Appendix 3 Detailed geology of West Lothian

Inverclyde Group

The oldest Carboniferous rocks in the Midland Valley of Scotland belong to the Inverclyde Group. It comprises the Kinnesswood, Ballagan, and Clyde Sandstone formations but the last named unit has not been definitively recognised in West Lothian. These formations are characterised by sandstone with pedogenic (soil profile) carbonate concretions (calcrete) and by silty mudstone containing thin beds of dolostone (cementstone) and limestone; also the absence of carbonaceous rocks especially coal seams and oil shales. They were laid down between 345m and 355m years ago (Tournaisian; Courceyan to earliest Chadian Stage). Locally in the Pentlands, the base of the group is taken at an unconformity on Lower Devonian and older strata. The Inverclyde Group was laid down whilst Scotland lay in low latitudes south of the Equator. At this time, the climate was generally considered to be semi-arid and seasonally wet. It is because of the semi-arid climate that the sandstone-dominated Kinnesswood Formation contains calcareous and dolomitic pedogenic (soil profile) horizons (calcrete) and the overlying Ballagan Formation is characterised by ferroan dolostone (cementstone), and evaporite (mainly gypsum).A rather discontinuous vegetational cover of the land surface was probably the norm.

Kinnesswood Formation

The Kinnesswood Formation consists predominantly of white, pink to red-brown, medium- grained quartzose sandstones that are cross-bedded and arranged in upward-fining units. Fine-grained, planar or poorly bedded sandstones, red-brown and pale green mudstones/siltstones and nodules and thin beds of concretionary carbonate (cornstone) also occur. Rip-up clasts of mudstone and carbonate are also found especially in sandstone sub-unit and unit bases. Lithic, matrix supported conglomerate and coarse pebbly sandstone are found at the base of the formation where it rests unconformably on older strata. The clasts, usually no more than 10cm, consist mostly of lavas and also vein quartz, quartzite, jasper, chert and wacke sandstone. The cross-bedded sandstones were deposited in river channels (and on river banks) apparently flowing mainly from the southeast and the fine-grained sandstones and mudstones represent overbank deposits formed on the associated floodplains. The carbonate nodules and beds that characterise the formation, are calcrete deposits that 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. The formation is estimated to be 100 m to 400 m thick in the Pentlands.

Ballagan Formation

The Ballagan Formation is characterised by grey mudstone and siltstone, with nodules and beds of ferroan dolostone (cementstone), the 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 frequently show evidence of brecciation. Both these features are associated with reddening of the strata that is otherwise much more common in West Lothian contrasted to the classical Ballagan outcrops such as at Ballagan Glen, Stirlingshire. Thin sandstone beds are commonly present, and thick localised sandstones are also found in the formation especially in West Lothian. Where present, the restricted fauna is characterised by the bivalve Modiolus latus, but ostracods are more abundant along with Estherids and Sprirobids.

The Ballagan Formation is interpreted as being laid down in coastal alluvial plains, lakes and marginal marine flats. These were subject to periodic desiccation with fluctuating salinity partly as a result of seawater being introduced by storm flooding events. The open sea lay to the east initially. Later it is more evident to the south of the Midland Valley of Scotland with the more marine faunas in the 'cementstones' being found in the Solway Firth Basin. The lack of sulphide in the mudstones and the sourcing of the magnesium and calcium ions in the cementstones has been explained by the limited events of seawater inundation of the alluvial plains and its lakes. Argillaceous limestone is present where lakes were deep enough to avoid post-burial dolomitisation. The inundations in general left no marine faunal record but

provided a strong geochemical signal in the sulphate evaporites, ferroan dolostones and Strontium isotopes. Because of the dominance of the siliciclastic component over the evaporitic, it has been concluded that the formation was laid down in a humid environment subject to drier periods of evaporation rather than a generally arid one. The maximum thickness of the formation of about 900 m is in the West Lothian area.

The detailed sequence of informal members in the Ballagan Formation is in ascending succession; Lower Shale (100m thick), Middle Sandstone (180 m to 400m thick), Upper Shale (400 m thick) and Upper Sandstone. The 'Upper Sandstone' of the Pentland Hills may actually belong to the Clyde Sandstone Formation. Elsewhere this last named formation 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 floodplain with well-developed overbank deposits. Distinguishing the Ballagan and Clyde Sandstone formations apart in the Edinburgh district is difficult because 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 than is its norm.

Strathclyde Group

The Strathclyde Group is a varied sequence of rocks, sedimentary and volcanic, characterised by the presence of carbonaceous beds, including coal and oil-shale. They were laid down between 345m and 326m years ago (Visèan; earliest Asbian to Brigantian Stages). The group is largely fluviatile and lacustrine in origin, with a few marine incursions from time to time. The base of the Strathclyde Group is taken at the base of the Arthur's Seat Volcanic Formation in the Lothians (342m yrs old). Strathclyde Group strata consist of interbedded sandstone, siltstone and mudstone with common seatearths, 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 may be common. The local Strathclyde Group strata are assigned to the Arthur's Seat Volcanic, Gullane and West Lothian Oil-shale formations.

Oil-shales and freshwater limestones are minor but important components of the group. These reflect the development of substantial lakes ('Lake Cadell', 2000-3000 km²) 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. The non- filamentous planktonic Botryococcus brauni appears to be a minor constituent of these oil shales and limestones. Cryptalgally laminated dolostones have been recognised as of the value of in regional correlation and as time markers of basin-wide 'regression'. Deposition of these carbonates was in a hydrologically closed, shallow, playa-type lake. 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, sub-tropical environment) or by local earth movements and vulcanicity. However a second category of closed lake is known in which microbial tufa carbonates accreted in shallow, volcanigenically supplied nutrient-rich sub-basins.

