Lothian geology an excursion guide

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Edinburgh Geological Society

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Preface

Edinburgh geology was first published in 1960 and its successor, The geology of the Lothians and south-east Scotland, in 1975. This third edition, Lothian Geology concentrates on the Lothian Region, and excursions outwith the region have been omitted. Several excursions have been updated or rewritten. New excursions include Building Stones of Edinburgh, Tantallon-St Baldreds, Lammermuir Deans, River North Esk, Paraffin Young Heritage Trail, River Avon and Bathgate Hills. The excursions give opportunities to view the wide range of Palaeozoic sedimentary and igneous rocks in age found within the region, along with landforms and deposits resulting from the Quaternary glaciation. A new introduction describes the rocks, minerals, fossils and structures to be found in the region and the geological processes which produced them.

The excursion guide is aimed at professional and amateur geologists, students, teachers and schoolchildren. While much can be learned by oneself, more insight can be gained by joining geology classes and societies such as the Edinburgh Geological Society. All are encouraged to follow the 'Geological Code of Conduct'.

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Introduction

Edinburgh geologists are fortunate in the remarkable variety of rocks and landscape features to be seen in the Lothian Region, within a short distance of the city. From the beginnings of geology in the eighteenth century with the Father of Modern Geology. James Hutton. the area has attracted many geologists and been the scene of several fundamental discoveries in the science. The region offers the geologist opportunities to study stratigraphy, sedimentology, volcanology, structural geology. glaciology, the history of geology and the influence of geology on the environment. Some localities are suitable for collecting fossils, rocks and minerals.

The Lothian Region slopes up from the shores of the Firth of Forth to the watersheds formed by the Moorfoot Hills and Lammermuir Hills, which are made of Lower Palaeozoic rocks, across the Southern Upland Fault. Plains of glacially-covered Devonian and Carboniferous sedimentary rocks are broken by numerous crags and hills of volcanic and intrusive rocks of the same ages. New hills are man-made bings of colliery spoil and spent oil-shale, while quarries and pits have been cut to obtain limestone. dolerite, sandstone, clay, sand and gravel.

Drainage into the Forth follows the main Lower Palaeozoic structural grain parallel to the Southern Upland Fault. The main rivers, the Avon. Almond, Water of Leith, North Esk, South Esk and Tyne all flow from south-west to north-east. Tributary drainage flows north from the Moorfoot, Lammermuir and Pentland Hills. Population in the region centres around Edinburgh, and to a lesser extent at Livingston and in the Esk Valley. Intense cultivation has taken place on the low ground particularly in the granary of East Lothian, grading up to cattle and sheep pasture in the uplands. The higher rocky hills form peat- and heather-covered moorlands.

For the geologist the best exposures are along the coast, in some of the incised river valleys and in the volcanic uplands.

Access to the region is by bus, train or air (Map 1). Within the region a network of roads makes for good accessibility by car or private coach. Lothian Region Transport run service buses within the City of Edinburgh, and green and cream Eastern Scottish and Lowland Scottish service buses, based in St Andrew Square, serve the country areas (Map 5).

Rocks

Rocks are all formed of crystalline or amorphous minerals. Some rocks consist of only one sort of mineral but the great majority of rocks are composed of several kinds of mineral. There are three main groups of rocks, known as igneous, sedimentary and metamorphic. Only rocks of the first two groups occur in the Lothian Region.

Igneous rocks solidified from an originally molten material called magma. As the magma cooled crystals of different minerals grew, becoming interlocked. The composition of the magma and the rate of cooling determine the kind and size of minerals formed. Igneous rocks are classified by the type and proportion of these minerals, and whether the grain size is coarse, medium or fine. When molten magma reaches the surface it produces extrusive rocks in the form of lavas which cool quickly and hence are generally fine-grained. On the other hand, rising magma can solidify deep below the surface to form plutonic rocks which, as they cool slowly, tend to he medium- or coarse-grained.

Sedimentary rocks are mostly the result of weathering of many different kinds of rock, transport of pebbles. sand and mud by river, sea and wind action, and deposition of the detritus as layer after layer of sediment in sea, river, lake or on land. Sediments, accumulated and buried over enormous periods, harden as water is squeezed out and the individual grains are compacted and cemented together. Thus sands becomes sandstones, muds become shales and gravels become conglomerates. Other sedimentary rocks result from chemical precipitation out of solution, notably limestone, while yet other rocks incorporate remains of animal or plant life. e.g. shells may form a shelly limestone and plants may form coal. Detrital material in sedimentary rocks derives from pre-existing rocks, whether igneous, metamorphic or sedimentary. Sedimentary detritus may have been incorporated in earlier sediments and recycled several times.

One group of rocks not easily classified are pyroclastic rocks, derived from volcanic ash which falls through the atmosphere and is often deposited in water to form layered rocks. Although formed by sedimentary processes, the material is igneous in origin and these rocks are normally grouped with the igneous rocks.

Metamorphic rocks were originally sedimentary or igneous rocks which have been altered to new textures and minerals by the action of heat, pressure and friction, often during more than one episode. Thus shales have been altered to slates or schists, sandstones to quartzites or psammites, limestones to marbles and basic igneous rocks to amphibolites or epidiorites. Metamorphic rocks are virtually absent from the Lothian Region. However, low-grade metamorphic rocks form much of the adjacent Southern Uplands south of the Southern Upland Fault and high-grade metamorphic rocks form most of the Highlands north of the Highland Boundary Fault. Fragments of metamorphic rocks derived from both areas do occur locally, as boulders in Palaeozoic conglomerates and as glacially transported boulders called erratics.

Sedimentary rocks

Sedimentary rocks are commonly layered. Most, though not all, formed under water or in air by accumulation of detrital particles—dastic rocks. Others have formed by precipitation from solution through chemical or organic agency—organo-chemical deposits. These unconsolidated deposits have then been compacted, often cemented and may also have undergone chemical change (diagenesis) after deposition.

There are many different kinds of sedimentary rocks. They can be classified in various ways depending upon how the classification is to be used. Both elastic and organo-chemical rocks are common in the Lothian Region.

Clastic rocks, also known as fragmental or detrital deposits, are formed of fragments of earlier rocks. During the weathering and transportation processes which produce a new sedimentary rock the more resistant minerals of the original rock survive while other minerals break up and dissolve. A granite, which consists of quartz, feldspar and mica, will for example normally only contribute the highly resistant quartz to a elastic sediment. Mica and feldspar, being far less resistant, only occur in a elastic rock in which the material is of local derivation and has not travelled far.

Clastic rocks can be classified in the field in three separate categories, according to grain size:

Rudaceous rocks (grain size >1 cm) consist of pebbles, cobbles or boulders set in a finer matrix. In conglomerates the pebbles are rounded during transport, and the material of which they are composed is derived from older rocks often some distance away. Breccias have angular pebbles and are of more local derivation as the pebbles have not travelled far enough to have become rounded. These should not be confused with fault-breccias, formed in fault zones, where the rock has been smashed by fault movement.

Arenaceous rocks (grain size 0.1 mm-1 cm) include many kinds of generally sandy rock in which the rock has been sorted to dominantly one grain-size. Grits are coarse sandstone, or sandstones with angular grains. In sandstones the bulk of the rock consists of quartz particles, cemented by calcareous, siliceous, or ferruginous material or with a muddy matrix. Arkose is a less mature sandstone containing an appreciable amount of feldspar. Greywacke is an ill-sorted rock with much quartz, but with minerals and pebbles of different compositions in a very muddy matrix.

Argillaceous rocks (grain size <0.1 mm). Rocks of finer material with grain size 0.01–0.1 mm are known as siltstones. Mudstones with grain size less than 0.01 mm may have some fine quartz grains but are mainly formed of clay minerals and may also he calcareous or iron-rich. Shales are mudstones or siltstones which are fissile, splitting along bedding planes because they contain flat-lying clay minerals. Some limestones of detrital origin may be grouped here as they consist mainly of fragments of earlier limestones, or of shells and shell fragments.

Organo-chemical sediments are rocks that have precipitated from solution, often wholly or partly due to bacterial or other organic activity. Limestones consist of calcium carbonate ($CaCO_3$). Many limestones have formed entirely as chemical precipitates. Oolitic limestones for example consist of closely packed carbonate spheres, which grew where water saturated with calcium carbonate washed backwards and forwards over a shallow sea floor, often in warm, highly saline lagoons. Some limestones are converted to dolomite ($CaCO_3$. $MgCO_3$) which has a characteristic yellow colour. The chemical changes occurred in warm shallow water in the presence of CO_2, either contemporaneous with or later than deposition. Organic limestones, also known as bioclastic limestones, are formed from coral reefs or at least partly of shells and shell fragments. Other such limestones are laminated rocks, the result of lime precipitation by algal mats known as stromatolites, which trap and bind elastic material into many forms.

Ironstones and iron-rich rocks formed in various conditions. Hematite (Fe_2O_3) was precipitated under oxidising conditions, siderite ($FeCO_3$) formed in a moderately reducing environment, whilst the presence of pyrite (FeS,) is indicative of highly reducing conditions of formation. Some ironstones are secondary in origin forming long after deposition.

