CLACKMANNANSHIRE LANDSCAPE AND GEOLOGY

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The name Clackmannan is derived from the Stone (Clack) of Mannan which stands with the Mercat Cross and Tolbooth at the centre of the town. This account of the Wee County's geology is freely based on the Forth Naturalist and Historian's book *Central Scotland - land, wildlife, people* (1993).

LANDSCAPE AND GEOLOGY

The landscape of Clackmannanshire generally reflects the weathering characteristics of the bedrock, being upstanding where underlain by harder, mainly igneous rocks and low-lying where underlain by softer rocks such as mudstones and many sandstones. The view of Clackmannanshire from the National Wallace Monument highlights three distinct landscapes (photo below and back cover): - the steep scarp and high hills of the Ochils running eastwards through Menstrie and Dollar; the lowlying floors of the Devon and Forth valleys; and the rounded low hilly ground of the Clackmannan 'Ridge'. This tripartite division is also reflected in the generalized soil type map of the county (Figure 1). The classification used in this figure is based on that of Taylor and Nortcliff (1996, p.9). The Ochil Fault contributes a marked linear scarp feature to the landscape where it has brought hard rocks against soft. The scarp has slope gradients as high as 1 in 1.5 between 15m OD and 500m OD Summits in the Ochils (Figure 2) have an average height of about 2150ft/650m OD with the highest Ben Cleuch 2363ft/721m. By contrast, the highest point on the Clackmannan 'Ridge' is only about 400ft/120m (Figure 3).

The igneous and sedimentary rocks seen in the County are between 410 and 290 million years old. The geological map (Figure 4) shows the distribution of these rocks. They fall into two main suites with the older Lower Devonian volcanic rocks to the north of the Ochil Fault and the younger mainly Carboniferous sedimentary rocks to the south.

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Ochils—Devon and Forth floors/windings –distant Clackmannan

The succession is divided into formations and groups according to their lithological characteristics and these subdivisions are shown in stratigraphical order in Table 1.

Table 1. Lithostratigraphical Succession in Clackmannanshire

Quaternary		Grangemouth Formation
		Claret Formation
		Letham Formation
		Bothkennar Gravel Formation
		Abbotsgrange/Linwood formations
		Killearn Formation
		Kinneil Kerse Formation
		Loanhead Formation
		Broomhouse Formation
		Wilderness Till Formation
Carboniferous	Coal Measures	Middle Coal Measures
		Lower Coal Measures
	Clackmannan Group	Passage Formation
		Upper Limestone Formation
		Limestone Coal Formation
		Lower Limestone Formation
	Strathclyde Group	Lawmuir Formation
		Kirkwood Formation
		Clyde Plateau Volcanic Formation
Inverclyde Group	Clyde Sandstone Formation	
		Ballagan Formation
		Kinnesswood Formation
Upper Devonian	Stratheden Group	Knox Pulpit Formation
		Stockiemuir/Glenvale Formation/
		Burnside Formation
Lower Devonian	Arbuthnott Group	Ochil Volcanic Formation

Formations shown in bold italics are unknown from outcrop or borehole records, but are surmised to be present under Clackmannanshire.

Rocks of Devonian age (410-360 **million years ago)** - Table 1 and Figure 4

During the Devonian, Scotland was located south of the equator, having 'drifted' northwards from the southern polar latitudes which it had occupied in Precambrian times (>570 million years ago). The climate was hot and seasonally wet, with limited rainfall.

The oldest rocks cropping out in the County are of the Ochil Volcanic Formation in the Ochil Hills. The formation comprises over 2000m of subaerial basaltic and andesitic lava flows with interbedded terrestrial debris-flow conglomerates. In the upper part of the volcanic sequence there are more acidic flows of trachyandesite as seen on Craig Leith (OS 58, NS 875 980). Differential weathering of the bedding within the lava flows and volcaniclastic conglomerates, accentuated by severe glacial erosion during the ice ages of the last two million years, produced the step-like (trap) featuring of the prominent ridges on the scarp face of the Ochils. The flows

are sometimes fresh, compact and columnar jointed, but more often are autobrecciated (blocky lava), or generally weathered and decomposed. Only a small proportion of airall and waterlain volcanic ashes appears to be present in the succession.

The lava flows are often porphyritic mainly with small (l-3mm) white or grey crystals of feldspar in a fine-grained matrix. Altered small crystals (l-2mm) of olivine preserved as the red mineral iddingsite also occur. Flows with vesicles (gas cavities) are also common. Often the vesicles are filled, or partly filled with minerals such as calcite and quartz to form amygdales or geodes containing agate and amethyst etc. Commonly the amygdales and geodes weather out of the parent rock and can be recognised in soil or scree (eg. between Blairlogie and Menstrie) by the toad-skin appearance of the dimpled indented outer surface. Sometimes the outer skin is green in colour due to the presence of epidote or chlorite rather than of copper in the form of malachite as is often assumed.

The main vents, or the eroded roots of the andean-like volcanoes from which the flows were erupted have not yet been located and may lay deeply buried under the younger rocks preserved to the south of the Ochil Fault. Contrary to local opinion based on its cone-like landform, Dumyat (just in Stirlingshire) is not an extinct volcano. The only possible, small volcanic neck so far recognised is now under water in the Upper Glendevon Reservoir (NN 907 046).

The volcanic terrain of the Ochils formed part of the southern margin of a major subsiding sedimentary basin located in Strathmore to the north of the County. In this basin, large volumes of detritus, from the Caledonian mountains to the north, were moved in large river systems towards the sea, the then coastline being located in north Wales. Erosion of the volcanic terrane provided an input of sediment northwards to these rivers.

Several types of intrusive igneous rock are found in the Ochils that are of a similar age to the volcanic succession. At Tillicoultry, a coarse-grained diorite stock is found on the east bank of the Mill Glen (NS 920 980) opposite the highly visible scar of the working hardrock quarry of Castle Craigs. The largest stock is found on Elistoun Hill (NS 926 990). The contacts are subvertical between these stocks and the thermally metamorphosed and much indurated rocks of the Ochil Volcanic Formation into which they are intruded. There are also narrow and short dykes of porphyrite and acid porphyrite trending NNW, ENE and E. In central Scotland the Upper Devonian Stratheden Group, locally up to 1000m thick, was laid down unconformably on an eroded surface of folded Lower Devonian rocks including the Ochil Volcanic Formation. There is no evidence of any rocks of Middle Devonian age. Thus the unconformity represents a considerable interval of time during which tectonic uplift, faulting, folding, and erosion of the Lower Devonian rocks took place.

The mainly fluvial sandstones of the Stratheden Group are known to crop out in the adjacent areas of Stirling (Stockiemuir Sandstone Formation) and

Fife (Burnside, Glenvale formations). These rocks do not crop out in the County but are likely to be found at depth. At the top of the Devonian succession aeolian sandstones become interbedded with or replace the fluvial rocks. These strata of the Knox Pulpit Formation (c.lSOm thick in Fife) indicate that Scotland, though still south of the equator, had 'drifted' into a desert belt broadly similar to the present day Kalahari desert. These aeolian deposits, though not exposed, are known to exist in the far east of the County.

The sedimentary rocks of the Devonian period in Clackmannanshire contain no fossils, although some of primitive fish are recorded not far away at Wolf's Hole Quarry, Bridge of Allan (OS 57, NS 790 981). The paucity of fossil evidence elsewhere in Scotland makes definition of the junction between rocks of Devonian and Carboniferous age uncertain.

Rocks of Carboniferous age (360-300m years ago) - Table 1 and Figure 4

The oldest Carboniferous strata record a transition from the terrestrial environments of the Devonian to the marine or coastal environments which prevailed during most of this time period.