Other volcanic rocks occur in the group apart from those in the Arthur's Seat and Bathgate Hills Volcanic formations including the following named tuff horizons, Crosswood Ash, Seafield- Deans Ash, Port Edgar Ash and Barracks Ash. The Port Edgar Ash comprises tuffs of comminuted sedimentary debris which have been encountered in boreholes in the Society area [NT 10 79]. The Seafield-Deans Ash consists of a pile of tuffs, locally 90 m or more in thickness, occurring in the Seafield and Deans area [NT 01 66], where it takes the place of some oil-shale seams in the Pumpherston Shales.

The palaeoclimate during deposition of the Strathclyde Group was mainly humid (coals, oil- shales and sideritic mud grade palaeosols) but the presence of calcretes and calcareous mudstones ('marls') in the West Lothian Oil-Shale Formation point to periods of semi-arid climatic conditions through Asbian Stage times. Regular orbitally forced glacio-eustatic sea-level oscillations started abruptly around 330Ma (early Asbian) with a 100Ka periodicity and that these characterised the late Palaeozoic from then on. Prior to this time pre-Asbian climates were relatively stable with infrequent changes. Fluctuations in climate occurred during glacial sea level lowstands. It is only in the Brigantian

(Raeburn Shell Bed and younger marine beds) that any marine cycles are seen in the Strathclyde Group that might be associated with such a systematic mechanism.

Palaeocurrent flow in the Strathclyde Group is generally from the north throughout and Argon/Argon ages on detrital muscovites appear to link the flow direction with a source of the detritus in Scandanavia. This source area remained a major topographic high and supplied sediment to Scotland for over 100Ma because of post-orogenic uplift and exhumation events.

Arthur's Seat Volcanic Formation

The oldest rocks (earliest Visèan) in the Strathclyde Group in West Lothian belong to the Arthur's Seat Volcanic Formation. These extrusive igneous rocks belong to a suite of mildly alkaline basaltic lavas which is recognised across the Midland Valley and is chemically distinct from the Lower Devonian igneous rocks of the Pentlands. To aid description of the Dinantian alkali basaltic rocks of the Midland Valley, and to aid correlation of flows with the vents and plugs from which they originated, the alkali olivine basalts (mugearites and hawaiites) and their more coarse-grained equivalents have been classified on the basis of the nature and size of the phenocryst phases (Olivine, pyroxene and feldspars). Volcaniclastic rocks known as tuffs and lapilli-tuffs also occur; these may be air-fall or water-lain in origin. The formation is up to 200 m thick in this area and absent in places.

Gullane Formation

The Gullane Formation consists of a cyclical sequence predominantly of pale-coloured, fine- to coarse-grained sandstones interbedded with grey mudstones and siltstones. 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, into lakes that only occasionally became marine. Desiccation cracks, soft sediment deformation textures and bioturbation are sedimentological features typical of this formation. The Gullane Formation in the Edinburgh district is locally divided into informally named members. In ascending stratigraphical order, these are the Abbeyhill Shales, Granton Sandstones and Wardie Shales. The Abbeyhill Shales overlie the Arthur's Seat Volcanic Formation. These are grey and green mudstone and siltstone that may be bituminous and include thin ostracod-bearing limestones deposited in an overall non-marine environment.

The overlying sequence is known as the Granton Sandstones. This member includes thick beds of fluvial and lacustro-deltaic, off-white, cross bedded, sandstones interbeddded with siltstones and mudstones with a couple of thin marine bands. The Wardie Shales overlie the Granton Sandstones. These comprise mudstone, siltstone and thin sandstones beds with oil-shale, dolostone and ironstone with the thin marine Muirhouse Shrimp Bed near the base of the succession (in west Edinburgh). The thin non-marine dolostones contain ostracods and algal bodies. The Dalmahoy Oil-shale occurs locally at the top of the Wardie Shales. Further marine bands in the Gullane Formation include the Woodhall, Campbell Park, West Mills (Lower and Upper) and Redhall marine bands.

West Lothian Oil-Shale Formation

The West Lothian Oil-Shale Formation is characterised by several, well-developed 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 limestones with rich and relatively diverse faunas. Thick, pale green-grey or grey argillaceous, calcareous beds containing supposed volcaniclastic detritus 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 environment of deposition was of fluvio-lacustrine deltas, subject to periodic inundation by incursions of marine water, with large freshwater lagoons rich in algae and other organic matter in which accumulated oil-shales. Sections in most parts of the formation can be seen on the coast from South Queensferry to Blackness. The formation is laterally equivalent to part of the Bathgate Hills Volcanic Formation in

the west and north. The top is drawn at the base of the Hurlet Limestone. The maximum thickness of the formation is in excess of 1120 m in West Lothian. The formation is divided into a lower Calders Member and an upper Hopetoun Member.

The lower part of Calders Member comprises a succession of mudstones, siltstones and sandstones with thin beds of argillaceous limestone and dolostone, and oil-shale. The member is on average about 290 m thick. The Redhall 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 Oil-Shale. Strata in the upper part of the member include the Pumpherston Shell Bed, a fossiliferous mudstone with a marine fauna and the overlying Pumpherston Oil-Shale that is a well-known mined horizon within the Calders Member in the Livingston district.