The most important carbonaceous deposits are coal and oil-shale. Coal formed in fresh-water environments from peat, the altered remains of plants, the shapes of which can sometimes still be seen, though plant specimens are better preserved in the associated siltstones and mudstones. Many varieties of coal can be distinguished. Bituminous coals have alternate bright, clarain, and dull, fusain, layers in which different types of plant remains occur, and have prominent joints, cleats. Cannel coal is unlaminated and dull, consisting mainly of plant spores, the remains of oil-bearing algae, and fine detrital material. Oil-shales are fine-grained rocks similar to cannel coal, in which the organic matter of algal origin is mixed with a higher proportion of detrital material, and from which oil can be extracted by heating. The oil-shales were deposited in a large lake.

Sedimentology, the detailed study of sedimentary rocks in the field and in the laboratory, can reveal a great deal about the environments in which the rocks were deposited. Thus different kinds of conglomerates and sandstones could have been deposited on a beach, as an alluvial fan, as a flash-flood deposit or in a braided river meandering through a flood plain. Siltstones and mudstones on the other hand form in quieter conditions. The fine fraction of which they are composed took longer to settle out of suspension and often was carried far from land. Limestones usually accumulate in warm shallow waters where there is little input of terrigenous material. Seatclays are grey carbonaceous clays found below coals and are a kind of fossil soil.

All inferences about the nature of the depositional environment must of course he related to the regional context. Any fossils in the rocks may also give useful indications as to the nature of the original environment.

Sedimentary Structures. As well as composition and grain size, other indicators about the nature of the depositional environment are the sedimentary structures often found within the rock. These structures can he formed during deposition, produced after deposition, or are the result of contemporaneous activity of organisms in the sediment—trace fossils.

Structures formed in water-laid elastic sediments deposited in alluvial channels, include laminar beds, ripple-marks, and cross-bedding. When the current bringing in the sediment was very weak, the upper surface of the sediment remained unmarked and the layers have a flat surface. As the current increased, however, ripple-marks formed. In very fine sediments these would form at a low current velocity; coarser sands would require a higher current strength. Tidally influenced ripples are symmetrical due to the waves washing to and fro, but ripples in a unidirectional current are asymmetrical, the steeper slope facing upstream. With increasing current strength, much larger megaripples form, and eventually subaqueous dunes and sandwaves. When current strength is extreme and the sediment coarse, dune-like structures known as antidunes move upstream against the current, as sand is continually streamed off the surface of one dune to be built up on the facing slope of the next. Finer sediment at this velocity forms planar beds for the current moves so rapidly that no structures can form. When a great deal of sediment comes down at moderate current velocities, climbing ripples of sloping piled-up sets, a few centimetres thick will form; they can be seen in section migrating obliquely upwards through the sediment.

A very common type of structure in sedimentary rocks is cross-bedding, in which the laminar beds, foresets, form slightly curving sigmoidal surfaces lying obliquely to the horizontal. These are likewise due to the movement of sand particles in migrating subaqueous dunes or sandwaves. Windblown sand can form dunes in which the sets are even larger, several metres thick. The water-lain sets may be tabular, with more or less planar surfaces bounding the units. On the other hand, the lower surface may, in cross-section be curving and erosional in cases where a migrating channel has cut into earlier formed channels, before deposition took place. This is known as trough cross-stratification. Cross-bedding directions are very useful indicators of current and transportation directions. Herringbone cross-bedding, where successive sets go in different directions, is typical of shallow tidal water.

Very significant sedimentary structures occur in greywackes (such as form much of the Southern Uplands and the North Esk Inlier). Greywacke beds carry a characteristic sequence of internal structures indicating deposition by occasional turbidity currents, rapidly flowing down a slope and carrying suspended clouds of debris. The flow is initially erosional, then depositional. In the erosional phase of such a flow scurrying vortices cut characteristic bulbous, triangular flute-marks into the cohesive mud surface over which it flows. These immediately fill with coarse sand, which becomes finer towards the top of the unit so that the lower part of the unit is thus graded in terms of grain size. Towards the top of the unit the waning current has still been strong enough to form ripple-marks. Thereafter only the finest particles settle out of suspension as mud before the next turbidity current. Deposition was episodic, with long periods of quiescence alternating with rapid periods of deposition. Linear scrapes, known as tool-marks occur where a pebble or a shell within the flow has cut a groove in the mud. These sole-markings (all markings on the lower surface of a turbidite unit) are normally only seen on the lower surface of the sandstone unit when the underlying mud, now compacted to shale, has been washed away. Sole-markings may be modified after deposition by loading, when the heavy sand sinks down into the soft mud below, squeezing out the water and forming bulbous irregular masses called load-markings. Alternatively sediment may become contorted through slumping.

The churning activities of animals, dwelling on or in the sediment, and foraging on its surface or mining within it may also greatly affect the sediment after deposition, often destroying primary laminations entirely. This is known as bioiturbation. Some particularly clear trace fossils, on the other hand, seen in elastic and other sediments, are given biological names, even if their maker is unknown. Trace-fossils are often good environmental indicators. In general terms makers of vertical tubes and U-shaped burrows feeding on suspended particles are common in littoral and shallow water sediments, whilst animals which feed upon sediments, either by mining or by surface grazing, are commoner in deeper waters. Fossil soils, called seatclays or seatrocks, have been bioturbated and the sedimentary structures destroyed by roots and rootlets commonly preserved within them.

Igneous rocks

Igneous rocks are formed from molten rock (magma) which originates in chambers at depths of several kilometres under the earth's surface. They can be divided into extrusive rocks, formed where the magma reached the surface and erupted from volcanoes, and intrusive rocks formed by magma which failed to reach the surface and as a result solidified underground.

Volcanic eruptions from central or fissure vents produce lava flows during the less violent episodes, while volcanic ash and bombs, lithified into tuff and agglomerate, result from more explosive events. Most eruptions in the Lothian Region were subaerial. There are no records of pillow lavas derived from submarine volcanoes, though many tuffs between the lava flows are bedded and water-lain.

The form taken by intrusive rocks depends on the type of magma, the force of intrusion and the country rock (Figure 1). A sill is a sheet-like intrusion, commonly flat-lying, forced between layers of strata, as at Salisbury Crags. Vertical sheets, filling cracks discordant to the bedding, and called dykes, as can be seen on North Berwick shore. A laccolith forms where more viscous acid magma domes up the overlying strata to a mushroom shape; Traprain Law is an excellent example. A plug is a cylindrical intrusion filling a volcanic vent, as at Castle Rock, North Berwick Law and the Bass Rock. Other volcanic vents are filled with agglomerate, a mixture of blocks of country rock, volcanic bombs and ash, intruded with irregular minor dykes and sills. The nature of the infill varies with depth within the volcano (Leys 1982).

Only a small number of the many igneous rock types described worldwide are found within the Lothian Region. The common fine-grained rocks found as lavas vary from basic to acid, within the series basalt-andesite-trachyte-rhyolite. This series show a decrease in ferromagnesian minerals (mainly clinopyroxene) and an increase in feldspathic minerals (mainly plagioclase). Examples of all these rocks occur in the Lower Devonian lavas of the Pentland Hills. The Lower Carboniferous alkaline suite, however, is made up dominantly of olivine-basalts, with subordinate trachybasalts. These olivine-basalts are porphyritic and the scheme of MacGregor (1928), subdividing the basalts using the type and size of the phenocrysts, has been widely used on Geological Survey maps. Comparison with the chemical classification of Macdonald (1975) is given in (Table 1). Trachybasalts from this suite are mostly mugearites in which the feldspar is dominantly oligoclase.

(Table 1). Olivine-basalt nomenclature

MacGregor (1928)	Phenocrysts abundant	may occur	Macdonald (1975)
Markle	plagioclase	olivine iron oxides	macroporphyritic: olivine-plagioclase -iron oxides-phyric basalt, basaltic hawaiite or hawaiite
Dunsapie	plagioclase chnopyroxene olivine	iron oxides	macroporphyritic: olivine-plagioclase-clinopyroxene-iron oxides-phyric basaltic hawaiite or olivine-clinopyroxene-plagioclase-ohytic basalt
Craiglockhart	clinopyroxene olivine		ankaramite
Jedburgh	plagioclase olivine	iron oxides	microphyric: olivine-plagioclase siron oxides-phyric hawaiite, basaltic hawaiite or occasionally basalt
Dalmeny	divine	plagioclase clinopyroxene	microphyric: olivine-basalt or amine. plagioclasellinopyroxene-phyric basalt
Hillhouse	olivine	clinopyroxene	rnicrophyric: olivine-basalt or olivine-clinopyroxene-Phyric basalt

Iron oxide commonly occurs as iron-titanium oxides

Medium- and coarse-grained igneous rocks occur as intrusions. Most are related to the Devonian and Carboniferous volcanism. The great majority are of dolerite, the medium-grained equivalent of basalt. These may be undersaturated, with felspathoid minerals, as in the Namurian teschenite suite, or oversaturated as in the Stephanian quartz-dolerite and tholeiite suite. More extremely differentiated rocks are the mafic basanite-monehiquite suite and felspathoid-bearing phonolite, both associated with the Garleton Hills Volcanic Rocks.

