sill, forming a ridge [NT 265 737] to [NT 273 726] mainly just within the western perimeter of Holyrood Park, is a composite body with a 7 m thick core of olivine-clinopyroxene-plagioclase-macrophyric dolerite (Dunsapie-type) and a 2 m-thick envelope of aphyric hawaiite on either side; the boundary between the two types is diffuse.

6.2.1.3 DASSES SILL

The Dasses Sill [NT 2745 7315] to [NT 2743 7356], intruded about 100 m west of the Long Row lava (Chapter 4 and Plate 5), consists of several lenticular bodies, and is composite, with olivine-clinopyroxene-plagioclase-macrophyric dolerite (Dunsapie-type) enveloped by sodic trachyandesite ('benmoreite'). Based on the petrographical data by Boyd (1974), Girnal Craig [NT 2786 7258] is considered to be a continuation of the Dasses Sill to the south-east of the Lion's Haunch Vent, although Mitchell and Mykura (1962) had previously correlated it with the St Leonard's Sill.

6.2.1.4 WHINNY HILL INTRUSION

The Whinny Hill Intrusion is a sheet of clinopyroxene-olivine-macrophyric basalt (Craiglockhart-type), cutting the plagioclase-microphyric basaltic rocks (Jedburgh type) or hawaiite lavas of Whinny Hill. This intrusion, like those in the Lion's Haunch Vent, provides evidence of a return to more primitive magma after the extrusion of the highest preserved lavas on Whinny Hill, which are of mugearite composition.

A sill of olivine-clinopyroxene-plagioclase-macrophyric dolerite (Dunsapie-type) crops out from Sciennes [NT 262 725] northwards to St Mary's Street [NT 261 736]; its outcrop pattern suggests that it is transgressive into slightly older strata at its northern end.

6.2.2 Plugs and vents

All of the intrusions of the **Southern Scotland Dinantian Plugs and Vents Suite** in the Edinburgh district are located within the city centre (Figure 4). They are likely to have tapped the same magma chamber from which the Arthur's Seat Volcanic Formation was also erupted. Similarities in petrology have been used to link vents with individual lava flows (Clark, 1956; Black, 1966). Some vents have been completely filled with magma, which has crystallised to form a plug, but most are filled by pyroclastic rocks, which might have been partly intruded by magma forming sills or irregular intrusions. Six early Carboniferous plugs or vents are mapped within the city of Edinburgh: Edinburgh Castle Plug [NT 251 735]; the Lion's Haunch [NT 280 730] and Lion's Head [NT 275 729] vents (Plate 5) which are presumed to underlie the centre of the original volcanic cone (McAdam, 1993; Land and Cheney, 2000), and Pulpit Rock Plug; Crags Vent and Duddingston Plug.

6.2.2.1 EDINBURGH CASTLE PLUG

Edinburgh Castle Plug [NT 251 735] is a steep-sided basaltic plug, 300 m by 200 m and elongated to the north-west. It is homogeneous, and made of fresh olivine-microphyric basalt (Dalmeny type). However, the size of the abundant olivine microphenocrysts suggests it is transitional to olivine-clinopyroxene-plagioclase-macrophyric basalt (Dunsapie-type). Because of this petrological similarity, Black (1966) inferred it to be the source of the widespread olivine-clinopyroxene-plagioclase-macrophyric basalt flow forming the Long Row and Loch Craig in Holyrood Park (Upton, 2003).

6.2.2.2 LION'S HEAD VENT

The Lion's Head Vent [NT 275 729] is about 300 m across (Plate 5), but has been truncated by the Lion's Haunch Vent. It contains a fill of pyroclastic breccia, with crude inward dipping bedding. The centre of the vent is filled with olivine-microphyric basalt (Dalmeny type), forming a plexus of dykes at the base but coalescing to form a coherent mass on the summit of Arthur's Seat. Flow 4 of the Arthur's Seat Volcanic Formation (Clark, 1956; Black, 1966) on Whinny Hill may have been erupted from this vent (Black, 1966; Upton, 2003).

6.2.3 Lion's Haunch Vent

The Lion's Haunch Vent [NT 280 730] is the largest of the six mapped plugs and vents, being 1200 m by 500 m. It is probably the source of Flow 5 of the Arthur's Seat Volcanic Formation and all succeeding lavas (Black, 1966). Much of the vent is filled with crudely bedded, very coarse-grained pyroclastic breccia, with clasts up to 2 m across. However, in the south-west of the vent and along its northern margin it contains lava flows that dip toward the interior, with intercalated sedimentary rocks that were possibly deposited in a volcanic crater lake (Black, 1966). Crow Hill [NT 278 728] and Dunsapie Hill [NT 282 731] are plug-like masses of olivine-clinopyroxene-plagioclase-macrophyric basalt (Dunsapie-type) within the Lion's Haunch Vent, while Samson's Ribs [NT 275 725] is a sheet-like mass of plagioclase-microphyric basaltic rocks (Jedburgh type) or hawaiite, bounded to the south-west by the margin of the vent. It shows spectacular columnar jointing.

There are three smaller vents; the Pulpit Rock, the Crags Vent and the Duddingston Plug. The *Pulpit Rock* [NT 276 735] is a plug of clinopyroxene-olivine-macrophyric basalt (Craiglockhart-type). It was considered by Black (1966) to be the source of the adjacent Whinny Hill lava flow III (3A and 3B of Land and Cheney, 2000), due to their very similar petrography. The Crags Vent [NT 269 733] is elongated in an east-north-east direction and is filled with agglomerate, which is indurated by the later intrusion of the Salisbury Crags Sill. The Duddingston Plug [NT 283 726] is an intrusion of olivine-clinopyroxene-plagioclase-macrophyric dolerite (Dunsapie-type), south-east of the Lion's Haunch Vent, which intrudes basaltic tuffs overlying the basal lava flow of the Arthur's Seat Formation. It was possibly a feeder conduit for a parasitic volcano on the southeast flank of the Edinburgh volcano (Upton, 2003).

Dykes

Several dykes of doleritic composition have been identified in Edinburgh city centre (BGS, 2003) between Castle Rock [NT 251 735] and Holyrood Park [NT 27 73]. These dykes are of alkali dolerite and olivine-pyroxene-feldspar macroporphyric alkali dolerite (Dunsapie type) (BGS, 2003). They are part of the **Midland Valley Carboniferous to early Permian Alkaline Basic Dyke Suite** and are similar in composition to lavas of the Arthur's Seat Volcanic Formation. Dyke trends range from north-northwest to north-east.

6.3 INTRUSIONS YOUNGER THAN THE ARTHUR'S SEAT VOLCANIC FORMATION

Several mafic sills cut rocks of the Gullane and older formations in the Edinburgh district and Firth of Forth. They are components of the Midland Valley Carboniferous to early Permian Alkaline Basic Sill Suite. The principal sills of this group are the onshore Salisbury Crags, Corstorphine Hill and Lochend sills, the offshore Cramond Island, Inchkeith and Inchmickery sills and the Hawkcraig Point sill on the south coast of Fife. They consist dominantly of analcime-bearing olivine-dolerite (teschenite), but accumulations of cumulus olivine (picrite, Corstorphine Sill) and more evolved differentiates (analcime-monzogabbro, Lochend Sill) are present locally.

6.3.1 Salisbury Crags Sill

The Salisbury Crags Sill (Figure 4) forms a prominent feature in Holyrood Park [NT 274 727–270 737]. The maximum thickness is 40 m, thinning sharply south-east of the Crags Vent [NT 269 733]. At 'Hutton's Section' [NT 270 729], the magma has prised off sections of the underlying strata (Plate 11) and is reputed to have first demonstrated the intrusive nature of sills (Upton, 2003). The rock is analcime-olivine-dolerite (teschenite). Thin veinlets of microsyenite cut the main body of the sill, and veins of haematite up to several centimetres wide also cut the intrusion.

Plate 11 Salisbury Crags Sill, Hutton's section [NT 2715 6467]; basal contact of teschenitic microgabbro sill with the underlying baked, thinly bedded sandstones and calcareous mudstones of the Ballagan Formation showing evidence of forcible intrusion (P005831) BGS © UKRI

6.3.2 Corstorphine Sill

The Corstorphine Sill has an arcuate outcrop [NT 205 763 to NT 224 740] over 5 km long around the southern part of the Granton (Drylaw) Anticline, and forms the ridge that is Corstorphine Hill. The sill has a maximum thickness of 140 m. It consists largely of analcime-olivine-dolerite (teschenite), but an olivine cumulate layer, described as picrite, was at one time exposed in the disused railway cutting [NT 200 755] (Peach et al., 1910). This layer is approximately 8 m above the base of the sill and 5–10 m thick. The underlying thermally metamorphosed mudstones (with nonmarine bivalves) are exposed in the Pavement Quarry (NT 204 750). Black carbonaceous sandstone at Ravelston Quarry [NT 209 737] was also baked by the sill above. The sill crops out 1.3 km farther to the east on the eastern limb of the broad Newhaven Syncline (Figure 2). It trends north-north-east from Bell's Mills [NT 238 738] southwards to Gorgie [NT 2295 7210] with a separate outcrop, slightly lower in the Gullane Formation, at Craiglockhart [NT 232 714]. At Bell's Mills the analcime-olivine-dolerite sill is a maximum thickness of about 20 m and cuts strata close to the Wardie Coal and as at Craiglockhart the sill has split into two leaves.

6.3.3 Lochend Sill

The Lochend Sill crops out east and north of Lochend Loch [NT 277 748] in eastern Edinburgh, and was previously described as an 'essexite' (Peach et al., 1910, p.292). It is an analcime monzogabbro, consisting mostly of augite, sodic plagioclase and alkali feldspar, with abundant spots of white material believed to be secondary after analcime or leucite. The intrusion is probably composite and it may be brecciated. It is probable that a later differentiate (the monzogabbro) has intruded a more normal analcime-olivine-dolerite locally.

6.3.4 Cramond Island Sill

The Cramond Island Sill [NT 197 785] forms the bedrock of a tidal island on the south coast of the Firth of Forth on the eastern margin of the Edinburgh district. The sill occupies the centre of a minor anticline of north-west trend, and its thickness is unknown. It is analcime-bearing olivine dolerite (teschenitic) and intruded into strata of the Gullane Formation below the Charles Hill Volcanic Member of the Anstruther Formation (see Chapter 4).

6.3.5 Inchmickery Sill

Exposures of the Inchmickery Sill, comprising teschenitic dolerite, form a line of small islands or skerries within the Firth of Forth, in the northwest part of the Edinburgh district. The crop of the sill extends from Inchmickery in the south [NT 208 805] north-northeastwards to Cow and Calves [NT 206 811], Oxcars [NT 203 818] and Car Craig [NT 199 831]. Here, the sill is intruded into the top of the Charles Hill Volcanic Member of the Anstruther Formation.

On Inchkeith [NT 294 827], one of the larger islands in the Firth of Forth, several sills were recognised by Davies (1936) intruding the Kinghorn Volcanic Formation (Visean). The sills are vesicular and appear to have been intruded under a thin sequence of cover rocks. They are petrologically similar to, and almost certainly coeval with, the lavas of Inchkeith, being olivine-microphyric basalt (Dalmeny type) and olivine-clinopryoxene-microphyric basalt (Hillhouse-type), or dolerite and analcime-olivine-dolerite (teschenite). This suggests that some of the analcime-olivine-dolerite sills south of the Firth of Forth and west of the Pentland Fault may also be of this age.

6.3.6 Hawkcraig Point Sill

The Hawkcraig Point Sill occupies Hawkcraig Point [NT 201 849] on the north coast of the Firth of Forth. It is an olivine analcime-microgabbro and its eastward continuation extends into the adjacent Kirkcaldy district as a line of small islands or skerries.

6.4 STEPHANIAN

A suite of quartz-dolerite dykes emplaced during the late Carboniferous in the Edinburgh district are a component of the tholeiitic intrusions that are abundant in the Midland Valley of Scotland and northern England. They belong to the **Central Scotland Late Carboniferous Tholeiitic Dyke Swarm** of the **North Britain Late Carboniferous Tholeiitic Suite**. The dykes are associated with emplacement of the Midland Valley Sill Complex (Loughlin and Stephenson, 2003), and crosscut and demonstrably postdate sedimentary rocks of the Upper Coal Measures in the north of the Midlothian Coalfield [NT 33 72]. U-Pb TIMS zircon dating of the Midland Valley Sill in the adjacent Livingston district gives an age of 307.6+/-4.8 Ma (Monaghan and Parrish, 2006), now regarded as late Carboniferous. Within the Edinburgh district the quartz dolerite dykes intrude younger Carboniferous rocks underlying the southern coastal area of the Firth of Forth. The most southerly known occurrences of these dykes in Edinburgh are in Polwarth (NT 231 715), Musselburgh (NT 343 723) and Wallyford (NT 380 723). All the dykes are of quartz-dolerite, typically 2 to 10 m thick, but a few examples reach 20 m. Most of the dykes trend 080 to 100º, and have subvertical contacts. Chilled margins up to 0.5 m wide are common. A quartz dolerite dyke of 1 to 2 m width can be readily seen intruding the Salisbury Crags Sill at Cat's Nick [NT 2674 7321] in Holyrood Park although the dyke suite is not otherwise well exposed within the Edinburgh district. However 1 to 3 m wide dykes near St Bernard's Well at Stockbridge in the banks of the Water of Leith [NT 245 742] are described by Waterston (in McAdam and Clarkson, 1996) and examples about 5 m wide occur on the northern side of Calton Hill [NT 263 744], described in a geological walk leaflet by McMillan et al. (2003). The average grain size of the central parts of the dykes is 1 to 1.5 mm. The quartz-dolerites are characterised by ophitic clinopyroxene and by micropegmatitic intergrowths of quartz and alkali feldspar in the groundmass. Ilmenite forms 2 to 5 % of the rock, and there is a devitrified mesostasis associated with rare interstitial quartz. Labradorite (An_{62}) phenocrysts are very rare, and there are no other phenocrysts.

7 Structure and tectonic evolution

The oldest (Ordovician; Caradoc) strata in the Edinburgh district occur on the very southern margin of the sheet (Figure 1) in the footwalls of the north-east trending Lammermuir Fault (Portpatrick Formation around [NT 380 560] and Southern Upland Fault (Marchburn Formation around [NT 250 560]) (Figure 2). The general trend of the strike of these units is also north-east. These strata are generally subvertical in the Portpatrick Formation, but overturned in the Marchburn Formation, with the strata younging north-west. Little or no information is available in the district about the nature of any folding in these rocks because of lack of exposure. The regional structural pattern of subvertical strata was generated during the closure of the Iapetus Ocean when the palaeocontinent of Laurentia (with 'Highland' Scotland forming part of the southern margin) approached the smaller Avalonian terrane (including 'proto England') and palaeocontinental Baltica. Subduction of the Iapetus Ocean Plate beneath Laurentia caused the accretion of ocean floor sediments of the Leadhills Supergroup on to the southern edge of the Laurentian Plate, imposing the tectonic fabrics. These sediments together with younger turbidite strata of the Southern Uplands are preserved within a series of fault-bounded (tectonostratigraphical) tracts such that the overall younging direction of the entire accreted sedimentary pile is southwards, but strata of individual tracts generally young north-westwards. The faults are thought to have originated as southward-directed thrusts which formed shortly after deposition of the turbidite sequences. The tracts and their bounding faults were rotated into their near-vertical attitude due to a combination of ongoing accretion, and subsequent continental collision following final closure of Iapetus.

During latest Silurian to Early Devonian times post-closure uplift involving the strike-slip reactivation of Caledonian faults resulted in the formation of the Southern Uplands as a structural high (see Chapter 3). Sedimentary and volcanic rocks were deposited with marked unconformity on the turbidite succession. In Late Devonian to early Carboniferous times there was regional onlap of sediments of the 'Old Red Sandstone' lithofacies onto the earlier sedimentary and volcanic strata (Chapter 4). In the district, for example, the March Burn Formation is overlain with marked disconformity by the Inverclyde Group (late Devonian/ early Carboniferous).

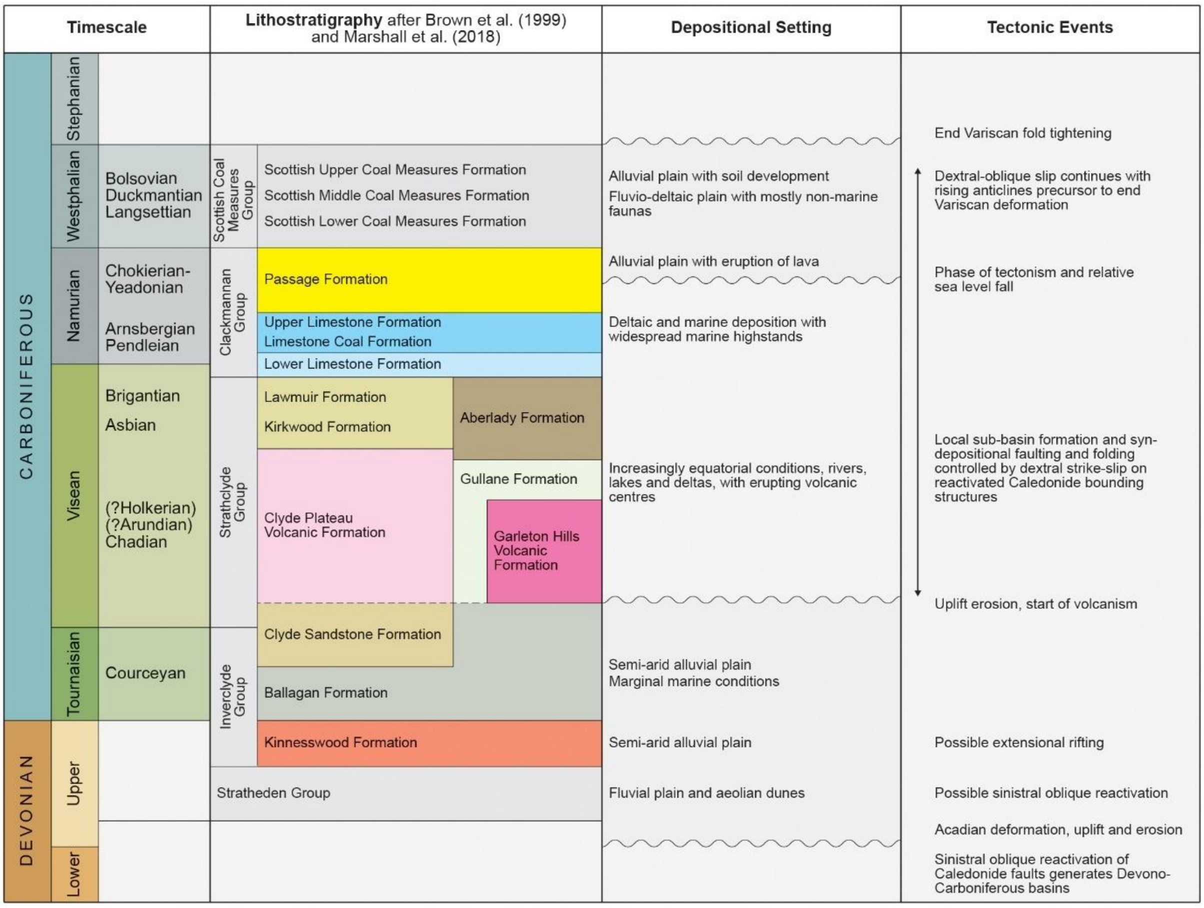
Early Silurian (Llandovery) mudstones and siltstones of the Reservoir Formation (North Esk Group) occur in a small area at Craigentarrie [NT 196 644] in the Pentland Hills. This is one of two small inliers, the other being Bavelaw Castle [NT 170 625] in the Livingston district, linked to the major Silurian North Esk Inlier (Sheet Scotland 32W). At Craigentarrie the Reservoir Formation strata dip north and north-east at 38º to 80º. Farther south-west in the North Esk Inlier [NT 150 585], the Reservoir Formation forms the lowest known part of a (Llandovery to Wenlock) succession comprising the Deerhope, Cockrig, Wether Law Linn and Henshaw formations. These generally strike north-northeast, are steeply dipping and young towards the northwest. Only minor folding has been recorded in the North Esk Group (Mitchell and Mykura, 1962). The structural pattern of subvertical strata was generated in the latest stages of the closure of the Iapetus Ocean as part of the Caledonian Orogeny. The sequence represents continental slope (Reservoir and Deerhope formations) to shelf-sea and terrestrial rocks (Henshaw Formation) of the southern margin of the Laurentian palaeocontinent, deposited in one of several fault-controlled basins (Clarkson and Upton, 2006). By the end of the Silurian, Avalonia/Baltica had collided obliquely with Laurentia, and faults such as the Southern Upland and Loganlee faults (Figure 2) underwent sinistral lateral movements resulting in uplift of the North Esk Group strata (Clarkson and Upton, 2006). As a consequence, a marked unconformity separates these strata from the overlying Siluro-Devonian Greywacke Conglomerate Formation (unconformity seen in the Livingston District) and Pentland Hills Volcanic Formation (Lanark Group). The base of the Inverclyde Group, the Kinnesswood Formation, also overlies these rocks with a younger, marked unconformity.

In this district, the Greywacke Conglomerate Formation (Lanark Group) occurs in a small fault bounded block (Figure 1) at Bell's Hill [NT 203 645] and although its relationship to the Pentland Hills Volcanic Formation is uncertain, it is thought to be an unconformable contact. In the Livingston District (Sheet Scotland 32W), the Greywacke Conglomerate underlies the Swanshaw Sandstone Formation and Pentland Hills Volcanic Formation. The Pentland Hills

Volcanic Formation was the result of mantle melting associated with the northerly subduction of the Iapetus Ocean Plate beneath the Laurentian continent. Volcanic activity continued after the subsequent continent-continent collisions of the three continents. The structure of the Pentland Hills Volcanic Formation in the Pentland Hills is broadly north-east striking and southeast dipping, cut by generally northerly and easterly trending faults. The faulting represents post-Early Devonian tectonism associated with the Acadian Orogeny. In Edinburgh, the Pentland Hills Volcanic Formation dips towards the north-north-east in the Braid Hills [NT 248 695] and on Blackford Hill [NT 255 707], between the north-east trending Pentland and Murieston (and Duddingston) faults. The Loganlee Fault (Figure 2) is also acknowledged as having a long history of activity, with small thrust and strike-slip movement of pre-Late Devonian ages (Mitchell and Mykura, 1962).

The post-Early Devonian structures of the Edinburgh district (Figure 2) fit into the tectonic history for the Late Palaeozoic of the Midland Valley. Browne et al. (2003; table 1) and Ritchie et al. (2003) described the role of alternating phases of strike-slip displacement across pre-existing Caledonide faults (such as the Southern Upland Fault) in the foreland of the evolving Variscan Orogeny. Underhill et al. (2008) further developed this understanding and described the integration of seismic data from the Firth of Forth with other data from neighbouring onshore areas. These provided insights into the structural evolution and petroleum habitat of the Midland Valley. Their results demonstrated that the NNE to SSW striking Midlothian– Leven Syncline was a major growth fold during the Late Palaeozoic under a predominantly dextral strike-slip regime, with the flanking Burntisland (Sheet Scotland 40E) and D’Arcy–Cousland (Figure 2) anticlines on either side. The synsedimentary fold controlled depositional thicknesses and facies in Visean–Westphalian times. The growth fold underwent tightening during late Carboniferous (Variscan) deformation events.

Table 9 Revised lithostratigraphical framework and summary tectonostratigraphical events for the Late Devonian and Carboniferous of the Midland Valley of Scotland (Browne et al., 2003; Marshall et al., 2018) BGS © UKRI



Timescale			Lithostratigraphy after Brown et al. (1999) and Marshall et al. (2018)			Depositional Setting	Tectonic Events
CARBONIFEROUS	Stephanian						End Variscan fold tightening
	Westphalian	Bolsovian Duckmantian Langsettian	Scottish Coal Measures Group	Scottish Upper Coal Measures Formation Scottish Middle Coal Measures Formation Scottish Lower Coal Measures Formation		Alluvial plain with soil development Fluvio-deltaic plain with mostly non-marine faunas	Dextral-oblique slip continues with rising anticlines precursor to end Variscan deformation
	Namurian	Chokierian-Yeadonian	Clackmannan Group	Passage Formation		Alluvial plain with eruption of lava	Phase of tectonism and relative sea level fall
		Arnsbergian Pendleian		Upper Limestone Formation Limestone Coal Formation		Deltaic and marine deposition with widespread marine highstands	
				Lower Limestone Formation			
	Visean	Brigantian Asbian	Strathclyde Group	Lawmuir Formation Kirkwood Formation	Aberlady Formation	Increasingly equatorial conditions, rivers, lakes and deltas, with erupting volcanic centres	Local sub-basin formation and syn-depositional faulting and folding controlled by dextral strike-slip on reactivated Caledonide bounding structures
		(?Holkerian) (?Arundian) Chadian		Clyde Plateau Volcanic Formation	Gullane Formation Garleton Hills Volcanic Formation		Uplift erosion, start of volcanism
	Tournaisian	Courceyan	Inverclyde Group	Clyde Sandstone Formation Ballagan Formation		Semi-arid alluvial plain Marginal marine conditions	
DEVONIAN	Upper			Kinnesswood Formation		Semi-arid alluvial plain	Possible extensional rifting
			Stratheden Group			Fluvial plain and aeolian dunes	Possible sinistral oblique reactivation
	Lower						Acadian deformation, uplift and erosion Sinistral oblique reactivation of Caledonide faults generates Devono-Carboniferous basins

Browne et al. (2003) and Underhill et al. (2008) suggested that sinistral oblique reactivation of Caledonide faults such as the Southern Upland and Highland Boundary faults generated the Devono-Carboniferous basins. In this district, the Late Palaeozoic succession begins with the Kinnesswood Formation (Inverclyde Group), deposition of which was associated with extensional rifting following or linked to sinistral oblique reactivation. Poorly constrained isopachyte maps of the Late Devonian to early Carboniferous strata (e.g. Browne et al., 1986, fig.17) suggest a pattern consistent with rifting. This phase ended with uplift, erosion and the volcanic activity represented by the Arthur’s Seat and Garleton Hills Volcanic formations at the base of the Strathclyde Group. Subsequently, during deposition of the Strathclyde Group, local basin formation took place associated with syndepositional faulting and folding controlled by dextral strike-slip faulting on bounding faults. In the Edinburgh district, key evidence for these interactions from seismic sections is lacking, and formation isopachytes are only satisfactory for identifying syndepositional folding for the late Carboniferous deposits. In the early Carboniferous Strathclyde Group, the Gullane, West Lothian Oil-Shale and Aberlady formations may be associated with sub-basinal development, controlled by or associated with syndepositional folding, but clear evidence is lacking.