The Hopetoun Member is on average about 830 m thick in the Lothians. It consists of a sequence of mudstones, siltstones, sandstones and calcareous mudstones ('marl') with thin beds of oil- shale, coal, limestone and dolostone. The lower boundary of the Hopetoun Member is defined at the base of the Burdiehouse Limestone. The limestone is a lacustrine deposit, 6–9 m thick, containing abundant fossilized ostracod, plant and fish remains and the roof mudstones contain Lingula and a poor marine fauna. In the Harburn mines [NT 041 584] it was recorded as a cream or grey limestone, with conchoidal fracture. The overlying Camps Oil-shale is well recognised in the Livingston area. The Under Dunnet Oil-shale is a little higher in a generally argillaceous succession and the marine band in its roof is the Dunnet Shell-Bed. The main part of the Dunnet, Champfleurie, Broxburn, Fells, Grey, Mungle, Raeburn and Fraser Oil- shales historically have been mined. The marine mudstones of the Raeburn and Fraser Shell-Beds have been recognised in West Lothian with the Basket Marine Band and Under Limestone developed near the top of the Hopetoun Member. Interbedded with the argillaceous succession are thin dolostone beds such as the Barracks and Fells Limestone, and bedded to massive pale greenish-grey limestones or calcareous mudstones (marl) such as the Broxburn and Houston Marls. Mined coal seams include the Houston Coal that in places is in two leaves and of inferior quality and ranges in thickness from 0.6 to 2.0m; the Two Foot Coal from 0.4 to 0.6m and of inferior quality; the Hurlet Coal up to 2.4 m in leaves, pyritous and of low quality. Above the Hurlet Coal, the base of the Hurlet Limestone which defines the top of the Hopetoun Member, is correlated across the Midland Valley of Scotland.

The East Kirkton Limestone represents a world famous, development of non-marine limestone belonging to the Hopetoun Member intercalated within the Bathgate Hills Volcanic Formation. It lies below the Hurlet Limestone but its stratigraphical relationship to the Under Limestone is not known. The East Kirkton Limestone is only exposed at a disused quarry [NS 990 690] at East Kirkton. At this locality it dips 20 to 45 degrees to WSW. The limestone and mudstone sequence is between 9 and 19m thick, comprising mainly laminated limestone with some nodular, spherulitic and massive limestone beds and lenses interbedded with black mudstones, thin ironstones and reworked tuffs. The limestone contains siliceous laminae and lenses of chert which may be the result of contemporaneous hot spring waters. Locally within the limestone beds there are stromatolites (algae), clusters of gypsum crystals and thin lenses of coal. Within the black mudstone and laminated limestone beds, there is a sparse but diverse terrestrial early fauna and flora which has been extensively collected (1985-1992) and studied by a team from the National Museums of Scotland. The bulk of the fossils consist of plants (gymnosperms and pteridosperms) and dominantly land-living animals, including the oldest known terrestrial tetrapods (amphibians and reptilomorphs), terrestrial/aquatic eurypterids, scorpions, millipedes, a mite and a harvestman. The arthropods included Hibbertopterus scouleri and sparse articulated vertebrate skeletons of the genera Acanthodes, Balanerpeton, Cosmoptychius, Elonichthys, Eurynotus, Rhadinichthys, Silvanerpeton and Tristychius. Terrestrial taxa include a species of the genus Ophiderpeton. The fauna also includes the 'famous' very early stem-group amniote Westlothiana lizziae. Charred wood fragments occur within this sequence and suggest that the surrounding forest was subject to forest fires which may have driven the land animals to their deaths in the lake. The overlying mudstone and reworked tuff contain, besides ostracods and bivalves, a relatively diverse fish fauna which is more typical of the formation and it is inferred that the water body had become connected to the larger Lake Cadell. This suggests that the East Kirkton Limestone was the result of temporary lacustrine conditions with an exceptional chemistry allowing preservation of a terrestrial fauna but lacking the normal aquatic fauna.

Bathgate Group

The Bathgate Group is a persistent group of volcanic rocks which interdigitate with the sedimentary rocks of the upper part of the Strathclyde Group and the larger part of the Clackmannan Group. In the West Lothian the group comprises the Bathgate Hills Volcanic Formation.

Bathgate Hills Volcanic Formation

The Bathgate Hills Volcanic Formation occurs in the north-western part of the district and is up to 600 m thick and is intercalated with and replaces sedimentary formations. The basal beds of the formation are tuffs which lie at a widespread horizon just above the Two Foot Coal in the Hopetoun Member. Towards the top of the volcanic pile, olivine-basalt lava becomes predominant, occurring in layers or flows with vesicular or rubbly tops. The central parts of lava flows are commonly hard, compact and very fresh, hence well exposed at outcrop. The top and base of flows are typically amygdaloidal and/or scoriaceous with much hydrothermal alteration and are consequently less well exposed, giving rise to a conspicuous ridged topography (trap featuring) in places which reflects the alternating hard and 'soft' parts of the flows. Kaolinised or reddened tops to flows seen in boreholes, particularly in the central part of the Bathgate Hills indicate subaerial erosion. However, thin impersistent intercalations of sandstone, mudstone, seatclay and coal are common, indicating that, for much of the time, the lavas did not accumulate to any great height above sea level. Coals and seatclays with rootlets are commonly developed directly on top of lava flows and fragments of fossil wood have been found incorporated in the base of flows, including some 'trunks' in apparent position of growth recorded at Grangepans by Cadell in 'The Story of the Forth' in 1925. In the northern part of the outcrop, between Linlithgow and Bo'ness, there is evidence to suggest that magma was erupted on to, or even intruded into, wet unconsolidated sediments. Lavas are commonly brecciated and amygdaloidal with much hydrothermal alteration and calcite veining. Irregular blocks of lava and rounded pillow-like masses are wrapped in a matrix of disturbed sediment, and sediment infills cavities or occurs as clasts within the lavas. Petrographically the lavas are remarkably uniform. All are microporphyritic with phenocrysts of olivine and variable amounts of clinopyroxene up to 2mm in diameter. Microphenocrysts of plagioclase feldspar are extremely rare. Large areas of basalt are exposed in a belt running through the Riccarton Hills but this belt dies out to the north. A more widespread belt of basaltic rocks lies to the west and is exposed on the hills to the north and south of Linlithgow. The basalts and tuffs are thought to have erupted from local volcanic vents, such as those now exposed to the south-east of the extrusive rocks at Tar Hill and The Binns. These vents are now filled with volcaniclastic rocks (agglomerate).

