Chapter 3 Overview of the succession and structure

‘Glencoe Caldera-volcano Complex’ is the new term applied here to include all of the volcanic and sedimentary rocks, coeval intrusions and volcanotectonic structures that relate to development of a volcano centred in the vicinity of the ‘cauldron’ originally defined by Clough et al. (1909). The caldera-volcano complex and its associated metamorphic substrate and host rocks are the subject of a new geological map at 1:25 000 scale (British Geological Survey, 2005), which includes several cross-sections. An overview of the entire succession and structure is provided here as an introduction and framework to set the scene for the following detailed descriptions and explanations of the successive volcanic stratigraphical units. The succession and structure are now interpreted in terms of caldera development that was tectonically influenced, incremental and piecemeal (Moore and Kokelaar, 1997, 1998), and in which successive depocentres enlarged and migrated with time. Many units of the volcanic succession are newly recognised or have revised names (see below). Erosional unconformities are common between successive units and in some instances there are minor intervening fluvial sedimentary strata; these are mostly palaeocanyon-confined conglomerates or thin sandstones that are too limited in outcrop to portray at 1:25 000 scale and have not been named. The volcanic and sedimentary rocks are collectively named the Glencoe Volcanic Formation. The volcanic formation unconformably overlies a ‘basement’ of intensely deformed metasedimentary rocks that are part of the Neoproterozoic to early Palaeozoic Dalradian Supergroup, which dominates the Grampian Terrane, between the Great Glen and Highland Boundary faults (Plate 1).

Dalradian metamorphic ‘basement’

The Dalradian metasedimentary rock sequence (Table 1), which is described in detail in the second edition of the Geological Survey memoir (Bailey, 1960) and by Hickman (1975), represents deltaic, intertidal and shallow marine sedimentation on a slowly subsiding rifted continental shelf that was to become the passive margin of the Laurentian Supercontinent (Anderton, 1985; Wright, 1988). The alternating quartzites and pelitic to semipelitic schists of the Lochaber Subgroup form a nearshore sequence reflecting periodic changes in sea level. Incursions of sand from deltaic areas to the south resulted in tidal sand bodies (the quartzites), which become finer grained and taper out north-eastwards towards more distal areas, now represented by the more uniformly semipelitic Loch Treig Schist and Quartzite Formation of the Glen Spean area (Key et al., 1997). Evidence for lagoonal basins with carbonate deposition is first seen in the upper part of the Leven Schist Formation, where thin metacarbonate and calcsilicate beds are found locally in the otherwise dominantly semipelitic rocks. Such metacarbonate and calcsilicate facies become dominant in the Ballachulish Limestone Formation, and in the vicinity of the Glencoe fault-intrusions these rocks are altered to calcsilicate hornfels. The overlying Ballachulish Slate Formation is generally graphitic and pelitic, representing anoxic basin conditions, but it is only present in the area of the 1:25 000 geological map as thin tectonic slices of black schist.

The Dalradian strata were deformed and metamorphosed at depths of between 15 and 30 km during the early to mid Ordovician (about 470 million years ago; Soper et al., 1999), largely in what is referred to as the Grampian Event of the Caledonian Orogeny. Several phases of folding can be recognised and, although there is now general agreement on the overall geometry of the major folds, there are various interpretations of their relative ages and how they relate to each other.

Interpretations of the structure of the area to the north and north-east of the Glencoe Caldera-volcano Complex have been published by Bailey (1934, 1960), Treagus (1974) and Hickman (1978) (see Stephenson and Gould, 1995, fig. 22). All of these authors agreed that the dominant structure is a large, recumbent, north-west-facing, isoclinal D_1 fold termed the Kinlochleven Anticline (Figure 6). The axial plane trace of this anticline is cut by the Glencoe fault-intrusions to the north of Meall Dearg [NN around 165 595]. To the west of here, strata from the Eilde Schist Member to the Leven Schist Formation are on the upper limb of the fold; they are the right way up and dip generally to the west. To the east of Meall Dearg, the strata are on the lower limb and are generally inverted. This limb has been affected by further close to tight, steeply inclined folds (D_1 or D_2 depending on author), and hence the strata vary considerably in their orientation (The regional fold phase D_2 was originally termed D_3 locally by Treagus, 1974). A complex antiform, containing both D_1 and D_2 folds according to Treagus (1974) and termed the Mamore Antiform (D_2) by Hickman (1978), is responsible for a core of

Binnein Quartzite Member to the north of Sròn Gharbh [NN 180 595]. The wide outcrop of Eilde Flags Formation around the Devil's Staircase [NN 215 575] lies in the core of the D_2 Blackwater Synform and farther east, close to the margin of the Rannoch Moor Pluton around [NN 235 570], outcrops of the Eilde Quartzite and Eilde Schist members define the core of the Blackwater Antiform ($_{D2}$; Treagus, 1974) or Treig Syncline (D_1; Hickman, 1978).