Fossils

Fossils are the preserved remains of animals and plants which are commonly found in different kinds of sedimentary rock. They include not only 'body fossils' but also trace-fossils discussed above (p. 9). The majority of fossils preserved in rocks are the remains of marine invertebrates. Less commonly, more unusual fossil assemblages which contain brackish or freshwater fossil fish and amphibians, have accumulated in deposits in lagoons or estuaries.

The importance of fossils in geology is twofold. Firstly, they provide an unrivalled means of stratigraphic correlation.

Although the Earth's history is very long, some 4600 million years, only rocks deposited in the last 570 million contain abundant remains of fossil animals, represented by their hard shells buried soon after death. From that time, marking the start of the Cambrian system, the faunas change continually reflecting the origins, zenith and extinction of particular kinds of organisms, and of the communities they lived in. Each level of the rock record thus possesses a unique assemblage of fossils, characteristic of that time period during which the rocks were deposited and of no other. The succession of such faunas is the basis of *biostratigraphy—the* division of the rock record into ordered stratigraphic units, recognisable by their fossil remains. Fossils give a relative chronology; one can immediately recognise a fossil assemblage containing trilobites, for example, as belonging to the Palaeozoic, for thereafter trilobites died out, and later rocks never contain their remains. When faunas replace each other in rapid succession, particular time-units or zones can be defined accurately, and such zones may span less than a million years. Fossils of course, cannot give more than a relative time scale, absolute dates in terms of millions of years have to be supplied by other techniques such as radiometric dating.

Fossils have been used in stratigraphy for more than 150 years, but increasingly they have also been found of great value in interpreting ancient sedimentary environments. Thus faunas which lived in shallow open seas for example have a very different aspect to those which inhabited quiet brackish water lagoons. Moreover fossil assemblages with bivalve shells still held together were probably deposited in quiet water, whilst storm-generated shell banks can be distinguished by the randomly orientated and often fragmentary shells.

The rocks in the Lothian Region consist entirely of Palaeozoic rocks which in places have a cover of Quaternary sediments. The Silurian is marine, lagoonal and freshwater to desert, the Devonian is entirely fluviatile and desert, while the Carboniferous has alternating marine, lacustrine. estuarine and lagoonal environments.

In early marine sediments the commonest fossils (Figure 2), (Figure 3) are the *brachiopods,* a kind of two-valved shellfish which fed upon suspended particles. The brachiopods lost their dominance at the end of the Palaeozoic, though there are some living forms. The *bivalves,* superficially similar in being two-valved, though quite unrelated since they are molluscs, took over as the main sea-floor dwelling filter-feeders. In both the Silurian and the Carboniferous of the region are found environments favouring *corals,* which like their living counterparts can be solitary or compound. In the Carboniferous some corals formed flat-lying banks though not truly reefs. Various kinds of *echinoderms,* (the calcite-plated group that includes sea urchins and starfish), are found in both Silurian and Carboniferous, especially commonly in the latter. *Crinoids,* or *sea* lilies, are echinoderms, superficially like flowers, which attached to the sea floor by a long stalk, and used their radiating arms to trap suspended sediment. Many limestones are largely composed of the plates and stems of these fragile animals. *Bryozoans,* also preserved in limestones, are delicate calcite colonies with hundreds of tiny cavities in each of which lived small polyp-like animal, also a suspension feeder. Common in the Silurian but rare in the Carboniferous are *trilobites,* an entirely extinct group of mobile sea floor dwelling arthropods which had a trilobed outer body and often large compound eyes. These moved over the sea floor upon rather feeble legs, and may have fed as scavengers or mud-ingesters. Deeper water sediments, especially black shales of Silurian age, contain the remains of *graptolites,* another extinct group, which were delicate floating colonies of small polyp-like animals, feeding on suspended material and micro-organisms in the plankton. These lived in the open sea and because they drifted widely across seas and into quiet shallow water, they are of great stratigraphical value.

Many fossils found in the region are often very well preserved. In limestones, the shells can retain their original form and are often relatively unaltered chemically. The outer surfaces of the shells are clearly seen when the rock is cracked open. In calcareous mudstones the shells are commonly crushed. On the other hand (as in the Silurian of the North Esk Intier), the shells may be dissolved but leave their imprint on the matrix. These moulds may show delicate details of both external and internal structures, for example the scars of the muscles which brachiopods used to open and close their shells.

Some Carboniferous rocks in the Lothian Region which were deposited in a large freshwater or brackish lake and contain some unusual fossils (Figure 4). These sediments have the remains of *fishes, crustaceans* of shrimp-like form, freshwater molluscs, and the small bivalved crustaceans known as *ostracods;* an assemblage of animals quite different from those living in the seas.

Plants first developed widely and their remains became abundant in the Carboniferous. Remains of fronds, stems and even large trunks of these plants, mainly forest trees of fern and horsetail type, such as *Calamites,* are found in mudstones, siltstones and sandstones. Roots and rootlets of the trees, *Stigmaria,* are widely preserved in seatclays and seatrocks below coal seams.

Structural geology (Figure 5)

Sedimentary and extrusive igneous rocks are normally laid down in horizontal layers, called strata. Only in stable shield areas of the earth's crust do these remain undisturbed. Elsewhere the rocks are affected sooner or later by movement of the plates that form the earth's crust. The strata then become variously squeezed and stretched, raised and lowered, buckled and cracked, heated and intruded with molten rock, eroded off and buried beneath further layers.

Strata which have buckled are said to be folded. *Folds* can take many forms, such as *symmetrical* or *asymmetrical, overturned, recumbent* or *isoclinal.* An arched fold is called an *anticline;* a trough fold is *a syncline.* As a result of folding the strata may remain horizontal or be shallowly, steeply or vertically inclined. The amount and direction of the maximum slope of a bedding plane is called the *dip.* The *strike* of the bed is the horizontal line at right angles to the direction of dip. The *axis is* the direction of a fold while the *axial plane* depends on the orientation of the *fold limbs.* Axes and axial planes can vary from horizontal to inclined or vertical. Where the axis of a fold is inclined the anticline or syncline is said to be *plunging.* All the rocks in the Lothian Region show the effects of folding in the constantly varying dips. Folds are only rarely exposed, though shallow folds can be seen on the shore, as at Yellowcraig and Catcraig.

Instead of yielding to stress by folding, rocks may fracture and form *faults.* A *normal fault* is produced by tension, a *reverse* or *thrust fault* by pressure and a *transcurrent* or *tear fault* results from relative lateral movement. The *throw* of a fault, the amount of movement, can vary from a centimetre or two to a kilometre or more, as in the Southern Upland Fault. Most of the faulting that has affected rocks in the Lothian Region is normal faulting with fault-planes dipping at 60° to 70°. A notable exception is the Pentland Fault, a major reverse fault. Faults are rarely exposed, partly because fracturing of the rocks make them particularly vulnerable to erosion. Faulting, however, can be inferred from the juxtaposition of rocks of different ages and by the presence of steeply-dipping strata.

Breaks in deposition and the effects of folding can be seen in a structure called an *unconformity.* Older rocks, having been tilted or folded, uplifted and subjected to erosion, have later horizontal layers of sediment deposited on top, at an angle to the older layers. This *angle of unconformity* remains, even if the rocks are subject to further tilting or folding. Arguably the most famous unconformity in the world, where Hutton demonstrated the concept in 1788, is that at Siccar Point. Major unconformities represent periods of mountain-building and folding, and may be used to mark boundaries between different geological systems or groups of strata.

Geological history

The rocks underlying the Lothian Region are typical of those found in the geological heartland of Scotland, the Midland Valley. These rocks belong to only three geological periods, the Silurian, the Devonian (or Old Red Sandstone) and the Carboniferous, covering an age span from over 400 million years ago to about 280 million years ago. The geographical distribution of the rocks is shown on (Map 2). The geological divisions, their age, their typical lithologies and the environments in which they formed are described in (Table 2).

In *Silurian* times the area was close to the edge of the Iapetus Ocean, filling with sediment as the ocean closed. Shallow tropical seas abounded with brachiopods, trilobites, molluscs, sea-lilies, starfish and ostracods on the sand, silt or mud sea-bed, while rare planktonic graptolites lived in the waters above. Early jawless fish inhabited coastal lagoons and inland lakes. A transition occurs from grey marine strata of fossiliferous sandstones, siltstones and mudstones, to red terrestrial sandstones later in the Silurian as arid land emerged from the seas. As the sediments changed with changing conditions, so did their contained fauna which was precisely adapted to their environment. Massive mountain-building of the *Caledonian Orogeny* left the once-horizontal Silurian strata tilted vertically (North Esk Inlier and the Pentland Hills Excursions). By late Silurian times the Highland Boundary Fault and the Southern Upland Fault had become active, and the Midland Valley came into existence as a down-faulted block between mountainous terrain to north and south.

