Scottish Borders geology: an excursion guide

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(Front cover)

(Frontispiece 1)

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Introduction

The Scottish Borders Region is an area of rolling hills mainly formed by Lower Palaeozoic greywackes. Long river valleys such as those of the Whiteadder, Ettrick, Teviot and Jed waters, drain to the north-east along the structural grain of the rocks, into the River Tweed. More mellow landscapes in the Merse are produced by a glacial drumlin cover on softer Devonian and Carboniferous sedimentary rocks, locally punctuated by abrupt volcanic hills. Cliffs along the entire North Sea coast spectacularly expose the geological structure of the region.

Population is concentrated in the valleys around market, mill and rugby centres such as Hawick, Galashiels, Melrose, Kelso, Selkirk and Jedburgh. Sheep-farming is dominant on the upland hills, whereas the proportion of arable farming becomes larger eastwards into The Merse. Forestry clothes ever increasing portions of the region.

Access to the region is by train to Berwick on the Edinburgh to London east coast line, by air to Edinburgh or Newcastle airports, or by bus to any of the major towns. Within the region private car or coach is advisable; most roads are readily accessible but many are not served by public transport. Local service buses, of which Lowland Scottish is the main operator, link the main towns and villages (Map inside front cover).

Geological history

Geographically a part of the Southern Uplands, the greater part of the region is underlain by a thick sequence of Ordovician and Silurian greywackes, siltstones and shales (Plate 1). These form a distinctive geological terrane separated from the Midland Valley of Scotland to the north-west by the Southern Upland Fault and locally overlain with marked unconformity by Old Red Sandstone strata. The foundations for our modern understanding of Lower Palaeozoic geology in the south of Scotland were laid by Charles Lapworth in 1878. That was the year of publication for his seminal work *The Moffat series* which not only established a comprehensive stratigraphy for the region but, in so doing, erected a biostratigraphical zonal scheme, based on graptolites, which has remained fundamentally unchanged to this day. Aided by Lapworth's insight into what had previously been regarded as an enormous thickness of intractable shales and greywackes, the subsequent Geological Survey revision by Ben Peach and John Horne made remarkable progress between 1888 and 1898; remarkable since much of the work was done during the winter months when the Highlands were considered inaccessible. The resurvey culminated in the publication of the monumental memoir *The Silurian Rocks of Scotland* (Peach and Horne 1899) which, following contemporary practice, regarded the Ordovician as the 'lower Silurian'. This account, and the new series of revised geological maps, illustrated Peach and Horne's interpretation of the Southern Uplands as a relatively thin sequence subjected to widespread and intense, tight to isoclinal folding. The basal shale sequence, unravelled by Lapworth and identifed as the Moffat Shale, was thought to be exposed in the hinge zones of periclinal antiforms; hence the characteristic 'flattened bull's eye' structure of the shale inliers shown on the Geological Survey maps based on that phase of mapping. Unhappily these structures owed more to interpretation than to observation since actual fold hinges were rarely seen and Peach and Horne had no way of deducing the sedimentary younging direction of steeply inclined greywacke sequences. That facility allowed the next major advance in Southern Uplands' geological understanding but had to await developments in sedimentology during the middle part of this century. Nevertheless, the principal stratigraphic domains recognised are still valid and Peach and Horne's nomenclature remains in common usage: a Northern Belt consists entirely of mid to late Ordovician strata, shales and greywackes in the Central Belt range up through the Llandovery (early Silurian), and the Southern Belt is restricted to the Wenlock (mid-Silurian). Various aspects of the Northern and Central belts are addressed by the excursions in this guide and the belt boundaries are shown in (Figure 1) and (Figure 2).

The greywacke, siltstone and shale sequences are now interpreted as repetitive cycles, the deposits from a succession of turbidity current flows. Each individual flow, a high-density mass of sediment suspended in water, moved rapidly down the flanks of an ocean basin. As it lost momentum the transported sediment settled to the ocean floor, first the largest grains followed by successively smaller particles. Thus the greywacke sandstones produced are commonly graded with beds showing a coarse-grained base and a fine-grained top. The very fine-grained sandstone and siltstone forming the uppermost part of the bed are often laminated and may show cross-lamination produced as the sediment was reworked by the waning turbidity current from which it was deposited. Between turbidity flows normal pelagic sedimentation laid down black shales which, in the Southern Uplands, are locally graptolitic. Bed thickness, lithological texture and the relative proportions of the different components present (greywacke : laminated siltstone : shale), are governed by the size and frequency of the turbidity flows and the position of the depositional area in relation to the source of the flow. Ideally, differing 'turbidite' lithological sequences can be related to their position within the huge submarine fans built up by, perhaps, many thousands of individual flow events. With time the turbidite sequence advanced across the pelagic deposits of the ocean floor so that the transition from one facies assemblage to another is diachronous. In the north of the Southern Uplands greywacke rests directly on Llandeilo shale and chert whereas, farther south in the Central Belt, the shale extends well up into the Llandovery (Figure 3). In its fullest development Lapworth (1878) recognised three stratigraphic divisions within the Moffat Shale; a lower unit of Llandeilo–Caradoc age (the Glenkiln Shale), a middle unit of Caradoc–Ashgill age (the Hartfell Shale), and an upper unit of Llandovery age (the Birkhill Shale).