The basal pyroclastic deposits of the Bathgate Hills Volcanic Formation extend upwards, generally to the level of the Hurlet (West Kirkton) Limestone, and locally to the Petershill Limestone (=Mid and Main Hosie limestones). Excavations have revealed a 4m-thick section of these deposits above the East Kirkton Limestone in East Kirkton Quarry, which has been formally named the Geikie Tuff . The pyroclastic rocks are usually green, grey green or purple brown with broad colour banding. Bedding is generally poor, although sporadic graded bedding and load casts suggest subaqueous deposition. Clasts are poorly sorted and are usually subangular to subrounded, although beds of ellipsoidal lapilli are common. Texture is variable and grain size varies widely from fine ash tuffs to pyroclastic breccias with clasts up to 8cm long. The clasts are almost entirely of fine-grained basalts, commonly amygdaloidal, or of reworked tuffs. Layers and lenses of chert and abundant spherulites of carbonate, which are a feature of the East Kirkton Limestone, have been interpreted as evidence of hot-spring activity associated with the volcanicity, but others have argued that the carbonate features are lake-floor precipitates formed within a volcanic setting, but without hot-spring activity.

The overall regional setting of the Bathgate Hills volcanicity has been described and a detailed account given of the interaction between eruption, erosion, clastic deposition and carbonate precipitation in Lower Limestone Formation time. Jameson (1987) envisaged the volcanic rocks accumulating above sea level to form islands surrounded by coastal plains, restricted lagoons and a variety of carbonate reef facies, which accumulated during longer periods of volcanic quiescence. This succession was terminated by subaerial exposure and erosion followed by renewed volcanic activity. The model accounts for the difficulties encountered in trying to correlate the various limestones within and adjacent to the volcanic succession, since many of them were probably only local developments on the fringes of ephemeral land areas. Most of the earlier volcanic deposits accumulated at or close to sea level, probably on vegetated coastal plains, in coal-forming swampy conditions or in shallow restricted lagoons. This is well demonstrated by borehole sections through the basal, predominantly pyroclastic rocks which have numerous horizons of seatclay with rootlets and fossil wood, coaly strata, and other clastic sediments with shallow water sedimentological features.

Carbonaceous shales and argillaceous carbonates in the Silvermine area, which are interpreted as lagoonal, contain syn-sedimentary Pb-Zn mineralisation. This, and the siliceous 'sinter' deposits in the freshwater East Kirkton Limestone are possible indicators of hydrothermal activity associated with the vulcanicity. Later, as the coastal lagoons became infilled by sedimentation and pyroclastic activity, or were overwhelmed by lava flows, the volcanicity became predominantly subaerial in the centre of the Bathgate Hills. Here, lava flows commonly have kaolinised or reddened tops and intercalations of sedimentary rocks are few. Elsewhere, however, in more distal areas such as Bo'ness and Bathgate which remained close to sea level, coal-bearing strata continued to accumulate in considerable thicknesses between eruptions and there is good evidence for interaction between lava flows and wet, unconsolidated sediment.

Eventually, as volcanic activity waned, a marine transgression spread over the whole area and, by the end of Upper Limestone Formation time, limestones such as the Calmy and Castlecary were deposited without interruption across the site of former volcanic islands.

Clackmannan Group

The Clackmannan Group includes 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 especially of limestone) and proportions differing in each of the formations. 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, likewise, show an underlying similarity, being related to the repeated advance and retreat of fluviodeltaic systems into an embayment of varying salinity. Scotland during the Namurian and succeeding Westphalian was located more or less on the Equator. Its climate was essentially tropical with extensive swampy forests (mires and 'mangrove' swamps) rapidly producing large trees that subsequently died to produce great thicknesses of peat that with time and deep burial became transformed into coal. The Lower and Upper Limestone formations contain the highest proportion of marine deposits, while alluvial deposits dominate the Passage Formation; the Limestone Coal Formation occupies an intermediate position. 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 the West Lothian Oil-shale Formation of the Strathclyde Group. This group is mostly Namurian in age (but ranges from late Viséan Series to early Langsettian Stage of the early Westphalian Series).

Lower Limestone Formation

The Lower Limestone Formation comprises repeated upward-coarsening cycles of limestone, mudstone, siltstone and sandstone. Thin beds of seatrock and coal may cap the cycles. The limestone beds are fossiliferous and pale to dark grey in colour, most were deposited in a tropical marine environment. The mudstone (which may also contain marine fossils) and siltstone are predominantly grey to black. A few non-marine 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. Except locally, coal seams are thin (<0.3 m) and few in number in the Lower Limestone Formation. Other minor lithologies in the formation include cannel coal and blackband ironstone (interleaved mud ironstone and coal). Conspicuous beds of limestone are a distinctive characteristic of the Lower Limestone Formation. The Hurlet Limestone defining the base of the formation, the Inchinnan Limestone, the Blackhall Limestone, the Main, Mid and Second Hosie limestones and, defining the top of the formation, the Top Hosie Limestone. The Hosie Limestones are well seen in the Skolie Burn in the SSSI section between [NS 9885 6249] and [NS 9871 6242]. The rocks of the Lower Limestone Formation are the youngest Visèan strata in West Lothian. They have been assigned to the Brigantian Stage. The thickness of the formation is not well constrained but in the range of 100 to 200 m.

The formation is predominantly of lower coastal plain, shallow-water marine origin as is shown by the presence of marine fossils in the limestones and many of the mudstones. Upper coastal plain lakes are represented by the few nonmarine faunal bands known. However, largely marine deltaic environments are represented by the upward-coarsening cycles and delta distributary and fluvial ones by the upward-fining cycles. The marine deltas were probably of lobate form, based on the limited occurrence of lake deposits and of seatrocks and coal seams.

In the Bathgate Hills the formation is interbedded with and replaced by basaltic tuffs and lava flows of the the Bathgate Hills Volcanic Formation and the key limestone horizons are more difficult to identify, may be undeveloped or be fused together.