During the following *Devonian* Period these high barren mountains left by the orogeny were eroded by water, wind and heat down to level plains. The resulting red continental sandstones gave the period its local name of Old Red Sandstone. In *Lower Old Red Sandstone* times giant alluvial fans ranged along the two boundary faults poured conglomerate (Lammermuir Deans Excursion) into the Midland Valley from the eroding northern and southern mountains. At the same time eruption of basaltic, andcsitic and acid lavas and tuffs formed the Pentland Hills Volcanic Rocks (The Pentland Hills and Blackford Hill Excursions). In the Middle Old Red Sandstone further earth-movements uplifted the Pentland Hills and initiated the Pentland and Colinton faults. Large rivers in the less arid *Upper Old Red Sandstone* times gave rise to red fluviatile sandstones with interbedded lacustrine siltstones and mudstones containing rare fish remains. Also present are cornstones, dolomitic limestones that represent leached soil horizons. Red sandstones of this age occur round the north flanks of the Pentland Hills, Moorfoot Hills and Lammermuir Hills and are exposed on the coast in the east (Siccar Point and Dunbar Excursions).

By the start of the *Carboniferous* Period the region had been worn down to low-lying, afforested coastal plains. Land and sea fought a constant battle for supremacy over the plains through the Carboniferous, producing repeated rhythmic cycles of marine, deltaic, freshwater and fluviatile sedimentation. At the start of each cycle dense lycopod forest swamps, resembling in many ways the mangrove swamps of today, gave rise to peat and coal. Subsidence of the land led to inundation by seas in which marine shells thrived in the muddy seabed and coral reefs flourished in clear tropical waters. Rivers built deltas of mud, silt and sand, reclaiming the land from the sea. In freshwater lagoons along the new coast and on the alluvial plains precipitation of lime produced freshwater limestones and thin cementstone beds, or flourishing micro-organisms gave rise to bituminous mudstones and oil-shales. Forests became re-established on the reclaimed land, the tree roots forming thick leached soils that are now represented by the seatearths or seatclays under each coal. At different times during the Carboniferous, conditions favoured thick development of particular parts of the cycles while other parts were thin or absent. Thus individual groups of strata have thick development of economic minerals such as coal, limestone, oil-shale, sandstone or fireclay, and the outcrop distribution of these minerals has influenced industrial and population growth within the region.

In the Midland Valley the Carboniferous strata are divided into groups, mainly on the basis of marine bands. In terms of age, the groups can be classified (Table 2) into the Dinantian (equivalent to the Carboniferous Limestone Series of England), the Namurian (equivalent to the Millstone Grit Series) and the Westphalian (equivalent to the Coal Measures).

The earliest *Dinantian* strata, belonging to the *Cementstone Group, are* thinly-bedded freshwater mudstones, siltstones and sandstones with thin lagoonal dolomitic limestones (cementstones) and poor non-marine faunas. These strata underlie much of the City of Edinburgh.

Volcanic activity returned throughout the region as the well-preserved Arthur's Seat Volcano poured out basaltic lavas and tuffs (Arthur's Seat and The Castle Hill Excursions), and other volcanoes erupted at Craiglockhart Hill and Corston Hill in the west. The contemporaneous Garleton Hills Volcanic Rocks, containing basaltic lavas and tuffs overlain by trachytic lavas and tuffs, extend from the north coast of East Lothian (North Berwick Excursion) to the Garleton Hills (Garleton Hills Excursion). Thick fluviatile or deltaic sandstones, such as the Craigleith Sandstone, Ravelston Sandstone and Hailes Sandstone and thick mudstones such as the Wardie Shales, are features of the *Lower Oil-Shale Group* which underlies northern Edinburgh and part of West Lothian (Wardie and Granton Shore and The Dean Excursions). Large quarries, like Hailes Quarry, are now mostly infilled and built over, concealing the industry which not only supplied high quality building stone for the New Town and suburbs of Edinburgh, but also exported to London and continental Europe. Also vanished is the West Lothian oil-shale industry which mined and distilled the oil-shale to produce oil and chemical by-products for over a century up to 1962. The main oil-shale seams worked were the Pumpherston Shale in the Lower Oil-Shale Group and the Camps, Dunnet, Broxburn and Fells seams in the *Upper Oil-Shale Group* (South Queensferry-Cramond Excursion). In East Lothian these lowest three groups of the Carboniferous have not been separately recognised, the strata being known as the *Calciferous Sandstone Measures* (North Berwick, Dunbar and Pease Bay to Cove Excursions). The earliest marine incursions which took place during deposition of the Lower Oil-Shale Group gave rise to marine bands, known variously as the Pumpherston Shell Bed, Macgregor Marine Bands or Cove Marine Bands. Long-lasting marine conditions were established later in *Lower Limestone Group* times. Clear tropical seas gave rise to thick fossiliferous marine limestones which can be correlated from East Lothian through Midlothian to West Lothian (Gosford Bay–Aberlady Point, Catcraig and Bathgate Hills Excursions). These limestones, formerly worked extensively, are now worked opencast at Oxwellmains, near Dunbar, and mined and quarried at Middleton, south of Edinburgh.

At the start *of Namurian* times debris from tropical forests produced the many thick coal seams of the *Limestone Coal Group.* Two prominent marine incursions in the otherwise deltaic sediments, the Johnstone Shell Bed and the Black Metals Marine Band, enable correlation of the coal seams. There are presently only two modern deep mines in the Midlothian Coalfield, one old mine in West Lothian and one large opencast site in the East Lothian Coalfield still remaining from the large number of collieries that once existed in the region. In the *Upper Limestone Group* the coal seams are thin as are the marine limestones which provide distinctive marker horizons. The Index Limestone marks the base, followed in upward sequence by the Lyoncross Limestone, the Orchard Beds, the Calmy Limestone and the Castlecary Limestone at the top (River North Esk Excursion). Dominantly fluviatile conditions in the succeeding *Passage Group* produced thick coarse-grained, feldspathic sandstones as in the Roslin Sandstone of Midlothian (River North Esk Excursion). In West Lothian thick leached soils left valuable economic fireclays (River Avon Excursion). During the Namurian thick teschenite sills were intruded which, because of their hardness, form prominent landmarks as at Salisbury Crags, Gullane Hill, Mons Hill (Arthur's Seat, Gosford and South Queensferry-Cramond Excursions) and are commonly quarried for roadstone and aggregate.

The start of *Westphalian* or *Coal Measures* times heralded a widespread return to tropical forests and left an heritage of thick workable coal seams. Marine incursions provided marker bands which are used for correlation into Lower, Middle and Upper Coal Measures (equivalent to Westphalian A, B and C). By the *Stephanian* the climate had become semi-arid. No deposits remain but deep weathering extended down into the Upper Coal Measures strata, reddening the rocks and destroying many coal seams. Also about this time the Midland Valley quartz-dolerite sill was intruded along with the suite of W-E trending quartz-dolerite dykes, as seen at Hound Point and Dalmahoy Hill (South Queensferry-Cramond, Garleton Hills and Dunbar Excursions).

Following the Carboniferous there was a major mountain-building event, the *Hercynian Orogeny,* which folded the rocks into gentle anticlines and basins such as the Midlothian and East Lothian coalfields. Some of the major faults associated with the folding trend SW-NE, as the Colinton, Pentland and Crossgatehall faults, and others trend W-E, as the Murieston, Middleton Hall and Ochiltree faults. Long epochs followed without any local record of the geological history. The region was land subject to erosion, with desert conditions during the Permian and Triassic eras, more amenable climates during Jurassic, Cretaceous and Tertiary times as southerly seas covered most of England. Late in the Tertiary era the east-flowing drainage pattern of Scotland formed on an east tilted slope, giving rise to the Forth and its main north-east-flowing consequent streams.

During the last million years, in the *Quaternary* or *Pleistocene,* the region has been affected by several ice ages. Ice built up in the southern Highlands and the Southern Uplands, merged in the Midland Valley and flowed eastwards across the Lothian Region, deflected to ENE by the Pentlands, Moorfoots and Lammermuirs. As the ice ground down the rocks it moulded the landscape along its direction of flow. This resulted in rock surfaces striated by rock-laden ice, in crag-and-tail features such as Edinburgh Castle and the Royal Mile (The Castle Hill and Blackford Hill Excursions) and in drumlins, oval-shaped mounds formed of till (boulder clay). Till, which blankets most of the low ground in the region, is the ground moraine of the ice-sheet and consists of rounded pebbles and boulders in a grey, brown or red silty or sandy clay. The matrix and the clasts are mostly of local origin varying according to the bedrock, but erratics from further afield, such as Highland schists, are also found.