The 'turbidite' beds within the Southern Uplands Lower Palaeozoic sequence range in thickness from several metres to only a few mm. Coarse, gravelly bases are widely developed, especially in the north, and the bases of the beds are commonly marked by a variety of 'bottom structures' produced by either of two main processes. Firstly, some bases are marked by broadly linear protuberances which are the casts of original hollows on the sea floor; hollows produced either by the scouring action of currents or the scraping of the seabed by solid objects carried along by the current. Secondly, very much more irregular bulges on the bases of beds were produced within the unconsolidated sediment pile as the greywacke sandstones, influenced by uneven loading as more sediment was deposited above them, sagged downwards into the underlying and more mobile silts and shales. The presence of such irregular 'load casts' confirms a surface as the base of a bed but the linear features in addition give some idea of the flow direction of the original ocean currents. Linear 'groove casts' simply indicate a trend such as NE-SW but where the linear features have a degree of asymmetry they are called 'flute casts' and can be used to calculate a specific azimuth for the flow direction. However, before such assessments can be made the beds must be geometrically restored to the horizontal which requires an understanding of the structural geology.

it is clear that most of the succession youngs towards the north-west, with many beds slightly overturned to dip steeply SE. Where folds are seen they are usually tight anticline - syncline pairs with either gently or very steeply plunging hinges. These do not interfere with the overall trend of younging towards the north-west but larger tracts of country, showing the reverse trend of younging towards the south-east, are difficult to relate to fold structures and seem more likely to be related to major faults. The dominance of NW-directed younging is also at odds with the overall age relationships across the Southern Uplands; a glance at any geological map of the area shows that the oldest rocks crop out in the north-west and the youngest in the south-east. This apparent paradox is brought about by a series of major strike faults, all with relative downthrow to the south (in terms of their present attitude), which divide the region into a number of discrete structural blocks (Figure 1). The oldest rocks in each block occur to the immediate north-west of the south-east boundary fault and thence the sequence youngs generally northwestward so that the youngest rocks in each block are at its NW margin. Progressively older strata form the base of each block sequentially towards the north-west

(Figure 2) to produce the overall stratigraphic pattern. In the northernmost structural blocks spilitic lava, chert and black shale form the base of the sequence, overlain by greywacke; in the more southerly blocks only shale is seen below the greywacke.

The structural and stratigraphic relationships seen in the Southern Uplands can most readily be produced by thrusting, whereby tectonic slices of older rock are emplaced above younger strata, followed by rotation of the thrust stack to the vertical. Such a process is inherent in the most widely accepted model for the development of the Southern Uplands, the 'accretionary prism' model formulated by Leggett *et al.* in 1979. This envisaged the greywackes being deposited in a deep ocean trench at an active continental margin of the early Palaeozoic Iapetus Ocean where the oceanic plate was subducting north-westward. As the oceanic plate descended its covering of sediment was scraped off and stacked at the continental margin in a series of thrust slices (Figure 2a). Since greywackes would only be deposited abovethe pelagic sediments covering the oceanic plate as it approached the trench, the age of the greywackes in each thrust slice becomes younger. Final rotation to the vertical was caused by continental collision as the ocean closed completely in the late Silurian or early Devonian. The accretionary prism model elegantly explains the overall geological relationships within the Southern Uplands but many more detailed structural and stratigraphic problems are still difficult to reconcile. In particular, a close examination of the compositions of individual sand grains within the greywackes show marked differences between adjacent beds in the same structural block and between the blocks themselves. These differences are particularly marked in the Ordovician sequence and form the basis of the lithostratigraphic divisions shown in (Figure 1) and (Figure 2). Two distinct provenances are indicated and palaeocurrent analyses of bottom structures suggest a mature continental margin to the north and north-east and an active volcanic island arc to the south and south-west. Hence, in an alternative interpretation, the early history of the Southern Uplands was within a back arc basin which Stone et al. (1987) developed into a sequential back arc to foreland basin thrust system following continent-arc collision (Figure 2)b in the early Silurian. Whichever model is preferred the essential thrust geometry is fundamentally the same and has one important rider; the thrust-related deformation was diachronous, with structures in the north-west of the Southern Uplands formed before those in the south-east. This process has been partly quantified by Barnes et al. (1989) but its understanding remains dependant on graptolite biostratigraphy, the same graptolites studied by Lapworth over one hundred years ago.

By the end of the Silurian, accretionary and igneous activity at the continental margin during the closure of the Iapetus Ocean had constructed a sizeable range of mountains. This was then subjected to erosion throughout the Devonian Period. During the early Devonian, depositional basins which developed in Lauderdale and north of Duns, were filled with thick breccias and conglomerates; contemporaneous volcanic activity produced mainly andesitic lavas in the Cheviot Hills and at St Abb's Head. Further orogenic activity in Middle Devonian times tilted the land surface prior to erosion so that the Upper Devonian has a marked unconformity at its base. The Upper Devonian sediments were deposited in a more extensive basin and record a transition to semiarid conditions in which fluvial sandstone and mudstone were deposited and cornstone represents original soil horizons.