The Hurlet Limestone has been recognised in the Mid Tartraven No.4 Borehole [NT 0062 7254] about 46m below the Blackhall (Tartraven) Limestone which crops out at Mid Tartraven. The Hurlet Limestone in this borehole is 6.66m thick, buff to grey, and massive with some crinoid and shell debris. At West Kirkton [NS 988 690], a temporary exposure at the water board site showed the Hurlet (West Kirkton) Limestone resting abruptly on volcanic breccias and overlain by calcareous and tuffaceous sandstones. At the base of this carbonate succession is a fine- grained grey impure limestone followed by dark grey silty mudstones and thin limestones with crinoid ossicles and brachiopods. The succeeding granular to fine-grained tuffaceous sandstone, 2m thick, is overlain by 5m of bedded bioclastic limestone with minor cherty patches.

At the now infilled West Kirkton Quarry [NS 9882 6879], also in the Bathgate Hills, the limestone contains a fauna of corals, brachiopods and crinoid fragments. The argillaceous marine strata stratigraphically above the limestone were particularly fossiliferous, with a diverse fauna of colonial corals, bryozoa, a greater variety of brachiopods, gastropods, and nuculoid and pectinoid bivalves. The Craigenhill Limestone horizon has not been positively identified in the Bathgate area, although there is a bed of limestone developed locally between lava flows, 25m above the Hurlet Limestone at West Kirkton [NS 9880 6905]. The Blackhall (Tartraven) Limestone has been identified in several sections where it is overlain by the richly fossiliferous Neilson Shell Bed. In boreholes near Mid Tartraven, the limestone sequence is between 7.9 and 12m thick and overlies a thin coal. The bulk of the limestone is bioclastic with abundant crinoid and some coral and bryozoan debris. However, the base of the limestone is darker, laminated and includes fissile calcareous mudstone which generally lacks fossils. This change in lithology could represent an upward change from lagoonal or estuarine conditions below to shallow- marine conditions.

The Neilson Shell Bed normally occurs in mudstones intercalated with and towards the top of the limestone or stratigraphically above it. The characteristic fauna of the Neilson Shell Bed, seen well, for example, at Breich Water [NS 9886 6276], is dominated by brachiopods including Crurithyris urii, gastropods including the discoidal form Straparollus (Euomphalus) carbonarius, common nuculoid bivalves, and orthocone and coiled cephalopods including goniatites. Within the southern Bathgate Hills, the Petershill (Hillhouse) Limestone is believed to be equivalent to the Main and Mid Hosie limestones. It is the thickest limestone in the succession and it is exposed in several disused quarries, e.g. [NS 984 695]. The limestone developed during an interval between outpourings of Bathgate Hills lavas. The succession has been described in terms of a lower, carbonate Reservoir Member and an upper, clastic Silvermine Member. The carbonate member at Petershill has been interpreted in terms of a transgressive-regressive sequence with two periods of subaerial exposure marked by erosion surfaces. The transgression is marked by the carbonaceous shales containing Lingula towards the base of the member. The depositional environment, as identified, ranges from a shoreward lagoon to the north, passing southwards into a near-shore turbulent zone and a reef-like build-up and thence into an offshore shallow shelf.

The exceptional development of limestone at Petershill is probably related to a volcanic rise on which limestone could accumulate without being swamped by clastic sediment. The Petershill Limestone must also have been deposited in a period relatively free from volcanic eruptions and in a moderately humid tropical environment. The marine bioclastic limestone exposed at Wairdlaw [NS 994 731] appears to be isolated within the Bathgate Hills Volcanic Formation. It also appears to lie at a higher stratigraphical horizon than the Petershill Limestone, although its faunal assemblage is similar to that at Petershill. It is possible, therefore, to correlate the Wairdlaw Limestone with the Second or Top Hosie limestones or more likely a combination of both since the volcanic rise continued to develop into Limestone Coal Formation times. At Wairdlaw, the limestones with coral colonies and interbedded mudstones are 4 m thick, overlain by mudstones containing Calamites (horsetails), Productus and scales of Palaeoniscus. The input of mud containing Calamites suggests the influence of nearby vegetated land.

Limestone Coal Formation

The Limestone Coal Formation 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 (3-10% of the total succession). The siltstone and mudstone are usually grey to black, while the sandstone is usually fine- to medium-grained and off-white to grey. Coal seams are common and many exceed 0.3 m in thickness. Minor lithologies include cannel, and blackband and clayband ironstone, the latter nodular as well as bedded. Beds containing large numbers of shells (coquinas) of Lingula or of the non-marine bivalves Naiadites and Curvirimula occur in the fine-grained rocks, including the ironstones and cannel. Because of the form of preservation, these shells usually do not form conspicuous musselbands like those of the younger strata of the Lower Coal Measures. Marine shells are present in some fine-grained strata but marine limestones are not a feature. Upward-fining parts of the succession, dominated by fine- to locally coarse-grained sandstone, are widely developed. The Johnstone Shell Bed and Black Metals Marine Bands can be correlated throughout the Midland Valley, but the coal seams are not so easily correlated and retain their local names. The Johnstone Shell Bed, a marine band towards the base of the formation includes one to two discontinuous beds of thin limestone (the Slingstane).

The Limestone Coal Formation is the oldest of the three subdivisions of the Clackmannan Group and it includes the strata stratigraphically above the Top Hosie Limestone at the top of the Lower Limestone Formation up to the base of the Index Limestone which is the lower boundary of the Upper Limestone Formation. The strata fall within the lower part of the Pendleian Stage (E1a) of the Namurian Series. The formation is over 100m thick. The upper part of the Limestone Coal Formation includes most of the coals which have been of economic importance thickness. The Wilsontown Main (=Bathgate Main), Bathgate Jewel, Woodmuir Smithy, China and Balbardie Gas coals were the most widely worked seams in the Bathgate area. From above the Petershill Limestone and its associated clastic sedimentary rocks, lavas (with some tuffs) occur throughout the Limestone Coal Formation. In the south, around Bathgate, lava flows probably occupy 50 per cent or less of the formation but they increase in thickness and number northwards, so that north of Cairnpapple Hill they replace all but the highest beds, which contain worked coals. Still farther north, virtually the whole of this part of the succession, up to just below the Index Limestone, consists of lavas and minor pyroclastic rocks. To the north of the M9 motorway, sedimentary intercalations between the lavas become thicker and more numerous, and pyroclastic rocks become more common in the Bo'ness Coalfield. The formation is of fluvial, deltaic, coastal to marine origins with the coal seams representing extensive tropical, afforested mires and swamps.