The Dalradian rocks to the west and south-west of the volcano complex were assigned by Bailey (1960) to the D_1 Ballachulish Syncline, which structurally overlies the Kinlochleven Anticline. The two recumbent regional folds are separated by the Ballachulish Slide, one of the major tectonic dislocations of the Grampian Highlands. The slide replaces much of the common limb and over most of this area it juxtaposes a widespread inverted sequence of Leven Schist Formation and Ballachulish Limestone Formation of the upper limb of the Ballachulish Syncline upon right-way-up rocks of the lower limb, generally at the level of the Glen Coe Quartzite Member and basal Leven Schist Formation (Bailey, 1960, figs 7G, 7H). The slide can be traced along the north-east side of lower Glen Coe, where it dips generally to the south-west, between Loch Leven and the Clachaig Hotel [NN 128 567]. From there the strike swings to the north-east close to the bounding faults of the volcano complex, and south-east-dipping strata of the Ballachulish Limestone Formation, much invaded by fault-intrusions, can be traced up the flanks of the Aonach Eagach to a point just to the east of Sgorr nam Fiannaidh [NN 143 583]. The slide is also present in several outcrops on the flanks of Glen Etive around Dalness, which have become known as the 'Etive Windows' (see 1:25 000 scale geological map section 3). In Gleann Chàrnan [NN 135 505] and Gleann Fhaolain [NN 155 515], near-identical structural inliers expose a right-way-up sequence of the Glen Coe Quartzite Member and Leven Schist Formation below the slide. On the south-east side of Glen Etive, outcrops of the Glen Coe Quartzite Member overlying the Leven Schist Formation on Stobh Dubh [NN 166 488] and faulted against the Leven Schist Formation on Beinn Ceitlein [NN 178 492] have less certain relationships. However, a capping of the Glen Coe Quartzite Member resting on the Leven Schist Formation on Beinn Maol Chaluim [NN 135 526] is demonstrably the right way up from current-bedding evidence and hence must overlie another slide at a higher structural level than the Ballachulish Slide. It should be noted that, in the classic section on the north side of Loch Leven (Figure 6)b, Hickman (1978) did not recognise the existence of a recumbent D_1 Ballachulish Syncline, only an upright D_2 Stob Ban Synform. To the west and south-west of Glen Coe, the Ballachulish Syncline, as described by Bailey (1960), is difficult to trace on existing maps and there have been no recent investigations. However, such a structure could be a continuation of the D_1 Beinn Sgulaird Recumbent Syncline identified to the south-west in Glean Creran by Litherland (1982).

Within the caldera-volcano complex, Dalradian rocks underlie the volcanic succession (see 1:25 000 scale geological map, section 1). In the west, around Loch Achtriochtan [NN 143 567], they are assigned to the Leven Schist Formation and, according to Bailey (1960, fig. 7E), they are all within the gently dipping inverted upper limb of the Ballachulish Syncline, above the Ballachulish Slide. In places adjacent to the bounding fault system, the strata dip steeply so that the slide and the immediately overlying Ballachulish Limestone Formation are exposed, for example at Meall Dearg [NN 165 589] and Coire Mhorair [NN 188 584] in the north and at Coire an Easain [NN 256 492] in the south-east. A perceived lower grade of regional metamorphism in the Leven Schist Formation inside the caldera-volcano complex was used as supporting evidence for the considerable subsidence of the central block (Elles and Tilley, 1930; Bailey, 1960). However, the evidence rested mainly on the absence of garnet, which is widely present in the Leven Schist Formation outside the caldera-volcano complex, and more precise determinations of metamorphic grade are lacking. In the east of the complex, between Stob Mhic Mhartuin [NN 208 574] and Coire an Easain, the Eilde Flag Formation and Eilde Quartzite Member crop out beneath the volcanic succession and are assumed to be part of the right-way-up sequence below the Ballachulish Slide.