Fifteen thousand years ago the ice-sheet began to melt and break up. The Pentland, Moorfoot and Lammermuir Hills became ice-free while valley glaciers and stagnating ice-sheets still occupied low ground. Meltwater from the ice cut numerous glacial drainage channels, many of which now form dry valleys. Some channels follow the contours where meltwater flowed along ice margins, other channels form steep chutes where the meltwater escaped under the ice. The most spectacular dry valleys cut across watersheds, as in the Pentland Hills from Bavelaw to Flotterstone (The Pentland Hills Excursion), and in the Lammermuir Hills at Aikengall (Lammermuir Deans Excursion). Glacial meltwater. eroding both till and bedrock, deposited gravels and sands as mounds, ridges and terraces, close to the ice margins. Silts and clays were deposited as lake alluvium or in estuaries and inlets of the sea, which then lay well above its present level.

Sea-levels fluctuated during and after the glaciation because of the trapping of sea-water into ice-sheets and isostatic adjustment of the land in response to the weight of the ice-sheet. The late-Glacial sea-level of the Forth ranged from over 30 m OD in the west to about 15 m OD in the east, whereas the main post-Glacial shoreline lies below 10 m OD, and forms extensive beach deposits with a prominent cliff at the back.

Lowering sea-levels rejuvenated rivers, and these cut gorges. River alluvium of gravel, sand, silt and clay was deposited in river terraces and flood-plains. Tides and longshore currents constantly transport and redeposit marine alluvium along the coasts.

Major alterations by man of the countryside bequeathed by nature include quarrying for limestone, aggregate, sand and gravel and other minerals; construction of bings of spent oil-shale and coal waste, and road and rail embankments; and reclamation of intertidal flats.

Maps

British Geological Survey maps are available for the whole region. Published 1:50000 or 1:63360 (*) maps can be purchased from BGS at Murchison House, West Mains Road, Edinburgh, EH9 3LA , or from Ordnance Survey stockists:

* Sheet 31	Airdrie	(Solid)
* Sheet 31	Airdrie	(Drift)
Sheet 32W	Livingston	(Solid)
Sheet 32E	Edinburgh	(Solid)
* Sheet 32	Edinburgh	(Drift)
Sheet 33W	Haddington	(Solid)
Sheet 33W	Haddington	(Drift)
Sheet 33E	Dunbar	(Solid)
Sheet 33E	Dunbar	(Drift)
Sheet 34	Eyemouth	(Solid)
Sheet 34	Eyemouth	(Drift)

There is also an Edinburgh Special Sheet (Solid and Drift) on the scale of 1:25000. Geological maps with complete coverage of the region at 1:10560 (six-inch) scale may be consulted at the British Geological Survey.

Publications

The Geology of Scotland gives an introduction to Scottish geology. The third editions of the BGS regional geology, *The Midland valley of Scotland* and *The south of Scotland*. provide a more detailed account. A recent sheet memoir is available for Sheet 32 (Edinburgh) and others are in preparation. A selection of the many books available as introductory reading on the various aspects of geology is included with the References at the end of this guide.

Geological Code of Conduct

The Geological Code is reproduced here as a reminder to all that geological outcrops not only belong to the landowner but are an irreplaceable heritage for everyone. There is a delicate balance between geological conservation and the need to study rocks in their natural environment. Some outcrops are unique, irreplaceable, self-evident, and often rightly protected. Other outcrops in shores, cliff and quarries have an abundance of material available for hammering and collecting. The authors ask the readers of this guide to follow the code. In particular, leave outcrops in the state you would expect to find them and maintain good relations with landowners so that other geologists may be welcome.

(Drafted by the Geologists' Association and supported by all Geological Societies in Britain)

In recent years there has been a rapid increase in geological field studies, which are inevitably concentrated on a finite number of important rock outcrops. Sheer collecting pressure is destroying the scientific value of an increasing number of sites, many of them irreplaceable. At the same time the volume of field work has caused concern to many site owners.

A code of conduct has, therefore, become essential if the quality of field facilities is not to deteriorate still further. Geologists must show themselves responsible users of the countryside.

General

1. Always seek permission in advance to enter private land.
2. Obey the Country Code (e.g. shut gates, leave no litter).

3. Do not allow rock waste to spread on to agricultural land, where it may result in injury to animals, or on to roadways, where a hazard may be caused to pedestrians and vehicles.
4. Do not interfere with machinery or other property.
5. Avoid courting danger to yourself and others from such hazards as an insecure cliff or rock face. Take care to prevent the dislodging of rock which might fall on people beneath. Never place yourself in danger if climbing cliffs or other rock faces.
6. No rock face should be left in a state more dangerous than when you arrived.
7. Exercise the standard precautions when working in mountainous and remote areas, e.g. inform someone of your intended route.
8. Do not explore underground unless you have the proper experience and equipment.
9. On coastal sections, make sure you know the local tide conditions.

Visiting quarries

1. Both arrival and departure must be reported. Make sure you have discussed with the manager or foreman where you may go and what local hazards to avoid.
2. The leader of a party should have visited the quarry in advance and must ensure that members do not become dispersed and out of sight.
3. Keep clear of vehicles and machinery and ensure you understand blast-warning procedures. Avoid sludge lagoons.

Collecting and field parties

1. Students should be trained to observe and record with sketches and photographs rather than to destroy by hammering.
2. Leaders. of field-meeting parties should instruct their members not to carry hammers except for use in the working portion of a quarry where permission has been given, in a waste tip or on fallen blocks and scree.
3. Never collect from stone walls and buildings. Do not undermine fences, walls, bridges or other property.
4. When collecting, take the minimum material necessary and avoid removing fossils, mineral or rock specimens from *in situ* outcrops unless they are to be used for serious study.
5. Collecting from educational purposes should only be carried out where there is a large supply of common fossils.
6. The use of replicas of fossils is commended for teaching purposes.
7. The leader of a field party should remember that he hears responsibility for ensuring that the spirit of this code is fulfilled. This may oblige him to remind his party of the need for care and consideration at all times and require him to act as supervisor when his own inclination might be to study and collect.

The research worker

1. No research worker has a special right to 'dig out' a site in the name of science. If you have to collect, leave some of the material intact—new research techniques may be available to future generations of geologists.
2. Special excavations should be backfilled where necessary to safeguard against creating a hazard to men and animals and, where required, to protect vulnerable outcrops from casual collecting.
3. Avoid the disfigurement of rock surfaces with brightly coloured numbers and symbols in public places.
4. By lodging them with a responsible institution, ensure that your research material and notebooks become available for posterity.

Societies, Universities and Schools

1. Foster an interest in geological sites and their wise conservation. Much may be done to help clean up overgrown sites (with permission of the owner and in consultation with the Nature Conservancy Council).
2. Create working groups for those amateurs who wish to do field work and collect, so that leadership is available to direct their studies and ensure that their specimens are effectively logged and housed.

3. Join your local County Naturalists' Trusts, as individuals or as groups, to ensure that effective action is taken to protect the sites you use.

Publication

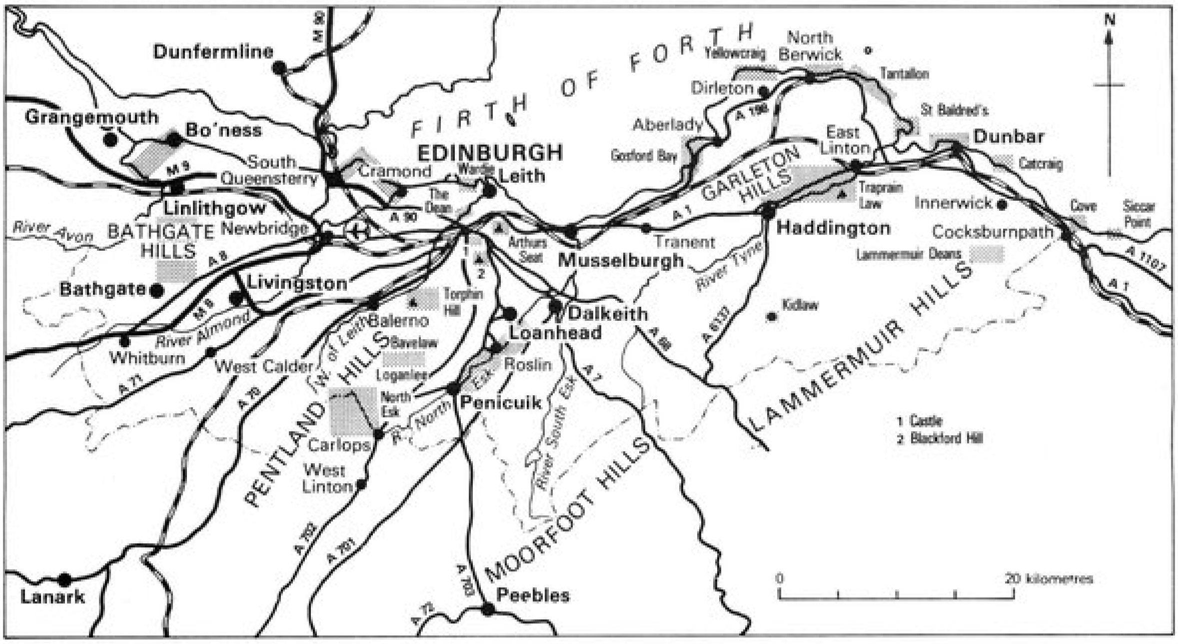
1. Take care that publicity does not lead to the destruction of vulnerable exposures. Where possible, without detriment to the scientific argument, avoid giving the precise locality of such sites. Help promote the establishment of a restricted access data centre where the details of such localities can be lodged.
2. It is requested that authors of introductory, educational and similar texts should draw attention to, or quote, the Code.