A dominant structural feature in the Edinburgh district is the Pentland Anticline, a broad domal feature trending and plunging north-east incorporating the Pentland Hills, Braid Hills, Blackford Hill and also central Edinburgh including Holyrood Park and Calton Hill. The south-east flank is marked by the Pentland Fault and the north-west by the Murieston and Colinton faults (Figure 2). This structure may partly reflect a longer history of folding than the uppermost Palaeozoic. It is a matter of conjecture as to whether the Pentland Hills was a ‘relative high’ during Carboniferous times or if uplift was caused by end Carboniferous inversion related to the Variscan Orogeny.

To the west of the Pentland Anticline are the West Lothian oil-shale fields (Carruthers et al., 1927). To the east, are the Pentland–Straiton oil-shale field and the Midlothian and East Lothian coalfields separated by the D'Arcy–Cousland Anticline. The structure of the West Lothian oil-shale field is a series of folds with generally north–south trending axes. The main folds are the Hailes and Newhaven synclines and the Granton Anticline, which have indistinct sigmoidal axial traces. The Newhaven syncline lies in a fault block between the Granton and the Ochiltree faults, with two minor folds to the west of the main axis in the Granton Harbour area (Granton Harbour Syncline and Wardie Anticline). The Granton Anticline axis is faulted to the north under Muirhouse by the Granton Fault, and may terminate against the Ochiltree Fault under the inner Firth of Forth.

The Pentland–Straiton oil-shale field is in the footwall of the reversed Pentland Fault. Structurally it consists of a pair of folds, a syncline west of Straiton adjacent to the Pentland Fault, and an anticline under Burdiehouse and Gilmerton, peripheral to and part of the steep westerly limb of the Midlothian–Fife Syncline. The axes are indistinctly sigmoidal and have been traced for over 5 km on a southwesterly trend.

The Midlothian Coalfield depositional basin can be regarded as a broadly northwards dipping, compound synclinal structure. The present shape of the syncline bears only a partial relationship to the original basin of Carboniferous deposition (Tulloch and Walton, 1958) as indicated by isopachyte maps (Figures 9 and 10). In the late Carboniferous (Clackmannnan Group), the formation isopachyte trends suggest that the depocentre was located subparallel to, or above the position of the northeast-trending Pentland Fault, located on the steeply dipping western flank of the structure. Southwards thinning relationships indicate the position of the Vogrie Fault, suggesting it may have been active. The late Carboniferous formation isopachytes also show thinning eastwards towards the D'Arcy–Cousland Anticline. Insufficient data are available for the early Carboniferous to confirm any relationship between the depositional basin and the structural pattern other than the general thinning of strata to the south. Overall, the Midlothian Coalfield basin appears to be a growth fold in the late Carboniferous with a possibility that its eastern margin was controlled by a rising D'Arcy– Cousland Anticline. The Midlothian Basin differs from the Leven Basin (Fife) in that the Pentland Fault has uplifted and truncated the western side of the former (Ritchie et al., 2003) against the Pentland Anticline. This occurred during the end Carboniferous compressional tectonics of the Variscan Orogeny.

The axis of the Midlothian Syncline, the main fold structure in the district, extends south-south-west from Musselburgh Bay [NT 330 740] to the Vogrie Fault south of Rosewell [NT 280 610]. South of this fault two synclines are recognised, the Penicuik Syncline, and to the east the less distinct and broad Rosebery Syncline. These are separated by the north-east-trending Southern Upland Fault, with the faulted Herbershaw Anticline in its easterly footwall. The Rosebery Syncline is bounded to the east by the north-trending Halkerston Fault with the sharply defined and faulted Halkerston Syncline in its western hanging-wall.

The Midlothian Syncline has a steeply inclined western limb that is overturned in places. Inverted Coal Measures strata were recorded at Newcraighall Colliery [NT 31 72] and dips of 80° to the east were recorded in the Limestone Coal Formation at Niddrie and Gilmerton collieries [NT 30 70]. At depth, the steeply dipping beds bend monoclinally into the gently dipping central part of the syncline (Tulloch and Walton, 1958, 118–19). The eastern limb of the syncline has westerly dips of up to 38°, also with a fairly sharp transition to gently dipping axial strata that, in the south of the Midlothian Syncline show the development of some minor folds (Figure 2). A seam compilation for the Great Seam Coal (Figure 17) that postdates the resurvey mapping indicates that there is a degree of complexity in the folding north of the Sheriffhall Fault, with apparent westerly offset of the fold axis between the surface Musselburgh Nine Foot Coal and the Great Seam at depth. The Penicuik Syncline, south of the Vogrie Fault, is a narrower structure but shows similar features to the Midlothian Syncline, with a steeply dipping westerly limb and moderately dipping easterly limb.

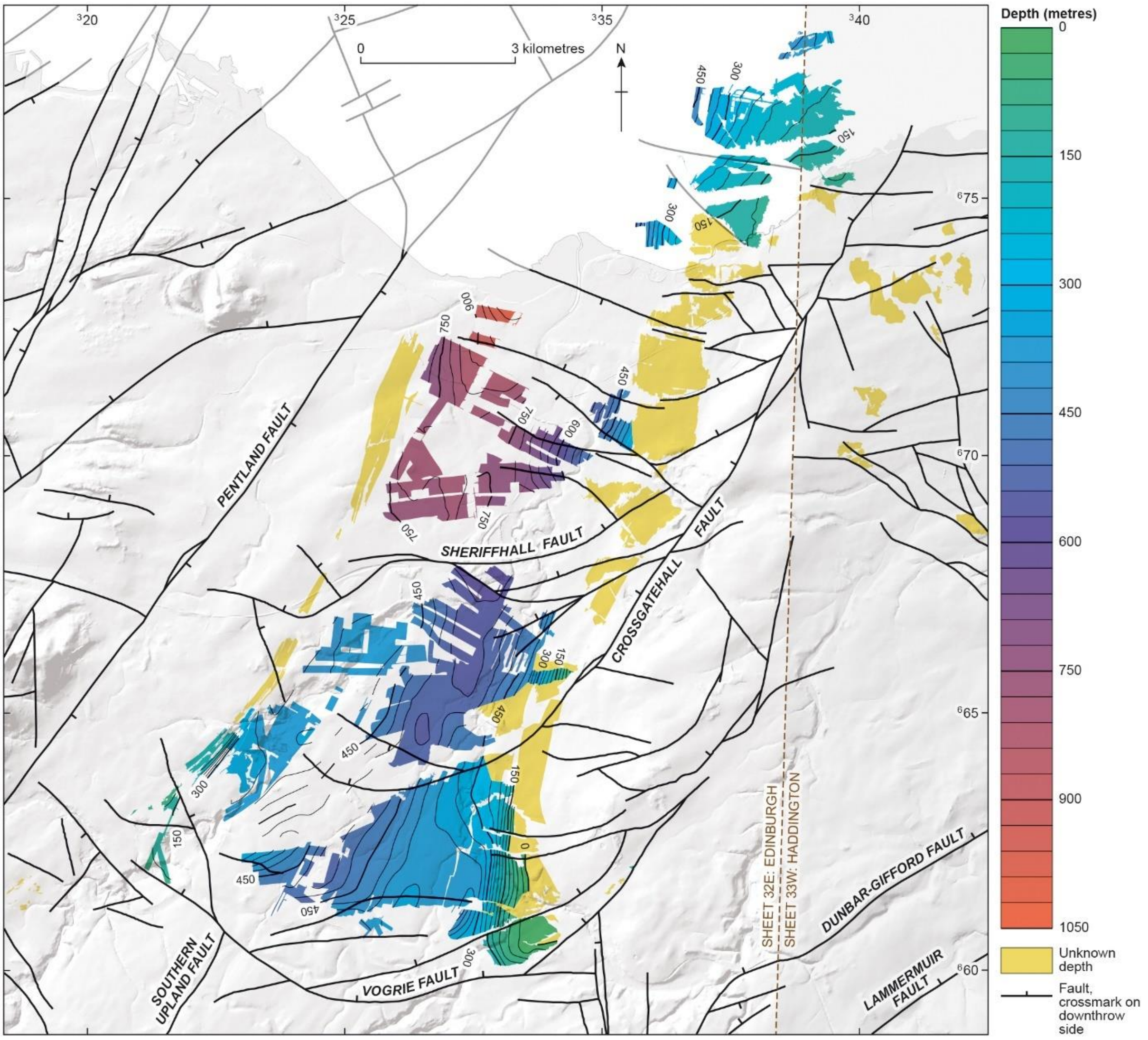


Figure 17 Stratum contours on the Great Seam Coal (Limestone Coal Formation). Contains NEXTMap Britain elevation data from Intermap Technologies^{TM}. BGS © UKRI

The D'Arcy–Cousland Anticline is a compound structure and extends from Prestonpans [NT 390 730] on the coast southwards to the Vogrie Fault near Gorebridge [NT 350 610]. It is the structure that divides the Midlothian Coalfield from the East Lothian Coalfield. Outcrops of the Lower Limestone Formation mark the location of the fold around D'Arcy House [NT 360 650] and Cousland village [NT 385 680]. Moderate dips are recorded on both limbs with both northerly and southerly axial pitches. The axis is curvilinear and dextrally offset by faulting. The D'Arcy– Cousland structure was drilled for oil and gas, and was in production for 10 to 20 years (Hallett et al., 1985). Hallett et al. (1985) illustrated the likely complexity of the anticline, with a highly disturbed deep anticlinal core cut by reverse faults that show normal near surface displacement. Strike-slip movement was deduced.

The Southern Upland Fault (SUF) (sensu lato) is a major, somewhat arcuate, east-north-east trending Caledonide crustal structure in southern Scotland (Floyd, 1994). Floyd (1994) distinguished the SUF (sensu stricto) from other similarly orientated and related faults that occur en echelon or as 'splays'. The review concluded that the Stinchar Valley Fault, SUF (sensu stricto) and the Firth of Forth Fault line represents the original sinistral strike-slip terrane boundary fracture between the Southern Uplands and the Midland Valley of Scotland. The farthest northeastern trace of the SUF (sensu stricto), hereabouts previously called the Leadburn Fault, is on the southern margin of the Edinburgh Sheet area [NT 240 560 to NT 275 607] where its surface expression ends on the footwall side of the curvilinear easterly trending Vogrie Fault. The vertical throw is therefore less than 90 m and perhaps only 40 m. In the

Edinburgh area Floyd (1994) recommended that the Vogrie, Crossgatehall, Firth of Forth, Dunbar–Gifford and Lammermuir faults should be separately named as each could represent part of the movement on the SUF (sensu stricto). Since the work of Floyd (1994), newly released seismic data show that the Firth of Forth Fault as originally understood no longer exists (Ritchie et al., 2003, Figures 1 and 2). The Crossgatehall Fault is now considered the most likely terrane boundary fracture continuing the SUF (sensu stricto) to the east-northeast. Ritchie et al. (2003) recognised a thick Late Devonian to early Carboniferous sedimentary succession in the hanging-wall of the Crossgatehall Fault offshore to the ENE of Edinburgh, and north of North Berwick under the Firth of Forth. They were unsure whether this basin was of extensional or transtensional origin. However, the footwall succession of comparable age, is much thinner and of marginal facies.

Immediately to the south of the Edinburgh district, the Lammermuir Fault (Figure 2) has a strong surface expression as the Moorfoot Hills escarpment near the former Broad Law granite quarry [NT 3450 5400].

The Pentland Fault (Figure 2) was first considered a reverse structure by Peach et al. (1910) and a gravitational survey confirmed this view (McLintock and Phemister, 1929) noting that the structure was steeply inclined. Lees and Taitt (1945) reported a reverse hade of 22° near Mortonhall, south Edinburgh based upon oil prospecting boreholes. Mitchell and Mykura (1962) described the Pentland Fault as a north-east-trending reverse fault that may be said in part to replace the south-east limb of the Pentland anticlinal fold. It was described as being a strike-slip fault of pre-'Upper Old Red Sandstone' (i.e. Late Devonian) origins. Tulloch and Walton (1958) provided some local detail about the Pentland Fault noting a vertical throw of 1000s of feet in the Liberton area of Edinburgh. It is likely that the Pentland Fault has a long history of movement as a normal fault with strike-slip phases, culminating at the end of the Carboniferous with a compressional Variscan reverse phase with inversion of the western side of the Carboniferous Midlothian Coalfield.

The Vogrie, Crossgatehall and Sheriffhall faults are the three main faults in the Midlothian Coalfield. Each fault has an arcuate trace (Figure 2), striking broadly eastwards across the Midlothian Syncline and turning north-eastwards through the complex D'Arcy–Cousland Anticline. The downthrows of these faults are usually to the north and they also hade in this direction.

The Vogrie Fault is exposed in the Gore Water [NT 347 610] and its apparent maximum vertical throw exceeds 300 m. Dextral offset of the Midlothian Syncline axis along this fault has been noted. In the directionally inclined Shewington Bore [NT26SE/172] (NT 2818 6042) the Vogrie Fault formed three zones of crush totalling to 2 m in about 4 m of strata between Passage Formation faulted against top Limestone Coal Formation. In the Shiells Bore 1/82 (NT26SE/157) [NT 2789 6092], the same fault zone was about 9 m thick, with stratal dips of 55º and higher. It was associated with hydrocarbons including oil and bitumen. At this point the fault throws Upper Limestone Formation against possible Inverclyde Group strata, the latter containing coarse conglomerates with clasts including felsite, andesite and quartzite.

The Crossgatehall Fault extends offshore from at least North Berwick to Port Seton, and then in a south-southwesterly direction into the Edinburgh district through Crossgatehall and Newtongrange, and then westwards across the Midlothian Syncline (Ritchie et al. 2003). The throw of the fault is generally to the north and west, exceeding 130 m in places. Locally the throw is to the east and south, supporting some element of strike or dip-slip movement [NT 380 700]. Tulloch and Walton (1958) present tenuous evidence for both sinistral and dextral sense of movement. They also associated the westward termination of workings in the Arniston Parrot Coal, just past Whitehill House [NT 295 620], with a series of small faults with a strike alignment of the Crossgatehall Fault and the SUF (sensu stricto) (at that time called the Leadburn Fault). They suggested that the two faults were continuous in pre-Coal Measures times and subsequently did not operate again.

The Sheriffhall Fault has an apparent maximum northern downthrow of 180 m and subhorizontal to inclined slickensides and grooves have been previously noted on the fault plane (Tulloch and Walton, 1958).

Under the Firth of Forth, the outcrop patterns of formations, folds and faults are largely speculative. There is some supporting borehole and mining data offshore of Musselburgh, and also mining data at the southern end of Seafield Colliery in Fife. Importantly, seismic interpretation was available north and east of Inchkeith (Ritchie et al., 2003), but the outcrop pattern of north-west-trending folding east and south of the island is based on sparse data.

The key features mapped offshore include the dextrally offset, faulted sigmoidal axis of the Midlothian–Leven Syncline and several easterly and north-easterly trending faults. These include the Inchkeith Fault, which has been interpreted as a late Carboniferous dextral strike-slip zone (Ritchie et al., 2003). Ritchie et al. (2003) also identified the Inchkeith High. Importantly their interpretation showed that the Pentland Fault terminated under the Firth of Forth and had no continuity with the newly recognised Mid Forth Fault. The original Firth of Forth Fault (Thomson, 1978), forming the north-easterly extension of the Pentland Fault, was considered to no longer exist. The Mid Forth Fault was interpreted as a Late Devonian to early Carboniferous extensional fault, with a small, mainly early Carboniferous depocentre in the hanging-wall block that was subsequently inverted in late Carboniferous times. Underhill et al. (2008) agreed that there was no basis for the Firth of Forth Fault, and that the Pentland Fault terminated in the Firth of Forth. However, they did not interpret the Mid Forth Fault and synthesised a differing structural history for that area.

A phase of north–south extension produced easterly trending fractures or faults that facilitated intrusion of the Central Scotland Late Carboniferous Tholeiitic Dyke Swarm (quartz-dolerite dykes) in the district during the Stephanian. Shore exposures of the dyke suite just east of this sheet in the Haddington district between Cockenzie [NT 339 754] and Port Seton [NT 407 759] harbours show that fractures filled by the dolerite have dextral offset. This phase of tectonic activity is related to regional scale rifting-wrenching after Variscan Orogenic events (e.g. Ziegler 1993; Wilson et al., 2004). Direct evidence for the basin’s post-Permian burial history is no longer present, but Underhill et al. (2008) inferred that the area had at least 1 km of cover prior to Palaeogene uplift.

In the Edinburgh district, recent observations of main cleat (bed normal joints in coal) in the Limestone Coal Formation seams at Blinkbonny Opencast Coal Site [NT 350 625] south of the Vogrie Fault have trends of 300–330°, 280–300° in several formations (Upper Limestone, Passage and Lower Coal Measures formations) on Joppa Shore [NT 320 735] and 310º in the Vogrie Burn [NT 376 635] (Limestone Coal Formation). These values are consistent with Rippon et al. (2006), who inferred that in Lothians and central Fife a consistent Carboniferous north-west maximum horizontal stress field is indicated by a regionally parallel cleat pattern. The pattern of cleat was related to Variscan stress fields across different tectonic settings in the near to far and distant fields. However, in the Oxenfoord Opencast Coal Site [NT 365 672] (Limestone Coal Formation), the values were more northerly around 330–350º possibly reflecting proximity to the Crossgatehall Fault and the D’Arcy–Cousland Anticline.

8 Concealed geology

Evidence for the interpretation of the concealed geology derives from boreholes, seismic data and from models of the regional gravity and magnetic data.

8.1 SEISMIC DATA

The structure of the crust underlying the Edinburgh district and, more broadly, the Midland Valley of Scotland, is inferred from the interpretation of seismic refraction data. The LISPB seismic experiment (Bamford et al., 1978) crosses the Edinburgh district (path shown on Figure 18) and provides a three-layer velocity model of the crust, with a relatively deep Mohorovičić discontinuity at about 35 km depth. A strong refractor in the upper crust is noted at about 8 km depth (Bamford et al., 1978).

The MAVIS seismic refraction experiments (Conway et al., 1987; Dentith and Hall, 1989, 1990) supported the overall crustal model described by Davidson et al. (1984) based on shorter quarry-blast seismic experiments in the central Midland Valley. Three refractors were identified along two east–west lines, suggesting a four-layer velocity model for the upper crust in the Midland Valley. The southern line, MAVIS-2, crosses the Edinburgh district within the Firth of Forth (Figure 18). The upper refractor, at depths of between 1.7 and 3.8 km, defines the base of the Late Devonian to Carboniferous sequence, which has velocities between 3.5 to over 5 km/s. The higher velocities correspond to known occurrences of thick Carboniferous lavas. Layer 2, with velocities of 5.3 to 6.0 km/s, extends to depths of between 3.5 and 5.0 km on MAVIS-2, and is presumed to consist of Early Devonian and Early Palaeozoic rocks (Conway et al., 1987). Layer 3, at depths greater than 5 km and with velocities close to 6.0 km/s, is assumed to be crystalline basement at relatively shallow depth.

The most reliable velocity discontinuity within the upper crust of the Midland Valley is at about 7–8 km depth. This has been identified on all the longer refraction lines (Bamford et al., 1978; Conway et al., 1987; Dentith and Hall, 1989) and it is considered to represent an important lithological contrast within the crust, probably the top of mafic granulite gneiss which has a velocity of about 6.4 km/s. This refractor, at such relatively shallow depths, is peculiar to the crust beneath the Midland Valley and the southern Highlands, and is part of the geophysical signature of this region.

This distinctive crustal structure, and the absence of clasts of Dalradian provenance in Early Palaeozoic rocks of the Midland Valley (Bluck, 1984) support the idea that the Midland Valley is a ‘suspect terrane’.

8.2 BOUGUER GRAVITY ANOMALY DATA

The locations of gravity measurements are shown in Figure 18, in which it is seen that data in the offshore part of the district are extremely sparse and preclude meaningful geophysical interpretation. In the onshore part of the district, Bouguer anomaly values (Figure 18) calculated with a reduction density of 2.75 Mg m^{-3} show a range from about –5 mGal to about +12 mGal, and reflect some of the major geological structures (Figure 2). Maximum values occur in the vicinity of mapped outcrops of Siluro-Devonian Lanark Group strata (Figure 1) north-west of the Pentland Fault. Minimum values occur over the Westphalian Scottish Coal Measures Group in the Midlothian Coalfield and the Tournaisian Inverclyde Group.

Steep gradients across the Pentland and Southern Upland faults form prominent features in the Bouguer anomaly data. The Pentland Fault juxtaposes low density (typically 2.55 Mg m^{-3}) late Carboniferous rocks with high density (typically 2.75 Mg m^{-3}) Siluro-Devonian lavas and strata at outcrop, and assumed higher density Silurian and Ordovician rocks at depth. A ridge in the gravity field on the south-east side of the Southern Upland Fault extends from the southern edge of the district north-east across the Carboniferous strata at least as far as the Vogrie Fault, suggesting that reactivation of this major structure has accommodated significant thickening of the late Carboniferous sequence in the Midlothian Coalfield. The data do not support a linkage between the Vogrie and Crossgatehall faults.

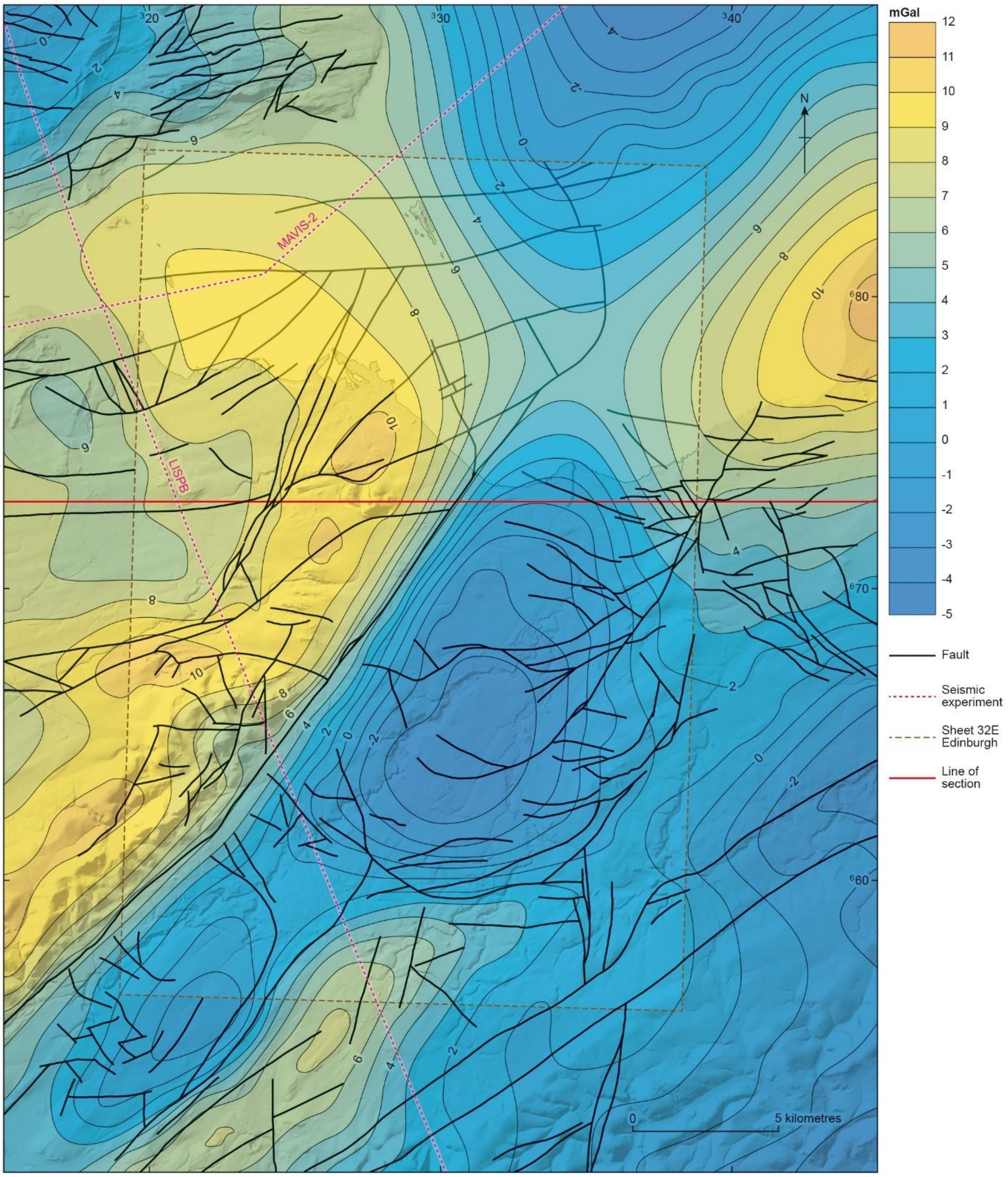


Figure 18 Bouguer gravity anomalies across the Edinburgh district (line of LISPB shown). Contains NEXTMap Britain elevation data from Intermap Technologies™. BGS © UKRI

The Arthur's Seat volcanic centre is associated with a small positive gravity anomaly with a ridge which extends to the north-west across the Firth of Forth to the picrite and teschenite intrusions on Inchcolm (Sheet Scotland 32W).