Inverclyde Group rocks are well exposed in the River Devon and its tributaries around Muckhart Mill (OS 58, NS 993 986) in the east of the County. At the base of the Inverclyde Group is the Kinnesswood Formation, about 150m thick. It consists mainly of fluvial sandstones containing nodules of limestone. These limestone masses, called cornstones, are formed by rapid evaporation pulling salts into the soil layer where they precipitate to form the nodules. The presence of cornstones indicate a semi-arid climate, a mature landscape with periods of tectonic quiescence and reduced rates of sedimentary basin subsidence.

The Kinnesswood Formation is overlain by the coastal lagoonal sedimentary rocks of the Ballagan Formation. This unit consists mainly of mudstone with thin beds of muddy limestone, ferroan dolomite (cementstone) and nodular gypsum/anhydrite (sabkha evaporites). The formation, up to 200 m thick, records the continuing environmental change from the semi-arid terrestrial environments of Devonian times to the tropical coastal marine environments of later Carboniferous times.

The Clyde Sandstone Formation, about 100m thick, consists largely of calcareous sandstones. They are fluvial in origin with conglomerates containing cementstone clasts and algal bodies. Uplift and erosion of part of the early Carboniferous basin may have provided the source of the sediments.

The oldest rocks in the Strathclyde Group are the Clyde Plateau Volcanic Formation; a large pile of lavas, up to 1000 m thick, which extends throughout much of central Scotland. The lavas are mostly basalts and were erupted from large, low-profile volcanoes, small cones and from fissures as in Iceland today. Pyroclastic tuffs, the product of volcanic ash falls, also occur within the sequence. The existence of this formation in Clackmannanshire is surmise (Table 1 and Figure 4).

The Kirkwood Formation consists of reworked volcanic detritus immediately overlying the Clyde Plateau Volcanic Formation. Elsewhere, this formation is up to 60m thick. As a reworked volcanic deposit, it could be present at depth under the County even if the underlying lavas are not. It is surmised that the formation may have been encountered at the bottom of the Inch of Ferryton Oilwell (and see p.15).

During the rest of Carboniferous time, Clackmannanshire may be envisaged as a small part of an extensive low-relief continental margin with a pattern of sedimentation comprising a series of depositional cycles. The cycle may be repeated many times in each formation although it may not be complete: with one or more rock types not represented. A single ideal cycle is illustrated in Figure 5 and by Browne and Mendum (1995, figure on p. 13).

The sedimentary cycles of deposition are normally about 5 to 10m thick but can be over 30m. Variations in the thickness, and in the extent to which different rock types occur, give a characteristic pattern of cycles to each formation into which the Carboniferous sequence is divided. The repetition of cycles is, in part, controlled by the migration of deltas and river channels in a generally subsiding basin as well as changes in world sea-levels and by regional earth movements. The rate of compaction of soft sediments is also a factor. At times, conditions were particularly favourable to the growth of lush, tropical to boreal vegetation. The death and partial decay of these forests produced extensive coastal peat bogs now represented by the numerous coal seams in parts of the succession.

The Lawmuir Formation at the top of the Strathclyde Group, known only from borehole records, consists of mudstones, siltstones, sandstones and rare thin limestone beds. The succession is a transitional one between terrestrial and marine conditions and represents the first elements of a marine transgression onto a major land area, elsewhere in part, formed by rocks of the Clyde Plateau Volcanic Formation. Because of faulting the thickness of this formation is unknown.

At the base of the Clackmannan Group is the Lower Limestone Formation. It is 100 to 200m thick and consists of sandstones, siltstones, mudstones and several fossiliferous marine limestones. These sedimentary rocks were deposited in a shallow sea which was regularly silted up as deltas built out seaward. Coal seams are thin and insignificant.

The Limestone Coal Formation is 250 to 500m thick. It consists predominantly of sandstones, siltstones, mudstones and many coals associated with bedded ironstones. These rocks were deposited in cyclic sequence on broad alluvial plains at the terrestrial end of an extending delta. Marine strata form only a minor part of the formation. Neither this unit nor the underlying Lower Limestone Formation are known at surface in the County.

The Upper Limestone Formation consists of deltaic sandstones, siltstones and mudstones with up to seven thin marine limestones. There are a few coals and only the Upper Hirst Coal is known to have been worked to any extent.

The seam is currently mined from the Longamu'l Mine Complex, File hut working panels are located to the east of Allo.i and to the north of Clackmannan. The formation is between 320 and 5()()m Ihk-k.

The Passage Formation varies considerably in thickness from .in average of 270m to only 100m in the east near Dollar. It consists predominantly of sandstones with subordinate poorly bedded siltstones and mudstones (including fireclays), one or two thin impure limestones and calcareous mudstones with marine fossils, and some thin coals. These rocks represent a return to terrestrial, fluvial conditions with occasional short-lived incursions of the sea. Seams of fireclay are present near the base and top of the Passage Formation. Nodular ironstones at the horizon of the No 3 Marine Bed were once worked at Vicar's Bridge near Dollar for the local Forth Ironworks. During the deposition of this formation, uplift of the area may have occurred leading to breaks in the sedimentation such that the base of the formation is locally marked by an unconformity.

The Coal Measures are represented by two, generally non-marine, formations that are not shown separately in Figures 4 and 6. The Lower Coal Measures (100 to 150m thick) consist of sandstones, siltstones, mudstones and seatearth with coals, deposited on broad alluvial plains at the landward end of a delta. At least nine coals in the Lower Coal Measures have been worked and some locally exceed 1 m in thickness.

The full thickness of the Middle Coal Measures is not present in the County. Only 150 to 170m remain, the rest having been removed by erosion since Carboniferous times. The succession is generally similar to the Lower Coal Measures and includes numerous coals, most of which are less than 1m thick. The base is marked by the Queenslie Marine Band which is a persistent bed of mudstone containing characteristic marine fossils. Ironstones mainly in the Middle Coal Measures were mined at the Devon Colliery alongside the Ironworks.

Intrusive Igneous rocks of Carboniferous and Permian ages

These intrusions are composed of dolerite, and occur mainly as sills but there are a few dykes. Dolerites are hard, generally medium-grained crystalline rocks. Two types are found in the County:- olivine-dolerite, which formed at various times during the Carboniferous; more commonly quartz-dolerite, which was intruded in the early Permian (c.295 m yrs). The quartz-dolerite forms the Midland Valley Sill that crops out prominently around Stirling and forms fault intrusions associated with the Ochil Fault at Alva, Tillicoultry and Dollar. It is quarried at Castle Craigs (NS 913 977).

GEOLOGICAL STRUCTURE

The general structure in the County is only indirectly illustrated by Figure 4 but a north/south horizontal section is presented in Figure 6. The oldest Devonian rocks crop out in the north. Here, the Ochil Anticline trends ENE and the northerly dipping limb is located to the north of the Ochil

Fault. The southerly dipping limb of this fold is truncated by this Fault. The axis of the Clackmannan Syncline, a broad downfold, roughly coincides with a north-south line through Alloa with the younger rocks to be found in the central parts of the County. The axis of the syncline corresponds imprecisely with the original centre of subsidence of the Upper Carboniferous sedimentary basin (ie the formations thin to the west and east from the basin centre). There are other smaller folds such as the anticline at Dollarfield (NS 960 970) and the synclines east of Alva (NS 890 970), Tillicoultry (NS 935 980) and Dollar (NS 970 986). The last three trend E-ENE and may be rollover folds related to the development of the Ochil Fault. The structure is dominated by the Ochil Fault. It has a maximum vertical downthrow to the south of about 3000m at Alva and Harviestoun. Here it brings the Lower Devonian volcanic rocks to the north against the Carboniferous Middle Coal Measures to the south. Other faulting is common, with vertical displacements ranging from metre scale (eg in the Windy Edge Pass in Dollar Glen) to more than 750ft/240m. The major faults are aligned roughly east-west or northwest-southeast. Displacement on the faults took place relatively soon after the strata were deposited and, although many fractures were probably reactivated subsequently, there is only one record of undoubted movement in historical times (the 1736 Dollar Earthquake).