Landowners

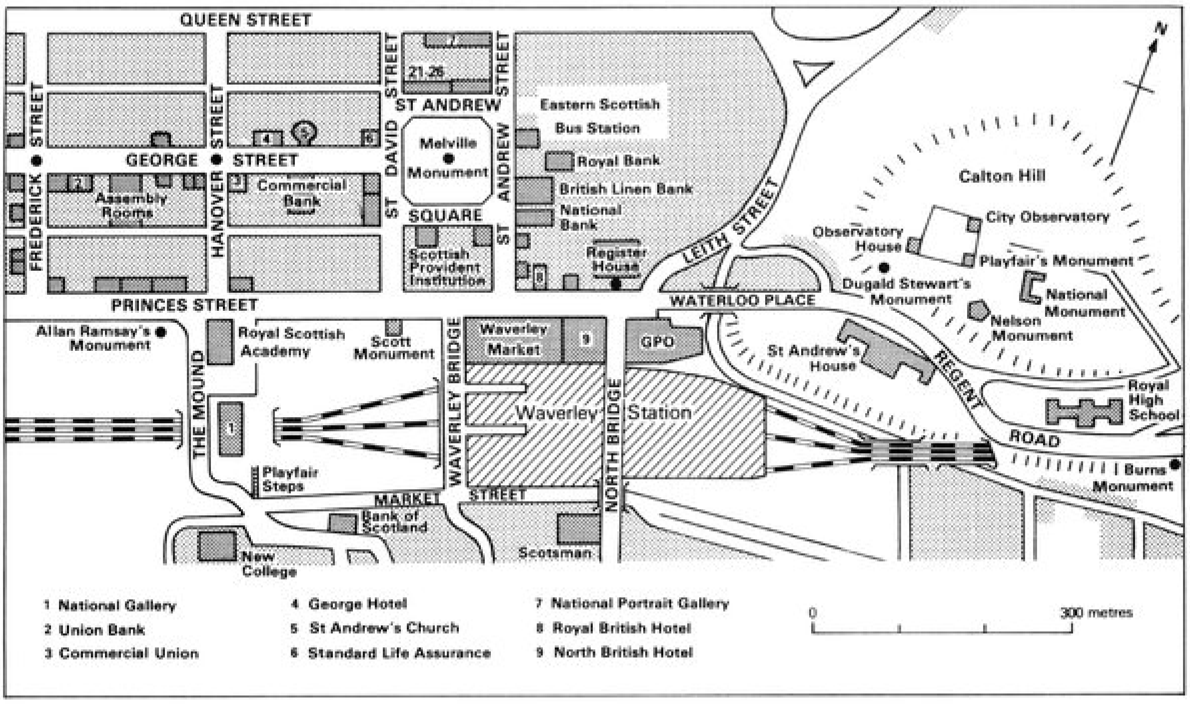
1. It is suggested that landowners should ascertain that visiting geologists and party leaders are familiar with this Code.
2. In the event of abuse of the Code, landowners are requested to take the name and address of the individual or party leader and the Institution or Society to which he belongs. Such cases could be referred to the Association through its librarian.

References

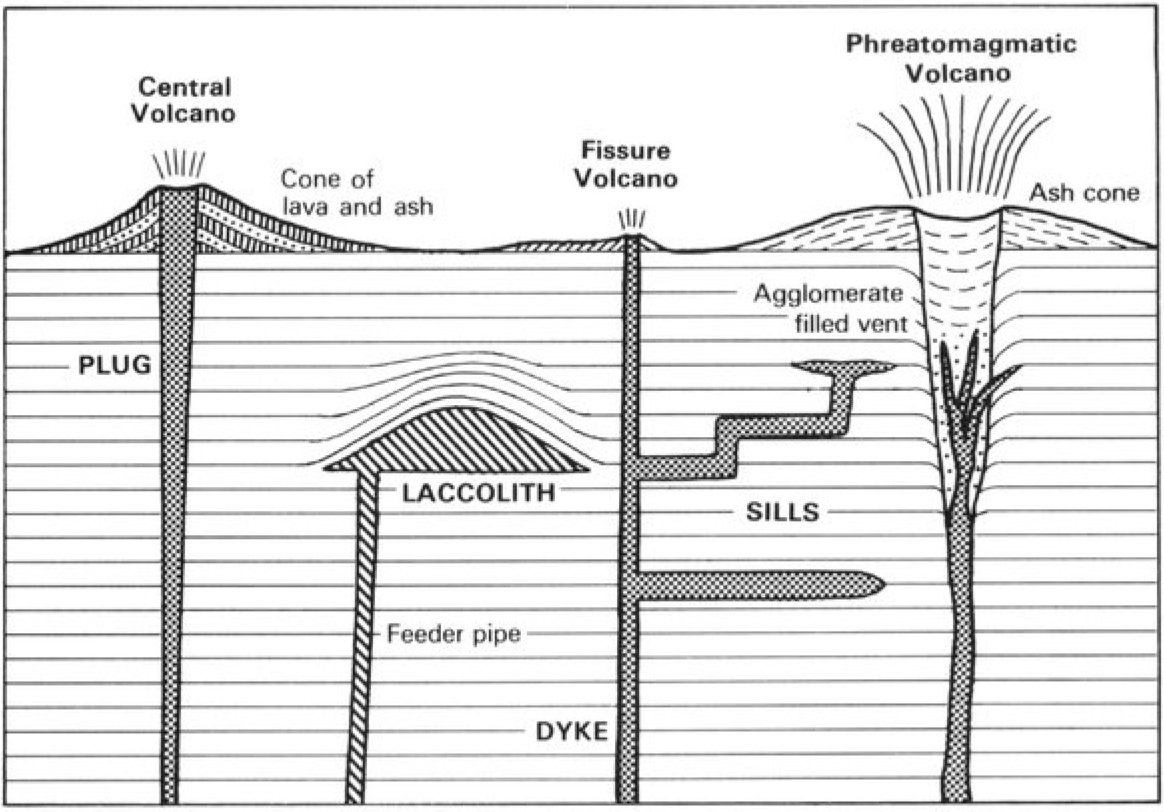
(Plate 3) Limestones and mudstones, Lower Limestone Group, cut by basalt dyke and overlain by glacial deposits, Oxwellmains North Quarry.



(Map 1) Lothian Region and the location of the excursions.



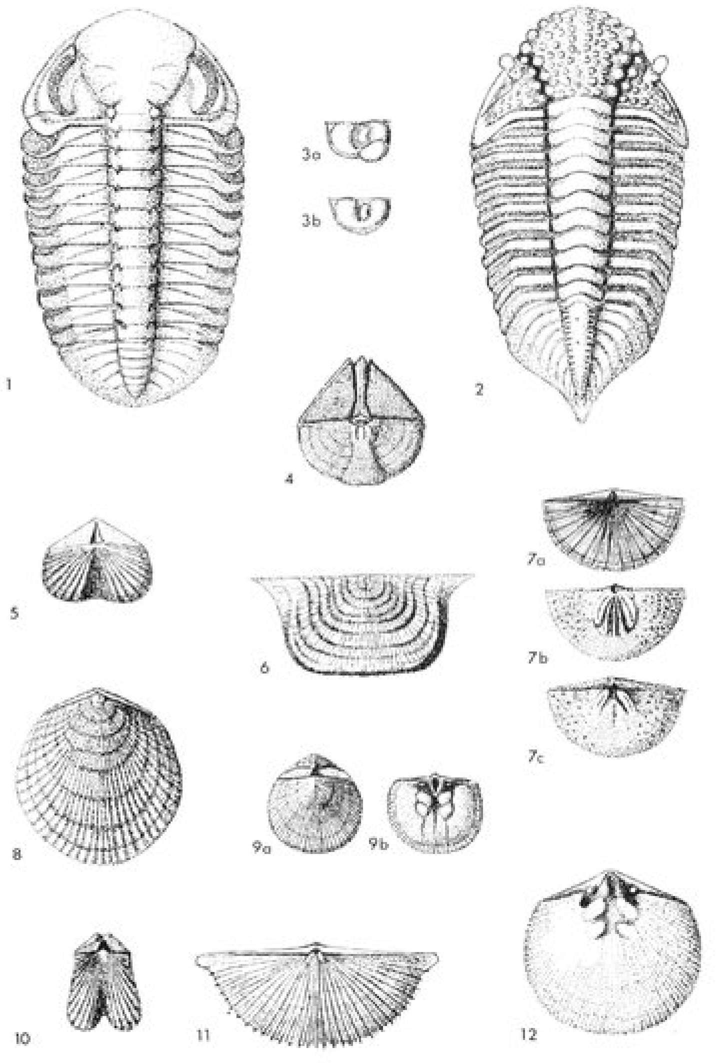
(Map 5) Edinburgh city centre.