The Dalradian rocks were modified further during the later phases of the Caledonian Orogeny. Following the Scandian Event there was substantial uplift and considerable strike-slip and dip-slip movements occurred on major crustal discontinuities (e.g. Treagus, 1991; Dewey and Strachan, 2003), such as the Ericht–Laidon Fault close to Glen Coe, the Great Glen Fault and the Highland Boundary Fault (Figure 3); (Plate 1). Contemporaneous magmatism included emplacement of the Rannoch Moor Pluton (Figure 3) and various minor appinitic intrusions, well before caldera-related explosive activity began at the Glencoe volcano. Erosion, presumably related to active uplift, produced a marked topography and was sufficiently rapid, at least in this vicinity, for the Rannoch Moor Pluton to be unroofed by the time of caldera volcanism (see pp.15; 40; 104).

Glencoe Volcanic Formation

A revised stratigraphy of the volcanic and related sedimentary rocks of the Glencoe Caldera-volcano Complex is summarised in (Figure 2)b and in (Table 2). The thick sequence of basaltic to andesitic sheets that was previously interpreted as a pile of lavas (Group 1 of Clough et al., 1909; Roberts, 1974; see (Table 2)) is reinterpreted as a stack of sills with intervening sedimentary strata. This reinterpretation is based on the recognition of peperites along the top contacts of the sheets; these are coarse- to fine-grained breccias with admixed vesicular sedimentary rocks, and they show that the sheets were intruded into unlithified wet deposits in which steam was generated (see Kokelaar, 1982, 1986). The sedimentary component of the sequence records fluvial deposition in a small basin taken to be a graben or half-graben. The igneous sheets and intercalated sedimentary strata are now referred to as the Basal Andesite Sill-complex. These rocks, as well as a former cover of lavas, were extensively eroded by rivers before the onset of the silicic magmatism that led to caldera formation. Preservation of the sills involved considerable fault movement, and it seems that the interval that separated the earlier magmatism from the initiation of caldera volcanism may have lasted for hundreds of thousands of years, possibly even longer.

The succession that reflects caldera development includes seven major silicic ignimbrites (rhyodacitic and rhyolitic compositions), each of which records a substantial explosive eruption with concomitant caldera subsidence. These ignimbrites are assigned to three distinctive members, each named after the vicinity of its thickest occurrence: Etive, Three Sisters and Dalness (Table 2). The upper surface of each ignimbrite shows evidence of fluvial erosion and incision. Alluvial-fan deposits, silicic tuffs, and various breccias are interstratified with the ignimbrites and are named after local features close to their type sections. In places, there are minor fluvial sedimentary rocks that have not been named. The various erosion surfaces and deposits between the ignimbrites indicate long intervals between the caldera-forming explosive eruptions, probably measured in several thousands to many tens of thousands of years. Thick andesitic units, comprising both lavas and high-level sills, lie between the silicic members and also register protracted intervals of time. It is tentatively estimated that the entire preserved caldera-related succession, which is not a complete record of the magmatism at this volcano, records between one and two million years of volcanism (see p.104).

The Etive Rhyolite Member consists predominantly of three flow-laminated rhyolites: the Lower, Middle and Upper Etive rhyolites (Table 2). These previously constituted the lower part of Group 2 of Clough et al. (1909) and much of the Lower Group 2 of Roberts (1974). Originally the rocks were thought to represent lava flows, but Moore and Kokelaar (1998) recognised that they formed from three discrete explosive eruptions, each associated with caldera subsidence. The lava-like quality of the three rather enigmatic units belies their explosive origins and reflects rapid near-vent deposition and coalescence of hot fragmented magma followed by fluid-lava-like laminar flow. The Etive rhyolites were erupted from vents that formed at the intersection of tectonic faults. Each rhyolite is underlain by fluvial or alluvial-fan sedimentary rocks, and silicic tuffs (Table 2).

The Lower Streaky Andesites occur as lavas and as sheets that intrude the Etive rhyolites. The characteristic millimetre- to centimetre-scale streaky texture is the result of incomplete mixing (here referred to as mingling) of coexisting rhyolitic and andesitic magmas. Earlier workers referred to these rocks as the Lower Group 2 Andesites (Table 2).

The succeeding Three Sisters Ignimbrite Member consists predominantly of two strongly welded (eutaxitic) ignimbrites: the Lower and Upper Three Sisters ignimbrites. These record two major explosive eruptions that differed in style from those that produced the lava-like Etive rhyolites. The ignimbrites are underlain and overlain by various sedimentary rocks and thick breccias (Table 2), and the assemblage mostly equates with the upper part of Group 2 of Clough et al. (1909). Roberts (1966a, 1966b, 1974), who first recognised the rocks as ignimbrite and referred to them as Upper Group 2, considered there to be only one eruption recorded at this level in the succession. In the original type section, at Coire nam Beitheach [NN 142 548], only the upper of the two welded ignimbrites is present and the lower unit initially was not distinguished.