The overall pattern of folding and faulting reflects the extensional origin of the geological structure of the Midland Valley of Scotland, but minor sideways slip in a dextral, right lateral, direction took place on some faults.

Earth movements (see also p.16) still occur in Clackmannanshire (Bain 1980 and Burton and Neilson 1979) but their epicentres mainly lie north of the Ochil Fault. Menstrie is closely associated with these modern tremors and features in over half the articles about them eg -

Alloa Advertiser, May 23rd, 1905

"The Menstrie Earthquake

The earthquake is stated to have been no slight tremor, but such a convulsion as to cause articles lying on tables or hanging on walls of houses to rattle considerably while people lying in bed seemed to feel that something was interfering with that part of the earth's surface on which Menstrie stands. The earthquake ... was of short duration with no rumbling noise or tremendous explosion. Such interferences are apt to militate against Menstrie as a health resort and summer retreat, for health and pleasure seekers are like ordinary people and care not to be tossed about on the earth's surface and probably meet the fate of Korah and his company who conspired against the priests of God".

The other inhabitants of the County were not to be outdone, as is shown in the following article:

Alloa Journal and Clackmannanshire Advertiser, September 23,1905

"A Shocking Occurrence .

It looks as though the midget county was about to make a name for itself

as a centre for seismic disturbances ... the district was visited by a pretty severe shock of earthquake, the second in two months. Time was when such occurrences, as far as this district were concerned were confined to ... Menstrie, and the inhabitants of that place had ... the monopoly of earthquake lore. Now things are different and the natives of Alva, Tillicoultry and Dollar and even the aristocratic dwellers in suburban Alloa are becoming quite expert in detailing the 'symptoms'. Apparently the fashionable thing to do immediately after the manifestations have passed away is to rush out of doors in neglige costume to ascertain the extent of the damage and compare notes with one's neighbours."

The mineralisation found in faults'and joints in the rocks of the southern Ochils is thought to be of early Permian age. It is associated with the major earth movements that terminated the deposition of Carboniferous sedimentary and volcanic rocks and imposed on them the previously described structural features. The metalliferous ores are most commonly of copper, as at Balquharn, Tillicoultry and Burn of Sorrow above Dollar, with the latter pair also yielding lead ores. Silver was found at Carnaughton Glen, west of Alva and spectacularly at the Alva Silver Glen mines c.1714. Here cobalt was later also extracted, for use in pottery glazes. The 1970s description of the mines and minerals of the Ochils has recently been updated to take account of Dr Moreton's research as to the true silver mine in the Silver Glen (Dickie et al 1994, H in figure 5) and a *Scots Magazine* article is *in press* - due May 1997. The most worked non-metalliferous mineral is barytes, often red in colour due to the presence of haematite. Myreton Hill above Menstrie was once a minor source of calcite for local iron foundries during the Napoleonic Wars when other European sources were unavailable. Neither the mines for barytes nor calcite operated for long, perhaps because of impurities such as haematite, but also because of difficulty of access. The Myreton site (NS 85069807) is unique in having the only track of industrial origin up the steep scarp face of the Ochils - refreshed some years ago by bulldozing to allow access to farm vehicles, it is now more conspicuous.

Post-Permian geological history

From the Permian onwards, Scotland remained as a positive landmass, with sedimentation confined to the fringes. The landmass continued to drift northwards through regions corresponding to the present day Sahara and into the temperate belt. Evidence of the changing environment caused by this northward drift is contained in rocks formed in the post-Permian period. Unfortunately Triassic, Jurassic and Cretaceous age sedimentary rocks are unknown anywhere in central Scotland. There is no evidence therefore of the major sedimentary and tectonic events which led to the development of the hydrocarbon-rich North Sea rocks during this time. However, a veneer of Cretaceous marine sedimentary rocks (chalk) may have been deposited.

The igneous activity associated with the break-up of the continental mass and the opening of the Atlantic in Tertiary times is not represented in the County. However, the basic topographic configuration of the Devon and Forth valleys may have been fashioned by prolonged erosion during this period. The ultimate consequences of the northward shift in latitude are the ice ages that occurred in the last two million years during the Quaternary Era.

QUATERNARY GEOLOGY - Table 1 and Figure 7

The Quaternary Era was a time of extensive glaciations. However, there is little reliable evidence of the older glacial (and interglacial) events that have affected central Scotland. Indeed, most of the accessible Quaternary deposits and features in the County are less than 30,000 years old (late-Devensian and Flandrian age). Geological history during Quaternary glacial periods is described in time 'slices' called stades and interstades. These represent colder and warmer climatic episodes within a glaciation. A simplified map showing the surface distribution of Quaternary deposits forms Figure 7 and the lithostratigraphical divisions are listed in Table 1.

Pre Dimlington Stade (> 27,000 years ago)

There may be pockets of sand and gravel and beds of glacial till that pre-date the Main late-Devensian glaciation of 27,000 years ago. If so, these deposits would be found in so-called 'buried channels'. These elongate, deep hollows in the bedrock surface are probably not ancient river valleys graded to sea-levels (much) lower than present. Rather, their form is probably that of closed basins, the shape suggesting that they are likely to be glacially related scours. A major bedrock depression exists under the Devon valley (100m below OD.) from west of Menstrie to east of Tillicoultry. Interestingly, there is no evidence of similar glacial overdeepening along the line of the Forth valley between Stirling and Kincardine Bridge even though there is to the west of Stirling and also under Grangemouth to offshore of Bo'ness.

Dimlington Stade (c.27,000-13,500 years ago)

The Main late-Devensian ice sheet of the Dimlington Stade eroded the landscape producing striated bedrock surfaces, roche moutonnes and crag and tail features. Both the promontory on which Stirling Castle is sited and Abbey Craig are examples of the last landform. Erosion by the ice removed pre-existing glacial and interglacial sediments and may also have contributed to major changes in the pattern of the pre-glacial (Tertiary) river-system in central Scotland. The ice deposited substantial spreads of glacial till (Wilderness Till Formation) at its base, which it commonly sculpted into streamlined ovoid mounds called drumlins that are typical of lowland ice deposition and erosion. These 'whaleback' ridges taper downstream, thereby indicating the direction of iceflow which in the County is to the east. Clackmannan Tower is located on one such feature (Figure 3), as is Gartmorn Farm steading seen to the north of the newly signposted viewpoint (NS 920 931) at Gartmorn Dam Country Park where typical drumlin scenery abounds. Other drumlins include Lornshill in Alloa.

The till (ground moraine) is generally 4 to 18m thick. Typically the till is dark grey, with a sandy, silty clay matrix containing 'floating' pebbles, cobbles and boulders. Not surprisingly, the local till contains much lava debris in the Ochils where it is found to heights of over 600m OD. on the valley sides.

In the Forth valley area at the acme of glaciation, the 1 km-thick Main late-Devensian ice sheet probably extended 30 or 40km beyond the coast of east Fife. After this ice sheet began to retreat about 16,000 yrs ago, substantial volumes of glaciofluvial sand and gravel (Broomhouse Formation) were deposited by the meltwaters. These ice contact deposits often have characteristic landforms such as mounds, eskers (ridges) and kettle-holes. Such deposits and features are present in the Devon valley east of Tillicoultry and include the Cunninghar ridge (NS 925 973). Meltwater transport was generally eastwards in the Devon valley towards Loch Leven in Kinross-shire, but also north-eastwards at an early stage through the valleys of the Ochil Hills to Glen Devon and to Glen Eagles.