In the south of the region the beginning of the Carboniferous was marked by an episode of volcanic activity. The basaltic Kelso Traps were erupted whilst associated plugs, vents and dyke swarms were intruded into the older Devonian and Silurian rocks. In the north of the region changing conditions produced a conformable transition from desert red sandstones into the tropical swamp accumulations of the Carboniferous. Extensive, slowly-subsiding depositional basins developed in the Merse, offshore from Berwick to the east and Cockburnspath to the north, though on land in the region only the lowest beds of the Carboniferous are now preserved.

Cyclical deposition dominated the Carboniferous Period. Carboniferous Limestone cycles are mainly fluviatile and the deltaic sandstones interbedded with finer siltstones and mudstones are indicative of quieter shallow lagoonal conditions. Cementstone bands and anhydrite layers, together with sun-cracks and rain-pits on some beds, indicate periodic dessication. Fossil remains are confined to plants and non-marine faunas of low diversity. Marine incursions became increasingly frequent later in the Carboniferous resulting in the formation of marine shell beds and marine limestone. During the intervening regressions coastal forests formed on the emergent land, their remains now seen as root-beds and seams of coal.

Apart from a few large Tertiary dykes, crossing the region with a generally NW–SE trend, there is no geological record of events from the Carboniferous until the Quaternary ice-age. For much of the last million years Scotland has been repeatedly covered by ice-caps. In the Borders region, ice generally flowed north-east, away from the high central part of the Southern Uplands, leaving striations, crag-and-tail features, roches moutonnees and drumlins as evidence of its passage. The drumlins, oval shaped mounds formed of till, have a widespread distribution but are particularly concentrated in the Merse. Everywhere the accumulated stone and clay ground moraine left by the ice-sheet blankets the low-lying ground and fills many valleys. Some 15 000 years ago, when the ice-sheet began to melt, some of the higher hills became free of ice whilst glaciers still filled the valleys. The glacial meltwaters cut channels, many now abandoned as dry valleys, deposited sand and gravel as eskers and kames, and carried silts and clays to be laid down as alluvium and raised beaches along the coast. Rivers have continued this erosion, depositing alluvial clay, silt, sand and gravel in their flood-plains. By contrast with other regions, man has had limited effect on the landscape through quarrying, metalliferous mining, and the construction of dams and embankments.

Graptolites from the Southern Uplands of Scotland

Graptolites are an extinct group of small colonial animals that dominated the plankton in the Ordovician and Silurian oceans. Their skeletons were built of a tough fibrous protein material and were constructed with wonderful regularity. Each colony accommodated many (sometimes >1000) individual polyp-like zooids, each of which inhabited a tubular cell or 'theca'. The regularity of each colony imparts to each a characteristic appearance and allows recognition of the various species, several hundred of which are known from southern Scotland.

Graptolites evolved rapidly, both the colonies and their constituent thecae adopting a wide variety of shapes, presumably representing adaptation to a variety of feeding strategies. The succession of species in time has been worked out, at least approximately; and thus their occurrences can be used to give relative ages to the rocks in which they became buried. This method, biostratigraphy, remains of the first importance in unravelling the structure of the Ordovician and Silurian rocks of the Southern Uplands and of many similarly complicated regions in other parts of the world.

Graptolites lived at some depth in the water column, and on death fell to the sea-floor. Their remains are most commonly found in stagnant, oxygen-starved sea-bottom conditions, often preserved as flattened silvery films. They are almost never found in sediments that formed where there was enough oxygen to allow scavenging benthic creatures to burrow through the sea-floor. Rarely they are found preserved in sandstones and mudstones laid down by turbidity currents.

Ordnance Survey maps

Landranger maps at a scale of 1:50 000 are advised for route-finding during the excursions. The following sheets cover the area:

Sheet 66 Edinburgh

Sheet 67 Duns and Dunbar

Sheet 71 Lanark and Upper Nithsdale Sheet 72 Upper Clyde Valley

Sheet 73 Galashiels and Ettrick Forest Sheet 74 Kelso

Sheet 75 Berwick-upon-Tweed

Sheet 78 Nithsdale and Lowther Hills Sheet 79 Hawick and Eskdale

Sheet 80 The Cheviot Hills

Bartholomew's 1:100 000 scale Sheet 41 (Tweeddale) and Sheet 46 (Firth of Forth) also cover the whole area.

Geological Survey maps

British Geological Survey maps are available for most of the region. The 1:250 000 Borders Sheet 55N 04W gives a synoptic coverage of southern Scotland and Northern England. Published 1:50 000 or 1:63 360 (*) maps can be purchased from BGS at Murchison House, West Mains Road, Edinburgh, EH9 3LA, or from Ordnance Survey stockists.