The succeeding Upper Streaky Andesites record a further phase of activity in which andesitic magma mingled with rhyolitic magma. These andesites occur in a plug that forms part of a vent infill and as numerous irregular sill-like sheets that ramify widely within the Three Sisters Ignimbrite Member. An extrusive counterpart is also distinguished, where the upper contact is an unconformity.

The Glas Choire Sandstone Member comprises various conglomerates, sandstones and siltstones that record a period of fluvial incision succeeded by alluvial-fan sedimentation and development of a temporary caldera lake partly filled with lacustrine turbidites. These deposits, which include reworked parts of underlying thick breccias that are assigned to the Three Sisters Ignimbrite Member, formed part of the Group 3 Agglomerates and shales of Clough et al. (1909).

The succeeding Bidean nam Bian Andesite Member comprises thick andesite and dacite lavas that form the striking upper cliffs of Bidean nam Bian [NN 144 543] and Stob Coire nan Lochan [NN 148 548]. Clough et al. (1909) referred to these lavas as the Group 4 Hornblende-andesites (Table 2); their substantial thickness and strikingly monotonous character suggest that the erupted magma was topographically ponded and formed one or more deep lava lakes.

The Dalness Ignimbrite Member comprises two welded (eutaxitic) ignimbrites, named the Lower and Upper Dalness ignimbrites, each underlain by a silicic tuff (Table 2). These ignimbrites are thickest near Dalness, which indicates a south-westwards shift of the main locus of intracaldera deposition. The Lower Dalness Ignimbrite corresponds to the Group 5 Rhyolite of Clough et al. (1909) and to the Group 5 Ignimbrite of Roberts (1974). Sedimentary rocks and silicic tuffs overlying the Lower Dalness Ignimbrite were previously called Group 6 Shales and grits, while what is now the Upper Dalness Ignimbrite would have been within the former Group 7 Andesites and rhyolites (Clough et al., 1909).

Structural framework of the caldera volcano

Rather than occupying the entire area delimited by the ring-fault, all of the five extensively preserved ignimbrites of the Etive Rhyolite and Three Sisters members show clear evidence that they were thickly ponded in volcanotectonic fault-bounded basins lying within (not formed by) the ring-fault. Similarly, their eruptive vents were sited within the ring-fault system (see pp.54; 64; 69). Moore and Kokelaar (1997, 1998) demonstrated that the Dalradian metamorphic basement and the lower strata of the Glencoe Caldera-volcano Complex are fragmented by numerous faults and fault zones. Two sets of faults acted repeatedly to define a main north-west-trending graben, the Glencoe Graben, which is approximately 4 km wide and cross-cut by several faults (Figure 7). The pattern of faults within the ring-fault is probably more complicated than is portrayed in the diagram. Many of the faults along the graben are probably splays from deeper discontinuities and thus are linked, although at times they acted independently or reversed their sense of downthrow, or both. In places, the faults or fault-zones acted as extensional hinges for flexural subsidence (downsag), with associated development of crevasse-like, downward-tapering fissures that in some instances were hundreds of metres deep. Determination of the structural framework that is described here depends on both accessible contacts and complete stratigraphical sections, and it is likely that there are additional structures that have not been detected in particularly rugged terrain and beneath drift. All of the structures that comprise the framework depicted in (Figure 7) are validated on more than one line of evidence.

The Glencoe Graben is bounded by the Northeastern and Southwestern graben faults (Figure 7), which are zones, up to 1 km wide, across which there was repeated, often large-scale, normal-sense movement with various surface manifestations. In many instances the bounding structures comprised one or more distinct faults and fault scarps, but, either locally or at different times, they were defined by more gradual thinning of units, particularly of ignimbrite and also of sills. This gradual thinning reflects topographical barriers with moderate slopes that formed either by flexural draping over a deeper fault or by splaying of numerous faults from a deep fault, each with a minor increment of displacement. Minor downthrow in the opposite direction to the main sense of downthrow (antithetic displacement) occurred in some places where several fault strands were involved. Locally the faults are marked by crevasses that opened up to the surface, and in some cases the faults were exploited by ascending magma and acted as conduits to vents. In several instances, wedge-shaped deposits of coarse avalanche debris provide evidence of a steep and active fault scarp in the immediate vicinity.