When a thick ice-sheet forms, it imposes a heavy load on the earth's surface. The crust responds by warping downwards, the amount of downwarp being greatest at the centre of accumulation and diminishing to zero a short distance beyond the edge of the ice-sheet. Unloading by melting of the ice is accompanied by crustal uplift (isostatic recovery) in the area of previous depression. The return of water to the oceans from melting land-based ice reverses the effect of world sea-level lowering that occurs during an ice age when water is extracted from the sea to form the ice. The interplay of the local isostatic recovery with world sea-level changes has caused fluctuations in relative sea-level in the Forth area. These are marked by raised beach features and by raised marine deposits.

During deglaciation, local relative sea-level was high in central Scotland and it is not uncommon to find raised marine sediments at about 40 to 45 m above OD. in the Forth and Devon valleys. In this area, the decaying glaciers retreated westwards towards the Highlands. In detail, the retreat of the glacier appears to have halted briefly at Stirling (c.13,500 years ago) where the valley is constricted at the Castle Rock. In the Devon valley, the Cunninghar ridge sand and gravel may have been deposited as the last act of the westward retreating glacier hereabouts. By about 13,000 years ago, the sea had invaded the upper Forth reaching Aberfoyle and occupied the Devon as far east as Dollar. The marine sediments associated with the deglaciation of the Forth valley are finely laminated clay and silt (Loanhead and Kinneil Kerse formations) which contain macro- and micro-fossils which indicate that the local climate was arctic.

The most conspicuous (to geomorphologists only!) of the former coastlines associated with deglaciation in the Forth is the Main Perth Shoreline, tenuously dated to around 13,500 years ago. It has not been recognised west of Alloa (see Figure 8A). The raised beach intertidal platforms may be recognised either by the landform or the presence of sand and gravel (Killearn Formation).

Windermere Interstade (13,500-11,000 years ago

Late-Devensian seabed sediments characteristic of the fully deglaciated sea lochs of the Forth and Loch Lomond area are usually rather massive-looking silty clays (Linwood Formation) which commonly contain many marine fossils. The fauna indicate that the climate was warmer than that before 13,500 yrs ago. Drop-stones in the sediments were probably derived from the melting of rafts of winter shore-ice rather than calved icebergs. The Abbotsgrange Formation in the Grangemouth area, by exception, consists of well-layered pro-delta sediments. Raised beaches, composed of sand and gravel, at Tullibody, Alloa and Kilbagie provide evidence that during the Windermere Interstade local relative sea-level fell from c.40m above OD to present, or below, before glaciers reappeared in central Scotland during the Loch Lomond Stade. During the Interstade the local landscape was largely devoid of trees except for stands of birch, and generally tundra-like with dwarf birch and shrubs, such as crowberry and juniper, sedges and grasses.

Loch Lomond Stade (11,000-10,000 years ago)

The Loch Lomond Stade ice accumulated on Rannoch Moor and in the high corries of the southwest Highlands and advanced into lowland areas to reach Callander and Lake of Menteith in the Teith and Forth valleys respectively. Beyond the ice margins such as in Clackmannanshire, the interstadial soils were destroyed and eroded as much of the local vegetation was killed by the cold leaving open tundra dominated by patches of grasses, sedges and dwarf shrubs. Frozen ground (permafrost) developed and frost wedge casts formed. Materials were also moved downslope by freeze-thaw action. Such solifluction deposits have not yet been identified on geological maps of the County, but they are likely to exist in the Ochils and mantling hillslopes in places on the Clackmannan 'Ridge'.

During the Loch Lomond Stade local relative sea-level in the Forth valley is known to have fallen below that of the present day (Figure 8B). In the Grangemouth area, where the Main Lateglacial Shoreline is widely developed at about OD, it is generally agreed that the level of the sea may have fallen to around 10m below OD. The associated shore platform is normally covered by the 'buried gravel layer' (Bothkennar Gravel Formation) which is usually only about a metre thick. Formation of the platform and the cliffline has been ascribed to enhanced marine erosion under the prevailing periglacial conditions, but shoreline inheritance may also have played a part.

Flandrian Interstade (< 10,000 years ago)

About 10,000 years ago, there was a major change in the climate that may have taken place in as little as a hundred years. This was associated with the disappearance of glacial ice from Scotland. From arctic conditions, the climate improved such that birch woodland was widespread within 1000 years. At the postglacial optimum about 6500 years ago, the local climate was warmer and wetter than at the present day and the local landscape dominated by mixed forests of birch, oak, hazel and elm.

From the low during the Loch Lomond Stade, local sea-level rose early in the Flandrian due to the return of water to the oceans from melting land-based ni' around the world. The 'High', 'Main' and 'Low Buried Beaches' (at about 8, 7m and over 6m above OD near Menstrie) in the Forth valley formed on the following fall of relative sea-level due to continuing isostatic recovery after the retreat and decay of the Forth Glacier (see Figure 8C). On the exposed surfaces of the deposits of clay, silt and sand, peat was able to accumulate and thus form the well known Sub-Carse Peat which is 0.2-lm thick in this area (Figure 8D). The basal peat on the 'Main Buried Beach' dates from about 9600 yrs ago and on the 'Low Buried Beach' from about 8800 yrs. The deposits of the buried beaches have been assigned to the Letham Formation which contains an impoverished estuarine fauna.

When the main Flandrian marine transgression started aabout 8000 yrs ago, most of the Sub-Carse Peat was drowned. Extensive fine-grained estuarine sediments of the carse clay were laid down (Claret Formation) in the estuary burying the peat and the underlying High, Main and Low Buried beaches (Figure 8D). The carse clay contains a diverse boreal fauna including the remains of large whales which have been found as far west in the Forth as Cardross near Menteith about 28km to the west of Alloa. Of course, whales have been known to reach Alloa in more recent times and on one occasion a local business man bought the carcase and toured the area charging to view it. Its skeleton is believed to be in the Natural History Museum in London.

In the period between 8000 years ago and the acme of the Flandrian transgression, around 6500 years ago, the whole of the Forth valley-floor west of Stirling silted up as did the Devon valley. At the acme, local relative sea-level reached a maximum of about 16 m above OD in the Aberfoyle area and 13 m above OD in the Devon valley because of the slope on the fossilised estuarine surface caused by the isostatic tilting of the land. This tilting was in response to the continuing relief of the much more significant Main late-Devensian ice loading rather than that of the Loch Lomond Stade.

The Main Flandrian Shoreline, with which these levels are associated, has been widely recognised in the Forth valley from east of Grangemouth to Aberfoyle. It is recognisable north of Cambus and west of TulIibody, in northern Alloa, south of Clackmannan Tower and in the Devon valley. When this shoreline formed about 6500 years ago, the sites of the Hillfoots burghs, Falkirk, Stirling and Aberfoyle were coastal. A Lower Postglacial Shoreline and extensive abandoned intertidal mudflats occur to the south of Alloa and Clackmannan. The Grangemouth Formation, which consists of clay, silt and sand, includes present-day and reclaimed intertidal and subtidal sediments.