8.3 AEROMAGNETIC ANOMALY DATA

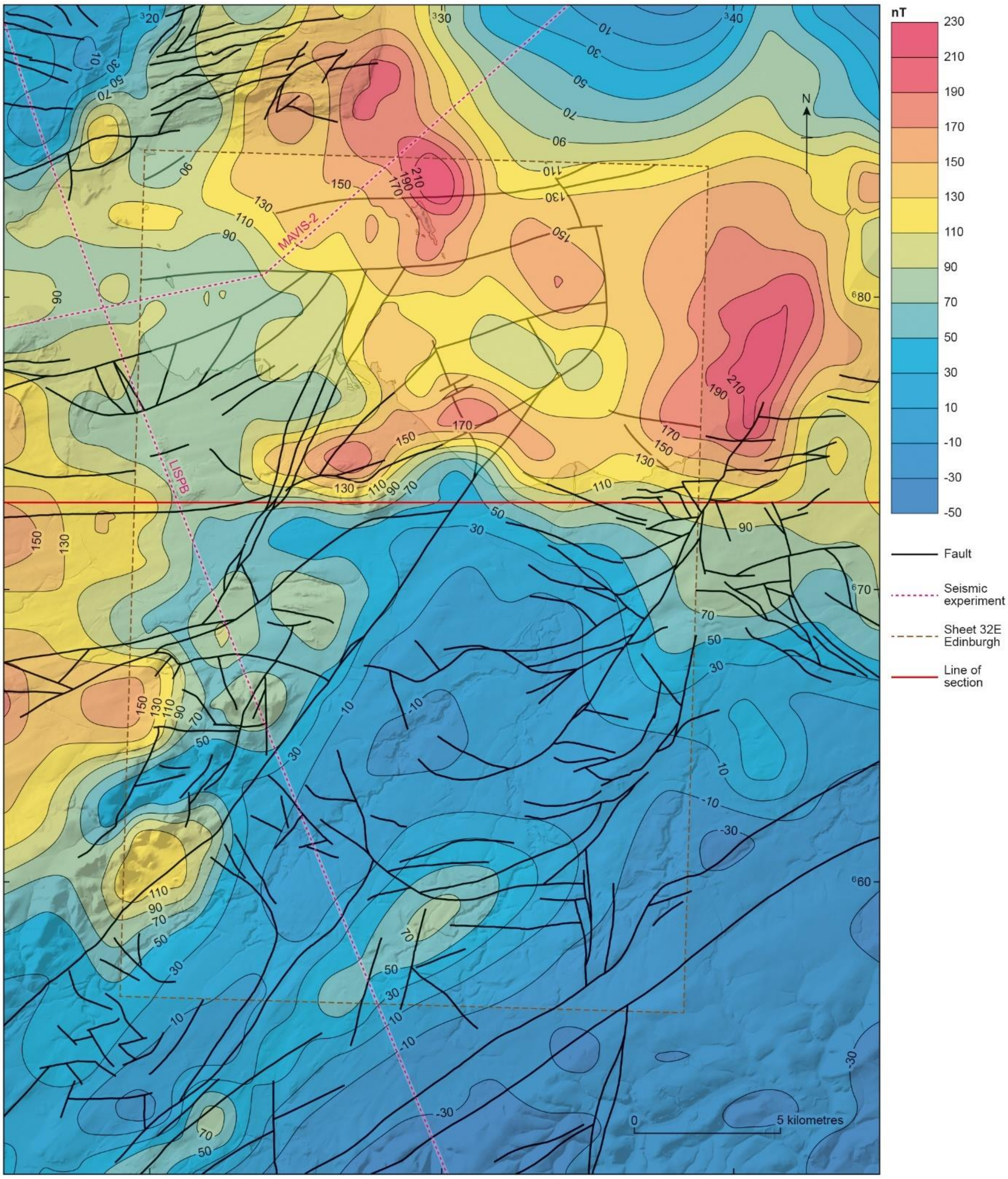


Figure 19 Aeromagnetic anomalies across the Edinburgh district. Contains NEXTMap Britain elevation data from Intermap Technologies^{TM}. BGS © UKRI

Contours of the total field magnetic anomaly (Figure 19) reflect the effects of the magnetisation of the upper crust, and over much of the district major magnetic anomalies correlate with mapped extrusive volcanic and intrusive igneous rocks.

The Siluro-Devonian rocks of the Pentland Hills Volcanic Formation (Lanark Group) are possibly up to 2000 m thick (Browne et al., 2002), and maximum magnetic anomaly values occur over the olivine-basalts and andesites of the Carnethy Volcanic Member that form the hanging-wall block of the Pentland Fault. A strong elongate magnetic anomaly to the north of the Arthur’s Seat Volcanic Formation has maximum values close to two thick quartz-dolerite dykes cutting Calton Hill [NT 2629 7424]. This anomaly extends westward across the Colinton Fault System, although here it is somewhat attenuated. To the east, the anomaly extends offshore, possibly as far as the extent of the Calton Fault.

The offshore part of the district is dominated by high-amplitude, short-wavelength magnetic anomalies that reflect the presence of magnetic (probably volcanic) units in the upper part of the sequence. Offshore to the east of the district, a 200 nT anomaly lies along the offshore extension of the Crossgatehall Fault, and is elongated in a north-northeasterly direction. This ‘Crossgatehall’ anomaly might be generated by a wedge of Carboniferous lavas in the footwall block of the Crossgatehall Fault offshore, or, alternatively, a basement feature.

In the south of the district, a magnetic anomaly of about 40 nT amplitude that trends north-eastward parallel with the Southern Upland Fault suggests continuity of the Early Palaeozoic basement beneath Carboniferous strata as far as the Vogrie Fault (Figure 2). The data give little support to a connection between this fault and the Crossgatehall Fault. A ridge in the magnetic field extends from this anomaly north-west across the Firth of Forth to link the lavas on Inchkeith and at Kinghorn. The Port Seton anomaly might be caused by a wedge of Carboniferous lavas adjacent to the Crossgatehall Fault offshore, or a basement feature.

8.4 2D MODEL PROFILE

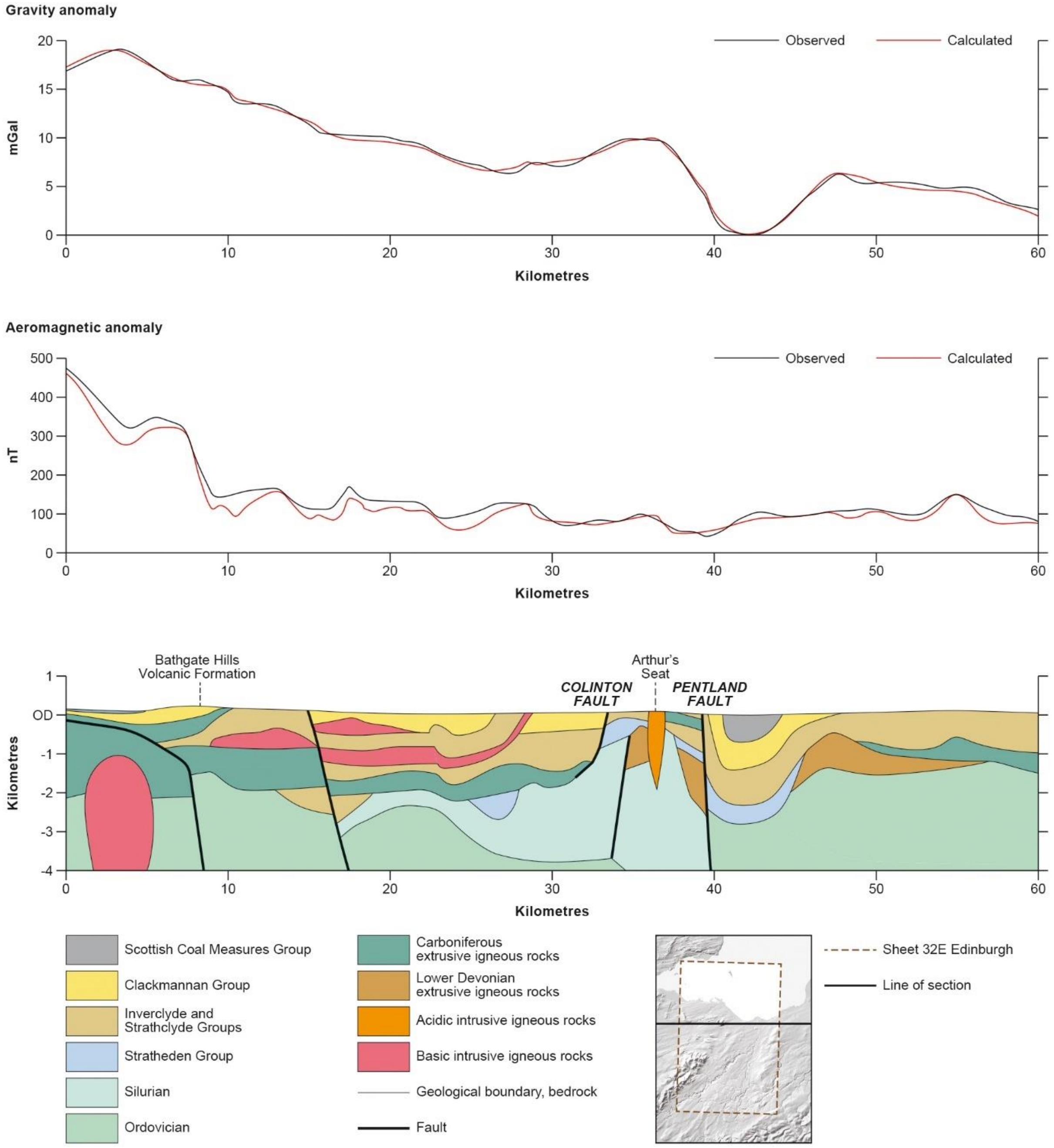


Figure 20 A 2D model of the gravity and magnetic data across the Edinburgh district, along line P1. Contains NEXTMap Britain elevation data from Intermap Technologies^{TM}. BGS © UKRI

A 2D model profile of the gravity and magnetic anomalies along an E–W section across the Edinburgh district (profile P1 in Figure 18) is shown in Figure 20. This is part of a full crustal model to a depth of 4 km which gives a possible explanation for most of the observed geophysical anomalies. In this model, Carboniferous strata in the Midlothian Coalfield are modelled to be about 2.5 km thick in a tight asymmetrical fold developed against the Pentland Fault.

To the west of the Pentland Fault, Siluro-Ordovician rocks are concealed beneath Carboniferous strata at a depth of about 1 km, while to the east of the fault they underlie the Midlothian Syncline at approximately 3 km depth. Within the Midlothian Syncline, Carboniferous rocks are seen to be underlain by about 0.5 km of Devonian strata, which are assumed to rest directly on rocks of Ordovician age. The upper part of the Pentland Fault itself is modelled as a steeply inclined planar structure.

Carboniferous volcanic rocks are seen to be present to both the west and east of the Midlothian Syncline, where their presence is not supported geophysically. Considerable lateral variation in magnetic susceptibility, possibly related to lithological or compositional changes, is required to explain adequately the observed pattern of magnetic anomalies.

8.5 3D MODEL

As part of studies for geothermal energy in the UK, Browne et al. (1985) provided a structure contour map on the base of the late Carboniferous sequence and a simple contour map on the base (sensu lato) of the Carboniferous sequence. Maximum depths of the late Carboniferous rocks occur within the offshore basin in the Firth of Forth, where depths are about 2.3 km below OD (Figure 21). Calculated gravity effects of the post-Tournaisian/Visean strata in the Midland Valley are up to about -16 mGal in the Firth of Forth Basin for a density contrast of -0.2 Mg m^{-3}.

Maximum depths of Carboniferous rocks also occur within the offshore basin in the Firth of Forth, where depths are about 4.5 km below OD. Calculated gravity effects of all the Carboniferous strata in the Midland Valley are up to about -20 mGal in the Firth of Forth Basin for a density contrast of -0.15 Mg m^{-3}.

The stripped gravity anomaly map, after removal of effects of Carboniferous strata (Figure 22), shows the Pentland Fault is still a significant feature in the gravity field. The north-eastern extension of the Southern Upland Fault (formerly the Leadburn Fault) is also still a strong feature, suggesting that either the depth or density model for the Carboniferous strata is incorrect or that the fault marks a significant density boundary in the pre-Carboniferous rocks. In the Edinburgh district, the most important feature of the stripped gravity anomaly map is the large positive anomaly offshore Port Seton, approximately coincident with the elongate magnetic anomaly west of the offshore extension to the Crossgatehall Fault. This anomaly is close to mapped Visean and Tournaisian volcanic rocks at Kinghorn, Inchkeith and at Garleton. A possible explanation is an early Carboniferous volcanic centre.

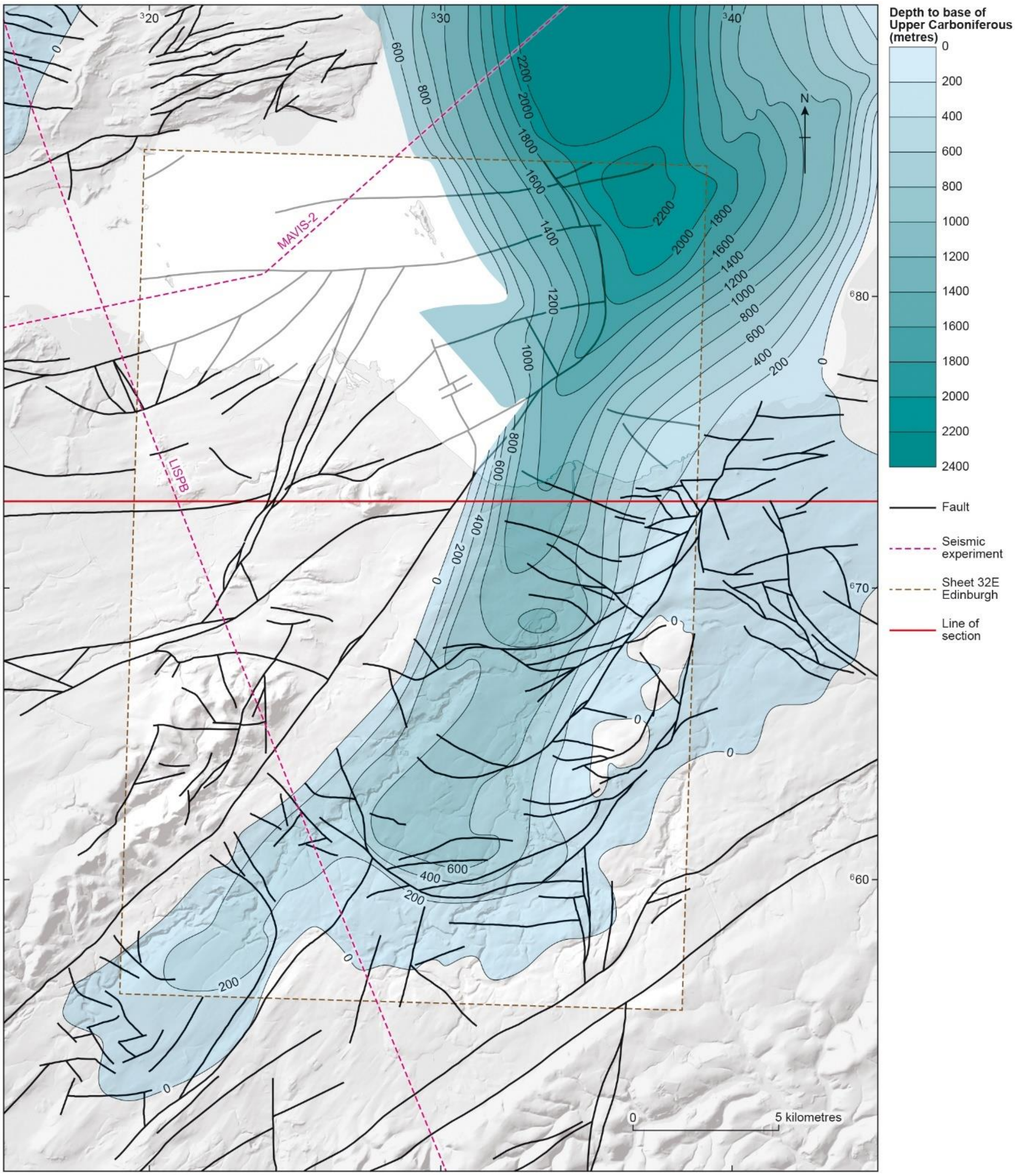


Figure 21 Depth below OD to the base of the late Carboniferous sequence across the Edinburgh district. Contains NEXTMap Britain elevation data from Intermap Technologies^{TM}. BGS © UKRI

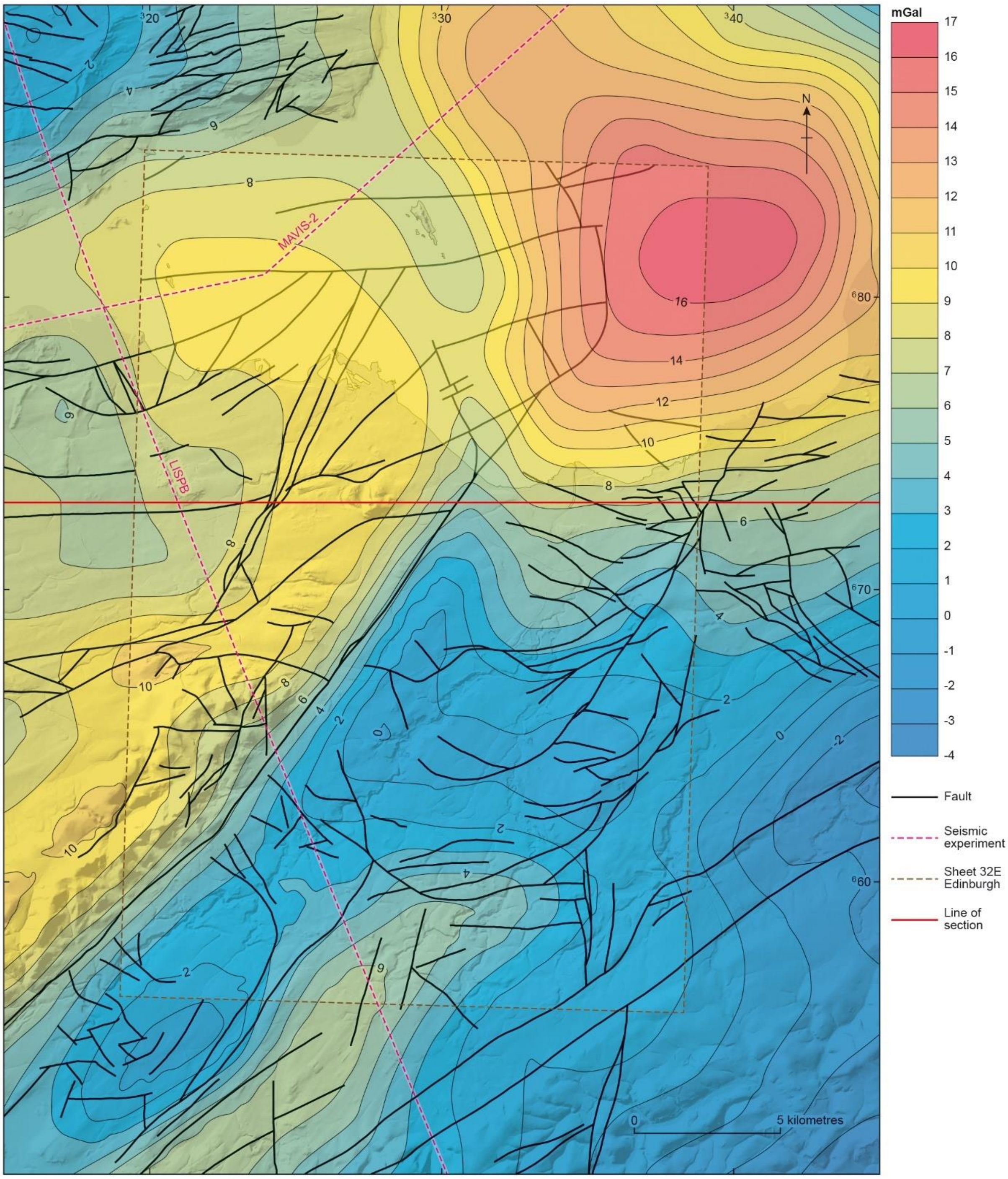


Figure 22 Gravity field after removal of the effects of Carboniferous strata. Contains NEXTMap Britain elevation data from Intermap Technologies™. BGS © UKRI

9 Quaternary geology

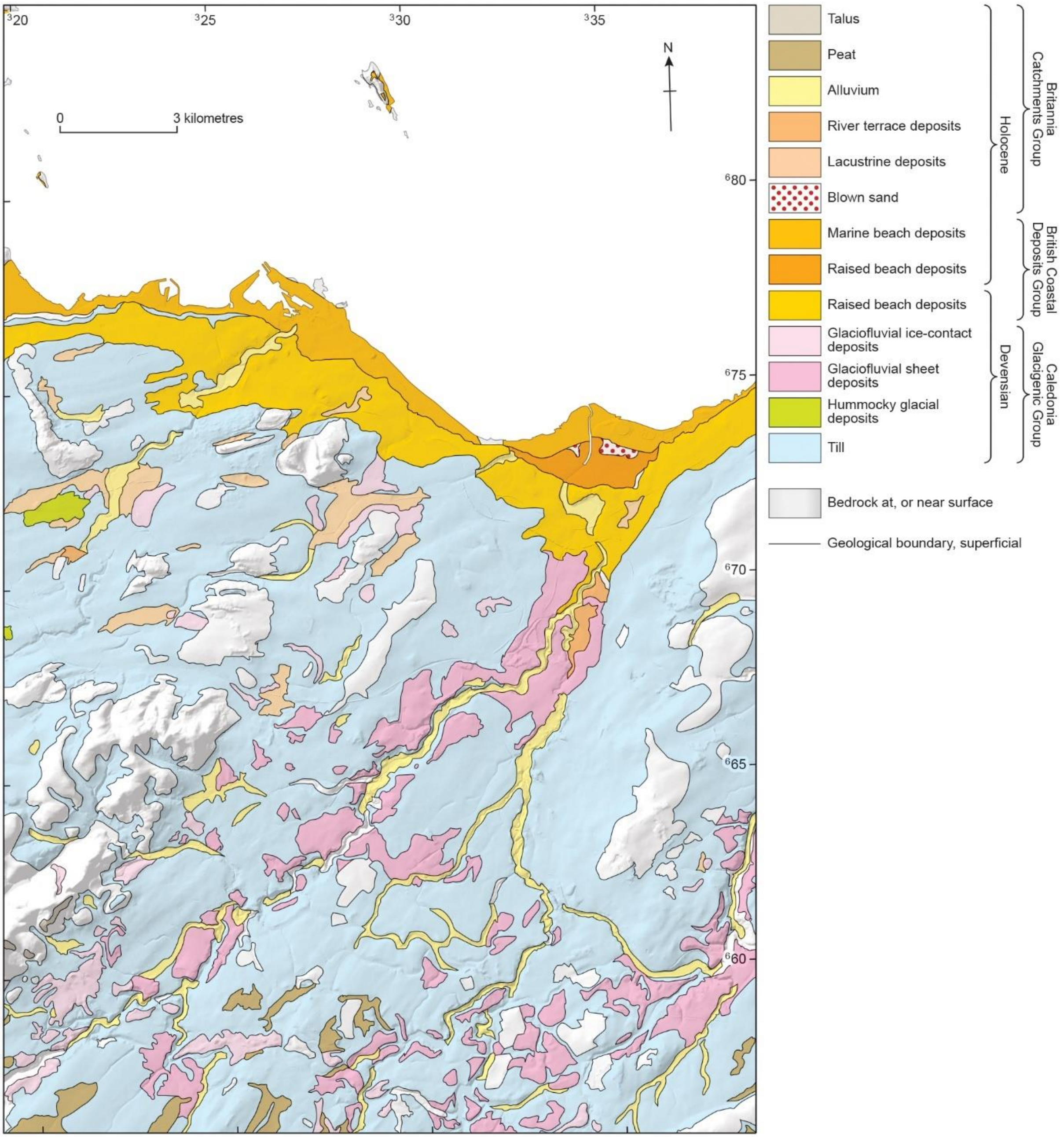


Figure 23 Distribution of superficial deposits in the Edinburgh district. Contains NEXTMap Britain elevation data from Intermap Technologies^{TM}. BGS © UKRI

No evidence has been preserved in the Edinburgh district of the latest Palaeozoic or of subsequent geological events that affected Scotland in the Mesozoic and Cenozoic. Early Cenozoic uplift of over 1 km has been suggested for Scotland (Underhill et al., 2008), and various authors have speculated on the pre-Ice Age landscape and river systems of central Scotland (George, 1974). Consideration of the burial history of strata offshore within the Edinburgh district by Underhill et al. (2008) indicates that Carboniferous sedimentation was followed by latest Carboniferous to early Permian Variscan uplift and erosion of strata, with resumption of sediment accumulation during the Mesozoic and former uplift from Palaeogene to the present. Detailed analysis of the burial and thermal histories within the Midlothian and Leven syncline by Vincent et al. (2010) indicated erosion of up to 660 m of strata associated with end Carboniferous Variscan uplift, followed by deposition of up to 1.9 km of strata during the Permian to the Palaeogene period, when maximum depth of burial was achieved prior to later Cenozoic uplift.

The Quaternary period (Holocene, Pleistocene and Pliocene in part), representing the last 2.6 million years of Earth history, was a time of extensive glaciations in Scotland. However, there is little reliable evidence in the Edinburgh district of any of the older glacial (and interglacial) events that affected central Scotland. Indeed, most of the accessible Quaternary deposits and features are less than 30 000 years old (Late Devensian to Holocene). Figure 23 is a simplified map showing the surface distribution of Quaternary deposits in the district, and Nextmap imagery highlighting surface landforms is depicted in Figure 24. Most formation names used informally in the text are from the work of Browne and McMillan (1989) in the Clyde valley area, modified by McMillan et al. (2005).