Faults and fault scarps that define part of the Northeastern Graben Fault are well exposed in the steep crags on the flank of Am Bodach [NN 167 576] and can be traced above the cottage at Allt-na-Ruigh [NN 179 570] to the vicinity of the rocky prominence known as The Study [NN 183 564]. Farther south-east, the fault-zone is unexposed for almost 3 km where there are extensive superficial deposits. It is again exposed on the north-west flank of Stob Dearg at Coire na Tulaich [NN 218 547] and also on the south-east face near the prominent deep gully known as The Chasm [NN 225 539].

The fault-zone here is almost 1 km wide. South-east of Glen Etive, in lower parts of Cam Ghleann, fault strands and extensive zones of brecciation are exposed in the quartzitic basement and locally the fault traces are marked by tuff and breccia-filled dykes, some with invasive rhyolite [NN 247 522]. At a shallower level, a large volcanotectonic crevasse forms the major bounding structure for over 2 km south-eastwards onto the lower eastern slopes of Meall a' Bhùiridh [NN 2562 5078], where it is cut by strands of the ring-fault and the associated intrusion.

Faults and fault scarps of the Southwestern Graben Fault are well exposed in the steep north-facing cliffs of Stob Coire nam Beith, close to the prominent Summit Gully [NN 138 548]; a small horst occurs between constituent fault strands towards the north-east [NN 1400 5495] (Figure 14), p.51. The fault-zone is intermittently exposed in the north-west-trending ridge of Bidean nam Bian, such as at the foot of the towering Church Door Buttress at the head of Coire nam Beitheach [NN 1415 5442], but farther south-east it is largely buried by the Bidean nam Bian Andesites and is mainly marked by pronounced thinning of ignimbrites and sills. Farther south-east, the Clach Leathad intrusion obscures the structure.

A linear zone of maximum caldera subsidence between the graben-bounding structures, referred to as the Glencoe Graben axis, lies approximately 1 km from the Northeastern Graben Fault; fluvial incision occurred repeatedly along this axis or close to the fault.

The Glencoe Graben is cut at right angles (orthogonally) by several faults that were active during volcanism. From north-west to south-east they are: Ossian Fault, Queen's Cairn Fault, Devil's Staircase Fault, Glen Etive Fault, and White Corries Fault (Figure 7). The middle three lie along the major north-east-trending valleys of the Lairig Eilde, the Lairig Gartain and Glen Etive, respectively, and these define the fault-bounded caldera-floor blocks represented in the massifs of the Three Sisters, Buachaille Etive Beag, Buachaille Etive Mòr, and Stob a' Ghlais Choire, each of which has a significantly different volcanic and sedimentary succession (see later detailed descriptions and also Bailey (1960, pp.132–149)). The Ossian Fault, in the north-west of the volcanic complex, is clearly exposed in cross-section on Aonach Dubh (see (Plate 4); (Plate 14a), p.55)), near the steep cleft known as Ossian's Cave [NN 155 563], which is where a post-caldera dyke has weathered out. Here the fault has two obvious strands roughly 200 m apart. The north-western strand was exploited by erosion that formed a palaeocanyon in the unconformity surface on top of the sill-complex (Plate 4). This feature, which is partially infilled with coarse fluvial conglomerate, establishes the early existence of the Ossian Fault. The later effects of the Ossian Fault on the strata immediately overlying the conglomerate are clear to see, but its trace towards the south-west is mainly buried beneath higher units. The fault is also obvious on the north side of Glen Coe, where it forms the deep gully adjacent to the cliffs of Am Bodach [NN 166 575] (Plate 14b). South-east of Glen Etive, the poorly exposed White Corries Fault is tentatively positioned south-east of Cam Ghleann [NN 24 51]; its location is inferred from aspects of the stratigraphy on Meall a' Bhùiridh [NN 25 50] and in Coire an Easain [NN 25 49] (see pp.49; 64).

Many of the rectilinear caldera faults are truncated by the ring-fault system and its associated intrusions (Figure 7), and outside the ring-fault their possible extensions are largely obscured by later intrusions. However, the Devil's Staircase Fault, locally exploited by dykes, is traceable north-eastwards beyond the ring-fault [NN 226 570] and forms part of the regional Etive–Laggan Fault. Moore and Kokelaar (1997, 1998) considered that this and the adjacent Queen's Cairn and Glen Etive faults are splays from a deep north-east-trending crustal discontinuity. Similarly, the bounding north-eastern and south-western faults of the Glencoe Graben were inferred to splay from a deep north-west-trending crustal discontinuity, called the Glencoe Lineament (p.102). This feature evidently extended outside the ring-fault, as it persistently guided major fluvial drainage across the entire caldera complex. Minor dykes of andesite, dacite and rhyolite, which cut various levels of the volcanic succession but predate the Clach Leathad Pluton, mimic elements of the structural framework; they tend to lie parallel to the Glencoe Graben in the north-west, but towards the centre of the volcano complex, between the Queen's Cairn Fault and Devil's Staircase Fault, they strike roughly north–south (Figure 7), as if influenced by the cross-cutting structures. The most prominent multiple dyke of the area, part of the Etive swarm in Gleann Fhaolain [NN 15 51] (see Bailey and Maufe, 1916, fig. 28), evidently exploited a south-westward continuation of the Queen's Cairn Fault.