As central Scotland is an area of significant overall postglacial fall in sea-level, the consequent incision of the drainage has produced scenically attractive river gorges such as the River Devon at Rumbling Bridge and the Cauldron Linn Waterfall, and the spectacular, partly fault-controlled gorge of Dollar Glen. Features of river erosion in these gorges include potholes and

caves. During deglaciation, the waters of the upper part of the Devon catchment flowed eastwards to Loch Leven. The Rumbling Bridge Gorge, initiated as a late stage feature in deglaciation, probably represents a fine example of river capture, causing the headwaters to flow westwards to join the Forth. The River Devon in its lower reaches is meandering, locally with cut-off channels on the floodplain. Our influence on this river, floodbanks apart, include localised examples of uncontrolled waste disposal.

RESOURCES AND OTHER ENVIRONMENTAL ISSUES

Sand and gravel deposits are a valuable source of aggregate and have been extracted locally. Glaciofluvial deposits are the most common but the extensive alluvial cone deposits of the Devon valley may contain large quantities of sand and gravel and boulders. Bings of colliery waste have potential for use as bulk fill, for provision of mudstone for brick-making or for the recovery of their coal content. Tips in the region have been landscaped and much of the material redistributed and used in land reclamation and in industrial redevelopment. Locally the fine-grained deposits of the Claret (carse clay) and Loanhead formations could be exploited for brick and tile manufacture as the latter has been at Hilton near Alloa.

In the past the main natural resource within Clackmannanshire was deep-mined coal but prolonged extraction from over 250 shafts and adits sunk since about 1650 has depleted the reserves to such an extent that large-scale underground mining is now limited to extraction of the Upper Hirst Seam at the Longannet Complex. Polluting waters from abandoned mines have been, and are, an ongoing environment problem (Forth River Purification Board 1995-6). Opencast coal has already been obtained from the Lower Coal Measures. Opencast coal extraction can be an economic way of preparing unstable land underlain by shallow mineworkings for future development, but also environmentally disastrous for people and wildlife.

Hydrocarbons have been prospected for with little success at Inch of Ferryton (NS 90 90), south of Clackmannan by Tricentrol Oil. A local newspaper headline at the time declared 'Oil rigs in the Ochils?' wrongly suggesting an interest in Lower Devonian volcanic rocks. Commercial activity is centred currently on coal-bed methane.

There are resources of hardrock aggregate in the County from the outcrops of quartz-dolerite and especially in the thermally metamorphosed volcanic rocks which are currently exploited at Castle Craigs Quarry (NS 913 977), Tillicoultry. Sandstone is found throughout the local sedimentary sequence and some beds were formerly quarried for building stone. Sandstones of the Passage Formation have potential as a source of silica sand. Alloa is where much of the local crushed sandstone is processed into glass. There are resources of fireclay in the Passage Formation and to a lesser extent in the lower part of the Lower Coal Measures which could be worked opencast.

Metalliferous ores, including lead and barytes, are present in Lower

Devonian rocks. Silver and cobalt were once mined in the Ochil Hills as noted above at p.10.

Groundwater has not been a key resource in the area for water supply, but it is likely that its development, particularly in the Passage Formation, will take place as the cost of water increases. Alloa is noteworthy for its two breweries. The Thistle Brewery of Maclay and Co Ltd. is the only one in Scotland still with its own water supply. The brewing industry in Alloa was established in the late 19th century because of available 'Burton' type groundwaters in the underlying Carboniferous rocks. The sandstones of the Lower Coal Measures and Passage Formation are permeable to some extent, with faults and interbedded mudstones making the aquifer rather complex. Abundant recharge is available allegedly from the streams of the Ochil Hills. The Brewery has two 183m deep supply boreholes drilled in 1924 and 1952. During 1983, the older well dried up and a television inspection by the British Geological Survey revealed that the walls had become encrusted with iron hydroxide deposits. The cause of this precipitation was the mixing of shallow oxygenated water with deeper highly reducing waters which carried iron in solution. The well was reamed out to a bigger diameter and output then returned to normal.

Geothermal power may be available from deeply buried aquifers such as the aeolian sandstones of the Upper Devonian Knox Pulpit Formation (Table 1).

The importance of running waters to the area during the industrial revolution was reflected in the number of woollen mills, the wood dam in Tillicoultry Glen and lades to power drainage operations in the mines etc. The fast flowing streams emerging from the glens at the foot of the Ochil scarp have built alluvial cones where the marked change in slope causes rapid deposition of the transported sediments as the water velocity is suddenly checked. Historically these areas were perceived as dry sites relative to the then poorly drained valley floor and so the earliest Hillfoots settlements were located on them. However the Tillicoultry flood of August 1877, after a deluge of rain, was associated with a wall of water about 2m in height coming down the Burn with tragic and considerable financial consequences. In this town and also Alva, recent building has taken place on land once regarded as problematical because of drainage difficulties.

Although most geohazards affecting Scotland (as at p.9 above) are not likely to be on the scale represented by volcanic eruptions or large earthquakes with major loss of life, the financial burden caused by landslip, collapse of mineworkings etc. could be significant locally. Examples include

Alloa Journal, August 13,1927

There is a good deal of divergence of local opinion as to the cause. This may be ... due to the giving way of the underground workings of a long-disused colliery known as Harper's Neuk. It was understood that this colliery had been worked on what is known as the 'stoop and room'

principle, pillars of coal being left in as supports. However the Harper's Neuk colliery which was closed over 130 years ago was only in operation a short time. The theory is therefore gaining ground that the subsidences were due to a kind of earthquake possibly occasioned by some geological 'fault' in the strata beneath the area where the sinkings took place."

Alloa Advertiser, June 28,1952

> "River Devon Disappears 'No danger' says Coal Board Official.
>
> The Black Devon has disappeared - for its last two miles it is only a black mud channel, punctuated with old tyres and barrels, along which the tide swirls and falls back. The river water is going down a hole, possibly forty feet across, which, the guess is - leads to old Shore pit workings. On Wednesday it was discovered ... the water was running over a small waterfall and disappearing down into this hole. Not only river water was going down the hole. With every tide the salt water from the Forth came flowing up and poured down the hole, which is half a mile below the tidal limit. The Coal Board believe that new mining under very old workings has caused the supports in the old works to collapse, bringing down the roof and the bed of the river."

Alloa and Hillfoots Advertiser, May 1,1992

> "Probe into mystery of earth tremors
>
> Castlebridge Mine is to commission a major study to try to discover the cause of mysterious earth tremors which are shaking the Forestmill area. Frightened residents heard that pit officials are as baffled by the tremors as they are."

Landslips have happened in the Hillfoots in the areas of the brown forest soils and skeletal soils that cling to the steep face of the Ochils (Figure 1). One recent notable example occurred in the early hours of Sunday 4th November 1984, when a slope failure on Myreton Hill allowed c.350m of debris to slip downhill. A combination of soil cover type - Brown Forest Soil over glacial till with a sandy matrix, the intense storm on the 3rd/4th November (which followed a long period of above-normal precipitation) and the slope of the hillside (between 30° and 40°) contributed to the slip which resulted in Broomhall Cottage being inundated by the flow of debris. Up to 1m depth of material entered the house through doors and windows. Evidence of the force of the flow of material was provided by the formation on the transport slope of a natural trench up to 2m deep which was not evident before the event. The back feature of the 'Main Postglacial Shoreline' at the Pleasure Grounds in Alloa has also been affected by landslip. Coastal erosion and flooding may be enhanced by rising sea-level associated with the greenhouse effect thus threatening areas of reclaimed land east of Alloa and also the Inches.