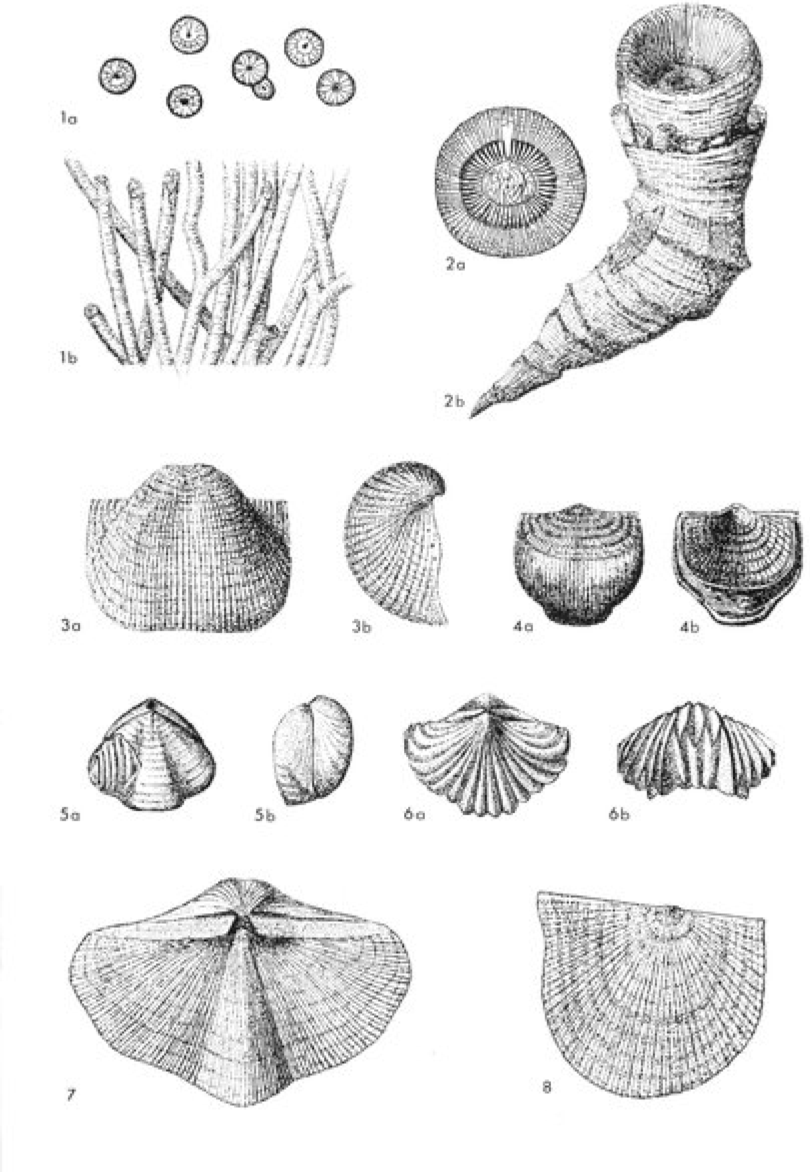
(Figure 1) Forms of extrusive and intrusive igneous rocks.

	MacGregor (1928)	Phenocrysts		Macdonald (1975)
		abundant	may occur	
Macroporphyritic (>2 mm)	Markle	plagioclase	olivine iron oxides	macroporphyritic: olivine-plagioclase ± iron oxides-phyric basalt, basaltic hawaiite or hawaiite
	Dunsapie	plagioclase clinopyroxene olivine	iron oxides	macroporphyritic: olivine-plagioclase-clinopyroxene-iron oxides-phyric basaltic hawaiite or olivine-clinopyroxene-plagioclase-phyric basalt
	Craiglockhart	clinopyroxene olivine		ankaramite
Microporphyric (<2 mm)	Jedburgh	plagioclase olivine	iron oxides	microphyric: olivine-plagioclase ±iron oxides-phyric hawaiite, basaltic hawaiite or occasionally basalt
	Dalmeny	olivine	plagioclase clino-pyroxene	microphyric: olivine-basalt or olivine-plagioclase-clinopyroxene-phyric basalt
	Hillhouse	olivine	clino-pyroxene	microphyric: olivine-basalt or olivine-clinopyroxene-phyric basalt

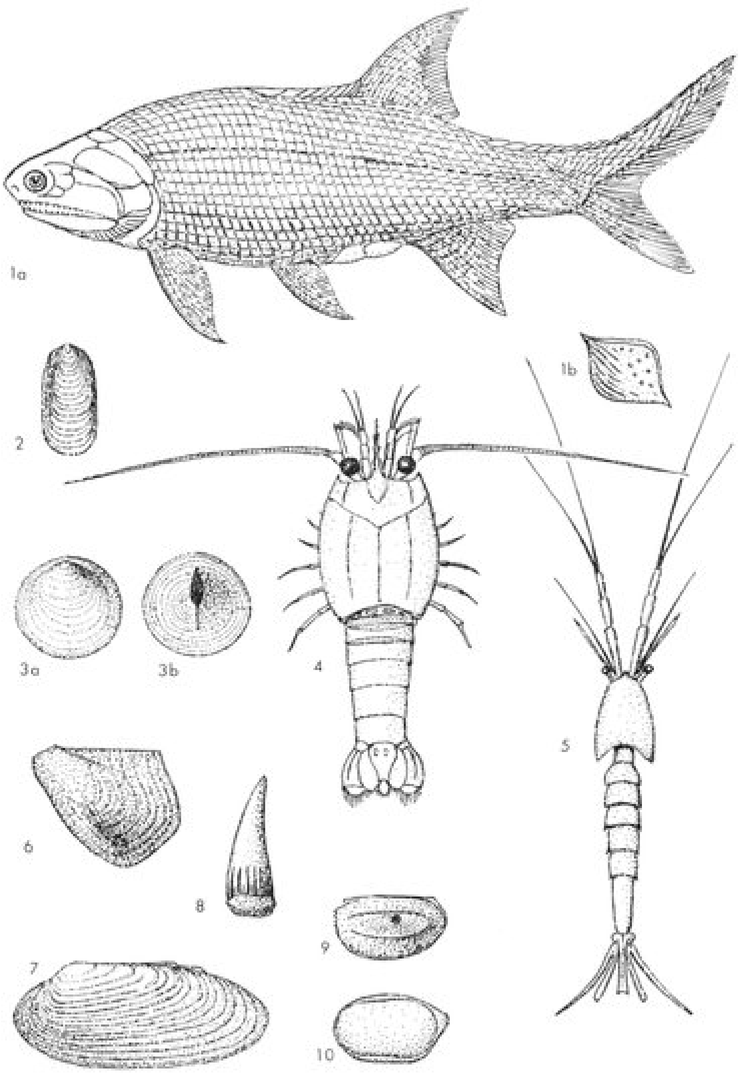
(Table 1) Olivine-basalt nomenclature.