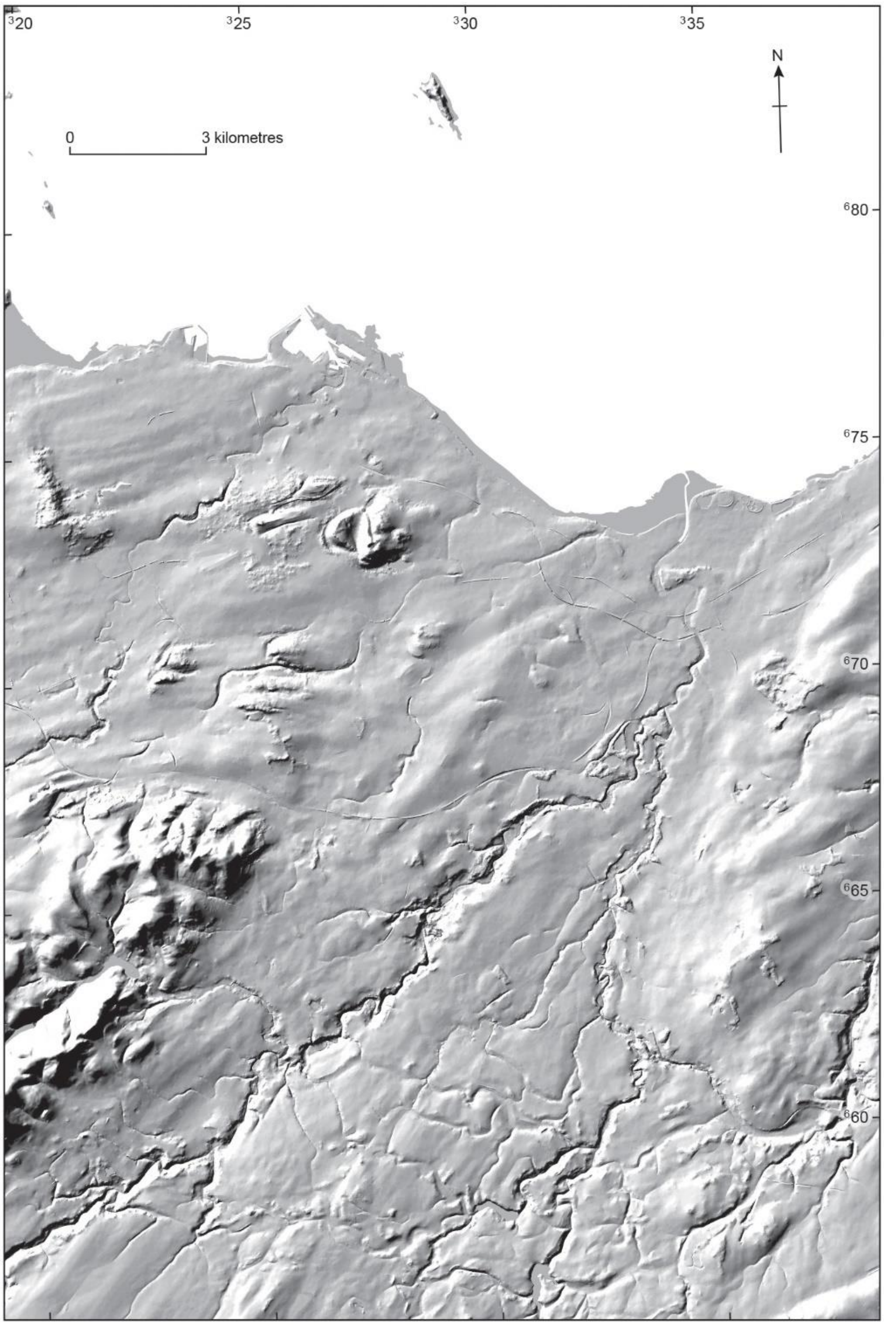


Figure 24 Nextmap image of the Edinburgh district (NEXTMap Britain elevation data from Intermap Technologies^{TM}) BGS © UKRI

9.1 HISTORY OF SURVEY AND RESEARCH

The Quaternary landforms and deposits of the Edinburgh area have a long history of research (e.g. Maclaren, 1828; Milne Home, 1840; Nicol, 1844; Chambers, 1853). These authors and those of the early Geological Survey memoirs (Howell and Geikie, 1861; Howell et al., 1866) recognised a broadly similar lithological succession, comprising ‘boulder clay’ (glacial till) overlain by sand and gravel, clay (used for brick manufacture) associated with raised beach deposits in the coastal fringe and by lake deposits in inland hollows, and lastly river alluvium. By 1840, following Louis Agassiz’s visit to Scotland, the interpretation of the depositional environments of boulder clay and erosional features (such as glacial striae) acknowledged the importance of glacial processes instead of the earlier diluvial and marine (ocean currents or megawaves) theories. Observation of glacial striae within the district by Agassiz (MacLaren, 1840) on what is now referred to as Agassiz Rock at Blackford Hill in part provided the evidence to support the interpretation of widespread glaciation of lowland Scotland (Gordon and Sutherland, 1993).

The existence of more than one unit of glacial till (then commonly termed boulder clay) in the district may have been recognised by Maclaren (1828, 1839, 1866) when he described the deposits seen in new cuttings for the Dalkeith railway, probably between the River North Esk viaduct [NT 324 672] and Newtongrange [NT 333 644]. Here Maclaren (1839, p.211) recognised a tripartite succession consisting of a lower till (black and bluish hues, stiff), an upper till (redder hue, looser texture, fewer and more angular clasts) and bedded sands above. This succession is similar to that seen in the River North Esk at the Hewan Bank GCR Site [NT 285 645] as described by Gordon and Sutherland (1993) and which has been widely recognised in the Lothians by Kirby (1966; 1968; 1969a and b). By 1866, in the second edition of his book, Maclaren believed that the two compositionally different tills were not only glacial in origin but were the products of one depositional event. However, it was Geikie (1877) who first recognised that more than one ice mass could have influenced glacial deposits in the district during the same glaciation. He understood that at the beginning of an ice age, separate ice masses could form in the Scottish Highlands to the north and the Southern Uplands to the south and both could advance into this district, his ‘debatable ground’. He saw the interaction of the two ice masses in the mixture of clast lithologies present in the glacial tills being derived from the Highlands and the Southern Uplands as well as more locally. Based on erratic types, Somervail (1879) recognised two directions of ice transport in the Pentland Hills, one from the south-west and the other to the south-east. Peach et al. (1910) noted that the character of the glacial till in the Edinburgh area was related to the underlying geology over which the ice had advanced. They believed in a composite ice-sheet from sources in the Highlands and Southern Uplands that had flowed generally eastwards through the Edinburgh area, but only identified a single rather than multiple till succession.

Subsequent studies by McCall and Goodlet (1952), Tulloch and Walton (1958) and Mitchell and Mykura (1962) echoed the Peach et al. (1910) view that the composition of the glacial till in the Midlothian area reflected the character of the local bedrock. However, McCall and Goodlet (1952) did conclude that the lower glacial till (e.g. Maclaren, 1828) was of Highland origin even though they did not recognise it separately. Other localities where two tills were recognised include the Redhall and Hailes sandstone quarries, and Bennie (1891) even provided photography of what he termed a washout down to rockhead within a till sequence. The thick and widespread deposits of sand and gravel overlying glacial till were considered by Peach et al. (1910) to have been deposited whilst ice was still obstructing drainage in the Forth valley (sensu lato) to the north, but after the southern ice had receded. They did note that the clast content of the gravels of the Midlothian area was dominated by ‘greywacke’ sandstone derived from the Southern Uplands. Mitchell and Mykura (1962) presented a generalised ‘glacial’ succession for the Edinburgh district (Table 10) that identified an upper ‘Southern Uplands Readvance Boulder Clay and Gravel’ above ‘Middle Sands and Gravels’ on a ‘Basal Boulder Clay’.

The sands and gravels of all authors are the same deposits. The two tills were regarded as having been deposited by the same glacial phase with most of the ice sourced from the western Highlands. However several strands of evidence outside this district (e.g. Sissons, 1958, 1961a, b) suggested that the last ice movements were from the south and southwest.

Table 10 Generalised ‘glacial’ succession for the Edinburgh district

Maclaren, 1828	Mitchell and Mykura, 1962	Kirby, 1966 and subsequent papers
	Southern Uplands Readvance Boulder Clay and Gravel	Roslin Till
Bedded sands	‘Middle’ Sands and Gravels	Burghlee Sand
Upper boulder clay; redder, looser texture		Intermediate Till
		Sand
Lower boulder clay, stiff, blackish and bluish	Basal Boulder Clay	Basal Till

Kirby (1966, 1968, 1969a, b, c) presented the results of a detailed study of the Lothian area using stratigraphical appraisal, clast counts and till fabric analyses. He recognised an impersistent five-part sequence (Table 10): Of the three glacial diamictons, the Basal Till was widely recognised and the Intermediate Till (upper, redder boulder clay of Maclaren, 1828) was best developed on higher ground in the south but absent near the coast, with the intervening Sand being absent in places. The Basal Till was deposited by easterly moving ice whereas the Intermediate Till was laid down by ice from the south. The third till forming the highest unit in the succession (cf. Peach et al., 1910; Anderson, 1940, 1941, 1942), the Roslin Till, was distinguished only where thick glaciofluvial sand and gravel intervened. The ice lobe that deposited the Roslin Till was alleged to have retreated northwards down slope from the watershed between the Esk and the Tweed and into Midlothian, depositing the glacial diamicton on top of the slightly older deposits. However Mitchell and Mykura (1962, p.114) report the Roslin Till involved in thrusts and minor overfolds, affecting the underlying cross-bedded sand with clay bands at the Burghlee Sand Pit [NT 2795 6515], Loanhead. These glaciotectonic structures indicate direction of movement to the north.

Quaternary deposits mapped within the Edinburgh district (BGS, 2006) are included within a lithostratigraphical framework for Quaternary and Neogene deposits of Great Britain (McMillan et al., 2005). Devensian glacigenic deposits within the district are a component of the Caledonia Glacigenic Group, late glacial to Holocene estuarine, marine and beach deposits are part of the British Coastal Deposits Group, and fluvial, lacustrine and peat deposits are included within the Britannia Catchments Group.

9.2 PRE-DIMLINGTON / LATE-DEVENSIAN STADIAL (>30 000 YEARS AGO)

In the Edinburgh district, there are deposits of sand and gravel (**Cadder Sand Formation of the Midland Valley Glacigenic Subgroup**) that may predate the Main Late Devensian glaciation that commenced about 32 000 years ago (Browne and McMillan, 1989). Henderson (1873) described deposits that he thought occupied channels cut into bedrock and noted the form of the local buried preglacial valley of the Water of Leith at Colinton at [NT 209 689]. The distribution of these sand and gravel deposits is generally limited to within the so-called ‘buried channels’, such as those of the Water of Leith (60 m thick channel fill at Murrayfield), Esk valley and under the Firth of Forth (Tulloch and Walton, 1958; pp.127–129). These are elongate hollows cut into the bedrock surface and may be closed basins cut by glacial scouring rather than pre- or interglacial river channels (Mitchell and Mykura 1962, fig.25). Minor ‘channel’ features described by both the previous authors (with depths in parenthesis) and all within the Esk valley include Temple (>40 m in Arniston Mains No. 23 Bore, NT35NW98 [NT 32590 58380]), Redside (>50 m in Rosebery No. 4a Bore, NT35NW6 [NT 30892 59130]), Gore (>33 m [NT 348 604]), Edgelaw (>62 m Rosebery No. 10 Borehole, NT25NE94 [NT 2960 5888]), Roslin (>54m in Loanhead No. 11 Bore, NT26SE27, [NT 2596 6313]), Whitehill (>33 m in Whitehill No. 8/52 Borehole NT36SW22 [NT 30120 62170]), Smeaton (>34 m in Smeaton No. 3 Borehole, NT36NE87, [NT 35180 69050]) and Niddrie (at The Wisp Pit near Redcroft NT 312 713).

Local deposits of laminated silt and clay have also been recorded within the ‘channel’ sequences at Smeaton [NT 3555 6890] (Tulloch and Walton, 1958; p.131). Henderson (1874, pp.391–395) recorded a succession of two tills interbedded with two units of sand and gravel at the extension northwards of the Redhall Sandstone Quarry [NT 2160 7055], Slateford. It is notable for the presence of laminated clay with plant remains within the upper till, under an enclosed bed of peat itself about 2.4 m from the surface (Henderson, 1874, Figure on p.393; Bennie and Scott 1891, pp.137–139). From the nonglacial deposits, plants, beetles, ostracods, molluscs and diatoms were recovered and identified.

9.3 DIMLINGTON STADIAL / MAIN LATE DEVENSIAN (ABOUT 30 0000 TO 14 700 YEARS AGO)

With the onset of cold conditions about 30 000 years ago, ice domes developed in the western Highlands in the Rannoch Moor area and in the Southern Uplands (Gordon and Sutherland, 1993). Sourced predominantly from the Highlands, the Main Late Devensian ice (Mitchell and Mykura 1962, fig.26) of the Dimlington Stadial moved generally eastwards into the district and beyond to reach its apparent maximum extent either some 50 to 80 km off the Angus–Fife–East Lothian coast at the Wee Bankie Moraine (Thomson, 1978), or farther east and possibly confluent with Scandinavian ice (Golledge and Stoker, 2006). It eroded the landscape producing striated and moulded bedrock surfaces, such as at Agassiz Rock [NT 259 702] (Plate 12) in the Hermitage of Braid (Rhind, 1836, Panton, 1873, Mitchell et al., 1960), rôche moutonnées as on Corstorphine Hill [NT 211 735] (McAdam, 2004) and crag and tail features; both the Castle Rock [NT 251 735] and Blackford Hill [NT 255 706] in Edinburgh are large examples of the latter landform type. Henderson (1872) briefly described crag and tail, glacial mouldings and scratches (striae) on Corstorphine Hill [NT 206 736]. Erosion by the ice removed pre-existing glacial and interglacial sediments (except in the bedrock depressions and very locally elsewhere).

9.3.1 Subglacial deposits

The ice deposited substantial, but generally thin (i.e. <10 m) spreads of glacial till (**Wilderness Till Formation** of the **Midland Valley Glacigenic Subgroup**) mainly on the lower ground, locally into streamlined ovoid mounds or drumlins. Conspicuous drumlins are very rare in the City of Edinburgh and absent in Midlothian, although some small, low ones occur in the west of the city from Barnton [NT 192 753] to Inverleith [NT 238 745], and at Clermiston [NT 196 745], Corstorphine/Craigleith [NT 225 748], and Juniper Green [NT 197 687] to Merchiston/Greenhill [NT 240 719]. The trend of most of these drumlins is slightly north of east. The till is usually a stiff to hard sandy, silty clay, with dispersed fine to coarse, angular to rounded gravel, cobbles and boulders (diamicton). It is an overconsolidated, cohesive engineering subsoil. In the older literature for the Edinburgh district, the presence of lines of boulders in the till and interbeds of sand and gravel have been noted and described (Henderson 1893, p.297). Offshore, the equivalent of the Wilderness Till is recognised as a seismostratigraphical unit named the Wee Bankie Formation (Thomson, 1978; Gatliff et al., 1994; Golledge and Stoker, 2006; Stoker et al., 2008) that is seismically acoustically chaotic. The unit is recorded to be as much as 40 m thick.

Plate 12 Glacial undercutting of andesite lava at Agassiz Rock SSSI [NT 2595 7022], Blackford Hill, view of north bank exposure in Braid Burn (P219270). In 1840 it was shown by Charles MacLaren to the famous Swiss geologist Louis Agassiz, who recognised the moulded and grooved surface as being the work of land ice, the first such recognition in Scotland BGS © UKRI

Large boulders (glacial erratics) received much attention in the early to mid-19th century. Not only did these constrain the direction of ice transport but with the associated striae contributed to the recognition of the work of glacial ice in Scotland. Perhaps the largest erratic found in Edinburgh (about 1905) was that of an Early Devonian trachytic lava (Plate 13) at the old Comiston Sand Pit [NT 2430 6890] (now Fairmile Park LGS) (Campbell and Anderson, 1909; Smith, 1994), that appears to be over 45 m long and up to 3 m thick resting on about 6 m of sand and gravel.

Plate 13 Cross-bedded glaciofluvial sands overlain by large trachytic glacial erratic, Fairmile Park Local Geodiversity Site [NT 2430 6890], formerly the Comiston sand pit; only fragmentary exposure of the erratic is currently visible (P215107) BGS © UKRI

9.3.2 Glaciofluvial, glaciodeltaic and glaciolacustrine deposits

When the Late Devensian ice-sheet started to retreat from the district, it also began to thin and melt in situ; initially the ice in the Esk valleys receded southwards towards the 'watershed' between the Edinburgh district and the catchment of the River Tweed to the south in the Southern Uplands, allowing meltwaters to flow eastwards by the Tyne valley near Vogrie (with its misfit modern river). Later, about 15 000 years ago, the main ice stream retreated westwards across the district along the Forth valley, back towards the source area in the Scottish Highlands (Gordon and Sutherland, 1993, p.559 and Figure 17.1). Before this latter phase of final retreat, substantial volumes of glaciofluvial sand and gravel sheet deposits (**Broomhouse Sand and Gravel Formation** of the **Midland Valley Glacigenic Subgroup**) accumulated in and around the Esk valley [NT 336 683] and Tyne valley [NT 377 632] formed by meltwaters and lakes dammed by the ice in the Forth estuary to the north. Meltwater channels (Plate 14) in the southern part of the Edinburgh district (including Penicuik and south of Gorebridge; Mitchell and Mykura, 1962; Plate IV) relate to a regional system of erosional features formed by deglaciation of central and Southern Scotland and the systematic eastwards transfer of meltwaters from the Middle Clyde, Medway and Tweed valleys (McMillan et al., 1981). Meltwaters flowed below, within, on top of and along the margins of the melting ice-sheet. Ice-contact deposits, forming mounds, eskers (ridges) and terraces with a few kettleholes, are common particularly in the valleys of North Esk and Tyne Water–South Esk rivers, and are the depositional elements of the deglaciation process.

Plate 14 Glacial meltwater channel; Craiglockhart, Edinburgh [NT 2275 7010], view from Wester Craiglockhart over channel to shoulder of Easter Craiglockhart to Arthur's Seat and Blackford Hill in distance (P637895) BGS © UKRI

Mitchell and Mykura (1962) and Aitken et al. (1984) described the glaciofluvial, glaciodeltaic and glaciolacustrine sand and gravel deposits of the district in some detail, the latter presenting new borehole data in support of a resource appraisal of the Dalkeith [NT 341 671] and Temple [NT 317 585] area. The Broomhouse Sand and Gravel Formation is probably the oldest deposit forming the flat terrace spreads of sand and gravel plastered on to the flanks of the Gore Water and River Tyne valleys in the far south-eastern corner of the district, occurring at heights of 200 to 240 m OD in the Borthwick [NT 3700 6000] area. In the Roseberry–Yorkston [NT 3100 5700] area and Fullarton–Mount Lothian [NT 2800 5700] farther west on the southern fringe of the district, the terrace flats are at about 260 m OD, and slightly lower (250 m OD) in the south-west at Dykeneuk–Netherton [NT 2400 5800] near Howgate. These spreads all appear to be early deposits related to meltwaters escaping along the south-eastern ice margin edge, via the Tyne valley eastwards towards the adjacent Haddington district and eventually to the Firth of Forth. In the North Esk valley south-west of Penicuik there are extensive areas of ice-contact deposits at heights of around 260 to 290 m OD that probably also relate to this early phase. However terraced spreads in the North Esk generally occur at lower levels; for example about 180 to 200 m OD in and around Penicuik. These deposits relate to a later time when the meltwaters were escaping down the valley of the North Esk River to the Firth of Forth ice front. The extensive spread of meltwater deposits in the Roslin, Bilston, Straiton and Loanhead areas [NT 26] that are widely overlain by the informally named thin Roslin Till Member occur at even lower levels from 180 m down to 110 m OD. If the Roslin Till is accepted as glacial in origin, then these surface levels may be unrepresentative of the original terrace flats, but in any case are indicative of a later meltwater event draining to lower impoundment levels as the main ice mass in the Firth of Forth melted down and retreated westwards.

Martin's (1981) hypothesis for this district is of a single major advance (Late Devensian), rapid retreat and wasting of a single ice-sheet with the lowering of the ice being predominantly towards the axis of the Forth. He envisaged ice-contact deposition in ice marginal basins within embayments in fault scarps and in major river valleys. Martin also supported Kirby (1969c) in recognising that the terrace deposits in the valley of the North Esk River formed an off-lapping pattern. He was also reluctant to link terraces to specific drainage channels. Indeed, heights of terraces were not seen as a way of correlating them if the sedimentary basin was determined by local conditions, such as ice dams and topographical highs near sediment sources supplied from side valleys.

The Old Pentland esker [NT 262 661] is a classic landform of its kind, but unlike many ice-contact features in the Edinburgh district, has not been damaged by sand and gravel extraction. Another esker (or possibly ice marginal feature) is at Campend by Sheriffhall [NT 315 685]. Martin (1981) described the main, now largely infilled sand and gravel pits of the district, and at Haveral Wood [NT 292 661] (an area of moundy topography before quarrying) he recognised a lower 'member' of heterogeneous lithologies from clay to gravel including diamicton. He identified fine-grained lacustrine and delta or fan front facies, with mean transport direction of the sediments towards the south-east; these deposits also become finer in grain size in this general direction. An upper 'member'; with a partly erosive base and consisting of diamicton on gravel, was interpreted as being a proximal ice marginal or supraglacial mass-flow/muddy sheet-flood complex (Martin, 1981, p.102, table 11.4). These deposits show normal synsedimentary faulting and bowl-shaped surface depressions.

At nearby Melville [NT 292 661], an area of level terrace before quarrying, just to the east of Haveral Wood, Martin (1981, p.100, table 11.3) recognised a lower 'member' of gravel, gravel and sand, and trough cross-bedded sand, passing northwards into sand, including laminated sand. These deposits were interpreted as subaqueous delta mouth, delta front and interlobe deposits with rare debris flows. These glaciodeltaic deposits are described as having a dominant north-eastward direction of transport. An upper 'member' of gravel with horizontal scoured base was also identified, with clast imbrication and crossbedding demonstrating north-easterly sediment transport. They were interpreted as subaerial (terrace), shallow braided fluvial delta-top facies. Both Melville and Haveral Wood are now landfilled and neither retains exposures of these sand and gravel deposits.

At Oatslie [NT 264 628] Martin (1981) also described an area of terrace seen in at least three workings. He recognised three 'members' comprising in ascending order sand, sandy gravel, and diamicton and mud. The sand was interpreted as delta front/interlobe deposits with transport direction to the east. A section seen in Oatslie Landfill [NT 259 627] in 2000 during the construction of a landfill cell, showed cross-sets with easterly transport but climbing ripple units rising westwards. The overlying gravel, with slightly angular scoured base, was seen as delta-top braided river deposits, with transport to the north-east. The diamicton and mud, with planar to undulatory base (the Roslin Till of other studies) was interpreted as a transgressive lacustrine drape with debris flows. At this long-lived multi-excavation site, landfilling operations still reveal sections in these deposits but not the overlying diamicton and mud (Roslin Till) facies. With reference to workings at Clippens [NT 267 660], now also landfilled, Martin (1981) described the sediments as similar to those seen at Oatslie with inferred transport direction to the north-east.

In Edinburgh, early workers described glaciofluvial deposits from Tynecastle Sandpit (Heart of Midlothian football ground) [NT 231 724] with large, striated boulders isolated in sand and gravel, sandwiched between two tills and also with till-filled downward tapering wedges (Milne Home 1874; Brown 1874; Richardson, 1874). Campbell and Anderson, (1909) as noted earlier, described glaciofluvial deposits at Comiston Sandpit overlain by a large erratic (Plate 13).

Kirby (1968) argued that the Roslin Till overlying the glaciofluvial deposits of the Esk valley was a glacially deposited diamicton, relating to a distinct glacial readvance. This was based on features seen in several of the quarries such as till-filled frost-wedge casts (Common and Galloway, 1958) penetrating the underlying sand and gravel (see the heated debate on this frost wedge topic between Anderson, 1940, 1941, 1942 and Carruthers, 1941, 1942), and also the distinctive clast content of the till, suggesting a northern or southern source for the ice (different authors came to contrary views). However, Anderson (1940) did not record bedding deformation in the top of the underlying sand and gravel. He did observe that where the ground falls away the 'boulder clay' cuts across (transgresses) the bedding planes of the glaciofluvial deposits. He also described a 'boulder clay'-lined channel cut into sand at Roslin.

Martin (1981) re-assessed the stratigraphy recognised by Kirby (1968), and in particular, the status of the Roslin Till. In essence, Martin saw the whole succession as one single phase of ice retreat, resembling modern glacial systems where outwash, debris flow, subglacial and other environments of deposition can be closely spaced and coeval. Indeed, Martin (1981) interpreted the Roslin Till as a transgressive lacustrine drape and debris flow lobes, covering other sediments laid down near or at a glacial margin. Unlike Carruthers (1941, 1942), Martin was sceptical of the frost-wedge cast evidence, and explained the cracks as being till-filled load pressure fabrics. Such till-filled cracks but in bedrock have been recorded from quite recent excavations in the former naval base at Rosyth (Sheet 32W Livingston). He also rejected the notion that Kirby's two lower tills were separate units. Rather, they reflected variations in flow conditions in one ice mass both normal and parallel to the flow direction, characterised by differing clast composition contents from either the Scottish Highlands or Southern Uplands.

A section seen in Oatslie Landfill [NT 2590 6310] in 2000, during the construction of a landfill cell, showed 2.45 m of dark brownish grey, distinctly blocky jointed, hard to stiff diamicton. Clasts ranged in size from 1–30 cm. The composition of the clasts included wacke sandstone, Early Devonian basaltic rock, Kinnesswood Formation conglomerate, ironstone, coal, Carboniferous sandstone and limestone, felsite and vein quartz. The diamicton contained at least one unit (up to 15 cm) of very stiff laminated silt and clay which may be a raft. The base of the diamicton was sharp and undulating on a centimetre scale. The dip of the contact was to the east at 25 to 45°. The underlying sequence consisted of 1.45 m thickness of interbedded firm to very stiff, pebbly clay/silt, with laminated fine to coarse sand showing thrust (with overfolding to the east) and normal faulting (2 cm scale) and polished surfaces. Pods and wisps of sand were quite common. Clearly this section correlates with Martin's (1981) diamicton and mud facies interpreted as a transgressive lacustrine drape with debris flows. However, the overall geotechnical and structural features of the above section suggest that the diamicton could have been laid down by a re-advance of ice over the deposits of a transgressive lake, perhaps dammed by this ice. The diamicton seen at Oatslie Landfill site in 2000 was at least 3.2 m thick, with lateral continuity.

In 1986 a temporary section during the construction of the Edinburgh City Bypass at Straiton [NT 2685 6700] also revealed a similar diamicton, more than 3 m thick overlying at least 2 m of mainly sand (Plate 15). The stiff to hard diamicton was well jointed and contained a wide range of clast types, including wacke sandstone, Early Devonian basaltic rocks, Kinnesswood Formation sandstone and conglomerate, ironstone, coal, shale, Carboniferous sandstone, felsite, vein quartz, jasper and large boulders of dolerite. Thrust faults, dipping approximately south-westwards at 20° to 70°, affected the undulating contact between the two units. The cross-bedded sand showed a southerly palaeocurrent direction.