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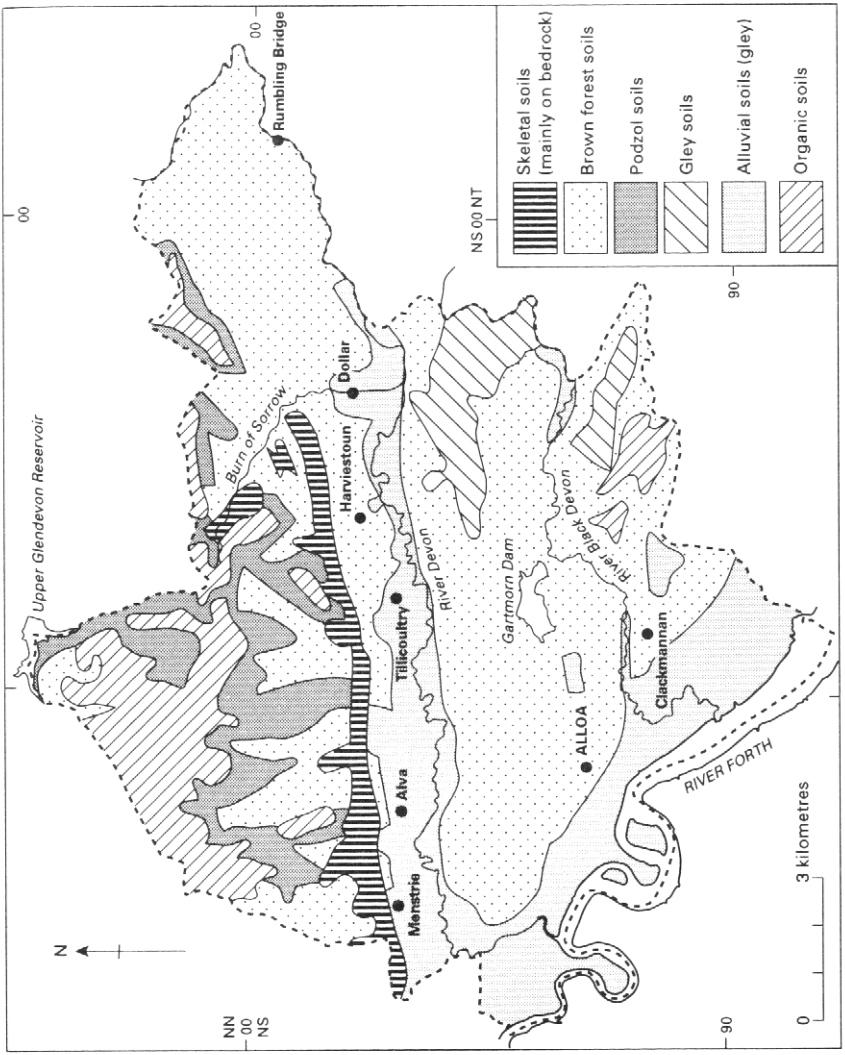

Figure 1. Clackmannanshire Soils.

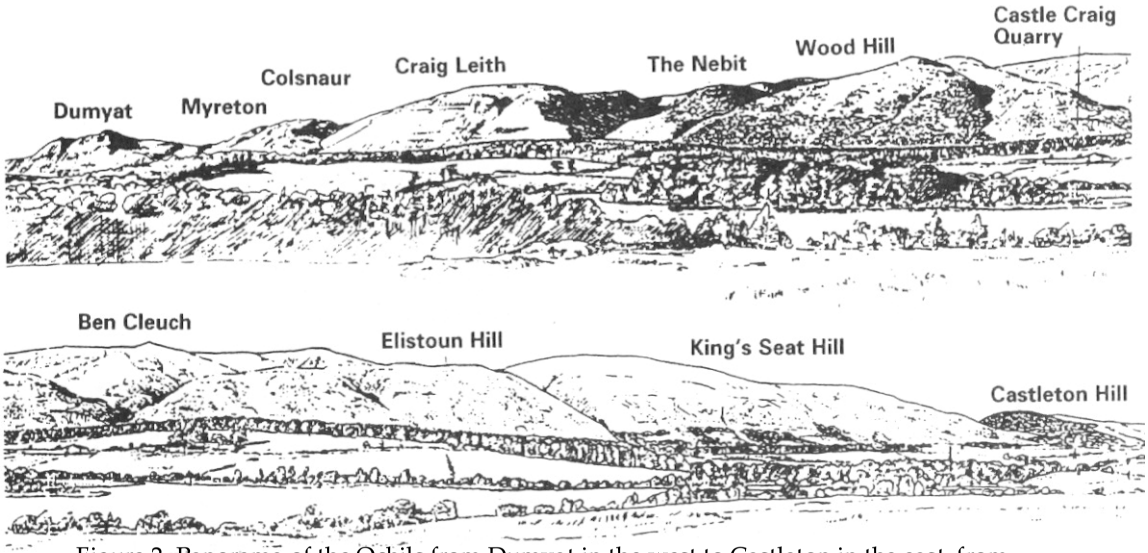

Figure 2. Panorama of the Ochils from Dumyat in the west to Castleton in the east, from viewpoint south of Gartmorn Reservoir (OS 58 920931)

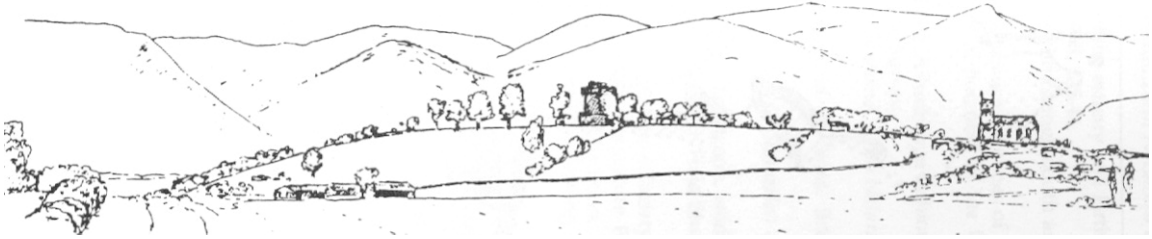

Figure 3. Clackmannan 'Ridge' - glacially streamlined drumlin hill underlying Clackmannan Tower, viewed from the south—ice movement was from west to east.