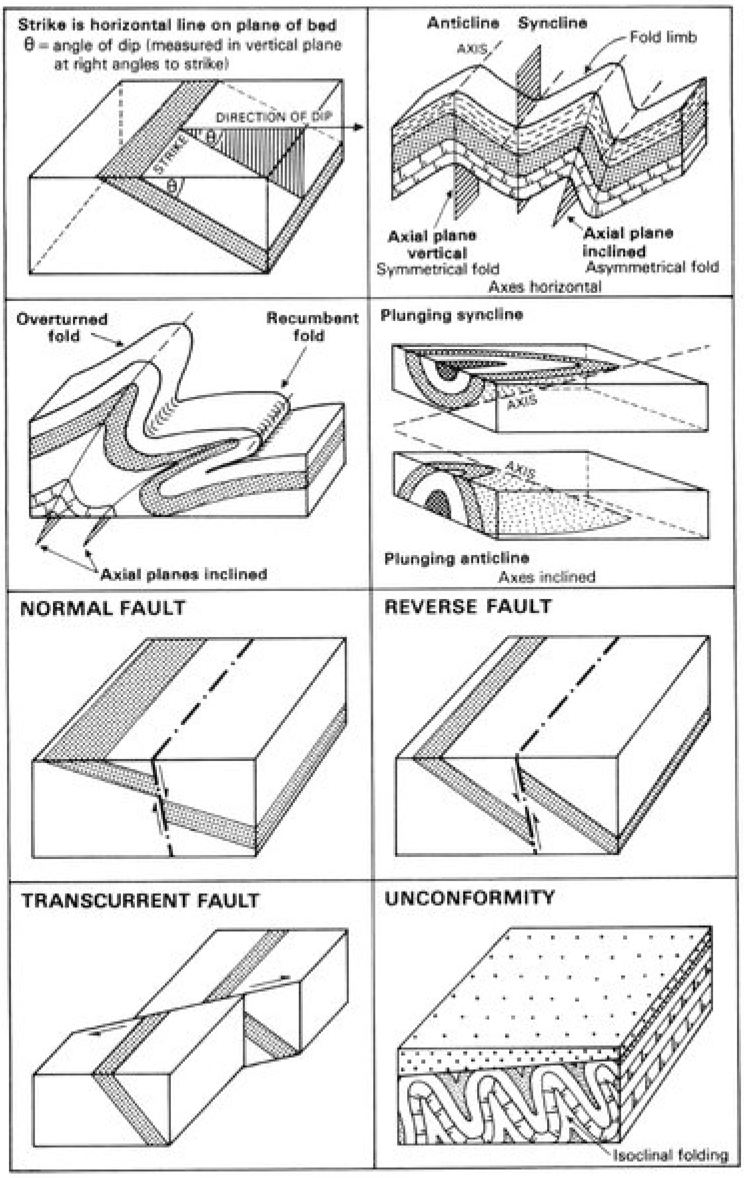
(Figure 2) Silurian (Upper Llandovery) fossils from the North Esk Inlier. 1. Acernaspis sufferta (Lamont) × 1. 2. Encrinurus expansus Haswell × 1. 3. Craspedobolbina (Mitrobeyrichia) impendens (Haswell), (a) female, (b) tecnomorph (male) × 5. 4. Cyrtia exporrecta Wahlenberg, internal mould × 1. 5. Skenidiodes lewisii (Davidson), shell preserved × 2. 6. Leptaena sp., internal mould, pedicle valve × 1. 7. Eopleciodonia penkillensis (Reed), (a) dorsal view, (b) brachial valve, internal mould, (c) pedicle valve, external mould × 1.5. 8. Atrypa resicularis (Linnaeus) shell preserved × 1. 9. Visbyella sp., (a) shell preserved, (b) internal mould of brachial valve × 1.5. 10. Dicoeodosia verneuiliana (Beecher), shell preserved × 1.5. 11. Coolinia applanata (Salter), shell preserved × 1 Dalejina polygramma pendandica (Davidson). internal mould × 1.



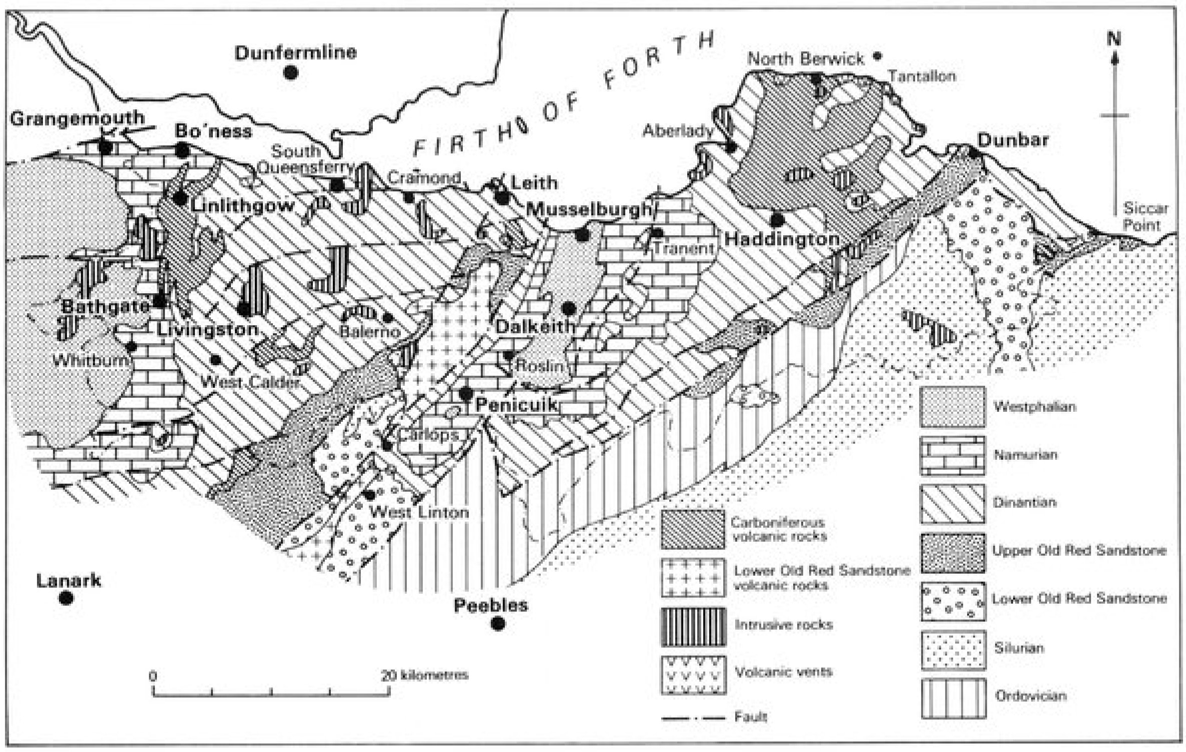
(Figure 3) Carboniferous marine fossils. 1. Lithostrotion junceum (Fleming). (a) transverse section of corollaites, (b) part of colony × I; Visean. 2. Aulophyllum fungites (Fleming), (a) transverse section, (b) single individual with rejuvenescent buds × 0.75; Viséan. 3. Dictyoclostus semireticulatus (Martin). (a) ventral view. (b) lateral view ×0.75; Viséan. 4. Eomarginifera setosa (Phillips), (a) ventral view. (b) dorsal view × I; Vistan 5. Composita ambigua (J. Sowerby), (a) dorsal view with part of the shell broken away exposing the spiralium.. (b) lateral view × 1; Visean. 6. Pugnoides pleurodon (Phillips). (a) dorsal view. (b) anterior view ×075; Viséan. 7. Spirifer striatus (Martin) × I; Visean. 8. Dunbarella papyracea (J. dc C. Sowerby) × 1; Westphalian.



(Figure 4) Carboniferous lagoonal and non-marine fossils. 1. Elonichthys robisoni Traquair, (a) restoration after Traquair × I; (b) caudal scale × 8; Viséan. 2. Lingula squamiformis Phillips × 1; Viséan-Namurian. 3. Orbiculoidea nitida Phillips. (a) brachial valve, (h) pedicle valve × 2; Viséan-Namurian. 4. Tealliocaris woodwardi Peach × 4; Viséan. 5. Waterstonella grantonensis Schram × 10; Viséan. 6. Naiadites modiolaris J de C Sowerby × 1; Westphalian. 7. Anthracosia planitumida Trueman × 1.5; Westphalian. 8. Rhizodus hibberti Traquair, tooth × 0.33; Viséan. 9. Beyrichiopsis plicata Jones and Kirkby × 16; Viséan-Namurian. 10. Cavellina spola Robinson × IS; Viséan. Lingula and Orbiculoidea are marine fossils tolerant of low salinity.



(Figure 5) Common geological structures, after P.McL.D. Duff.



(Map 2) Geological map of the Lothian Region.

PERIOD	EPOCH/SERIES	AGE	ENVIRONMENT	TYPE OF ROCK/DEPOSIT
		Present day		
QUATERNARY	Post-Glacial		Temperate land High sea level	River alluvium Low raised beach
		10 000		
	Late-Glacial		Sub-arctic Very high sea level Arctic	Peat High raised beach Sands and gravels
		15 000		
	Glacial		Ice-cap with interglacials	Boulder clay (till)
		1 million		
TERTIARY CRETACEOUS JURASSIC TRIASSIC PERMIAN	(Gap in geological record)		Land, temperate to desert Earthquakes Mountain building	
		280 million		Igneous intrusions
CARBONIFEROUS	Coal Measures		Coal swamps, seas, deltas	Coal-bearing sediments
	Passage Group		Rivers, deltas	Sandstones, fireclays
	Upper Limestone Group		Coal swamps, deltas, coral seas	Mixed strata
	Limestone Coal Group			Coal-bearing sediments
	Lower Limestone Group			Limestone-bearing sediments
	Upper Oil-Shale Group		Freshwater lagoons, deltas	Oil-shale-bearing sediments
	Lower Oil-Shale Group			Oil-shales, sandstones
	Arthur's Seat Volcanic Rocks		Volcanic eruptions	Lavas, tuffs, vents
	Cementstone Group		Coastal, shallow lagoons	Mixed strata
		345 million		
DEVONIAN (OLD RED SANDSTONE)	Upper Old Red Sandstone		Rivers, arid desert	Red sandstones
	Pentland Hills Volcanic Rocks		Volcanic eruptions, earthquakes	Lavas, tuffs, intrusions
	Lower Old Red Sandstone		Desert, floods, rivers	Red conglomerates
		395 million	Earthquakes, mountain building	
SILURIAN	Wenlock		Barren land	Red sandstones
	Llandovery		Shallow tropical seas	Fossil-bearing mudstones
		435 million		
ORDOVICIAN		*500 million*		
CAMBRIAN		*570 million*		

(Table 2) Geological timescale.