Plate 15 City of Edinburgh Bypass [NT 2685 9090], view south of temporary section during construction showing the Roslin Till, with thrust to right of lorry at sharp basal contact on underlying sands; (P265553) BGS © UKRI

9.3.3 Raised marine deposits (late Devensian)

The interplay of global sea-level change with local isostatic recovery following deglaciation (marked by crustal uplift following retreat of the ice sheet) has caused fluctuations in relative sea level in the district. These are marked by raised beach features and by raised marine deposits along the shores of the Firth of Forth. The changing coastline of the district in latest Late Devensian (<17 000–11 600 years ago) and Holocene times (11 600 years ago to present) has previously been appraised using these two lines of evidence (e.g. Cadell, 1913). During deglaciation, local relative sea level was high in central Scotland and it is not unusual to find raised marine sediments as high as at about 40 m above OD. In Edinburgh, the decaying Forth glacier retreated westwards towards the source in the Scottish Highlands, and by about 14 000 years ago the sea had invaded the Forth valley reaching as far west as Aberfoyle (Browne and Grinly, 1996). The characteristic marine deposits associated with the deglaciation of the Scottish east coast comprise red or brown clay, finely colour laminated in shades of pink and grey. These clays contain macro- and microfossils that are indicative of an Arctic climate, similar to the Errol Beds (Peacock, 1975; Paterson et al., 1981; now the **Errol Clay Formation** of the British Coastal Deposits Group). These deposits have only been identified with certainty in the Firth of Forth (as the seismostratigraphical unit of the St Abbs Formation by Gatliff et al., 1994), but probably occurred extensively in Portobello [NT 3005 7425] in a series of clay pits (Miller, 1864; Tait, 1934) that were worked from 1765 until the mid-20th century. The pits are now largely infilled. Small clay pits at Granton [NT 2350 7705] and Wardie [NT 2390 7665] may have been excavated in the same deposit. The large pond at the Figgate Park [NT 2990 7365] in Portobello is an unfilled clay pit, but no exposures are present. Tait (1934, figs 1 and 2), based upon the work of Miller (1864), noted that the lower clay (Errol Clay Formation equivalent) was up to 9 m thick, with marked laminations, isolated ice-rafted stones but no shells. Gatliff et al. (1994, p.93) provided brief notes on the offshore clays of the St Abbs Formation that are generally less than 10 m thick, but locally up to 20 m thick. They are seismically almost structureless, plastic and of soft to stiff consistency. Appendix Two in

Thomson (1978) described the characteristic cold-water fauna of foraminiferans and ostracods such as *Rabilimis mirabilis* and *Krithe glacialis* typical of a near normal-salinity arctic shelf sea.

The most conspicuous of the former coastlines associated with deglaciation in the Firth of Forth is the Main Perth Shoreline, a fragment of which is at about 21 m above OD in Burntisland (Sissons and Smith, 1965, fig.1), just to the north in the Kirkcaldy district. This feature, not recognised in the Edinburgh district, formed when the Forth ice had retreated westwards to Stirling, and is tenuously dated to around 13 500 years ago. It may have formed during a period of warmer climate, when isostatic recovery of the land and eustatic sea level rise was temporarily in balance. The main deposits of the Late Devensian beaches are sand and gravel that appear to overlie and also pass laterally into clay and silt. They were once seen in the Newhailes Sand Pit [NT 328 728] where clay beds were interleaved. Although there are no altimetric details, there are several distinct beach platforms up to 35 m OD in the district, and locally they have been mapped to almost 43 m OD at the top of Leith Walk, central Edinburgh [NT 260 743].

9.4 WINDERMERE INTERSTADIAL / BØLLING–ALLERØD (14 700 TO 12 900 YEARS AGO)

Late Devensian sea-bed silty clays (**Linwood Clay Member** of the **Clyde Clay Formation**) characteristic of the fully deglaciated Scottish sea lochs (e.g. Firths of Forth and Clyde) have not yet been proven onshore in the Edinburgh district, but the equivalent strata are inferred offshore to underlie the Firth of Forth (Gatliff et al., 1994; p.93) as the **Largo Bay Member** of the **Forth Formation**. This seismostratigraphical unit is up to 30 m thick, with subparallel seismic reflectors and a fauna showing that the climate was warmer than that at the time of deposition of the Errol Clay Formation (St Abbs Formation, deposited prior to 14 000 years ago). The Largo Bay Member may have accumulated during the Windermere Interstadial, although the upward decrease in faunal diversity may be in response to a cooling climate, reflecting the onset of the Loch Lomond (Younger Dryas) Stadial about 12 900 years ago. The Firth of Forth and other eastern Scottish coastal estuaries are considered by Peacock (2002) to have been occupied by cold water of near normal marine salinity, which after a few hundred years was replaced by more brackish conditions as sea level fell and the estuaries were infilled. The impoverished marine macrofauna resembles that of high boreal to arctic soft-bottom communities associated with high rates of deposition (Peacock, 2002). Some offshore faunal details are to be found in Thomson (1978, pp.45–46). Devensian raised-beach deposits and related glaciofluvial terraces around Musselburgh [NT 365 730], Portobello [NT 304 736] and Granton [NT 234 767] are mainly composed of sand and gravel, and provide evidence that during the Windermere Interstadial (prior to the reappearance of glaciers in Central Scotland during the Loch Lomond Stadial) local relative sea level fell from about 22 m above OD to at below present OD. Other evidence of falling base levels includes Late Devensian alluvial terraces in the River Esk (North and South) and Water of Leith valleys.

During the Windermere Interstadial (equivalent to the Bølling–Allerød Interstadial), the local landscape was largely devoid of trees and generally tundra like, with shallow lakes of significant size including the former Corstorphine Loch [NT 206 724] and Duddingston Loch [NT 282 724], with surrounding areas of associated marshland (Coope, 1968; Newey, 1970). The current elevation of the flatter land associated with these two lochs generally reaches heights of between 40 and 46 m OD. Given that in the upper part of the Quaternary succession there are a few metres of sediment including shell-lime sediment (‘shell marls’) [e.g. at NT 203 721], peat and silt, it is possible that Late Devensian marine deposits occur locally in hollows on till or bedrock surfaces at depth, concealed beneath the lake sediments. The Corstorphine Loch is known for the occurrence of deposits containing arctic plants, beetles and red deer bones (Bennie, 1894; Coope, 1968). The precise ages of these deposits are not known. Based upon species of beetles found in the late 19th century in silts from the succession in the former Corstorphine Loch, Coope (1968) suggested that the climate at this time was subarctic with a more continental aspect than at the present day. Tundra conditions would be expected but these sediments probably mark a period of relative climatic amelioration. Bennie and Scott (1891, pp.134–136) recorded an ‘interglacial’ fossiliferous deposit of sandy clay with two peat layers (on boulder clay) excavated over a period of years at Hailes Quarry [NT 209 706]. They recorded shells and ostracods from these deposits along with seeds and beetles (Bennie and Scott, 1891).

9.5 LOCH LOMOND STADIAL / YOUNGER DRYAS (12 900 TO 11 700 YEARS AGO)

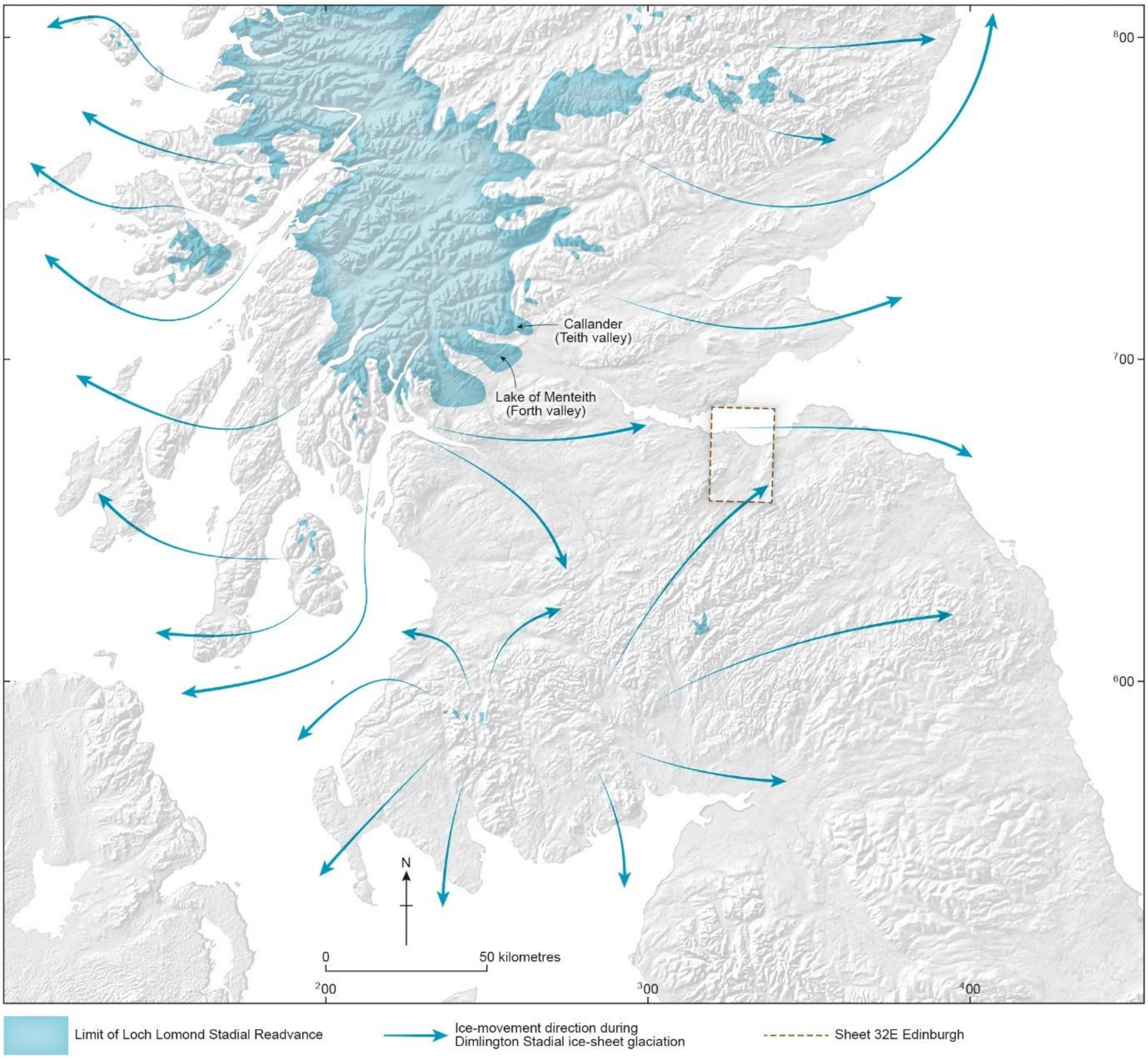


Figure 25 Limit of the Loch Lomond Readvance and general directions of Main Late Devensian ice sheet movement BGS. Contains NEXTMap Britain elevation data from Intermap Technologies$^{\mathrm{TM}}$. © UKRI

During the Loch Lomond (Younger Dryas) Stadial, ice again accumulated in northern Scotland and advanced southwards and eastwards into lowland areas (Figure 25), reaching as far east as Callander in the valley of the River Teith and Lake of Menteith in the valley of the River Forth (Gordon and Sutherland, 1993). Beyond these ice margins there is possible evidence of frozen ground including frost-wedge casts, but no significant evidence of this in the Edinburgh district. Local relative sea level in the Firth of Forth may have fallen below that of the present day, although doubt has been cast on this interpretation by Peacock (1998) for the Grangemouth area. On the southern shore of the Firth of Forth, west of the Edinburgh district in the vicinity of the Forth Road Bridge [NT 124 780], the Main Late Glacial-Shoreline is developed at about 4 m below OD (Sissons, 1974a, b), with a shore platform up to 300 m wide to the seaward side. Here, the shore platform is overlain by the Bothkennar Gravel Formation (Browne et al., 1984) of the Forth Clay Formation, which is about 1 m thick and previously known as the ‘buried gravel layer’ (Sissons, 1969; Peacock, 1998; Browne et al., 1984) The shoreline and the **Bothkennar Gravel Formation** are inferred to be present in the Edinburgh district, concealed beneath younger deposits. The origin of the Main Late Glacial Shoreline has been ascribed to enhanced marine erosion under the prevailing periglacial conditions, but shoreline inheritance may also have played a part.

At Corstorphine [NT 223 728], a broad spread of alluvial fan sand and gravel has been identified overlain by Holocene lake deposits (Ballantyne and Harris 1994, p.251). Periglacial activity would also have enhanced the development of the talus slopes of Salisbury Crags [NT 267 732] in Holyrood Park (now almost completely vegetated) and at other steep slopes in the Edinburgh district, such as the Pentland Hills [NT 20 62]. The distinctive pink unvegetated scree slopes of Caerketton Hill [NT 234 664] probably developed through this period. Sissons (1971) carried out a detailed geomorphological study of central Edinburgh and recognised boulder gravels on the north-western and southern sides of Calton Hill, up to 9 m and 22 m thick, respectively. The size and angularity of the deposits and their position beneath steep rock features were interpreted as evidence for periglacial solifluction. Sissons (1971) also interprets a 2 m to 3 m-thick layer of distinctly bedded stony clay in Holyrood Park at [NT 2675 7369] (Our Dynamic Earth exhibition centre) as a solifluction layer derived from the steep slopes of Holyrood Park during a period of periglacial (Loch Lomond Stadial) climate.

9.6 HOLOCENE (<11 700 YEARS AGO)

The major change in the climate to warmer conditions about 11 700 years ago, heralding the Holocene, may have taken place in a few hundred years (Gordon and Sutherland, 1993). This was associated with the disappearance of glacial ice from Scotland and thawing of ground ice. From arctic conditions, the climate improved such that at the postglacial optimum, about 7400 years ago, the local climate was warmer and wetter than at the present day.

When the main Holocene marine transgression started about 8500 to 9000 years ago, local relative sea level within the Edinburgh district again rose above that of the present day and formed the Main Postglacial Shoreline, with a marked former coastline feature and deposits of shelly sand and gravel forming the beach platform. The largest areas of Holocene raised-beach deposits of the British Coastal Deposits Group are at Leith, east of the Water of Leith [NT 275 760], and at Musselburgh [NT 350 726], with narrow strips between these. Their heights are about 8 m OD. The Main Postglacial Shoreline formed about 7400 years ago. Small areas of shelly clay and silt are also known, such as the clay pits at Abercorn, Portobello [NT 301 739] (Miller, 1864; Tait, 1934) with periwinkle and tellinid shells and *Scrobicularia*. Miller (1864) described two units, an ‘upper clay’ that occupies a channel cut down into a ‘lower clay’ (Miller, 1864; pp.110–124). To the west of this locality, he also reported deposits similar to the ‘upper clays’ with plentiful remains of oysters and *Cardium, Patella, Pecten* and *Buccinum* at Fillyside Bank [NT 287 755]. Offshore in the Firth of Forth, the sands and clays of the **St Andrews Member** of the **Forth Formation** seismostratigraphical unit best represent the Holocene marine and coastal succession in the district. The St Andrews Member is up to 40 m thick and is characterised by oblique seismic reflectors (Gatliff et al., 1994, p.93). Faunal data are included in Thomson (1978, pp.45–46) that record the unit’s essentially modern aspect.

By about 4500 years ago sea level had fallen to its present-day position. Present beach deposits are generally of sand and gravel and form fans where the main River Esk [NT 345 740] and Water of Leith [NT 270 770] and streams enter the sea. As central Scotland is a region of significant overall postglacial fall in sea level, the rivers Esk and Water of Leith sometimes occupy deep, narrow incised valleys, cut into Quaternary sediments and underlying bedrock, with fragmentary river terraces preserved locally along the main river valleys.

Rockfalls and landslides, as seen in Roslin Glen between Polton [NT 296 654] and Roslin Powder Mill [NT 266 623], are quite common and include active mass movement features and deposits (Plate 16). Martin (1981; p.88) ascribed normal faults seen in sand and gravel at the now restored Haveral Wood [NT 292 661] and Melville quarries [NT 292 661] to modern slope instability.

Plate 16 Springfield Mill, west bank of River North Esk, Polton Bank [NT 2850 6468] View of 1980 landslide looking south-south-west, showing 10–15 m. high foot scarp and numerous subsidiary scarp features up slope. Landslide toe (removed) formerly extended across River Esk almost to left-hand edge of photograph, between tall brick building (lower left) and wire fence behind (P219748) BGS © UKRI

Large lochs (Cadell, 1893; 1913; folded coloured map opposite p.142) still existed into historic times at Corstorphine [NT 206 724] (partly drained in 1670 and finally in 1837) and Duddingston [NT 283 720], with other small lakes such as the Craigcrook Loch [NT 210 737], Jordonvale (Morningside) Loch [NT 242 710], Lochend Loch [NT 277 749] and the Nor' Loch (Princes Street Gardens [NT 255 737]). The Nor' Loch is not shown on Cadell's 1913 map as its more recent history suggests it was artificially impounded about 1450 (Cadell, 1893) and had ceased to exist by 1816. There is scant evidence for the supposed South Loch at the south side of Edinburgh Castle and Royal Mile [NT 253 737] and for the Holyrood Loch [NT 268 736] perhaps finally drained in the mid-15th century. However, Cadell (1913, p.138) recorded site data for gasometers (replaced by the exhibition centre 'Our Dynamic Earth' [NT 267 739]) that show >5 m of clay, peat and marl that may represent part of such lake deposits. The Borough Loch at The Meadows [NT 255 726] was also described by Miller (1864), and was partially drained after 1722 and finally drained in 1842; 1.7 m thickness of shell-lime sediment ('shell marl') were reported near surface in the Meadows, containing freshwater molluscs including *Limnaea*, *Valvata* and *Pisidium*. Interestingly the waters of this loch were once used for brewing beer.

10 Applied Geology

Unless otherwise stated, the text in this section reflects the views and status at the time that the original document was written. Significant edits and updates by A Monaghan have been added in bold italics.

The Edinburgh district has a long history of mineral extraction and light industrial, commercial and tourist development, with World Heritage Status granted to the stone-built, historic city centre of the Old and New Towns. Mining and quarrying activities have declined in recent years to the extent that deep mining of coal has ceased. The brewing industry with its use of local water resources is also much less important today. However, for future planning and development it is essential to have knowledge of the mineral resource potential of the district, whether related to energy sources, bulk minerals, or groundwater. Information is also needed about other geological conditions which may affect planning for future development of the district, such as geohazards related to ground conditions and stability, groundwater pollution, coastal erosion or the conservation/ preservation of the natural geological and geomorphological heritage.

10.1 RESOURCES ENERGY SOURCES

Deep-mined coal

With the abandonment of the Monktonhall Colliery [NT 3244 7080] in September 1997, and sealing of the Blinkbonny Mine Adit [NT 3538 6269] near Gorebridge in 2003, underground mining of coal ceased in the Edinburgh district after a long history (Martin, 1905). Historically, the most extensively worked coal seams were the North, South, Bryans Splint, Peacock, Blackchapel, Stairhead and Great Seam coals in the Limestone Coal Formation; the Fifteen Foot, Nine Foot, Salters, Cowpits Five Foot, Musselburgh Jewel, Rough and Splint coals in the Coal Measures, and the North Greens Coal in the Lower Limestone Formation. The Geological Survey Memoir by Tulloch and Walton (1958) remains the best guide to the detailed geology of the Midlothian Coalfield.

With current technology, desirable seam thickness in excess of 1.4 m, and suitable barriers against ingress of mine waters from abandoned workings, future potential by conventional methods of longwall extraction is most likely to be under the Firth of Forth in Musselburgh Bay. The main remaining potential for commercial extraction is in the lower part of the Middle Coal Measures, the Lower Coal Measures, the Limestone Coal Formation and to a much lesser extent in the Passage and Lower Limestone formations. The underground gasification of coal seams (at least 2 m thick) at high temperatures into syngas (mixture mainly of carbon monoxide, hydrogen, and methane), by injection of steam and air or oxygen, could tap resources to depths of 1200 m that are now considered uneconomic for deep mining onshore and offshore.

The Scottish Government imposed a moratorium on underground coal gasification in 2015.

Opencast coal

With the privatisation of the coal industry, there was a very active interest in opencast coal in the Edinburgh district, particularly for sites in the Scottish Coal Measures Group and the Limestone Coal Formation. As of 2015, the most recently active sites included Blinkbonny [NT 3538 6269] by Gorebridge, Newbigging [NT 2750 5950] by Rosewell and Oxenfoord [NT 3650 6700] east of Dalkeith, and Shewington (almost adjacent to Newbigging); all four were in the Limestone Coal Formation. Restoration is now complete at the Gourlaw Site [NT 2800 6100], also by Rosewell, that exploited Lower Coal Measures coals. By UK standards most Midlothian coals are low in sulphur (<1 %), but may exceed 4 % (e.g. the North Coal = Arniston Parrot Coal).

In 2022, Scottish Government announced a preferred position against coal extraction. Recently, the UK Government confirmed that bans will be put in place on licensing for all new future coal mining projects.

Oil shale

Cadell (1905) provided an early description of the geology of the oil shale fields of the Lothians, and the economic importance of oil shale at that time was underlined by the analyses of new localities in Edinburgh (e.g. Wardie Harbour) presented by Crampton and Tait (1910). Oil shale was mined until 1898 at the Clippens Oil-shale Works [NT 2690 6610] at Burdiehouse and Straiton, south of Edinburgh (Carruthers et al., 1927). Here the Under Dunnet (Pentland), Broxburn and Fells shales in the West Lothian oil-shale Formation (Strathclyde Group) were extracted from several pits and adits, the Pentland Shale to a depth of over 350 m. The approximately 2 m thick Under Dunnet Shale was the main seam worked, and yielded 26 gals of crude oil and 20 lbs of ammonium sulphate per tonne of shale. The Fells Shale exceptionally yielded 34 gals per tonne. Drilling for hydrocarbons on the D'Arcy–Cousland Anticline proved the existence of two 'thick' oil-shales in the Cousland and D'Arcy areas on the east side of the Midlothian Coalfield. The report by Cameron and McAdam (1978) is the most recent assessment of these Lothian resources.

Hydrocarbons

Hydrocarbon prospectivity in the Edinburgh district has focused on the oil-shale-bearing Strathclyde Group strata. These are the West Lothian Oil-shale Formation and the East Lothian equivalent Aberlady and the underlying Gullane formations. Drilling for hydrocarbons first took place in Scotland in 1919, with the second well drilled in 1919–1922 at D'Arcy Farm [NT 3624 6480] (Hallett et al., 1985). Natural gas (estimated 300k cu. ft. per day from a depth of 724 ft) and oil were struck but the latter not in encouraging quantities (50 barrels at 1810 ft). During 1937 to 1940, nine wells were sunk in the Cousland–D'Arcy area. There was little oil (30 000 barrels by end of production in 1965), and natural gas was produced from 1957 to 1967 (e.g. Midlothian No. 3 (NT36SE/15) [NT 3645 6481] and No. 6 (NT36SE/18) [NT 3640 6462] wells producing 36 k cu. ft. of gas per day). Between 1947 and 1954 further wells were sunk at Cousland. In 1984, the Burdiehouse and Straiton Oil-shale Field was the subject of both shallow and deep test drilling for hydrocarbons. Deep drilling also tested the Carrington area [NT 3120 6107] west of Gorebridge and Cousland–D'Arcy in the same period. St Catherine's Well (Balm Well) in Liberton [NT 2732 6836] is the surface expression of a breached oilfield on the Pentland Fault structure. The well is a listed Local Geodiversity Site (LGS).

Underhill et al. (2008) provided a new understanding of the tectonic and basin subsidence history that explains the occurrence of hydrocarbons. Burial of early Carboniferous oil-shale source rocks beneath the Midlothian–Leven Syncline appears to have been the primary driver in the maturation and up-dip migration of waxy crude oil into clastic reservoirs located in the adjacent anticlines. Oil charging is thought to have taken place during the late Carboniferous, then renewed during Mesozoic reburial, and continues locally today (Balm Well) despite significant early Cenozoic uplift.

Methane gas was generally not a problem in deep coal mines in the Lothians, so there may only be a limited potential for coalbed methane extraction. Seams over 0.4 m thick and with seam gas contents of rather greater than 1 m^3 per tonne (but ideally 2 m or more), are of interest at depths from about 200 m to 1200 m.

Shale gas and shale oil prospective resources have been estimated within strata of the Strathclyde Group buried beneath the Midlothian Coalfield (Monaghan, 2014). In 2015, the Scottish Government put in place a moratorium on unconventional oil and gas development covering shale oil and gas, as well as coal bed methane extraction.

Geothermal energy

This section has been extensively updated to match the current status of geothermal energy.

Initially, Lothian was not a key area in an investigation of low enthalpy geothermal energy in the Midland Valley of Scotland (Browne et al., 1985; 1987). A potentially suitable aquifer in Fife, the Late Devonian Knox Pulpit Sandstone Formation or its lateral equivalent, might exist at depth below the Midlothian Coalfield, but equivalent strata are definitely absent under south Edinburgh from evidence in the Blackford Avenue No.1 Bore (NT27SE/111) [NT2580 7144]. Here, the Kinnesswood Formation at the top of the Stratheden Group rests unconformably on the Early Devonian Pentland Hills Volcanic Formation. More recently, with growing interest in direct use geothermal heat, where estimated temperatures and heat-in-place of the Kinnesswood Formation have been modelled > 50°C (deeper than 1.4 km) below northernmost parts of Edinburgh city and the Midlothian Coalfield (Kearsey et al., 2024). Sandstones within the Gullane and Passage formations with favourable aquifer properties also have potential for shallow open loop geothermal energy using ground source heat pumps.

Extracting heat from underground mine waters at between 10-25 ºC using heat exchangers and ground source heat pumps has been demonstrated for buildings at Shettleston in Glasgow, Cowdenbeath in Fife and at Gateshead. In the Edinburgh district, a feasibility study on mine water geothermal heat was undertaken for the Shawfair Village development on the site of the Monktonhall Colliery [NT 3200 7040], where rising minewater levels are controlled by discharge to lagoons with reed beds to remove ferric ions. The Blindwells mine water treatment site located immediately east of the area covered by the Edinburgh sheet pumps mine water from workings of the Limestone Coal Formation in the Prestonpans area. With a flow rate of 295 L/s, it is identified as having a large, 6.9 MW potential for mine water heat from a treatment scheme, as well as being located next to a major building development of houses and a new school (Bailey et al., 2016; Walls et al., 2022). A major research project is examining whether waste heat from a data centre could be stored, transported and extracted using the disused, flooded mine workings as a ‘geobattery’ in the Bush-Roslin-Bilston area on the western side of the Midlothian Coalfield (Fraser-Harris et al., 2022). Closed-loop ground-source heat-pump technology is also relevant to exploiting the geothermal resource of this district.