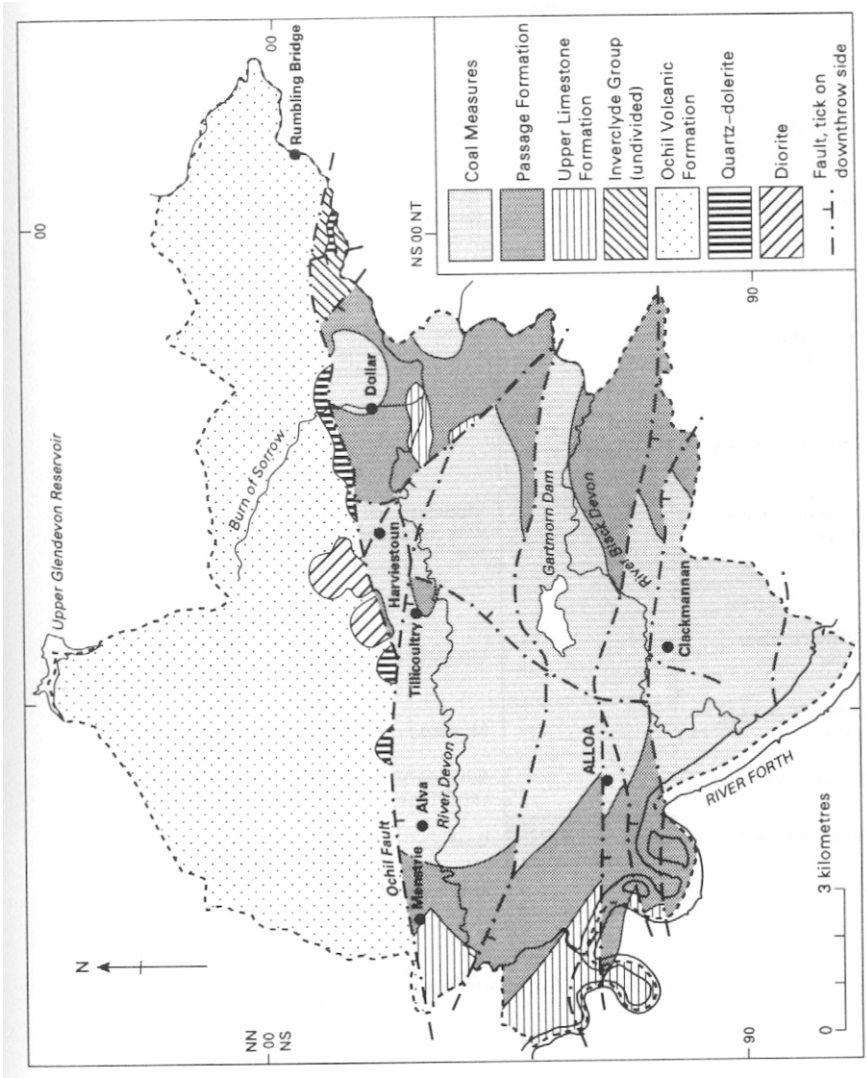

Figure 4. Bedrock geology map of Clackmannanshire.

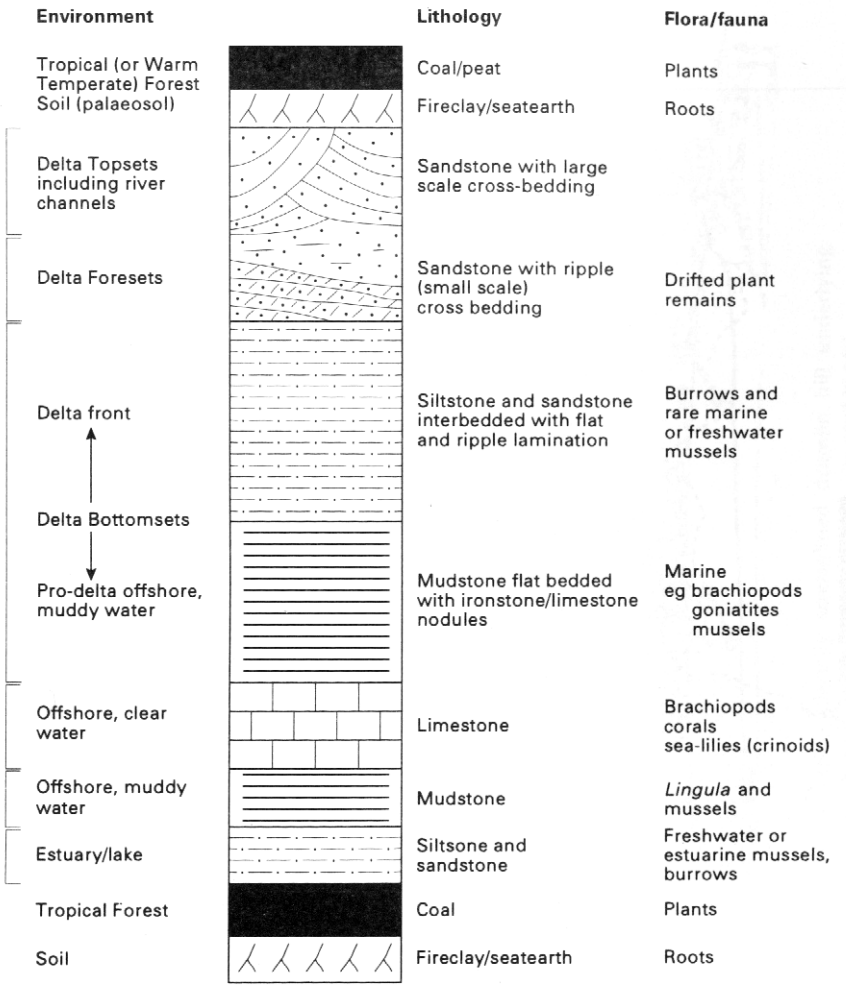

Figure 5. Typical Carboniferous sedimentary cycle.

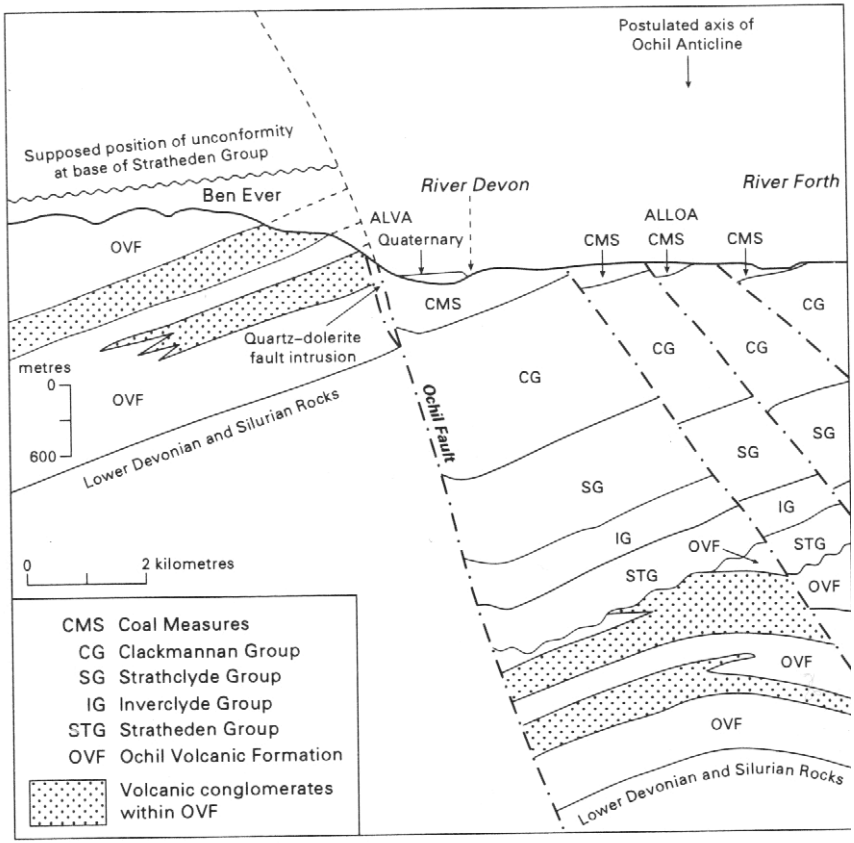

Figure 6. North-south geological cross-section from Ben Ever to the River Forth.