Scotland series

Sheet 15E Leadhills	(Solid)	1987
Sheet 15E Leadhills	(Drift)	1981
Sheet 16W Moffat	(Drift)	1987
Sheet 16E Ettrick	(Drift)	1987
Sheet 17W Hawick	(Solid)	1982
Sheet 17W Hawick	(Drift)	1982
Sheet 17E Jedburgh	(Solid)	1982
Sheet 17E Jedburgh	(Drift)	1980
Sheet 24W Biggar	(Solid)	1981
Sheet 24W Biggar	(Drift)	1979
Sheet 24E Peebles	(Solid)	1983
Sheet 24E Peebles	(Drift)	1983
Sheet 25W Galashiels	(Solid)	1985
Sheet 25W Galashiels	(Drift)	1985
Berwick-upon-Tweed*	(Solid and Drift)	1969
Sheet 33E Dunbar	(Solid)	1980
Sheet 33E Dunbar	(Drift)	1978
Sheet 34 Eyemouth	(Solid)	1982
Sheet 34 Eyemouth	(Drift)	1983

England and Wales series

Sheet 1 & 2 Berwick-upon-Tweed and Norham	(Solid and Drift)	1977

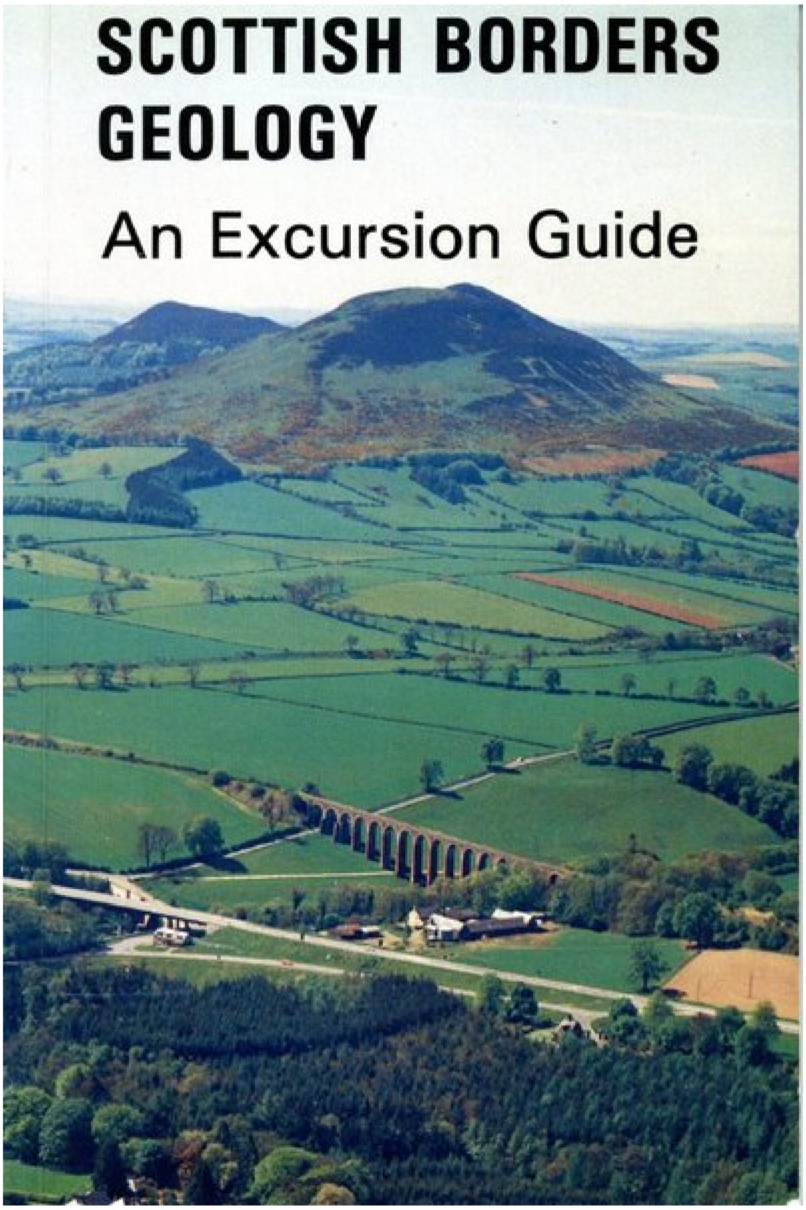
For Sheet 18 Morebattle and the east half of Sheet 25 (Kelso) only hand coloured maps are available. A special sheet at 1:25 000 covering the solid geology of the Moffatdale area and an accompanying booklet in the *Classic areas of British geology* series are currently (1992) in press. These and geological maps at 1:10 560 scale which are available for much of the region, may be consulted at the British Geological Survey office, Murchison House, West Mains Road, Edinburgh.