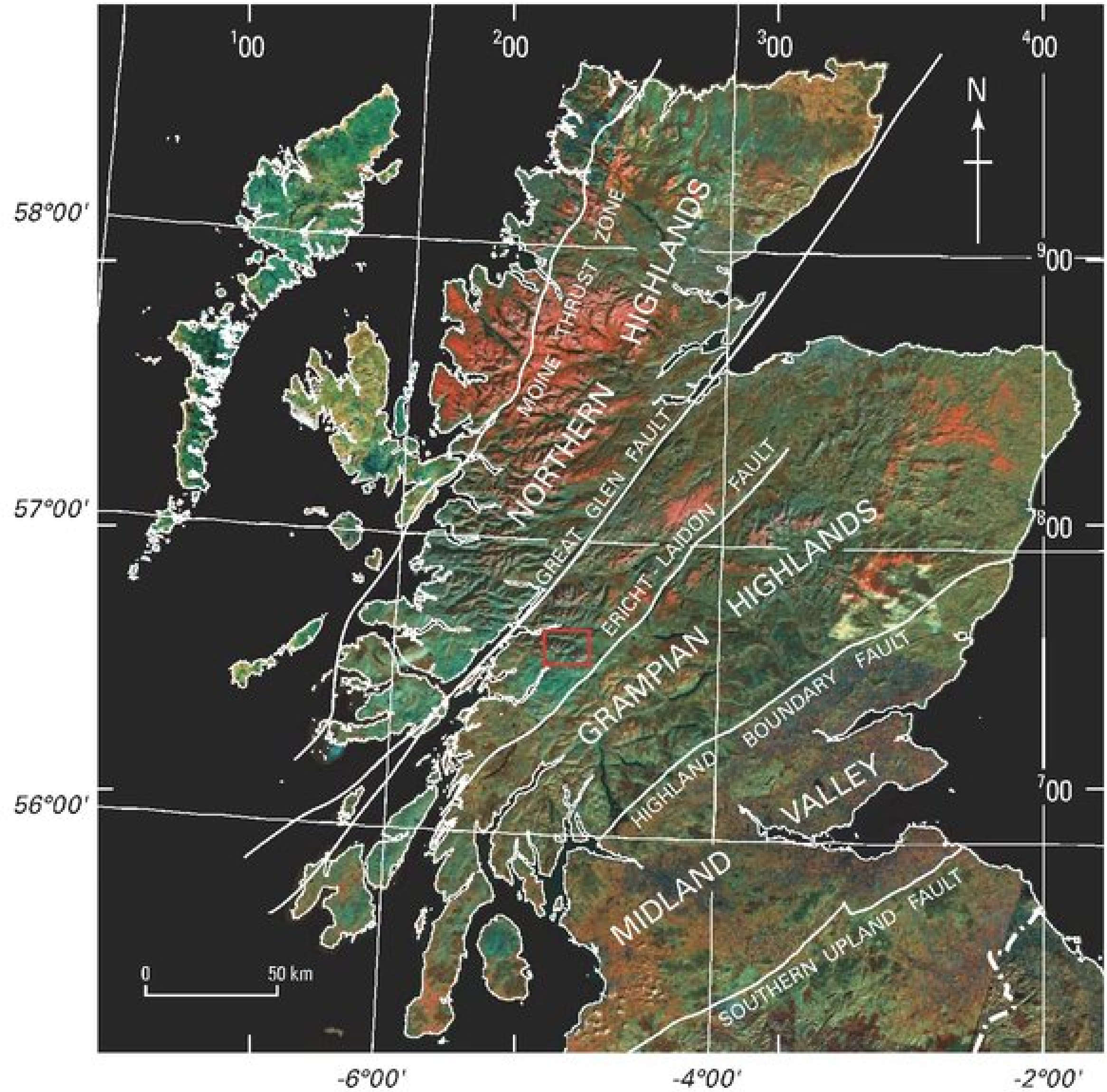
The apparently simple, smoothly curving continuity of the ring-fault, as originally depicted by the Geological Survey (e.g. Clough et al., 1909, p.627; Bailey, 1960, p.132), is partly conjectural, because of incomplete exposure and partial obliteration by intrusions, and in places is an artefact of the ways in which the variously inclined and sharply intersecting fault planes trace across the steep topography. Constituent faults of the ring-fault system along the north, north-east and south-west (two strands) of the volcano complex are quite planar and generally parallel to the earlier Glencoe Graben except for several distinct right-angled steps in their traces (fault jogs). The fault traces at the north-west and south-east ends of the system connect to the longer sides via sharp angular bends (pp.85; 86). In a horizontal plane, as if the topography were flat, the overall shape of the fault system would appear rectilinear to polygonal, consistent with the considerable orthogonal faulting of the basement that was already present by the time of activity on the ring-fault system. Faults that constitute the ring-fault system cut the youngest part of the Glencoe Volcanic Formation, and it seems that many of them only developed large-scale downthrow after accumulation of the early ignimbrites that form most of the preserved volcanic succession (Etive Rhyolite Member and Three Sisters Ignimbrite Member). Even then, as in the earlier volcanotectonic history, it is probable that subsidence on the ring-fault system was not coherent, with certain sections moving more than others or at different times.