Upper Limestone Formation

The Upper Limestone Formation is characterised by repeated upward-coarsening cycles comprising grey limestone overlain by grey to black mudstones and calcareous mudstones, siltstones and paler sandstones capped by seatrocks and coal. The limestones contain marine faunas and are usually argillaceous. The sandstones are generally off-white and fine- to medium-grained. The coals are usually less than 0.6 m thick. Minor lithologies present include ironstone and cannel. Upward-fining sequences of coarse- to fine-grained sandstones passing up into finer-grained rocks are also present. The base of the formation is taken at the base of the Index Limestone. The top is drawn at the top of the Castlecary Limestone where not eroded penecontemporaneously by incising river channels. The main limestones are the Index, Orchard, Calmy and Castlecary limestones. The rocks of the Upper Limestone Formation form the middle of the three Clackmannan Group units within the Namurian Series. They are assigned to the late Pendleian (E1) and Arnsbergian (E2) stages. The Castlecary Limestone at the top of the Formation lies just below the top of the Arnsbergian Stage. The formation is predominantly of shallow-water marine shelf and deltaic origin but also in part of lacustrine origin. The presence of paleosols, including coals, shows that subaerial delta top and lower alluvial plain environments existed. However, the heavily bioturbated striped beds (usually thinly interbedded siltstone and sandstone) indicate that delta lobe abandonment was a common event with subsequent marine reworking of the delta top. The existence of alluvial plain environments is also confirmed by the presence of the upward-fining channel sandstone bodies. These are particularly well developed where associated with significant intraformational unconformities, such as that which cuts out the Castlecary Limestone. Limestone and hard calcareous mudstone represent only 1% - 3% of the total lithology in this formation reflecting higher siliciclastic input and perhaps less stable shelf depositional setting. Coal seams account for no more than 3% of the succession and sandstones about 50%.

Above the Index Limestone a persistent development of lavas, up to 40m thick, is present between Kipps Hill [NS 986 738] and Bathgate. It has also been traced westwards in boreholes and mine workings as far as Barbauchlaw [NS 927 681] and Polkemmet [NS 934 640]. In boreholes and mines between Hilderston Farm [NS 968 711] and Mosside Farm [NS 975 670], the development of lavas is present between the Index and Orchard limestones, but east of Gormyre [NS 974 729] it may extend upwards almost to the Calmy Limestone. Some of the flows on Kipps Hill are very fresh glassy basanites with well-developed columnar jointing. To the north, between Bowden Hill [NS 976 745] and Cockleroy [NS 989 743], the continuation of these lavas is 'confused' by sills of quartz-dolerite and WNW-trending faults and their outcrop appears to merge with lavas below the Index Limestone. Thin beds of tuff have been recorded both below and above the Orchard Limestone near Kinneil Mills [NS 977 783] on the River Almond; and a thick bed of green tuff, directly beneath the Calmy Limestone is well exposed in a wooded glen [NS 979 734] south of Lochcote Reservoir. Volcanic rocks also occur from above the Calmy Limestone to the base of the Castlecary Limestone in a borehole at Easter Jaw [NS 8718 7452]. The youngest recorded volcanic activity in the district occurs above the Castlecary Limestone in the base of the Passage Formation. On the south side of Bowden Hill [NS 979 744] a trench exposed 2.6m of tuffs some 5m above the top of the Castlecary Limestone and tuffs are recorded at this level in a borehole at Melonsplace [NS 9506 7425].

Passage Formation

The Passage Formation is characterised by an alternation of fine- to coarse-grained sandstones (with some conglomerates) and structureless clayrocks (including some high-alumina seatclay and fireclay). The clayrocks are commonly mottled reddish brown and greenish grey. Upward- fining cycles or non-cyclic sediments predominate over upward-coarsening cycles. Bedded grey and black siltstones and mudstones are also present, and beds of limestone, ironstone, cannel and coal. Marine bands, represented mainly by mudstone but also inconstant limestones and ironstones are to be found in the lower half of the unit. Marine faunas become progressively impoverished upwards. The formation is over 100m thick around Levenseat thickening to more gradually northwards. The strata range in age from the upper part of the Arnsbergian Stage of the Namurian into the Langsettian Stage of the Westphalian. The post-Arnsbergian stages are thin and incomplete and faunal or microfaunal evidence for the presence of the Chokierian and Alportian stages is lacking. The top of the formation is placed at the base of the Lowstone Marine Band. Where the marine band does not occur the base of the Lowstone (Armadale Stinking) Coal is used. Coal seams form 0%–4% of the succession and sandstones average about 55%. A period of uplift, erosion and regression in the early part of the Passage Formation brought about a change from the deltaic conditions with major marine incursions, which prevailed during the Upper Limestone Formation, to predominantly meandering fluviatile deposition with an influx of coarse detritus from the north. The relatively thick beds of limestone and marine mudstone that are characteristic of the underlying formation are much thinner in the lower part of the Passage Formation and are vestigial in the upper part. At the top of the formation fluvial sedimentation is replaced by the fluviodeltaic conditions of the overlying Coal Measures.

The sandstones of the Passage Formation are white, pale grey or yellow in colour and tend to occur mainly in beds which are coarse grained at the base and become finer grained upwards.