Publications

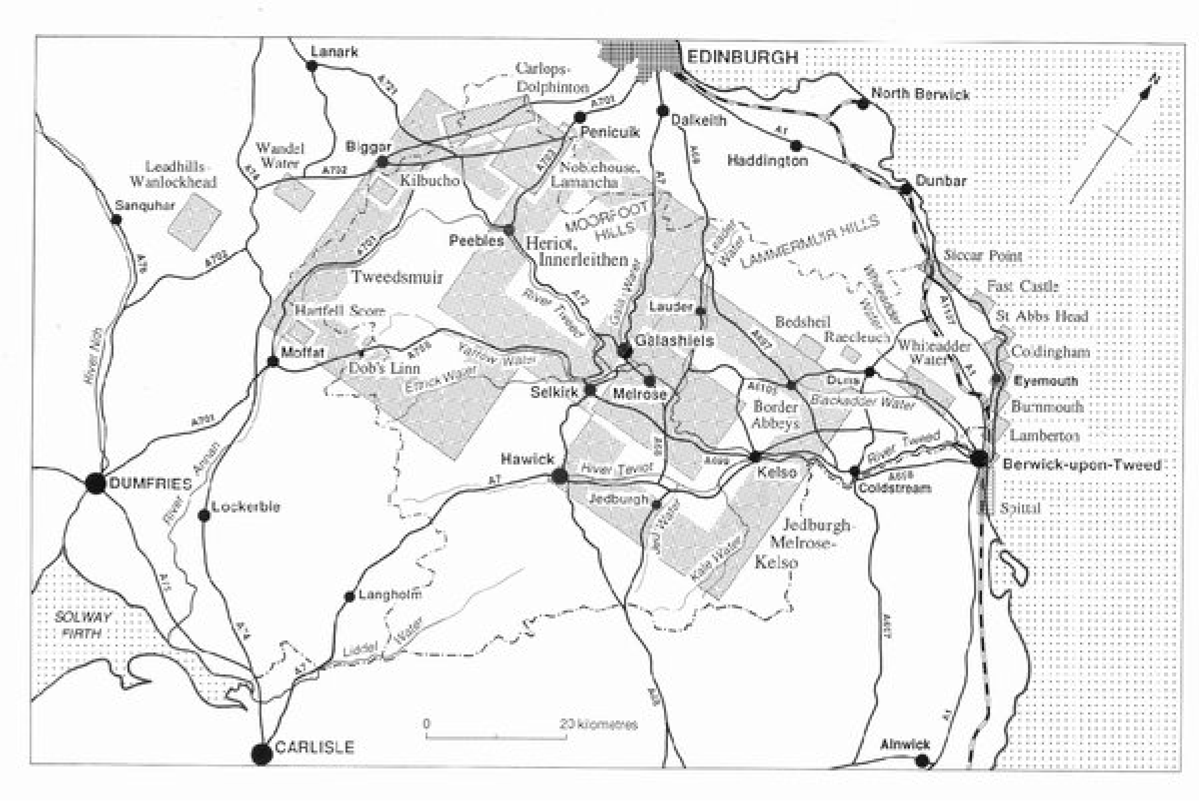
The third edition of the *Geology of Scotland* (Craig 1991) gives an introduction to Scottish Geology. The third edition of the BGS British Regional Geology, *The South of Scotland* (Greig 1971), provides a more detailed account of the local geology. A sheet memoir is available for Sheet 34 (Eyemouth). A selection of the many books available as introductory reading on various aspects of geology is given in the References.

P. Stone and A.D. McAdam

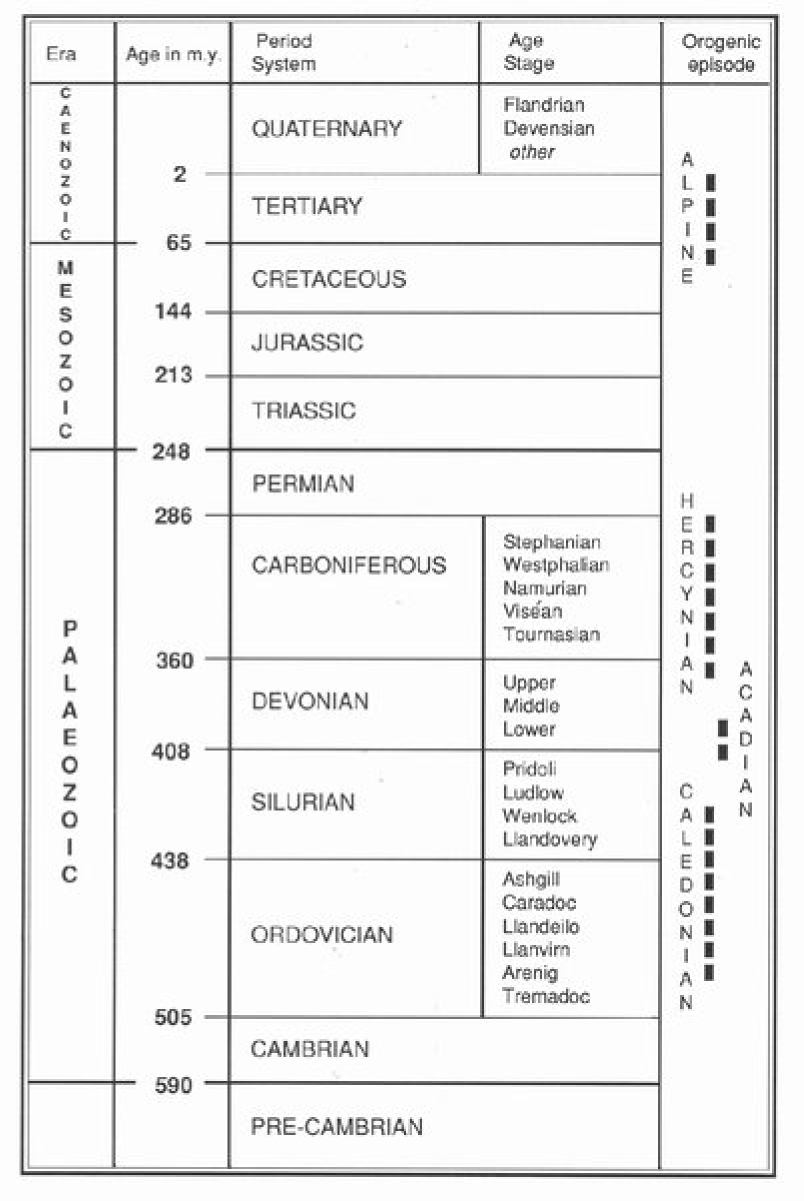
References



(Front cover) Front cover.