The ‘fault-intrusion’ complex of Clough et al. (1909) comprises numerous discontinuous intrusions that crop out extensively along and outside the ring-fault system (Figure 7); there are only a few (coeval) small intrusions inside the system. The early Geological Survey geologists made much of the fact that the inner contacts of the ring-intrusions are mainly smoothly planar, mostly with distinct chilled margins (some were later shown to be a separate rhyolite). From these features they argued that the intrusions had invaded the ring-fault and that where the fault was not exposed its original presence could be inferred from the continuity of an intrusion.

Numerous north-east-trending dykes, referred to as the Etive Dyke Swarm (Clough et al., 1909; Bailey and Maufe, 1916; p.100), cut both the caldera volcano rocks and the Clach Leathad Pluton; many, but by no means all (p.99), are related to late silicic magmatism towards the south-west, centred in the vicinity of the Etive Pluton (Anderson, 1937; (Figure 3)). The dykes have not been remapped or reappraised since the early work, and only some of them are represented on the 1:25 000 scale geological map (British Geological Survey, 2005), but their emplacement bears on the overall structure of the Glencoe volcano complex. Measurements of the cumulative width of Etive dykes cutting the Clach Leathad Pluton in the River Etive north-east of Alltchaorunn [NN 20 51], not far from the centre of the volcano complex, yielded a total of 306 m for 31 dykes in an outcrop length of 1036 m (Clough et al., 1909); this is almost one third of the outcrop in a north-west to south-east direction, amounting to 42 per cent extension. Although it was acknowledged (C T Clough in Bailey, 1960, pp.199–200) that this was probably too high a value to apply generally, later workers (e.g. Taubeneck, 1967) have used the original result to infer that the overall shape of the volcano complex, as defined by the ring-fault system, would have been subcircular before the Etive dykes were intruded. However, examination of the major outcrops across the whole volcano complex reveals that the dykes do not widely constitute as much as one third of the rock in a north-west to south-east transect. In some of the main ridges, as in Beinn Fhada [NN 17 55] and Buachaille Etive Beag [NN 19 55], the extension may amount to some 20 per cent overall, but it is considerably less elsewhere. At three other transects of the Etive swarm, with a total of 120 dykes, Anderson (1937, table 1) determined extension amounting to 9.3, 9.4 and 18.2 per cent. It is reasonable to suppose that the section from which the original measurement was derived is more highly populated by Etive dykes than elsewhere within the main massifs, because it is located in the vicinity of a pre-existing crustal weakness, recognised now as the Glen Etive Fault (a splay of the basement discontinuity represented by the Etive–Laggan Fault; p.28). The Etive dykes may well have exploited this weakness, as well as the other north-east-trending faults: for example, the Devil’s Staircase and Queen’s Cairn faults. Thus the overall extension is probably no more than about 10 to 15 per cent and the original outline shape of the Glencoe Caldera-volcano Complex would have been significantly elongate in a north-west to south-east direction before emplacement of the Etive dykes, and not nearly circular, as some have suggested.