The upward-fining sandstones may occur singly or as a series with the base of each resting on a scoured surface cut into the underlying beds. The coarser sandstone in the lower part of each unit may contain scattered small pebbles or angular clasts of siltstone or mudstone. Locally, fossilised drifted tree trunks occur in the basal parts of the thicker sandstone beds. The finer beds may be ripple laminated and include partings of siltstone and mudstone. The single upward-fining sandstones are commonly less than 5m thick. Thicker sandstones, formed from a series of upward-fining sandstone units, may be up to 24m thick. The thinner sandstones are considered to be simple channel fills and the thicker sandstones may represent the deposits of meander belts.

The petrography and provenance of the Passage Formation sandstones has been studied. These sandstones were derived from a low-grade metamorphic source intruded by acid igneous masses comparable to the Upper Dalradian rocks of the Highlands. A sandstone in the lower part of the formation at Leven Seat [NS 943 580] has been worked for many years as a silica sand and used for moulding sand and several other non-industrial uses. The sandstones pass up by gradation into siltstone and mudstone. The argillaceous strata range in colour from dark grey or pale grey to mottled lilac, reddish brown and yellow. Some mudstones are bedded, particularly the marine mudstones, but in many cases both

the siltstone and mudstone show little sign of bedding. The original stratification is believed to have been obliterated by root systems and soil-forming processes. Rootlets can be seen in the darker beds but partial oxidation as a result of the lowering of the water table has removed carbon from the variegated, pale coloured rocks making rootlets less obvious. The rocks are thought to be the overbank deposits of a large river system. The kaolinite clay of which the muds are composed may have been a product of tropical weathering. The mudstones were economically the most important of the rock types in the Passage Formation. They include seams with the properties of fireclay which have been worked in several places, although the industry is dormant at the present time. A thin bed of tuffaceous siltstone close above the Castlecary Limestone has been recorded north-west of Torphichen [NS 967 723]. This is believed to be the highest stratigraphical level at which the Bathgate Hills Volcanic Formation occurs.

No.2 Marine Band tends to be the most persistent of the marine horizons in the Passage Formation, although it also is liable to have been eroded and replaced by sandstone. It most often consists of a marine shale with a thin limestone up to 1m thick. The limestone is known as the Roman Cement Limestone and, in places, it is characterised by the presence of abundant ribbed brachiopod shells (orthotetids). There is also a fossiliferous clayband ironstone, known as the Curdly Ironstone, close above the No.2 Marine Band, which was formerly worked in the Levenseat area.

The interval between No.2 Marine Band and the Netherwood Coal contains fireclays that have been worked at various localities and are collectively known as the Glenboig Lower Fireclays. They are overlain by the Levenseat Sandstone. Coals are present higher in the formation but for the most part are very thin and impersistent. The Bowhousebog Coal is the most persistent up to

1m thick locally, but it tends to be sulphurous and of poor quality. It has only been worked in a small way, usually with fireclay. The Glen Coal occurs near the top of the formation. It has been worked around Armadale and its lateral equivalent, the Crofthead Slatyband Ironstone was worked extensively during the last century around Fauldhouse. The Bonnybridge Upper Fireclays occur around the position of the Bowhousebog Coal and have been worked around Whitburn.

Coal Measures Group (Scotland)

The Coal Measures Group (Scotland) is sub-divided into three formations; Upper, Middle and Lower. Only the Lower Coal Measures and, to a minor extent, the Middle Coal Measures are represented in West Lothian. The Group comprises sandstones, siltstones and mudstones with coal and seatearth. The strata are generally grey in colour. The Coal Measures were deposited in a warm and humid climate and palaeomagnetic evidence indicates that, at that time, the area lay in equatorial latitudes. The strata are believed to have been deposited in delta-plain and alluvial- plain environments with drainage generally from a large continental area to the north. The sediments accumulated under conditions of continuous but non-uniform subsidence modified by eustatic (ice age driven) changes in sea level. Periodic brief incursions by the sea left important marine horizons which are the basis of the subdivision of the succession. A wide range of alluvial and lacustrine environments of deposition is represented. These include tropical wetland forested mires and soils (coal and seatearth), floodplain (planty or rooted siltstone and mudstone), river and delta distributary channel (thick sandstones), prograding deltas (upward-coarsening sequences) and shallow lakes (mudstones with non-marine faunas). Marine bands are rare but provide important stratigraphical markers.

Lower and Middle Coal Measures

The Lower and Middle Coal Measures comprise sandstone, siltstone and mudstone in repeated cycles commonly 8-12 m thick 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 and many exceed 0.3 m in thickness amounting cumulatively to 5%–8% of the total succession. Minor lithologies include cannel and blackband and clayband ironstone, the latter nodular as well as bedded. Bands composed mainly of non-marine bivalves, the characteristic

'musselbands', usually occur in mudstone or ironstone with two, the Auldshiels and the Kiltongue persistent enough to be named. Upward-fining parts of the succession, dominated by fine- to coarse-grained sandstone, are widely developed

and thick multistorey sandstones are a feature. Cumulatively these amount to about 53% of the unit. There are more than 11 seams that have been mined in the Lower Coal Measures. The main seams formerly mined are the Colinburn, Armadale Main, Armadale Ball, Mill, Shotts Gas, Lower Drumgray, Mid Drumgray, Upper Drumgray, Kiltongue, Ladygrange and Airdrie Virtuewell coals. Middle Coal Measures are restricted to a small area west of Fauldhouse where the Airdrie Blackband Coal may have been mined. These seams are still being exploited today in opencast sites. The Lower Coal Measures are over 150 m thick.

Intrusive igneous rocks

Various intrusive and extrusive igneous rocks are exposed in West Lothian, including teschenitic dolerite, quartz dolerite, olivine basalt, trachybasalt and minor trachyte.