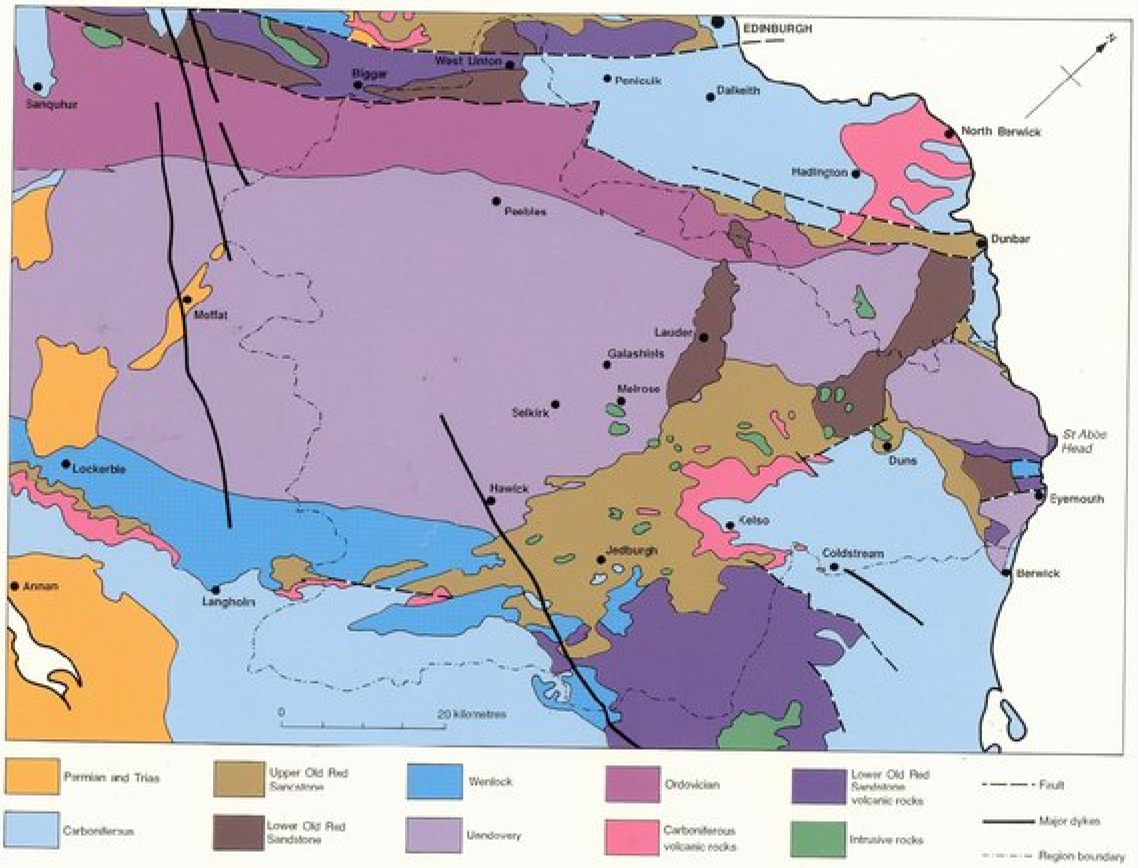


(Frontispiece 1) Border region and the location of the excursions.