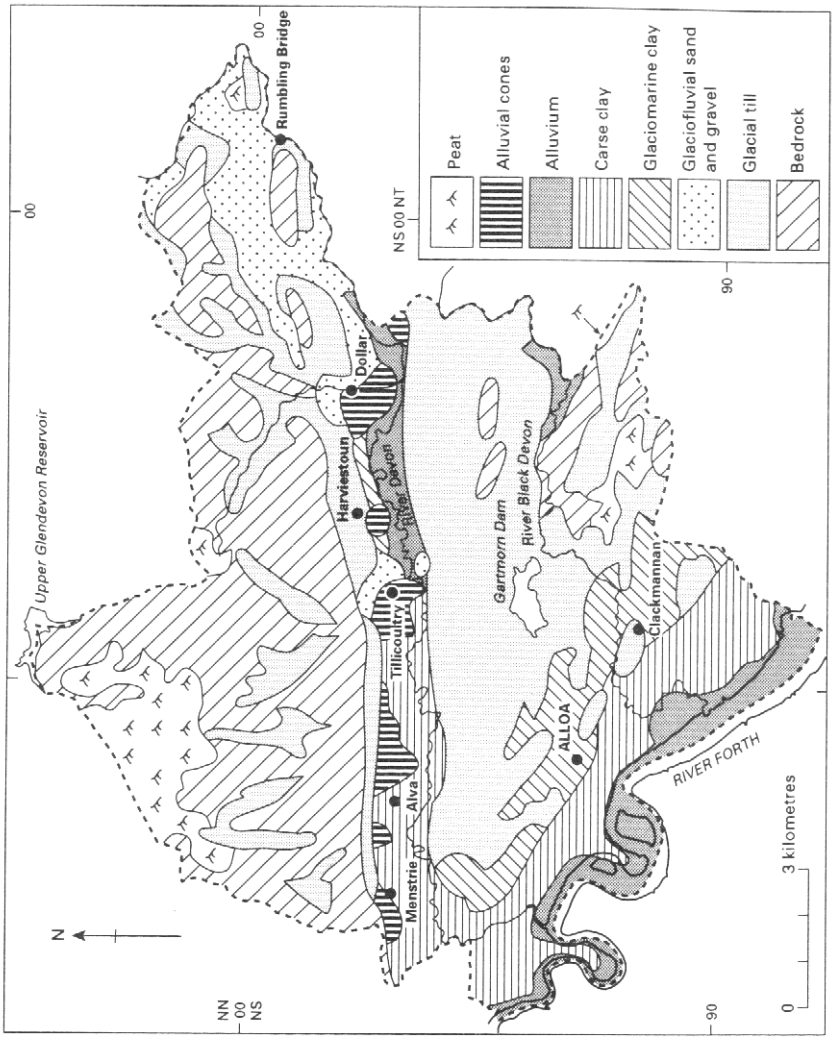

Figure 7. Quaternary geology of Clackmannanshire.

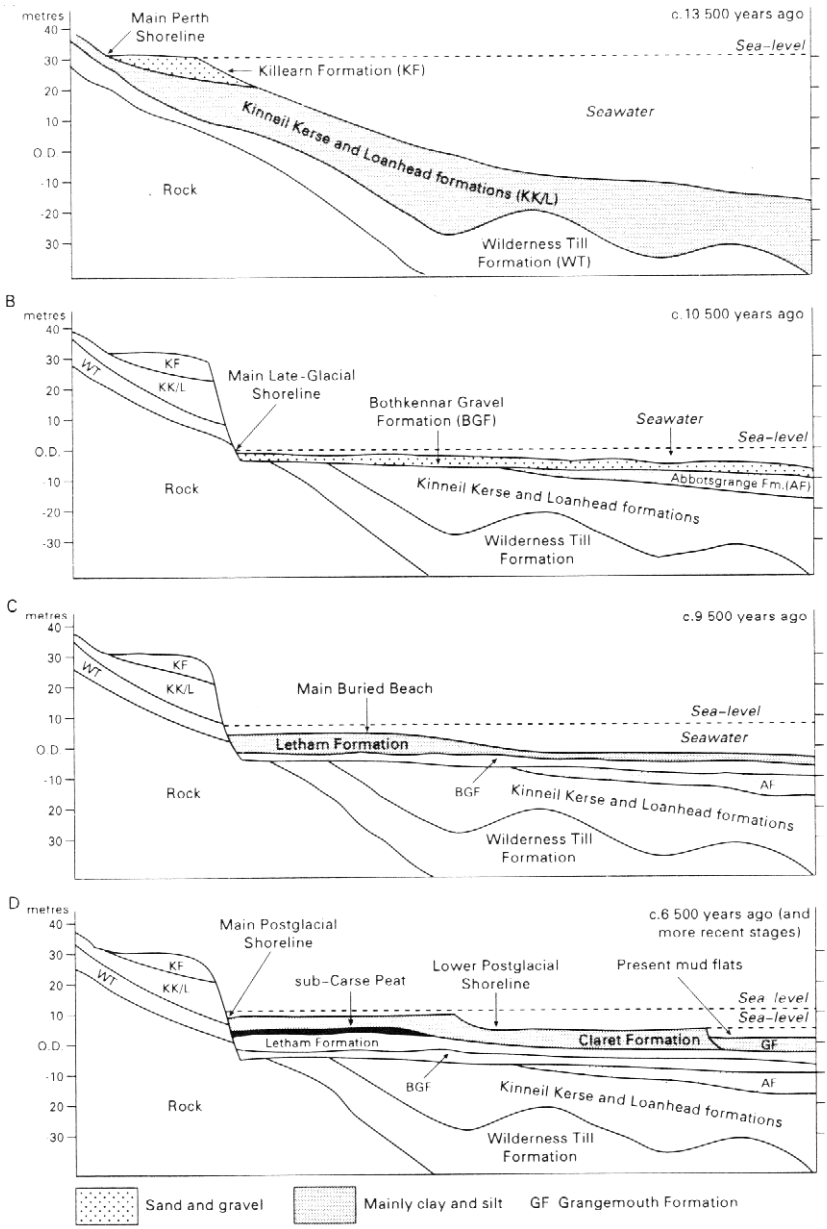

Figure 8. Diagrammatic sections throuhh time to show relationships between the Quaternary sediments, former beaches and sea levels, in the Alloa area of the Forth.

Reviews (Naturalist)

Loch Lomond: showing the West Highland Way, Ardlui to Milngavie. Ordnance Survey, Outdoor Leisure map 39, 1:25,000 (2///mile). ISBN 0-319-26065-8. £5.40.

Double sided, full colour, it traces the route of the Way right from Milngavie to Inverarnan and Glen Falloch, and the whole length of Loch Lomond. Its great detail includes mountain rescue facilities and visitor information - car parks, boat hire, and cruising bases, camp sites, information centres, picnic areas, viewpoints, public toilets, youth hostels.... Spread out for study it takes up a full 4' x 3' of floor. The southern area side, landscape format, stretches from Milgavie to Balmaha, includes the south end of Loch Lomond, the Clyde river from Dalmuir/Erskine Bridge through Dumbarton to the Firth beyond Greenock into the south end of Loch Long. The other side, picturewise oriented, details the Way Balmaha to Inverarnan and Glen Falloch; eastwards from Inversnaid through Loch Arklet and Loch Chon with Stronachlachar and part of Loch Katrine; westwards are upper Loch Long, Arrochar, the Alps, Loch Sloy.

Truly here is a real mine of information, and pleasure.

LC

Discovering the River Forth. William F. Hendrie. John Donald ISBN 0.85976.438.9. £2.50.

This interesting and informative book takes the reader through 18 chapters for a walk down the shores of the Forth from Aberfoyle to Queensferry. The narrative, which is easy to read and in a lively style, is interspersed with reminiscences of the author, and a wide variety of historical anecdotes ranging from a secret nuclear bunker at Aberfoyle, to the early Carron engineer presented with the seeds of a new root vegetable by the King of Sweden - now known as 'swedes'! The material covered is exclusively 'social' history, and no attempt is made to include any 'natural' history.

The title is also somewhat misleading in that, according to many sources (e.g. Royal Society, Edinburgh, 1987), the 'Forth' from Aberfoyle to Stirling is 'River', Stirling to Queensferry being tidal, and progressively saltier, is regarded as 'Estuary'; and beyond Queensferry is 'Firth'.

Whilst the book has an index, it has no references on sources of further reading - which might have included some natural history! Even substantial quotations are inadequately referenced. This is a considerable shame as readers have no help to delve further into any topic that may take their fancy. Despite these reservations it is a treasury of information on the towns and villages of the 'Forth Valley', and we can only hope that author and publisher might remedy these matters in any future editions.

D. McLusky