Alkali-dolerite sills

Sills of alkali-dolerite generally occur in the eastern part of the district. They intrude the Lower Carboniferous sedimentary succession of the Strathclyde Group stratigraphically mainly below the Bathgate Group volcanic rocks of the Bathgate Hills. These dolerites are generally medium to fine-grained and of olivine-basalt composition. They are similar petrographically and compositionally to the lavas of the Bathgate Hills and could be coeval with them. However, a sill of this type also crops out to the south of the volcanic rocks, over a distance of 8km from Blackburn southwards to Rusha Farm [NS 992 609], and at Pate's Hill [NS 990 595] where the outcrop is displaced towards the west by faulting. This sill is emplaced higher in the sedimentary succession within and near the base of the Clackmannan Group (Lower Limestone Formation) at about a constant stratigraphical level, just below the Top Hosie Limestone. The sill is composite, with an upper layer of analcime-dolerite (teschenite) overlying a basal picrite. The junction between the layers is sharp, but with no chill on either side, and is sinuous in places. The main distinction between the layers is in the relative proportions of olivine and plagioclase, both rock types having abundant analcime and little hornblende or biotite. The analcime-dolerite was formerly quarried for roadstone and the picrite (or 'leckstone') was used for the soles of baker's ovens on account of its unusually low thermal conductivity. Several quarries in the Blackburn area are all now filled, but a quarry at Rusha Farm used to show about 6m (1992) of analcime-dolerite overlying 4.5m of dark greenish grey picrite. The analcime-dolerite is also exposed in the Breich Water, in a railway cutting [NS 989 620] at Addiewell and in Longhill Burn [NS 989 598]; at the last locality the sill underlies baked, decalcified shale. An olivine- dolerite, formerly quarried at Boghall [NS 994 683], near Bathgate, and shown as a circular outcrop on the map, is probably an intrusion of some sort. The quarry is now completely filled and has been built upon. Within the volcanic sequence, outcrops of particularly fresh rock with well-developed columnar jointing could be interpreted as contemporaneous sills within the lava pile. However, they could also comprise the more massive, central part of lava flows. The Hillhouse Sill, seen above the Petershill Limestone at Hillhouse Quarry [NT 004 747], shows transgressive junctions with these Clackmannan Group (Lower Limestone Formation) sedimentary rocks. By far the most extensive sill is in the Houston-Uphall area but there are no longer any surface exposures of this sill and any small old quarries have long since been infilled

.It is best known from old borehole records that indicate it is over 70 m thick.

Quartz-dolerite sills

The quartz-dolerite sills of West Lothian form part of the south-western margin of the Midland Valley Sill Complex. The outcrop of this major sill is imperfectly annular and characteristically dips inward towards the centre of the carboniferous sedimentary basin. It has been suggested that the morphology and emplacement of the Midland Valley Sill were controlled by the shape of this pre-existing Carboniferous syn-sedimentary basin. The thickest parts of the sill occur within the centre of the basin, which had a syndepositional dip of up to 5 degrees towards its centre at the time of emplacement. No obvious feeder dykes have been identified within the thickest central part of the sill. Emplacement was at least in part controlled by down-dip gravitational flow of the magma from a series of feeder dykes located on the flanks of the sill. These dykes extend above the level of the sill. Magma first accumulated in the bottom of the basin and from there advanced up-dip under pressure of head fed by the dykes. The quartz-dolerite sill is well exposed in and around Torphichen particularly on Gormyre Hill [NS 976 727], Cow Hill [NS 970 740], Bowden Hill [NS 976 745] and in the village

of Torphichen itself [NS 967 723]. The sill is quarried in a number of places and is an important source of crushed rock aggregate.

The quartz-dolerite sills occur as broadly concordant sheets up to 120m thick with locally transgressive dyke-like bodies that cut across the regional dip of the country rocks. These sills form prominent topographical features, for example at Cockleroy [NS 990 745] and Wairdlaw [NS 996 732], with typically brown coloured, spheroidal-weathering outcrops. A steeply inclined transgressive step within the Midland Valley Sill Complex extends from the eastern end of the sill outcrops east of Cockleroy southwards for 5km via the Knock [NS 991 712], to just east of East Kirkton Quarry [NS 990 690]. At Craigs [NS 995 703] a NNW-SSE-trending sill dips moderately steeply ENE and cuts across bedding within the overlying tuffaceous rocks with minor limestones of the Bathgate Hills Volcanic Formation. These rocks are disturbed and show signs of a weak thermal metamorphic overprint. A similar transgressive relationship is observed at the Knock, where a NNW-SSE-trending sill, dipping at approximately 60 degrees ENE, cuts basaltic lavas. Binny Craig RIGS is an example of a sill and NS- trending dyke step where the sill is chaning horizon within the sedimentary country rocks. Craigton Quarry shows discordant, stepped contacts of the sill roof with the country rocks of the Strathclyde Group (West Lothian Oil-shale Formation).

Quartz-dolerite dykes

The quartz-dolerite dykes generally form narrow, steeply inclined bodies which can be traced laterally for up to 10km. The dykes were intruded along the prominent set of east-west-trending faults, with in many instances emplacement occurring more or less contemporaneously with fault movement. The Lenzie-Torphichen Dyke is intruded along the Avonbridge Fault and the Midland Valley Sill is present at different stratigraphical levels on either side of the fault. Individual dykes are up to 50 m thick and are commonly offset in an en-echelon manner. Contacts with the country rocks are typically sharp. Fine-grained margins are usually present. Country-rock xenoliths are rare within the dykes. Characteristic of the quartz-dolerites throughout the district are zones of alteration to 'white trap'. These zones of hydrothermal alteration are commonly closely associated with faults and frequently show traces of mineralisation (including calcite, pyrite, baryte and occasional chalcopyrite), and are commonly accompanied by an impregnation of hydrocarbons. It has been suggested that the alteration has been produced by volatiles released during the distillation of oil shales by the heat of the intrusions. These dykes are well seen at Beecraigs Quarry (climbing wall), Parkley Fisheries and Ochiltree Mill quarries.