Peat

As of 2014, the only areas of surface peat workings in the Edinburgh district were at Auchencorth [NT 1950 5600] and Springfield [NT 2300 5600] mosses. They were exploited for horticultural use, not for fuel.

10.2 BULK MINERALS

Sand and gravel

McAdam (1978) described the resources of the former Lothian Region of which the Edinburgh district is a part. The main potentially commercial occurrences of sand and gravel are (as of 2014) in the Dalkeith–Temple area, described in detail by Aitken et al. (1984), who reported borehole and trial pit data. There is (as of 2020) currently one active quarry at Temple (Temple Quarry) [NT 3325 5775], and two active quarries at Upper Dalhousie [NT 3100 6300] (Cameron et al., 2020). The defunct largely landfilled pits at Clippens [NT 2675 6590], Haveral Wood [NT 2900 6600] and Melville [NT 3000 6650] were excavated in Late Devensian terraced or moundy glacial meltwater deposits, or sand and gravel from beneath the cover of the Roslin Till. Any special sand resources such as sand for bottle glass manufacture are described in MacPherson (1986b).

Building stones

Many sandstones in the Carboniferous succession of the Edinburgh district were formerly used as building stone (MacGregor, 1945), with those from the Strathclyde Group and Inverclyde Group generally considered superior to those from the Clackmannan Group and Scottish Coal Measures Group. None of the quarries which worked these sandstones are active in the district today, presenting serious difficulties in terms of identifying petrographically similar sandstones for local repair and conservation work (Hyslop and McMillan, 2004). Several quarries, formerly supplying blonde-coloured sandstone but now mainly infilled, are present in the district including in the Strathclyde Group: Hailes [NT 2075 7050], Redhall [NT 2160 7055], Ravelston [NT 2100

7365] and Craigleith [NT 2250 7450] in Edinburgh, and Currie [NT 3738 5965] and Straiton [NT 2750 6650] in Midlothian. At least seven quarries around Craigmillar Castle [e.g. NT 2845 7100 and NT 2910 7110] formerly worked 'pink' sandstones of the Kinnesswood Formation at the base of the Inverclyde Group. Sandstones from quarries in other parts of the Carboniferous succession have also locally provided some building stone. These include sandstone from the Limestone Coal Formation at Joppa Quarry [NT 3137 7300] and Millstone Brow Quarry at Gorebridge [NT 3560 6140], and from the Lower Coal Measures at Bonnyrigg [NT 3070 6540 and NT 3125 6575] and Cowpits [NT 3490 7070] near Whitecraigs. Some, such as the Castle Quarry in the Passage Formation at Dalhousie Castle [NT 3245 6345], may have been almost single purpose. McMillan et al. (1999) and Hyslop (2004) described in detail the building stones (sandstones) of Edinburgh.

Hardrock

Several old quarries in igneous rocks in the Edinburgh district have been exploited as hardrock aggregate. The Devonian lavas (and associated intrusions) of the Pentland Hills Volcanic Formation have been used, such as the defunct Blackford [NT 2600 7025], Mortonhall [NT 2475 6925], Torphin [NT 2000 9905] and Silverburn quarries [NT 2000 6055]. The Carboniferous lavas of the Arthur's Seat Volcanic Formation and Carboniferous vent intrusions are largely untouched. The Carboniferous alkali-dolerite sills, such as those at Salisbury Crags [NT 2700 7300] and Corstorphine Hill [NT 2022 7495], were exploited in the past for setts and kerbs, dimension stone, roadstone, concrete and over-size stone. Quartz-dolerite dykes associated with the Midland Valley Sill Suite have also been worked, for instance on the Royal Musselburgh Golf Course [NT 3774 7387]. Merritt et al. (1984) described these resources and their uses as part of a review of the whole of central Scotland. The most voluminous and most highly prized (because of its high polished stone values) resource is the quartz-dolerite that is of very restricted occurrence in the district and is currently not being worked.

The desirable hardrock characteristics are least consistent for the Devonian and Carboniferous lava flows, for they tend to change thickness more rapidly, be less laterally persistent, and pass into much inferior slaggy and autobrecciated phases.

Limestone

Historically, limestone beds of 3–15 m in thickness were usually considered to be of workable thickness (Robertson et al., 1949; Muir et al., 1956). In the Edinburgh district these occur in the Lower Limestone Formation in the Clackmannan Group, and in the West Lothian Oil-shale and Aberlady formations in the Strathclyde Group. They have only been extracted where the limestone beds were at outcrop, as the superficial deposits as overburden are usually too thick to permit exploitation. Until closure in May 1962 the Burdiehouse Limestone in the Strathclyde Group was quarried and mined at and around Clippens Mine (Robertson et al., 1949) at Burdiehouse–Straiton [NT 2730 6635]. It is about 8 m thick and a relatively pure limestone, that was used as a flux in smelting iron, for plastering and cement, and for agriculture.

In the Lower Limestone Formation, the Hurlet (Gilmerton), Blackhall (North Greens) and Second Hosie (Bilston Burn) limestones have been quarried and mined. The Hurlet (Gilmerton) Limestone has been quarried at Mount Lothian [NT 2765 3575] and Middleton [NT 3578 5770], on the eastern side of the Midlothian Coalfield, and on the western side it was mined at Gilmerton (Ferniehill [NT 2940 6910] and Hyvot's Bank [NT 2875 6875]. It was also quarried at Niddrie House [NT 3020 7130]. The Blackhall Limestone (North Greens), up to 27 m thick, was worked on a minor scale at Bilston [NT 2710 6490], and was the most extensively wrought seam at Mount Lothian [NT 2685 5610] and nearby Fullarton. It was worked also at Esperston on Chester Hill [NT 3415 5650], Middleton [NT 3540 5760], Upper Side [NT 2915 5590] and Currie Lee [NT 3805 6230]. In most cases only the purer lower part of the limestone was of commercial interest. The Second Hosie (Bilston Burn) Limestone, up to 15 m thick, was worked at Bilston [NT 2720 6490] and in the Esperston quarries [NT 3440 5725]. In addition, the Blackhall (North Greens) Limestone, up to 30 m thick, has been mined and quarried in the inliers of the Lower Limestone Formation at D'Arcy [NT 3550 6450] and Cousland [NT 3720 6835] where only the basal 3 m were mined. Cement manufacture took place at Cousland

(Cartwell Quarry). Here, mining had ceased before May 1979. MacPherson (1986a) described all these resources as part of the central belt of Scotland.

The last working operation was adjacent to the limeworks at Middleton [NT 3570 5840]. Lime has been used for a variety of purposes including agriculture and plastering and to dampen down dust in coal mines. A further use is in calc-silicate bricks.

Ochre

Historically, yellow ochre (hydrated iron oxide) has been quarried (and possibly mined) at Bilston Glen where the Hurlet (Gilmerton) Limestone [NT 2695 6490] had been altered to what was described as ‘coarse ochre’, 7 m thick (Robertson et al., 1949).

Fireclay

Fireclay occurs throughout most of the Carboniferous sequence (except the Inverclyde Group). A fireclay below the Index Limestone in the Limestone Coal Formation was extracted at Joppa [NT 3150 7350] for firebrick, pipes and gas retorts. Merritt (1985) described the fireclay resources of central Scotland including this district.

Common shale for brick

Common shale occurs throughout the Carboniferous. There are probably plentiful potential resources of common shale in the Scottish Coal Measures Group, Upper Limestone Formation, Limestone Coal Formation, Lower Limestone Formation and the Strathclyde Group. All of these sources have been used at some time in the past. Seatclay and seatearth were worked from the Coal Measures at Whitehill Colliery [NT 2865 6215], and from the Limestone Coal Formation at Ramsay [NT 2885 6580] and Roslin [NT 2620 6310] collieries. Elliot (1985) described these resources along with those of the whole central belt of Scotland. The most recent account for the whole of Britain is by Bloodworth et al. (2002).

Brickclay

Late Devensian glaciomarine silty clays were worked on a small scale at Portobello [NT 2990 7365], Wardie [NT 2390 7665] and Granton [NT 2350 7705], where they were up to 9 m thick. At Joppa, bricks, tiles and pottery etc were produced. Glaciolacustrine clays have been extracted at Smeaton [NT 3555 6890], Eskbank [NT 3220 6605], Upper Dalhousie Farm [NT 3070 6300] and Newtongrange [NT 3300 6500]. Elliot (1985) contains the most recent statement on brickclay in the Edinburgh district.

Colliery Waste

Bings (tips) of colliery waste have potential for use as bulk fill, for provision of mudstone for brickmaking or for the recovery of their coal content. Many bings in the district have been worked for brick making (e.g. Niddrie [NT 3075 7150] that is now part of the Fort Kinnaird shopping complex) or landscaped, and much of the material has been redistributed and used in land reclamation and in industrial redevelopment. The burnt red shale forming the Straiton Oil-shale Bing [NT 2650 6650] was remodelled and planted to become a local nature reserve.

Ironstones

Past mining of both nodular and bedded clayband ironstone and blackband ironstone is known in the district, with the Lower Limestone and Limestone Coal formations being the chief sources. Blackband ironstones (0.45 m) in the Lower Limestone Formation were mined in the Gilmerton and Moredun areas of south Edinburgh. Several ironstones in the Limestone Coal Formation have been mined, especially the Loanhead No. 1 above the Bryans Splint Coal and Loanhead No. 2 below the Great Seam Coal (Tulloch and Walton; 1958, fig.11). The latter was mined at Mauricewood, Burghlee, Ramsay and Roslin collieries.

10.3 GROUNDWATER RESOURCES

Groundwater is present in almost all rock types and deposits across the area, but with large contrasts between the mode of storage and transmission. The resource has been exploited for water supply and other uses, but also managed in other ways; for example, mine dewatering has been an important aspect of coal extraction in the Midlothian coalfield.

Aquifer characteristics

The oldest rocks in the area, the volcanic and associated strata of the late Silurian to Early Devonian Lanark Group forming the Pentland Hills, have amongst the lowest values for hydraulic conductivity and porosity in the district. The hardened and compacted nature of the volcanic rock mass leaves only void spaces such as fractures as potential for groundwater storage. As a result, only small quantities of groundwater are present within these rocks. This, combined with the upland nature of the ground, restricts rainfall recharge to the aquifer and groundwater movement within it. Consequently, groundwater discharge is mainly via many small springs on the lower slopes of the Pentlands.

Data are sparse for the hydrogeological characteristics of the Carboniferous rocks. The sedimentary strata of the Tournaisian, Visean and Namurian that occupy almost all of the remainder of the area include rocks with a wide range of aquifer properties. Mudstone, the dominant rock type within the Ballagan and Aberlady Formations, has very low permeability values approaching 10-6 m/d. Other formations in which fine-grained sandstone and siltstone predominate, such as the Gullane and Kinnesswood formations in Edinburgh, the West Lothian Oil-shale Formation and the strata of the Midlothian coalfield have generally higher values for permeability and porosity. The Passage Formation, which crops out extensively in Midlothian, contains significant thicknesses of medium- and coarse-grained porous sandstone with hydraulic conductivities approaching 1 m/d, and porosity in the range 0.15 to 0.25. Fracture flow predominates even within the more permeable sandstone units, accounting for over 80 % of the total groundwater flow.

The most permeable superficial deposits are those that contain significant amounts of sand and gravel. These are limited, in the main, to deposits flanking the valley of the River Esk in Midlothian. However, owing to the location of much of the glaciofluvial sand and gravel on relatively high ground, a large proportion is unsaturated with groundwater. Narrow strips of river alluvium along the floor of the valley form localised aquifers which are thought to have high values for transmissivity and porosity.

Groundwater use and management

Until the end of the 18th century, wells and spring supplies were the principal source of water for residents of Edinburgh and Midlothian. Many houses in the city had shallow wells in their gardens and others were supplied from some of the more high-yielding springs, such as those at Comiston [NT 239 693] which provided up to 900 m^3/day to the city via a 5 km-long pipeline. These sources were eventually superseded by surface supplies brought in from the new reservoirs at Talla [NT 120 210] and Fruid [NT 100 190] in the Borders. However, groundwater continued to play a part in the life of the Edinburgh district. Many breweries were established in the old Town because of the presence of hard groundwater containing significant amounts of sulphate. Deep shafts and boreholes were sunk, some to over 300 m depth, but, owing to the low hydraulic conductivity of the fine-grained sandstones and siltstones, water yields were rarely more than 4 l/s even where several were linked by tunnels in order to increase the flow. Currently (as of 2014), groundwater abstraction in Edinburgh is small, with low-yielding boreholes present at, for example, Edinburgh Zoo and the Scottish Parliament at Holyrood. However, use is (as of 2014) expanding where boreholes have been drilled to exploit geothermal energy for heating.

The thicker sandstones of the Edinburgh area, such as the Craigleith and Ravelston sandstones, have not been exploited, but it is thought that they hold potential for development of the groundwater resource, either for water abstraction or for geothermal use.

Springs emerging within Devonian volcanic strata in the Pentland Hills were exploited in the Penicuik area because of the clarity of the water. Consequently, several paper mills were built and some were still in operation until the 1970s. Many of the springs are (as of 2014) still used for local private and public supplies.

The development of collieries in the Midlothian coalfield led to the abstraction of many thousands of cubic metres per day of groundwater in order to keep the mines dewatered. Notable examples were the Lady Victoria, Newcraighall and Monktonhall collieries.

Groundwater quality

The significant calcite content of the early Carboniferous strata has resulted in generally hard groundwater in the Edinburgh area. This was excellent for brewing, with some sources recognised as being superior to others including for example, the Tailor's Hall well in the Cowgate. Early examples of groundwater protection were seen at the William Younger Brewery at Holyrood, where local contamination by phenolic waste from a nearby gas works that threatened water quality was limited by the deliberate pumping of water from a 'scavenger' borehole.

Since the closure of deep coal mines east of Edinburgh, there have been a small number of instances of mine water rebound resulting in acid mine drainage to surface watercourses.

10.4 GEOLOGY AND PLANNING FOR LAND-USE DEVELOPMENT

Environmental geological assessment of part of the Edinburgh district was carried out by BGS in the 1980s when a series of Environmental Geology Maps was published (Floyd et al., 1983). These maps provided details of the resources available and the main types of geological hazards likely to be encountered, as well as the generalised bedrock and Quaternary geology.

There is (as of 2014) an increasing demand to manage developments that affect the visual impact of the landscape, and even initiate landscape improvements. In addition, there is a growing awareness of the value of the geological heritage in the rock exposures and the natural landscape, not only for scientific study by the geological community, but also for general education and appreciation and tourism.

10.5 GEOHAZARDS

Foundation Conditions

Rock, till, and sand and gravel generally provide sound foundation conditions below the top weathered zone. Faulting can produce zones of broken rock or can juxtapose rocks with greatly varying geotechnical properties. Engineering properties of rocks vary markedly depending on the rock type. Poor foundation conditions can also be caused by superficial deposits at the surface, such as peat, clay and silt, alluvial deposits in general, and man-made deposits (e.g. landfill). Foundation conditions may also be affected by variably compressible buried superficial deposits, like peat and soft clay (e.g. Ravelston Park area [NT 217 743]), and by liquefaction of silt and fine sand. All these deposits require careful site investigation. Some culverted burns, such as the Jordan Burn [NT 245 710] in Morningside in Edinburgh, have in the past been known to be associated with subsidence problems and damage to properties.

Abandoned mineworkings

Abandoned mineworkings in the Lothians (Hutton, 1998), mainly for coal but also for oil shale, limestone and ironstone, present a hazard where collapse of workings may propagate to the surface. The main threat is from stoop-and-room workings because of stoop (pillar) or roof failure; the problem is of most concern where old workings are within 30 to 40 m of rockhead, unless the covering Quaternary deposits are particularly deep and incompressible. Potential foundation problems are possible, but not restricted to, anywhere within the outcrops of the Lower and Middle Coal Measures, Limestone Coal Formation, Lower Limestone Formation, West Lothian Oil-shale Formation and Aberlady Formation. Shafts and adits present localised subsidence/ collapse hazards that need attention (Wilson et al., 1910), but can also be the loci of gas accumulations or emissions. In July 2008, a caver died after becoming unconscious entering an old mine adit at The Wisp, part of the former Niddrie Collieries [NT 3065 7125] that ceased operations around 1926.

Well-known crownhole collapses in the Clippens Mine within the Burdiehouse Limestone include the event in November 1986, at Straiton Caravan Park [NT 2700 6625], and at Clippens Landfill [NT 2660 6590] opposite IKEA in March 2000. The sequential collapse of the Ferniehill Mine [NT 2930 6910], in the Hurlet (Gilmerton) Limestone in 2000, resulted in severe damage to properties, the evacuation of residents, and demolition of these and other properties because of safety concerns (Plate 17). Site investigations resulted in extensive grouting work at Ferniehill and other nearby localities (ArupScotland, 2001). There was also an independent inquiry instigated by City of Edinburgh Council. Earlier events (1980) in this area had led to the closure of Hyvot’s Bank Primary School [NT 2870 6810]. During the 1960s a massive crownhole formed on the outcrop of a steeply dipping coal seam in the Limestone Coal Formation at The Drum [NT 3000 6900], Gilmerton. Extensive rerouting of the East Coast Main Railway Line near Wallyford [NT 3800 7300] on to a piled concrete foundation was caused by the existence of unstable, shallow dipping Limestone Coal Formation mineworkings. Other mining related events have included the emergence of ochreous waters flooding roads in Joppa [NT 315 735], and emission of gases on the nearby foreshore [NT 330 734] causing liquefaction of beach sediments. Historic attempts to limit mining subsidence damage are shown by the dwellings in places like Old Craighall [NT 3340 7050] and Millerhill [NT 3220 6928], which have metal straps as girdles to prevent structural distortion.

Plate 17 Mining subsidence event early November 2000 to March 2001 at Ferniehill [NT 2940 6920], Gilmerton over the Hurlet (Gilmerton) Limestone mineworkings. Note tilting of cottage on its raft foundation and structural damage to properties, infrastructure and also open cracks in ground (P100365) BGS © UKRI

Steep slopes

The stability of superficial deposits on steep slopes may be affected by loading and/or excavation, making them susceptible to landslide and debris flow. Similarly, the stability of bedrock in cliffs and steep-sided excavations may depend on its resistance to weathering and the presence of joints, faults and inclined bedding planes. Movement on such planar features may give rise to minor rockfalls as well as significant landslides. Landslides are (as of 2014) common problems along the valleys of the Esk rivers, as seen at the persistently active landslide at Hewan Bank Wood [NT 2850 6470], Polton (Baird and Smellie, 1980) and upstream at the Roslin Gunpowder Factory [NT 2675 6265]. Both of these landslide areas occur in Quaternary sediments where groundwater is concentrated along the contact of sand and gravel on till or till on rock. The toes of the landslides are eroded by the River North Esk particularly during flood events. In recent years rockfalls at Salisbury Crags [NT 2703 7297], Castle Rock [NT 2500 7355] and Samson’s Ribs [NT 2735 7250] have prompted major stabilising works including rock bolting, rock netting and descaling. Along the Water of Leith, steep slopes in bedrock mudstone near Belford Road in the Dean Village [NT 2425 7395] were affected by landslides that led to road closure and similarly in Quaternary deposits at Colinton Village [NT 2100 6890].

Coastal erosion and inland flooding

The coastline in this district is generally receding where not protected by hard defences, and beach recharge has been implemented as at Portobello Beach [NT 310 740]. Shore-front bedrock exposures in SSSIs, such as Wardie [NT 245 771] and Granton [NT 215 771], are (as of 2014) potentially under threat from the major Granton Waterfront Regeneration project if elaborate promenades are constructed in part to restrict erosion and flooding and enhance the beaches. Even if the rock exposures are unaffected by new structures, changes to the beach profile may change the amount of strata exposed.

The recognition of a possible tsunami sand deposit on the east coast of Scotland (Long et al. 1989) formed in response to unusually high sea waves created by a submarine landslide in the North Sea, is an indication that offshore events may affect the coastline unpredictably in other ways.

Inland and coastal flooding may be enhanced by any rise in sea level and increased storminess associated with global warming. Major flood defence schemes have been implemented for the Water of Leith and the Braid Burn. These schemes include new flood walls, lifting clearances of bridges and using reservoirs and public parks as holding zones. The Roseburn district, including the Murrayfield Rugby Stadium [NT 225 730], is one of the prestigious areas afflicted by flooding.

Earthquakes

The possibility of small magnitude earthquakes and ground vibrations caused by humankind’s own activities may be a significant factor in planning the location of sensitive developments like high-tech factories. On 18th January 1889, the magnitude 3.2 ML Edinburgh Earthquake was felt particularly in west of the city with its epicentre near Harperrig Reservoir (Musson 1994, p.69) on the north side of the Pentland Hills. The strongest effects noted were general alarm, doors shutting and clocks stopping and starting. The most recent quakes in the district are the 21st December 1986 Rosewell and the November 30th and December 7th Penicuik 2007 events, all magnitude 2.3 ML. Now that deep mining has ceased, so have the Musselburgh Earth Tremors (Walker, 1997), thought to have been associated with longwall mining at the former Monktonhall Colliery.

Groundwater pollution

In 2000, the EU Water Framework Directive expanded the scope of water protection to all bodies of water, surface water and groundwater. In the Edinburgh district (see earlier section on groundwater quality), groundwater was (as of 2014) abstracted for private supplies from Carboniferous sandstones and Quaternary sand and gravel, mainly for farming. In these, high nitrate levels are (as of 2014) a concern and are commonly the product of wartime ploughing of permanent grasslands.

Rising ferruginous minewaters, following deep mine closure (Wood et al., 1999) is thought to be a pollution threat to supplies. The outburst of ferruginous water from recently closed coastal mines would result in polluted coastal waters and rivers and streams, with major deleterious ecological effects. The minewaters from Monktonhall are treated onsite in reed beds [NT 3240

7000]. Notorious plumes of ochreous water (as of 2014) discharge to the South Esk at Dalkeith [NT 3370 6670].

Pollution plumes from former and active landfills are (as of 2014) local problems because, until recently, such landfill sites were unlined, on the basis that pollutants would be ‘diluted and dispersed’.

Landfill

Landbanks for landfill tended to be orientated towards former quarries and disused or active sand and gravel workings. Most of the City of Edinburgh’s waste now (as of 2014) goes by rail to the Dunbar Limestone Quarry for disposal. However, landraise has also been practised as at The Drum [NT 2975 6875] Gilmerton. Landfill gas is (as of 2014) known to occur at closed sites at Hailes Quarry [NT 2075 7050] and Blackford Quarry [NT 2600 7025].

10.6 GEOLOGICAL HERITAGE

McAdam and McKirdy (2003) described the landscape and geology of Edinburgh and West Lothian in the popular ‘Landscape fashioned by Geology’ series. Geological walks are found in the excursion guides to the Lothians (Craig and Duff, 1975; McAdam and Clarkson 1986, 1996; Mitchell et al., 1960; Monckton, 1913, 1914; Wells, 1927). The general geology of the Lothians and Edinburgh has recently been popularised by Clarkson and Upton (2006). The geology of the Water of Leith is described in Jamieson (1984). Local Biodiversity Action Plans published for Edinburgh, Midlothian, East Lothian and West Lothian, refer briefly to the geodiversity of the respective areas. The Royal Park of Holyrood and Calton Hill are both SSSI’s, and the general history of volcanic activity in the Edinburgh district and throughout Scotland has recently been popularised by Upton (2004). Local geological walks form an integral part of the Edinburgh International Science Festival and the Scottish Geology Festival.

Tourism is very significant to the local and national economy, and the landscape and geological heritage of the district contribute to its popularity as a visitor destination. Currently geological information is prominently and attractively presented on boards in Princes Street Gardens [NT 2514 7380] and at Hutton’s Section in Holyrood Park [NT 2720 7284]. Braid Hill [NT 2485 6949] has a geological viewpoint indicator. There is considerable potential for similar educational information on Corstorphine and Craiglockhart hills. James Hutton, the father of modern geology, is honoured by a memorial garden at the site of his long-demolished house in The Pleasance on St John’s Hill [NT 2638 7348]. Lothian and Borders RIGS Group have published a leaflet about Hutton (Porteous and Brown, 2006). Our Dynamic Earth [NT 2675 7370], adjacent to the Scottish Parliament and on the north-west side of Holyrood Park, is a major Science Interpretation and Tourism Centre. Large standing stones representing the geological history of Scotland are installed in the plaza in front of Our Dynamic Earth. There is also an interpretative view board of the geology of Holyrood Park on the south side of the building.

Local Geodiversity Sites (formerly known as Regionally Important Geological and Geomorphological Sites) have been listed with the relevant local authorities, and comprise The Balm Well (Liberton) [NT 2732 6836], Bilston Burn [NT 2700 6490], Calton Hill [NT 2620 7420], Craigleith Quarry [NT 2270 7455], Craigmillar Castle [NT 2880 7085], Corstorphine Hill [NT 2065 7385], Dreghorn Link Road [NT 2310 6840], Ellen’s Glen [NT 2845 6900], Fairmile Park [NT 2430 6890], Hermitage of Braid and Blackford Hill [NT 2545 7065], Hewan Woods [NT 2850 6455], Joppa Shore [NT 3205 7345], Ravelston Woods [NT 2170 7420], The Pinnacle [NT 1900 6200] and Torphin Quarry [NT 2000 6755].

Geological trail leaflets exist for Holyrood Park (Land and Cheney, 2000), Blackford Hill (Land, 1999), Calton Hill within the Edinburgh World Heritage Site (McMillan et al., 2003), Craigleith Quarry RIGS (Arkley et al., 2005), Craiglockhart and the Seven Hills of Edinburgh (Porteous, 2008), Joppa Shore (Wilkinson, 2008), Ravelston Park and Woods (Porteous and Browne, 2003) and Corstorphine Hill (McAdam, 2004). The general geology of the Water of Leith is also briefly described in a LGS leaflet (Skelley, 2008). Named stones are carved on the Royal Mile (Caithness flagstone) and at the Scottish Parliament Buildings (kerbstone of quartz-dolerite from Caldercruix Quarry). The Canongate Wall at the Parliament Building [NT 2672 7390] contains unnamed inset samples of found (on- and off-site) stones, and carved stones from around Scotland. The Stones of Scotland Sculpture RIGS [NT 2660 7445] (that also has a leaflet; Urquhart, 2006) on the Royal Park Terrace, and another sculpture at the entrance to Craigleith Quarry (Sainsbury's Blackhall Store) [NT 2252 7440], are further examples of rock art heritage.