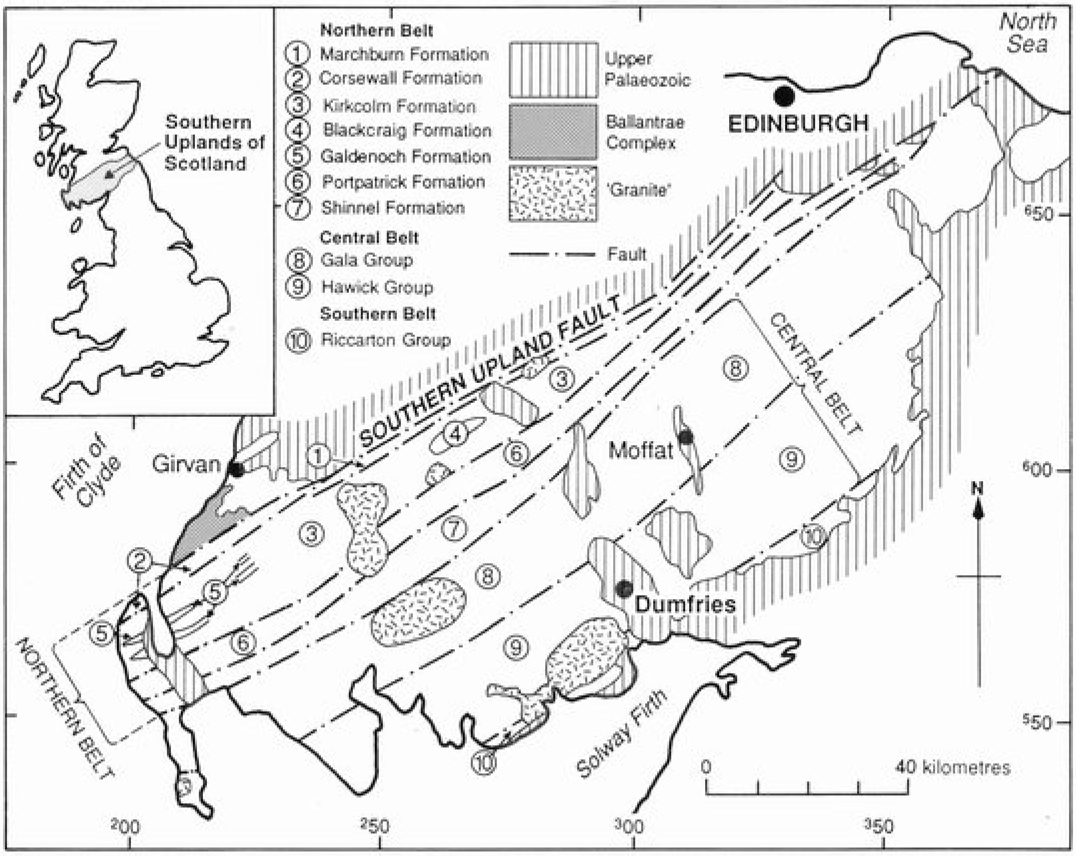


Era	Age in m.y.	Period System	Age Stage	Orogenic episode
CAENOZOIC		QUATERNARY	Flandrian Devensian *other*	ALPINE
	2	TERTIARY		
MESOZOIC	65	CRETACEOUS		
	144	JURASSIC		
	213	TRIASSIC		
PALAEOZOIC	248	PERMIAN		HERCYNIAN
	286	CARBONIFEROUS	Stephanian Westphalian Namurian Viséan Tournasian	
	360	DEVONIAN	Upper Middle Lower	ACADIAN
	408	SILURIAN	Pridoli Ludlow Wenlock Llandovery	CALEDONIAN
	438	ORDOVICIAN	Ashgill Caradoc Llandeilo Llanvirn Arenig Tremadoc	
	505	CAMBRIAN		
	590	PRE-CAMBRIAN		

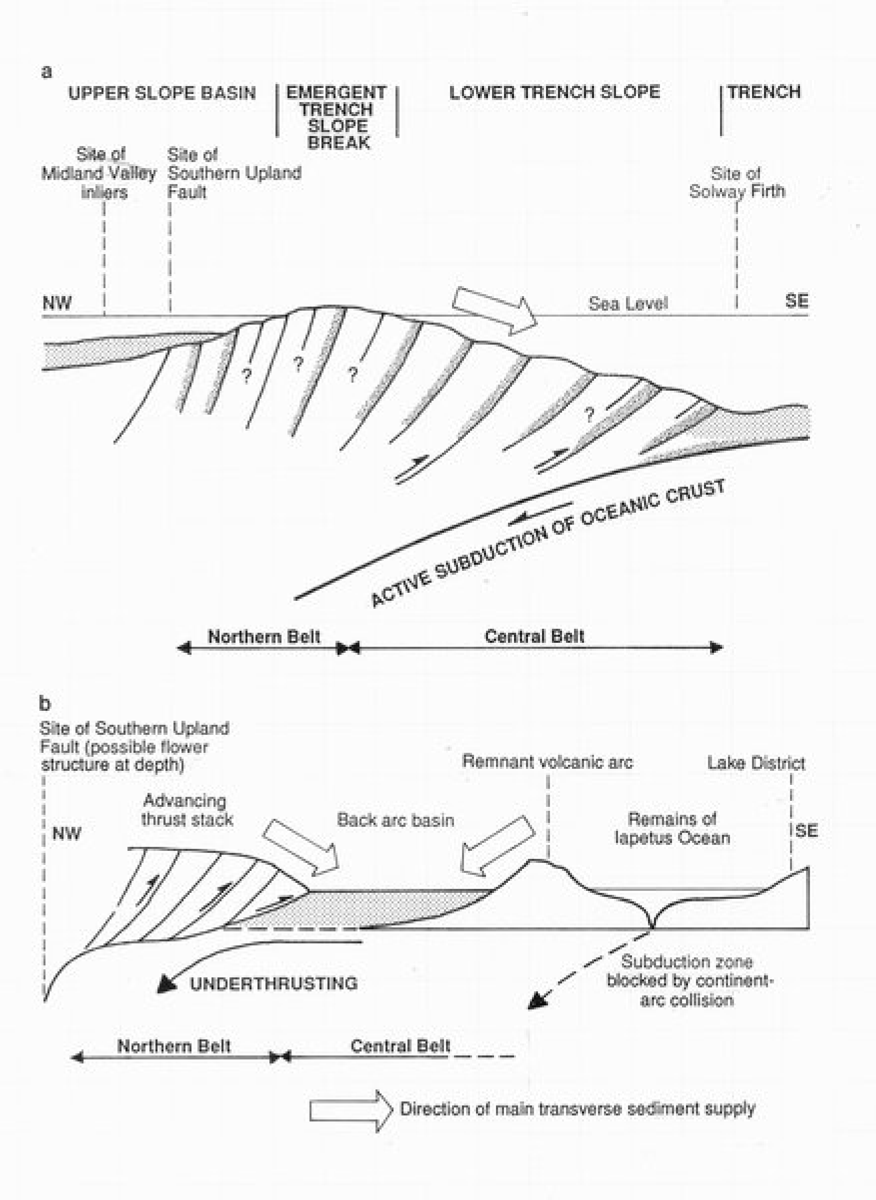
(Frontispiece 2) Geological column, timescale after Harland (1989).



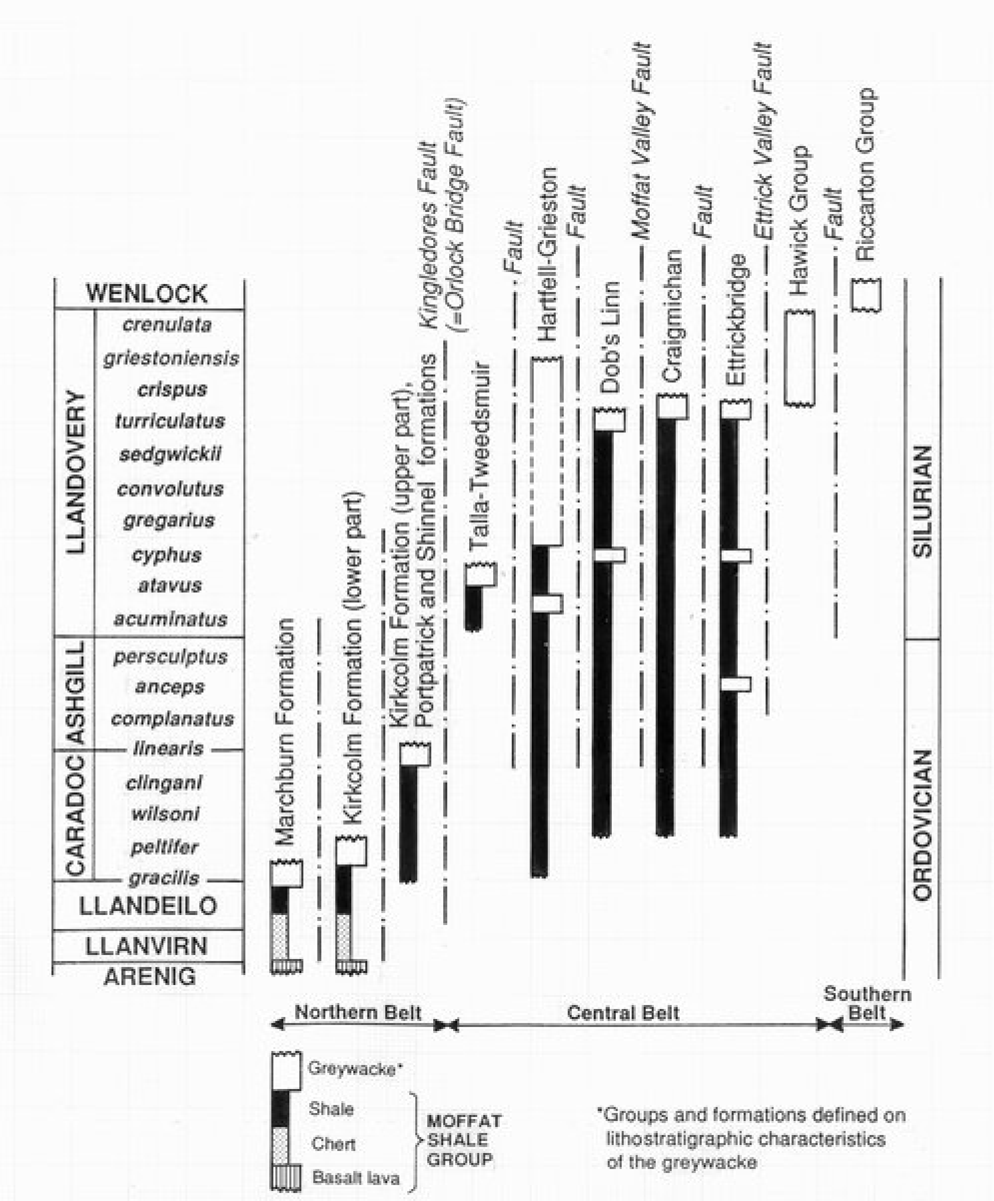
(Plate 1) Geological map of the Scottish Borders area.



(Figure 1) Southern Upland geological map.



(Figure 2) Southern Uplands: structural development.



(Figure 3) Southern Uplands:biostratigraphy.