Nationally, Quaternary sites at Agassiz Rock [NT 2593 7020] and Hewan Bank [NT 2850 6455], were listed in the GCR of the Quaternary of Scotland (Gordon and Sutherland, 1993). Agassiz Rock is important in the history of Scottish geology (See Chapter 9). Hewan Wood is listed as a site for Quaternary lithostratigraphy but an enlarged area was listed as a Local Geodiversity Site based upon active landslide and fluvial erosion processes. The Joppa Shore section is included in the Upper Carboniferous (Cleal and Thomas, 1996) and Lower Carboniferous GCR (Cossey et al., 2004) reviews, based on the sections exposed in the upper part of the Upper Limestone Formation (including the Calmy and Castlecary limestones) the Passage Formation and part of the Lower Coal Measures. Bilston Burn also appears in the Lower Carboniferous review for sections particularly in the upper part of the West Lothian Oil-shale Formation, and the Lower Limestone, Upper Limestone and Passage formations. The Limestone Coal Formation strata are largely buried as a result of culverting of Bilston Burn and landfilling of the glen when the bing was formed at Bilston Glen Colliery. Key horizons still to be seen in the stream section include the Hurlet, Blackhall, Second Hosie and Top Hosie limestones (between [NT 2690 6490] and [NT 2727 6485]), and the Orchard Beds, and Calmy and Castlecary limestones (between [NT 2810 6485] and [NT 2850 6485]). Holyrood Park with Arthur's Seat Volcano (and Calton Hill) is included in the Carboniferous and Permian Igneous Rocks of Great Britain GCR (Stephenson et al., 2003). The Gullane Formation at Wardie Shore [NT 245 771] and the interbedded Sandy Craig and Kinghorn Volcanic formations on Inchkeith [NT 2940 8300] and tetrapod bones are described in the Fossil Fishes of Great Britain GCR (Dineley and Metcalf, 1999). Wardie is also recognised for its early Carboniferous palaeobotany (Cleal and Thomas; 1995). Granton Shore [NT 215 771] is described in the GCR of Fossil Arthropods of Great Britain (Jarzembowski, 2010) because of the famous Muirhouse Shrimp Bed.

References

Agassiz, L. 1841. On glaciers, and the evidence of their having once existed in Scotland, Ireland, and England. *Proceedings of the Geological Society of London*, Vol. 3, 327-332.

Aitken, A M, Lovell, J H, Shaw, A J, and Thomas, C W. 1984. The sand and gravel resources of the country around Dalkeith and Temple, Lothian Region. Description of 1:25 000 sheets NT 25 and 35, and NT 26 and 36. *British Geological Survey*, 140.

Aldridge, R J, Briggs, D E G, and Clarkson, E N K. 1986. The affinities of conodonts - new evidence from the Carboniferous of Edinburgh, Scotland. *Lethaia*, Vol. 29, 279-291.

Anderson, J G C. 1940. Glacial drifts near Roslin, Midlothian. *Geological Magazine*, Vol. 77, 470-473.

Anderson, J G C. 1941. Glacial drifts. *Geological Magazine*, Vol. 78, 470-471.

Anderson, J G C. 1942. Glacial drifts. *Geological Magazine*, Vol. 79, 202.

Andrews, J E, and Nabi, G. 1998. Palaeoclimatic significance of calcretes in the Dinantian of the Cocksburnspath Outlier (East Lothian-North Berwickshire). *Scottish Journal of Geology*, Vol. 34.

Andrews, J E, Turner, M S, Nabi, G, and Spiro, B. 1991. The anatomy of an early Dinantian floodplain: palaeoenvironment and early diagenesis. *Sedimentology*, Vol. 38, 271-287.

Arkley, S L B, Browne, M A E, and Hyslop, E. 2005. Craigleith Quarry Geological Trail. Edinburgh, Lothian and Borders RIGS Group.

Arup Scotland. 2001. The City of Edinburgh Council Southeast Edinburgh Strategic Study. Gilmerton Limestone. Summary Report, December 2001.

Bailey, M T, Gandy, C J, Watson, I A, Wyatt, L M, and Jarvis, A P. 2016. Heat recovery potential of mine water treatment systems in Great Britain. *International Journal of Coal Geology*, Vol. 164, 77-84.

Baird, W, and Smellie, J. 1980. The Polton landslide of December 1979. *The Edinburgh Geologist*, Vol. 8, 9-14.

Ballantyne, C K, and Harris, C. 1994. *The periglaciation of Great Britain*. (Cambridge, England: Cambridge University Press.)

Bamford, D, Nunn, K, Prodehl, C, and Jacob, B. 1978. LISP-IV Crustal Structure of northern Britain. *Geophysical Journal of the Royal Astronomical Society*, Vol. 54, 43-60.

Barron, H F. 1998. Geology of the central Pentland Hills 1:10 000 Sheets NT16SE (Scald Law), NT15NW (Baddinsgill) and part of NT15NE (Carlops). *British Geological Survey Technical Report*, WA/98/41.

Beddoe-Stephens, B. 1998. Petrography of samples from the Pentland Hills. *British Geological Survey Mineralogy and Petrology Group Short Report*, MPSR/98/16.

Bennie, J. 1891. Note on a recent exposure of a 'washout' of strata in New Redhall Quarry. *Proceedings of the Royal Physical Society*, Vol. 10, 393-396.

Bennie, J. 1894. Arctic plant beds in the old lake deposits of Scotland. *Annals of Scottish Natural History*, Vol. 9, 46-52.

Bennie, J, and Scott, T. 1891. The ancient lakes of Edinburgh. *Proceedings of the Royal Physical Society*, Vol. 10, 126-154.

Black, G P. 1966. *Arthur's Seat. A history of Edinburgh's volcano*. (Edinburgh: Oliver and Boyd.)

Bloodworth, A J, Cowley, J F, Highley, D E, Bowler, G K, Ambrose, K, Browne, M A E, Cameron, D G, Henny, P J, Hopson, P M, Mcbridge, D M, Mankelow, J M, Mitchell, C J, Sumbler, M G, and Waters, C N. 2002. Brick Clay: Issues for planning. *British Geological Survey Commissioned Report*, CR/01/117N.

Bluck, B J. 1978. Sedimentation in a late orogenic basin: the Old Red Sandstone of the Midland Valley of Scotland. Pp. 249-278 in: *Crustal evolution in northwestern Britain and adjacent regions*. Bowes, D R, and Leake, B E (editors).

Bluck, B J. 1984. Pre-Carboniferous history of the Midland Valley of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 75, 275-295.

Bluck, B J. 2001. Caledonian and related events in Scotland - the Southern Uplands Terrane: tectonics and biostratigraphy within the Caledonian Orogen. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 91, 375-404.

Boyd, W W. 1974. *Geochemical investigation of composite bodies involving intermediate members of the alkali-basalt - trachyte suite.* Unpublished PhD Thesis, University of Edinburgh.

Brereton, R, Browne, M A E, Cripps, A C, Gebski, J S, Bird, M, Halley, D N, McMillan, A A, and Gebski, J S. 1988. Glenrothes Borehole: geological well completion report. *Investigation of the Geothermal Potential of the UK. British Geological Survey Technical Report*, WJ/GE/88/002.

Briggs, D E G, and Clarkson, E N K. 1983. The Lower Carboniferous Granton shrimp-bed, Edinburgh. *Special Papers on Palaeontology*, Vol. 30, 161-178.

Briggs, D E G, Clarkson, E N K, and Aldridge, R J. 1983. The Conodont Animal. *Lethaia*, Vol. 16, 1-14.

Briggs, D E G, Clark, N D L, and Clarkson, E N K. 1991. The Granton 'shrimp bed', Edinburgh- a Lower Carboniferous Konservat-Lagerstatte. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 82, 65-86.

British Geological Survey. 1988. Geothermal energy in the United Kingdom: review of the British Geological Survey's Programme 1984–1987. *Investigation of the Geothermal Potential of the UK, British Geological Survey*.

British Geological Survey. 2003. Edinburgh. Scotland Sheet 32E. Bedrock. (Keyworth, Nottingham: British Geological Survey.)

British Geological Survey. 2006. Edinburgh. Scotland Sheet 32E. Bedrock and Superficial Deposits. (Keyworth, Nottingham: British Geological Survey.)

British Geological Survey. 2023. British Geological Survey - Strategy 2023 to 2028 Understanding our Earth.

Brown, D J. 1874. On some of the glacial phenomena of the neighbourhood of Edinburgh, as observed in the Pentlands, Blackford Hill, Bruntsfield Links and Tynecastle Sandpit. *Transactions of the Edinburgh Geological Society*, Vol. 2, 351-357.

Browne, M A E. 1986. The classification of the Lower Carboniferous in Fife and the Lothians. *Scottish Journal of Geology*, Vol. 22 422-425.

Browne, M A E. 1998a. The base of the Lower Coal Measures in the Markinch, Dysart, Leven coalfield, Fife. *British Geological Survey Technical Report*, WA/98/43.

Browne, M A E. 1998b. The base of the Upper Coal Measures in the Markinch, Dysart, Leven coalfield, Fife. *British Geological Survey Technical Report*, WA/98/42.

Browne, M A E, Dean, M T, Hall, I H S, McAdam, A D, Monro, S K, and Chisholm, J I. 1999. A lithostratigraphical framework for the Carboniferous rocks of the Midland Valley of Scotland. *British Geological Survey Research Report*, RR/99/07.

Browne, M A E, Graham, D K, and Gregory, D M. 1984. Quaternary estuarine deposits in the Grangemouth area, Scotland. *Report of the British Geological Survey*, 16/3.

Browne, M A E, and Grinly, D. 1996. The Landscape and Geology of Clackmannanshire. *The Forth Naturalist & Historian Journal*, Vol. 19.

Browne, M A E, Hargreaves, R L, and Smith, I F. 1985. The Upper Palaeozoic Basins of the Midland Valley of Scotland. *Investigation of the geothermal potential of the UK, British Geological Survey Technical Report*, WJ/GE/85/02.

Browne, M A E, and McMillan, A A. 1989. Quaternary geology of the Clyde valley. *British Geological Survey Research Report*, SA/89/81.

Browne, M A E, Monaghan, A A, Ritchie, J D, Underhill, J R, Hooper, M D, Smith, R A, and Akhurst, M C. 2003. Revised tectonostratigraphical framework for the Carboniferous of the Midland Valley of Scotland, UK. *International Congress on Carboniferous and Permian Stratigraphy*, 68-70.

Browne, M A E, and Monro, S K. 1989. Evolution of the coal basins of central Scotland. *XI Congres International de Stratigraphie et de Geologie du Carbonifere Beijing 1987*, Compte Rendy 5, 1-19.

Browne, M A E, Robins, N S, Evans, R B, Monro, S K, and Robson, P G. 1987. The Upper Devonian and Carboniferous sandstones of the Midland Valley of Scotland. *Investigation of the geothermal potential of the UK, British Geological Survey Technical Report*, WJ/GE/87/003.

Browne, M A E, Smith, R A, and Aitken, A M. 2002. Stratigraphical framework for the Devonian Old Red Sandstone rocks of Scotland south of a line from Fort William to Aberdeen. *British Geological Survey Research Report*, RR/01/04.

Browne, M A E, and Woodhall, D G. 1999. Geology of the Kirkcaldy district. *Sheet explanation of the British Geological Survey*, Sheet 40E (Scotland).

Bull, E E, and Loydell, D K. 1995. Uppermost Telychian graptolites from the North Esk Inlier, Pentland Hills, near Edinburgh. *Scottish Journal of Geology*, Vol. 31, 163-170.

Cadell, H M. 1893. A map of the ancient lake basins of Edinburgh. *Transactions of the Edinburgh Geological Society*, Vol. 6, 287-296.

Cadell, H M. 1905. The Geology of the oil shale fields of the Lothians. *Transactions of the Edinburgh Geological Society*, Vol. 8, 116-163.

Cadell, H M. 1913. *The Story of the Earth*. (Glasgow: James Maclehose and Sons.)

Cameron, I B, and McAdam, A D. 1978. The oil-shales of the Lothians, Scotland: present resources and former workings. *British Geological Survey Report*, 78/28.

Cameron, D G, Evans, E J, Idoine, N, Mankelow, J, Parry, S F, Patton, M A G, and A Hill. 2020. Directory of Mines and Quarries, 2020: 11th Edition. (Keyworth, Nottingham, British Geological Survey). OR/20/036.

Campbell, A C, and Anderson, E M. 1909. Notes on a transported mass of igneous rock at Comiston Sand-Pit, near Edinburgh. *Transactions of the Edinburgh Geological Society*, Vol. 9, 219-224.

Carruthers, R G. 1941. Glacial drifts. *Geological Magazine*, Vol. 78, 317-318.

Carruthers, R G. 1942. Glacial drifts. *Geological Magazine*, Vol. 79, 153-154.

Carruthers, R G, Caldwell, W, Bailey, E M, and Conacher, H R J. 1927. The oil-shales of the Lothians. Third Edition. *Economic Memoir of the Geological Survey, Scotland*.

Cater, J M L. 1987. Sedimentology of part of the Lower Oil-Shale Group (Dinantian) sequence at Granton, Edinburgh, including the Granton “shrimp-bed”. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 78, 29-40.

Cater, J M L, Briggs, D E G, and Clarkson, E N K. 1989. Shrimp-bearing sedimentary successions in the Lower Carboniferous (Dinantian) Cementstone and Oil Shale Groups of northern Britain. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 80, 5-15.

Chambers, R. 1853. On glacial phenomena in Scotland and parts of England. *Edinburgh New Philosophical Journal*, Vol. 54, 229-281.

Chisholm, J I, and Brand, P J. 1994. Revision of the late Dinantian sequence in Edinburgh and West Lothian. *Scottish Journal of Geology*, Vol. 30, 97-104.

Chisholm, J I, McAdam, A D, and Brand, P J. 1989. Lithostratigraphical classification of Upper Devonian and Lower Carboniferous rocks in the Lothians. *British Geological Survey Technical Report*, WA/89/26.

Clark, R H. 1952. The significance of flow structure in the microporphyritic ophitic basalts of Arthur’s Seat. *Transactions of the Edinburgh Geological Society*, Vol. 15, 69-83.

Clark, R H. 1956. III.—A Petrological Study of the Arthur's Seat Volcano. *Transactions of the Royal Society of Edinburgh*, Vol. 63, 37-70.

Clarkson, E N K, Harper, D A T, and Taylor, C M. 2000. Scottish Silurian shorelines. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, Vol. 91, 479-487.

Clarkson, E N K, and Upton, B J. 2006. *Edinburgh Rock: Geology of Lothian*. (Edinburgh: Dunedin Academic Press.)

Cleal, C J, and Thomas, B A. 1995. *Palaeozoic Palaeobotany of Great Britain*. Geological Conservation Review Series, No. 9. (Peterborough: Joint Nature Conservation Committee.)

Cleal, C J, and Thomas, B A. 1996. *British Upper Carboniferous Stratigraphy*. Geological Conservation Review Series, No. 11. (Peterborough: Joint Nature Conservation Committee.)

Cockburn, A M. 1952. Minor intrusions in the Pentland Hills. *Transactions of the Edinburgh Geological Society*, Vol. 15, 84-99.

Cockburn, A M. 1956. Notes on the geology of the eastern slopes of Blackford Hill, Edinburgh. *Transactions of the Edinburgh Geological Society*, Vol. 16, 307-312.

Common, R, and Galloway, R W. 1958. Ice wedges in Midlothian: a note. *Scottish Geographical Magazine*, Vol. 74, 44-46.

Conway, A, Dentith M, C, Doody J, J, and Hall, J. 1987. Preliminary interpretation of upper crustal structure across the Midland Valley of Scotland from two East–West seismic refraction profiles. *Journal of the Geological Society*, Vol. 144, 865-870.

Coope, G R. 1968. Fossil beetles collected by James Bennie from Late Glacial silts at Corstorphine, Edinburgh. *Scottish Journal of Geology*, Vol. 4, 339-348.

Cope, J C W, Ingham, J K, and Rawson, P F (editors). 1992. *Atlas of palaeogeography and lithofacies*. Geological Society of London Memoir. No. 13.

Cossey, P J, Adams, A E, Purnell, M A, Whiteley, M J, Whyte, M A, and Wright, V P. 2004. *British Lower Carboniferous Stratigraphy*. Geological Conservation Review Series. No. 29. (Peterborough: Joint Nature Conservation Committee.)

Craig, G Y, and Duff, P M D. 1975. *The geology of the Lothians and south-east Scotland; an excursion guide*. (Edinburgh: Scottish Academic Press.)

Crampton, C B, and Tait, D. 1910. On certain new localities for oil-bearing shale near Edinburgh. *Transactions of the Edinburgh Geological Society*, Vol. 9, 102-107.

Davidson, K A S, Sola, M, Powell, D W, and Hall, J. 1984. Geophysical model for the Midland Valley of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 75, 175-181.

Davies, L M. 1936. The geology of Inchkeith. *Transactions of the Royal Society of Edinburgh*, Vol. 58, 753–786.

Day, T C. 1933. *Arthur's Seat, a ruined volcano*. (Edinburgh: Oliver and Boyd.)

Dean, M T. 2000. A palaeontological and biostratigraphical summary of the Carboniferous of Scottish Sheet 32E (Edinburgh). *British Geological Survey Internal Report*, IR/00/51.

Dentith, M C, and Hall, J. 1989. MAVIS—an upper crustal seismic refraction experiment in the Midland Valley of Scotland. *Geophysical Journal International*, Vol. 99, 627-643.

Dentith, M C, and Hall, J. 1990. MAVIS: Geophysical constraints on the structure of the Carboniferous basin of West Lothian, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 81, 117-126.

Dineley, D L, and Metcalf, S J. 1999. *Fossil Fishes of Great Britain*. Geological Conservation Review Series. No. 16. (Peterborough: Joint Nature Conservation Committee.)

Dunham, R J. 1962. Classification of carbonate rocks according to depositional texture. Pp. 108-121 in: *Classification of carbonate rocks*. HAM, W E (editor). *Memoir of the American Association of Petroleum Geology*.

Elliot, R W. 1985. Central Scotland Mineral Portfolio: resources of clay and mudstone for brickmaking. *British Geological Survey Report*, WF/SC/85/001.

Flett, J S. 1899. On phenocrysts of micropegmatite. *Transactions of the Edinburgh Geological Society*, Vol. 7, 482-487.

Flett, J S. 1910. Petrological Chapters. In: *The geology of the neighbourhood of Edinburgh*, (2nd edition). Peach, B N, Clough, C T, Hinxman, L W, Grant Wilson, J S, Crampton, C B, Maufe, H B, and Bailey, E B (editors). *Memoir of the Geological Survey of Great Britain,* Sheet 32 (Scotland).

Floyd, J D. 1994. The derivation and definition of the 'Southern Upland Fault': a review of the Midland Valley – Southern Uplands terrane boundary. *Scottish Journal of Geology*, Vol. 30, 51-62.

Floyd, J D. 1996. Lithostratigraphy of the Ordovician rocks in the Southern Uplands: Crawford Group, Moffat Shale Group, Leadhills Supergroup. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 86, 153-165.

Floyd, J D. 2001. The Southern Uplands Terrane: a stratigraphical review. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, Vol. 91, 349-362.

Floyd, J D, Aitken, A M, Ball, D F, Laxton, J L, and Long, D. 1983. Environmental geology maps of south-east Edinburgh. *British Geological Survey Report*, SL/83/5.

Forsyth, I H, and Chisholm, J I. 1977. *The geology of East Fife*. Memoir of the Geological Survey of Great Britain. Sheet 41 with part of 49 (Scotland).

Francis, E H, Forsyth, I H, Read, W A, and Armstrong, M. 1970. *The Geology of the Stirling District*. Memoir of the Geological Survey of Great Britain. Sheet 39 (Scotland).

Fraser-Harris, A, McDermott, C I, Receveur, M, Mouli-Castillo, J, Todd, F, Cartwright-Taylor, A, Gunning, A, and Parsons, M. 2022. The Geobattery Concept: A Geothermal Circular Heat Network for the Sustainable Development of Near Surface Low Enthalpy Geothermal Energy to Decarbonise Heating. *Earth Science, Systems and Society*, Vol. 2, 10047.

Gatliff, R W, Richards, P C, Smith, K, Graham, C C, McCormac, M, Smith, N J P, Long, D, Cameron, T D J, Evans, D, Stevenson, A G, Bulat, J, and Ritchie, J D. 1994. United Kingdom offshore regional report: The geology of the central North Sea. (London).

Geikie, A. 1897. *The Ancient Volcanoes of Great Britain*. No. 1. (London: Macmillan.)

Geikie, J. 1877. *The Great Ice Age and its relation to the Antiquity of Man* (2nd edition). (London: Daldy, Ibister and Co.)

George, T N. 1974. Prologue to a geomorphology of Britain. *Institute of British Geographers Special Publication*, Vol. 7, 113-125.

Golledge, N R, and Stoker, M S. 2006. A palaeo-ice stream of the British Ice Sheet in eastern Scotland. *Boreas*, Vol. 35, 231-243.

Gordon, J E, and Sutherland, D G. 1993. *Quaternary of Scotland*. Geological Conservation Review Series. No. 6. (Peterborough: Joint Nature Conservation Committee.)

Gradstein, F M, Ogg, J G, and Smith, A G. 2004. *A Geologic Time Scale 2004*. (Cambridge: Cambridge University Press.)

Guirdham, C. 1998. *Regional stratigraphy, lithofacies, diagenesis and dolomitisation of microbial carbonates in the Lower Carboniferous West Lothian Oil-shale Formation*. Unpublished PhD Thesis, University of East Anglia.

Guirdham, C, Andrews, J E, Browne, M A E, and Dean, M T. 2003. Stratigraphic and palaeoenvironmental significance of microbial carbonates in the Asbian Sandy Craig Formation of Fife. *Scottish Journal of Geology*, Vol. 39, 151-168.

Hall, J. 1805. Experiments on whinstone and lava. *Transactions of the Royal Society of Edinburgh*, Vol. 5, 43-75.

Hallett, D, Durant, G P, and Farrow, G E. 1985. Oil exploration and production in Scotland. *Scottish Journal of Geology*, Vol. 21, 547-570.

Henderson, J. 1872. On Corstorphine Hill, near Edinburgh. *Transactions of the Edinburgh Geological Society*, Vol. 2, 29-33.

Henderson, J. 1873. On the evidence of the existence of an old water course previous to the deposition of the boulder clay at the water of Leith, above Colinton. *Transactions of the Edinburgh Geological Society*, Vol. 2, 196-201.

Henderson, J. 1874. On some sections of boulder clay, peat and stratified beds, exposed in a quarry recently opened at Redhall, Slateford, near Edinburgh. *Transactions of the Edinburgh Geological Society*, Vol. 2, 391-395.

Henderson, J. 1893. On sections exposed in the line of the Barnton Railway. *Transactions of the Edinburgh Geological Society*, Vol. 6, 297-300.

Hooper, M D. 2003. *The Carboniferous evolution of the Central Coalfield basin, Midland Valley of Scotland.* Unpublished PhD Thesis, University of Leicester.

Howell, H H, and Geikie, A. 1861. *The geology of the neighbourhood of Edinburgh* (1st edition). Memoir of the Geological Survey of Great Britain. Sheet 32 (Scotland).

Howell, H H, Geikie, A, and Young, J. 1866. *The geology of East Lothian, including parts of the counties of Edinburgh and Berwick* (1st edition). Memoir of the Geological Survey of Great Britain. Sheets 33, 34, and 41 (Scotland).

Hughes, R A, and Boland, M P. 1995. The Ordovician and Silurian rocks of the Scottish sheet 24E (Peebles). *British Geological Survey Technical Report*, WA/95/14.

Hutton, G. 1998. *Mining the Lothians*. (Catrine: Stenlake Publishing.)

Hutton, J. 1795. *Theory of the Earth*. (Edinburgh: W Creech.)

Hyslop, E K. 2004. The performance of replacement sandstone in the New Town of Edinburgh. *Historic Scotland Research Report* (Edinburgh).

Hyslop, E K, and McMillan, A. 2004. Replacement sandstone in the Edinburgh World Heritage Site: problems of source and supply. Pp. 777–784 in: *Proceedings of the 10th International Congress on Deterioration and Conservation of Stone*. Kwiatkowski, D, and Löfvendahl, R (editors). (Stockholm: ICOMOS, Sweden.)

Jackson, D I. 1998. written communication and specimen.

Jamieson, S (editor). 1984. *The Water of Leith*. (The Water of Leith Project Group.)

Jarzembowski, E A. 2010. *Fossil Arthropods of Great Britain*. Geological Conservation Review Series. No. 35. (Peterborough: Joint Nature Conservation Committee.)

Jones, N. 2007. The West Lothian Oil-shale Formation: results of a sedimentological study. *British Geological Survey Internal Report*, IR/05/046.

Kassi, A M, Weir, J A, McManus, J, and Browne, M A E. 2004. Lithofacies and sedimentary cycles within the Late Dinantian (late Brigantian) of Fife and East Lothian: is a sequence stratigraphical approach valid? *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 94, 95-113.

Kearsey, T I, Receveur, M, and Monaghan, A A. 2024. Modelled hot sedimentary aquifer geothermal potential of Upper Devonian strata in the Midland Valley of Scotland. *British Geological Survey Open Report*, OR/24/030.

Kirby, R P. 1966. *The glacial geomorphology of the Esk basin, Midlothian*. Unpublished PhD Thesis, University of Edinburgh.

Kirby, R P. 1968. The ground moraines of Midlothian and East Lothian. *Scottish Journal of Geology*, Vol. 4, 209-220.

Kirby, R P. 1969a. Variation in glacial deposition in a sub-glacial environment: an example from Midlothian. *Scottish Journal of Geology*, Vol. 5, 49-53.

Kirby, R P. 1969b. Till Fabric Analyses from the Lothians, Central Scotland. *Geografiska Annaler: Series A, Physical Geography*, Vol. 51, 48-60.

Kirby, R P. 1969c. Morphometric Analysis of Glaciofluvial Terraces in the Esk Basin, Midlothian. *Transactions of the Institute of British Geographers*, Vol. 48, 1-18.

Land, D H. 1996. Discovering Edinburgh's Volcano (poster). Edinburgh, Edinburgh Geological Society with Historic Scotland and Scottish Natural Heritage.

Land, D H. 1999. *Hermitage of Braid and Blackford Hill: scenery and geology of the park*, (leaflet) Edinburgh Geological Society.

Land, D H, and Cheney, R F. 2000. *Discovering Edinburgh's Volcano: a geological guide to Arthur's Seat*, (leaflet) Edinburgh Geological Society.

Lees, G M, and Taitt, A H. 1945. The Geological Results of the Search for Oilfield in Great Britain. *Journal of the Geological Society of London*, Vol. 101, 255-317.

Loftus, G W F. 1985. *The petrology and depositional environments of the Dinantian Burdiehouse Limestone Formation of Scotland*. Unpublished PhD Thesis, University of London.

Loftus, G W F, and Greensmith, J T. 1988. The lacustrine Burdiehouse Limestone Formation — a key to the deposition of the Dinantian Oil Shales of Scotland. *Lacustrine Petroleum Source Rocks*. Fleet, A J, Kelts, K R, and Talbot, M R (editors). *Geological Society of London Special Publication,* 40.

Long, D, Smith, D E, & Dawson, A G. 1989. A Holocene tsunami deposit in eastern Scotland. *Journal of Quaternary Science*, Vol 4, 61-66.

Loughlin, S C, and Stephenson, D. 2003. Tholeiitic sills and dykes of Scotland and Northern England. Pp. 215-230 in: *Carboniferous and Permian Igneous Rocks of Great Britain North of the Variscan Front*. Stephenson, D, Loughlin, S C, Millward, D, Waters, C N, and Williamson, I T (editors). *Geological Conservation Review Series,* No 27. (Peterborough: Joint Nature Conservation Committee.)

Macdonald, R. 1976. Petrochemistry of the Early Carboniferous (Dinantian) Lavas of Scotland. *Scottish Journal of Geology*, Vol. 11, 269-314.

Macdonald, R. 1980. Trace element evidence for mantle heterogeneity beneath the Scottish Midland Valley in the Carboniferous and Permian. *Philosophical Transactions of the Royal Society of London*, Vol. 280, 111-123.

MacGregor, A G. 1928. XIII. Classification of Scottish Carboniferous Olivine Basalts and Mugearites. *Transactions of the Geological Society of Glasgow*, Vol. 18, 324-361.

MacGregor, A G. 1945. The mineral resources of the Lothians, Wartime Pamphlet Geological Survey of Great Britain. 45.

MacGregor, A G. 1960. V - Divisions of the Carboniferous on Geological Survey Scottish Maps. *Bulletin of the Geological Survey of Great Britain*, Vol. 16, 127-130.

Maclaren, C. 1828. Changes on the surface of the globe. *The Scotsman*, 12 (918) 25 October, 683.

Maclaren, C. 1839. *Sketch of the geology of Fife and the Lothians, including detailed descriptions of Arthur's Seat and Pentland Hills*. (Edinburgh: Adam and Charles Black.)

Maclaren, C. 1840. Discovery of the former existence of glaciers in Scotland especially in the Highlands, by Professor Agassiz. *The Scotsman*, 24 (2165), 7 October, p. 3.

Maclaren, C. 1866. *A sketch of the geology of Fife and the Lothians including detailed descriptions of Arthur's Seat and Pentland Hills* (2nd edition). (Edinburgh: Adam and Charles Black.)

Macpherson, K A T. 1986a. Central Scotland mineral portfolio: limestone resources. *British Geological Survey Report*, WF/SC/86/1.

Macpherson, K A T. 1986b. Central Scotland Mineral Portfolio: special sand resources (silica sands). *British Geological Survey Report*, WF/SC/86/002.

Maddox, S J, and Andrews, J E. 1987. Lithofacies and stratigraphy of a Dinantian non-marine dolostone from the Lower Oil-Shale Group of Fife and West Lothian. *Scottish Journal of Geology*, Vol. 23, 129-147.

Marshall, J E A, Reeves, E J, Bennett, C E, Davies, S J, Kearsey, T I, Millward, D, Smithson, T R, and Browne, M A E. 2018. Reinterpreting the age of the uppermost 'Old Red Sandstone' and Early Carboniferous in Scotland. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, Vol. 109, 265-278.

Martin, J H. 1981. *Quaternary glaciofluvial deposits in central Scotland: sedimentology and economic geology*. Unpublished PhD Thesis, University of Edinburgh.

Martin, R. 1905. Coal-mining in the Musselburgh Coalfield. *Transactions of the Edinburgh Geological Society*, Vol. 8, 379-386.

McAdam, A D. 1978. Sand and gravel resources of the Lothian Region of Scotland. *Institute of Geological Sciences Report*, 78/1.

McAdam, A D. 1993. *Edinburgh; a landscape fashioned by geology*. (Perth: Scottish Natural Heritage and British Geological Survey.)

McAdam, A D. 2004. *Corstorphine Hill Regionally Important Geological Site* (leaflet). Edinburgh, Lothian and Borders RIGS Group.

McAdam, A D, and Clarkson, E N K. 1986. *Lothian Geology: an excursion guide* (3rd edition). (Edinburgh Geological Society.)

McAdam, A D, and Clarkson, E N K. 1996. *Lothian Geology: an excursion guide* (Reprint 3rd edition). (Edinburgh Geological Society.)

McAdam, A D, and McKirdy, A. 2003. *Edinburgh; a landscape fashioned by geology*. (Perth: Scottish Natural Heritage and British Geological Survey.)

McCall, J, and Goodlet, G A. 1952. Indicator stones from the drift of south Midlothian and Peebles. *Transactions of the Edinburgh Geological Society*, Vol. 14, 401-409.

McLintock, W F P, and Phemister, J. 1929. A gravitational survey over the Pentland Fault, near Portobello, Midlothian, Scotland. *Summary of Progress of the Geological Survey of Great Britain and Museum of Practical Geology*, for 1928, pt. 2, 10-28.

McMillan, A A, Gillanders, R J, and Fairhurst, J A. 1999. *Building Stones of Edinburgh*. (Edinburgh Geological Society.)

McMillan, A A, Hamblin, R J O, and Merritt, J W. 2005. An overview of the lithostratigraphical framework for the Quaternary and Neogene deposits of Great Britain (onshore). *British Geological Survey Research Report*, RR/04/004.

McMillan, A A, Land, D H, and McAdam, A D. 2003. *Calton Hill and Edinburgh's East End; geological walk* (leaflet). Edinburgh, Lothian and Borders RIGS Group.

McMillan, A A, Laxton, J L, and Shaw, A J. 1981. The sand and gravel resources of the country around Dolphinton, Strathclyde Region, and West Linton, Borders Region: Description of 1:25 000 resource sheets NT 04 and 14 and parts of NT 05 and 15. *Institute of Geological Sciences* (Edinburgh).

Merritt, J W. 1985. Central Scotland mineral portfolio: fireclay resources. *British Geological Survey Technical Report*, WF/SC/85/002.

Merritt, J W, Elliot, R W, and Aitken, A M. 1984. Central Scotland Mineral Portfolio: hard rock aggregate resources. *British Geological Survey Technical Report*, WF/SC/84/02.

Miller, H. 1864. *Edinburgh and its neighbourhood, geological and historical*. (Edinburgh: Adam and Charles Black.)

Milne Home, D. 1840. On the Mid-Lothian and East-Lothian coal-fields. *Transactions of the Royal Society of Edinburgh*, Vol. 14, 253-358.

Milne Holme, D. 1874. Notice of a striated boulder lately found in Tynecastle Sandpit, Edinburgh. *Transactions of the Edinburgh Geological Society*, Vol. 2, 347-350.

Mitchell, G H, and Mykura, W. 1962. *The geology of the neighbourhood of Edinburgh* (3rd edition). Memoir of the Geological Survey of Great Britain. Sheet 32 (Scotland).

Mitchell, G H, Walton, E K, and Grant, D. 1960. *Edinburgh Geology: an excursion guide*. (Edinburgh and London: Oliver and Boyd.)

Molyneux, S G, Barron, H F, and Smith, R A. 2008. Upper Llandovery–Wenlock (Silurian) palynology of the Pentland Hills inliers, Midland Valley of Scotland. *Scottish Journal of Geology*, Vol. 44, 151-168.

Monaghan, A A. 2014. *The Carboniferous shales of the Midland Valley of Scotland: geology and resource estimation*. British Geological Survey for Department of Energy and Climate Change, London, UK.

Monaghan, A A, Browne, M A E, and Barfod, D N. 2014. An improved chronology for the Arthur's Seat volcano and Carboniferous magmatism of the Midland Valley of Scotland. *Scottish Journal of Geology*, Vol. 50, 165-172.

Monaghan, A A, and Parrish, R R. 2006. Geochronology of Carboniferous–Permian magmatism in the Midland Valley of Scotland: implications for regional tectonomagmatic evolution and the numerical time scale. *Journal of the Geological Society*, Vol. 163, 15-28.

Monaghan, A A, and Pringle, M S. 2004. 40Ar/39Ar geochronology of Carboniferous-Permian volcanism in the Midland Valley, Scotland. *Geological Society, London, Special Publications*, Vol. 223, 219-241.

Monckton, H W (editor). 1913. *The Geology of the district around Edinburgh*. Geologists' Association Field Guide. (London: Stanford.)

Monckton, H W. 1914. The Geology of the district around Edinburgh. *Proceedings of the Geologists' Association*, Vol. 25, 1-50.

Muir, A, Hardie, H G M, Mitchell, R L, and Phemister, J. 1956. The limestones of Scotland: chemical analyses and petrography. *Memoir of the Geological Survey, Mineral Resources*, 37.

Musson, R M W. 1994. A catalogue of British earthquakes. BGS Seismic Monitoring and Information Service. *British Geological Survey Technical Report*, WL/94/4.

Mykura, W. 1960. The Lower Old Red Sandstone igneous rocks of the Pentland Hills. *Bulletin of the Geological Survey of Great Britain*, Vol. 16, 131–155.

Mykura, W, and Smith, J D D. 1962. Silurian. Pp. 10-21 in: *The geology of the neighbourhood of Edinburgh*, (3rd edition). Mitchell, G H, and Mykura, W (editors). *Memoir of the Geological Survey of Great Britain,* Sheet 32 (Scotland).

Neves, R, Gueinn, K J, Clayton, G, Ioannides, N S, Neville, R S W, and Kruszewska, K. 1973. 2.—Palynological Correlations within the Lower Carboniferous of Scotland and Northern England. *Transactions of the Royal Society of Edinburgh*, Vol. 69, 23-70.

Newey, W W. 1970. Pollen analysis of late-Weichselian deposits at Corstorphine, Edinburgh. *New Phytologist*, Vol. 69, 53-59.

Nicol, J. 1844. *Guide to the Geology of Scotland*. (Edinburgh: Oliver and Boyd.)

Panton, G A. 1873. Note on a striated and water worn cliff at Blackford Hill, near Edinburgh and on a sand hill there. *Transactions of the Edinburgh Geological Society*, Vol. 2, 238-242.

Paterson, I B, Armstrong, M, and Browne, M A E. 1981. Quaternary estuarine deposits in the Tay-Earn area, Scotland. *British Geological Survey Report*, 81/7.

Peach, B N, Clough, C T, Hinxman, L W, Wilson, J S G, Crampton, C B, Maufe, H B, and Bailey, E B. 1910. *The geology of the neighbourhood of Edinburgh* (2nd edition). Memoir of the Geological Survey of Great Britain, Sheet 32 (Scotland).

Peacock, J D. 1975. Scottish late- and post-glacial marine deposits. in: *Quaternary Studies in North East Scotland*. Gemmell, A M D (editor). (Aberdeen: Department of Geography, University of Aberdeen.)

Peacock, J D. 1998. The Bothkennar Gravel Formation (‘buried gravel layer’) of the Forth Estuary. *Scottish Journal of Geology*, Vol. 34, 1-5.

Peacock, J D. 2002. Macrofauna and palaeoenvironment of marine strata of Windermere Interstadial age of the east coast of Scotland. *Scottish Journal of Geology*, Vol. 38, 31-40.

Phillips, E R, Evans, J A, Stone, P, Horstwood, M S A, Floyd, J D, Smith, R A, Akhurst, M C, and Barron, H F. 2003. Detrital Avalonian zircons in the Laurentian Southern Uplands terrane, Scotland. *Geology*, Vol. 31, 625-628.

Phillips, E R, Smith, R A, and Carroll, S. 1997. Strike-slip, terrane accretion and the pre-Carboniferous evolution of the Midland Valley of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 88, 209-224.

Pickard, N A H. 1994. Sedimentology of the upper Dinantian Charlestown Main Limestone: implications for the controls on cyclothem deposition, eastern Midland Valley of Scotland. *Scottish Journal of Geology*, Vol. 30, 15-31.

Porteous, C. 2008. *Craiglockhart and the Seven Hills* (leaflet) Edinburgh, Lothian and Borders RIGS Group.

Porteous, C, and Browne, M A E. 2003. *Ravelston Park and Woods* (leaflet). Edinburgh, Lothian and Borders RIGS Group.

Porteous, C, and Browne, M A E. 2006. *James Hutton; a man ahead of his time* (leaflet). Edinburgh, Lothian and Borders RIGS Group.

Raymond, A C. 1991. *Carboniferous rocks of the eastern and central Midland Valley of Scotland: organic petrology, organic geochemistry and effects of igneous activity.* Unpublished PhD Thesis, University of Newcastle-upon-Tyne.

Read, W A, Browne, M A E, Stephenson, D, and Upton, B J G. 2002. Carboniferous. Pp. 251-299 in: *The Geology of Scotland*, (4th Edition edition). TREWIN, N H (editor). (London: The Geological Society.) ISBN 1-86239-105-x

Rhind, W. 1836. *Excursions illustrative of the geology and natural history of the environs of Edinburgh* (2nd edition). (Edinburgh: J Anderson.)

Richardson, R. 1874. Notice of a section in the building excavations at Tynecastle, West End, Edinburgh. *Transactions of the Edinburgh Geological Society*, Vol. 2, 358-360.

Ridgway, J M. 1982. Common Clay and Shale. *Institute of Geological Sciences* (London).

Rippon, J, Read W, A, and Park R, G. 1996. The Ochil Fault and the Kincardine basin: key structures in the tectonic evolution of the Midland Valley of Scotland. *Journal of the Geological Society*, Vol. 153, 573-587.

Rippon, J H, Ellison, R A, and Gayer, R A. 2006. A review of joints (cleats) in British Carboniferous coals: indicators of palaeostress orientation. *Proceedings of the Yorkshire Geological Society*, Vol. 56, 15-30.

Ritchie, J D, Johnson, H, Browne, M A E, and Monaghan, A A. 2003. Late Devonian–Carboniferous tectonic evolution within the Firth of Forth, Midland Valley; as revealed from 2D seismic reflection data. *Scottish Journal of Geology*, Vol. 39, 121-134.

Robertson, G. 1985. *Palaeoenvironmental interpretation of the Silurian rocks of the Pentland Hills*. Unpublished PhD thesis, University of Edinburgh.

Robertson, G. 1989. A palaeoenvironmental interpretation of the Silurian rocks in the Pentland Hills, near Edinburgh, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 80, 127-141.

Robertson, T, Simpson, J B, and Anderson, J G C. 1949. The Limestones of Scotland. *Memoir of the Geological Survey of Great Britain, Special Reports on the Mineral Resources of Great Britain*, XXXV.

Robins, N S. 1990. *Hydrogeology of Scotland*. (London: HMSO for the British Geological Survey.)

Sissons, J B. 1958. Sub-glacial stream erosion in Southern Northumberland. *Scottish Geographical Magazine*, Vol. 74, 163-174.

Sissons, J B. 1961a. The Central and Eastern Parts of the Lammermuir-Stranraer Moraine. *Geological Magazine*, Vol. 98, 380-392.

Sissons, J B. 1961b. Some aspects of glacial drainage channels in Britain. Part II. *Scottish Geographical Magazine*, Vol. 77, 15-36.

Sissons, J B. 1969. Drift Stratigraphy and Buried Morphological Features in the Grangemouth-Falkirk-Airth Area, Central Scotland. *Transactions of the Institute of British Geographers*, 19-50.

Sissons, J B. 1971. The geomorphology of central Edinburgh. *Scottish Geographical Magazine*, Vol. 87, 185-196.

Sissons, J B. 1974a. Late-glacial marine erosion in Scotland. *Boreas*, Vol. 3, 41-48.

Sissons, J B. 1974b. The Quaternary in Scotland: a review. *Scottish Journal of Geology*, Vol. 10, 311-337.

Sissons, J B, and Smith, D E. 1965. Peat bogs in a Post-glacial sea and a buried raised beach in the western part of the Carse of Stirling. *Scottish Journal of Geology*, Vol. 1, 247-255.

Skelley, E. 2008. The Geology of The Water of Leith. Edinburgh Geological Society.

Smedley, P L. 1986a. *Petrochemistry of Dinantian volcanism in northern Britain*. Unpublished PhD Thesis, University of Edinburgh.

Smedley, P L. 1986b. The relationship between calc-alkaline volcanism and within-Plate continental rift volcanism: evidence from Scottish Palaeozoic lavas. *Earth and Planetary Science Letters*, Vol. 77, 113-128.

Smith, M. 1994. Restoration of an old Edinburgh sand pit. *Earth Heritage*, 27.

Smith, R A. 1996. Geology of the Gass Water area, explanation of 1:10 000 sheet NS62SE: part of 1:50 000 sheet 15W (New Cumnock). *British Geological Survey Technical Report*, WA/96/22.

Smith, R A, Phillips, E R, Floyd, J D, Barron, H F, and Pickett, E A. 2000. The Northern Belt 100 years on: a revised model of the Ordovician tracts near Leadhills, Scotland. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, Vol. 91, 421-434.

Somervail, A. 1879. Observations on the higher summits of the Pentland Hills. *Transactions of the Edinburgh Geological Society*, Vol. 3, 191-221.

Stephenson, D. 1999. Late Silurian and Devonian volcanic rocks of Scotland: introduction. Pp 481–488 in: *Caledonian Igneous Rocks of Great Britain*. Stephenson, D, Bevins, R E, Millward, D, Highton, A J, Parsons, I, Stone, P, and Wadsworth, W J (editors). *Geological Conservation Review series,* No 17. (Peterborough: Joint Nature Conservation Committee.)

Stephenson, D, Bevins, R E, Millward, D, Highton, A J, Parsons, I, Stone, P, and Wadsworth, W J. 1999. *Caledonian Igneous Rocks of Great Britain*. Geological Conservation Review series. No. 17. (Peterborough: Joint Nature Conservation Committee.)

Stephenson, D, Loughlin, S C, Millward, D, Waters, C N, and Williamson, I T. 2003. *Carboniferous and Permian Igneous Rocks of Great Britain North of the Variscan Front*. Geological Conservation Review Series. No. 27. (Peterborough: Joint Nature Conservation Committee.)

Stoker, M S, Golledge, N R, Phillips, E R, Wilkinson, I P, and Akhurst, M C. 2008. Lateglacial–Holocene shoreface progradation offshore eastern Scotland: a response to climatic and coastal hydrographic change. *Boreas*, Vol. 38, 292-314.

Stone, P. 1995. Geology of the Rhins of Galloway district. *Memoir of the British Geological Survey*, Sheets 1 and 3 (Scotland).

Stuart, F M, Bluck, B J, and Pringle, M S. 2001. Detrital muscovite ^{40}Ar/^{39}Ar ages from Carboniferous sandstones of the British Isles: Provenance and implications for the uplift history of orogenic belts. *Tectonics*, Vol. 20, 255-267.

Syba, E. 1989. *The sedimentation and provenance of the Lower Old Red Sandstone Greywacke Conglomerate, Southern Midland Valley, Scotland*. Unpublished PhD Thesis, University of Edinburgh.

Tait, D. 1916. On bores for water and medicinal wells in the Wardie Shales, near Edinburgh. *Transactions of the Edinburgh Geological Society*, Vol. 10, 316-325.

Tait, D. 1925a. On the section in a borehole in the Calciferous Sandstone Series, Upper Old Red Sandstones and Lower Old Red Sandstone lavas, in the Grange district, Edinburgh. *Transactions of the Edinburgh Geological Society*, Vol. 11, 18-22.

Tait, D. 1925b. Notice of a shrimp-bearing limestone in the Calciferous Sandstone Series at Granton, near Edinburgh. *Transactions of the Edinburgh Geological Society*, Vol. 11, 131-134.

Tait, D. 1925c. The rocks between Leith and Granton, with historical notes on the working of the Wardie Coal. *Transactions of the Edinburgh Geological Society*, Vol. 11, 346-351.

Tait, D. 1934. Braid Burn, Duddingston and Portobello excavations, 1929-1931. *Transactions of the Edinburgh Geological Society*, Vol. 13, 61-71.

Thirlwall, M F. 1981. Implications for Caledonian Plate tectonic models of chemical data from volcanic rocks of the British Old Red Sandstone. *Journal of the Geological Society*, Vol. 138, 123-138.

Thirlwall, M F. 1988. Geochronology of Late Caledonian magmatism in northern Britain. *Journal of the Geological Society*, Vol. 145, 951-967.

Thomson, M E. 1978. IGS studies of the Firth of Forth and its approaches. *British Geological Survey Report*, 77/17.

Tipper, J C. 1976. The stratigraphy of the North Esk Inlier, Midlothian. *Scottish Journal of Geology*, Vol. 12, 15-22.

Trewin, N (editor). 2002. *The Geology of Scotland* (4th edition). (London: The Geological Society.)

Trewin, N H, and Thirlwall, M F. 2002. The Old Red Sandstone. Pp. 212-249 in: *The Geology of Scotland*, (4th Edition). Trewin, N H (editor). (London: The Geological Society.)

Tulloch, W, and Walton, H S. 1958. The geology of the Midlothian coalfield. *Economic Memoir of the Geological Survey, Scotland*.

Turner, M S. 1991. *Geochemistry and diagenesis of basal Carboniferous dolostones from southern Scotland.* Unpublished PhD Thesis, University of East Anglia.

Underhill, J R, Monaghan, A A, and Browne, M A E. 2008. Controls on structural styles, basin development and petroleum prospectivity in the Midland Valley of Scotland. *Marine and Petroleum Geology*, Vol. 25, 1000-1022.

Upton, B G J. 2003. Arthur's Seat Volcano, City of Edinburgh. Pp. 64-74 in: *Carboniferous and Permian Igneous Rocks of Great Britain North of the Variscan Front*. Stephenson, D, Loughlin, S C, Millward, D, Waters, C N, and Williamson, I T (editors). *Geological Conservation Review Series,* No 27. (Peterborough: Joint Nature Conservation Committee.)

Upton, B G J. 2004. *Volcanoes and the Making of Scotland*. (Edinburgh: Dunedin Academic Press.)

Upton, B G J, Stephenson, D, Smedley, P M, Wallis, S M, and Fitton, J G. 2004. Carboniferous and Permian magmatism in Scotland. *Geological Society, London, Special Publications*, Vol. 223, 195-218.

Urquhart, E. 2006. *Stones of Scotland* (leaflet). Edinburgh, Lothian and Borders RIGS Group.

Vincent, C, Rowley, W J, and Monaghan, A A. 2010. Thermal and burial history modeling in the Midland Valley of Scotland using BasinMod and HotPot. *Scottish Journal of Geology*, Vol. 46, 125-142.

Walker, A B. 1997. Musselburgh Earth Tremors 1996–1997. *British Geological Survey Technical Report*, WL/97/20.

Walls, D B, Banks, D, Peshkur, T, Boyce, A J, and Burnside, N M. 2022. Heat Recovery Potential and Hydrochemistry of Mine Water Discharges From Scotland's Coalfields. *Earth Science, Systems and Society*, Vol. 2, 10056.

Waterston, C D. 1996. City of Edinburgh, The Dean, Edinburgh - an excursion. In: *Lothian Geology: an excursion guide*, (3rd Edition. edition). McAdam, A D, and Clarkson, E N K (editors). (Edinburgh Geological Society.)

Wells, A K (editor). 1927. The Geology of the district around Edinburgh. *Proceedings of the Geologists' Association*, Vol. 38, 405-510.

Wilkinson, I. 2008. *Joppa Shore* (leaflet). Edinburgh, Lothian and Borders RIGS Group.

Williamson, I T. 2003. Garleton Hills, East Lothian. Pp. 56-60 in: *Carboniferous and Permian Igneous Rocks of Great Britain North of the Variscan Front*. Stephenson, D, Loughlin, S C, Millward, D, Waters, C N, and Williamson, I T (editors). *Geological Conservation Review Series,* No 27. (Peterborough: Joint Nature Conservation Committee.)

Wilson, M, Neumann, E R, Davies, G R, Timmerman, M J, Heeremans, M, and Larsen, B T. 2004. Permo-Carboniferous magmatism and rifting in Europe: introduction. *Geological Society, London, Special Publications*, Vol. 223, 1-10.

Wilson, R B. 1974. A study of the Dinantian marine faunas of south-east Scotland. Bulletin of *the Geological Survey of Great Britain*, Vol. 46, 35-65.

Wilson, R B. 1987. A study of the marine macrofossils of central Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 80, 91-126.

Wilson, W, Clough, C T, Lee, G W, and Tait, D. 1910. The recently exposed section on the Railway Line, south-east of Portobello, with comparisons. *Transactions of the Edinburgh Geological Society*, Vol. 9, 193-201.

Wood, S C, Younger, P L, and Robins, N S. 1999. Long-term changes in the quality of polluted minewater discharges from abandoned underground coal workings in Scotland. *Quarterly Journal of Engineering Geology*, Vol. 32, 69-79.

Wood, S P. 1975. Recent discoveries of Carboniferous fishes in Edinburgh. *Scottish Journal of Geology*, Vol. 11, 251-258.

Woodhall, D G. 2003. Burntisland to Kinghorn Coast, Fife. Pp. 74-77 in: *Carboniferous and Permian Igneous Rocks of Great Britain North of the Variscan Front*. Stephenson, D, Loughlin, S C, Millward, D, Waters, C N, and Williamson, I T (editors). *Geological Conservation Review Series*. (Peterborough: Joint Nature Conservation Committee.)

Wright, V P, and Vanstone S D. 2001. Onset of Late Palaeozoic glacio-eustasy and the evolving climates of low latitude areas: a synthesis of current understanding. *Journal of the Geological Society*, Vol. 158, 579-582.

Ziegler, P. 1993. Late Palaeozoic — early Mesozoic Plate reorganization: evolution and demise of the Variscan Fold Belt. Pp. 203-216 in: *Pre-Mesozoic geology in the Alps*. Von Raumer, J F, and Neubauer, F (editors). (Berlin Heidelberg: Springer-Verlag.)