While the preservation of the thick volcanic succession by faulting down within metamorphic basement remains perhaps the most striking feature of the Glencoe volcano, the original idea of coherent subsidence on a simple structure is no longer tenable. Much remains to be understood regarding the development of the bounding fault system, particularly in discriminating tectonic from volcanotectonic influences in fault development and in magmatic plumbing. These topics are more fully considered in later sections (pp.83; 92). From a historical perspective, it is interesting to contemplate how interpretations of caldera volcanoes might have differed in the past if this archetypal ‘cauldron’ had at the outset been described as involving tectonically fragmented crust and rectilinear to polygonal intersecting bounding faults. Would so many less-dissected volcanoes subsequently have been depicted as having simple continuous ring-faults around a coherent crustal block at depth? Similarly, would their inferred cross-sections have so frequently shown upwards-diverging bounding faults if the only cross-section of the Glencoe volcano showing this had been correctly drawn in the first place, without such divergence?

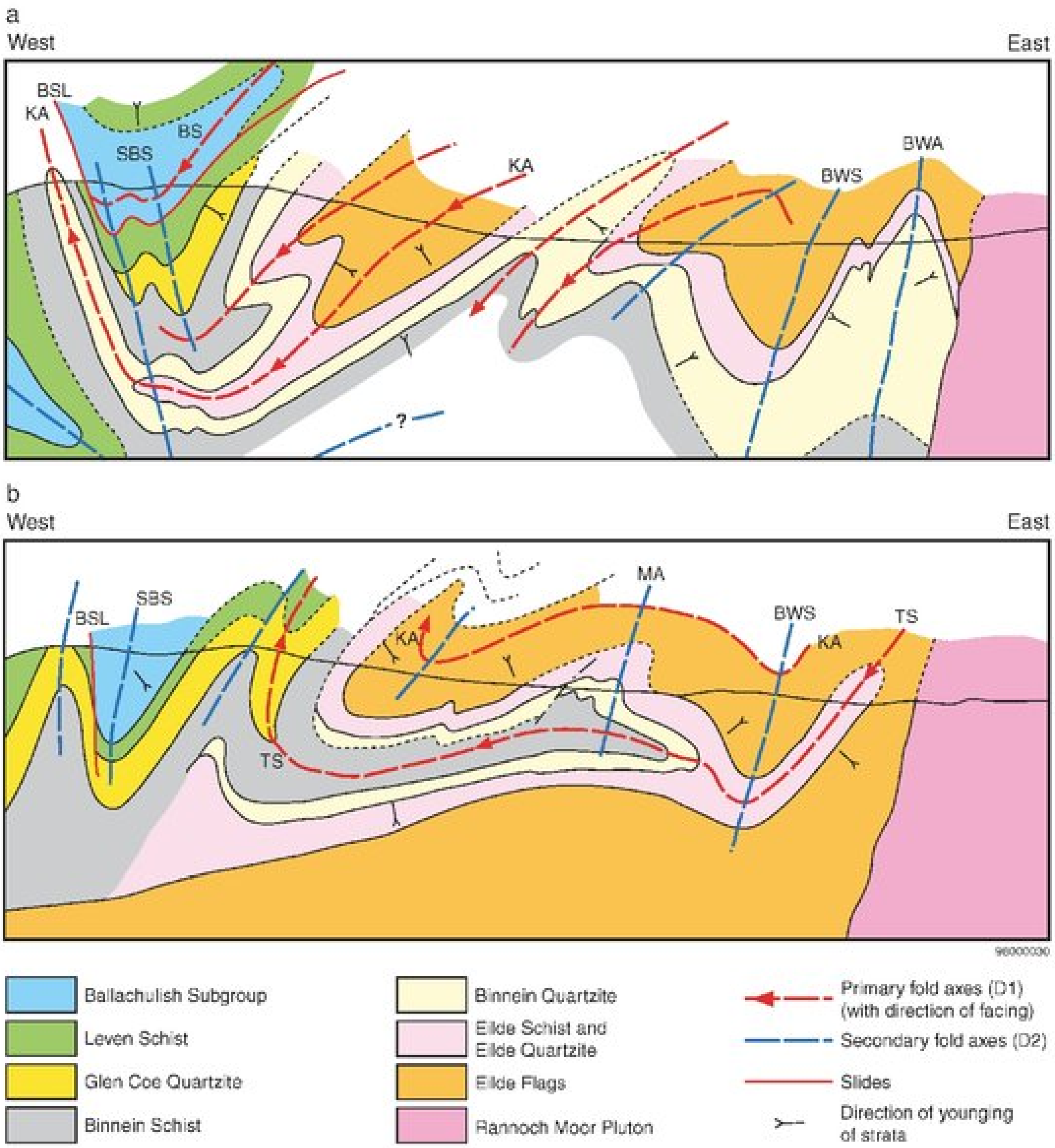
References



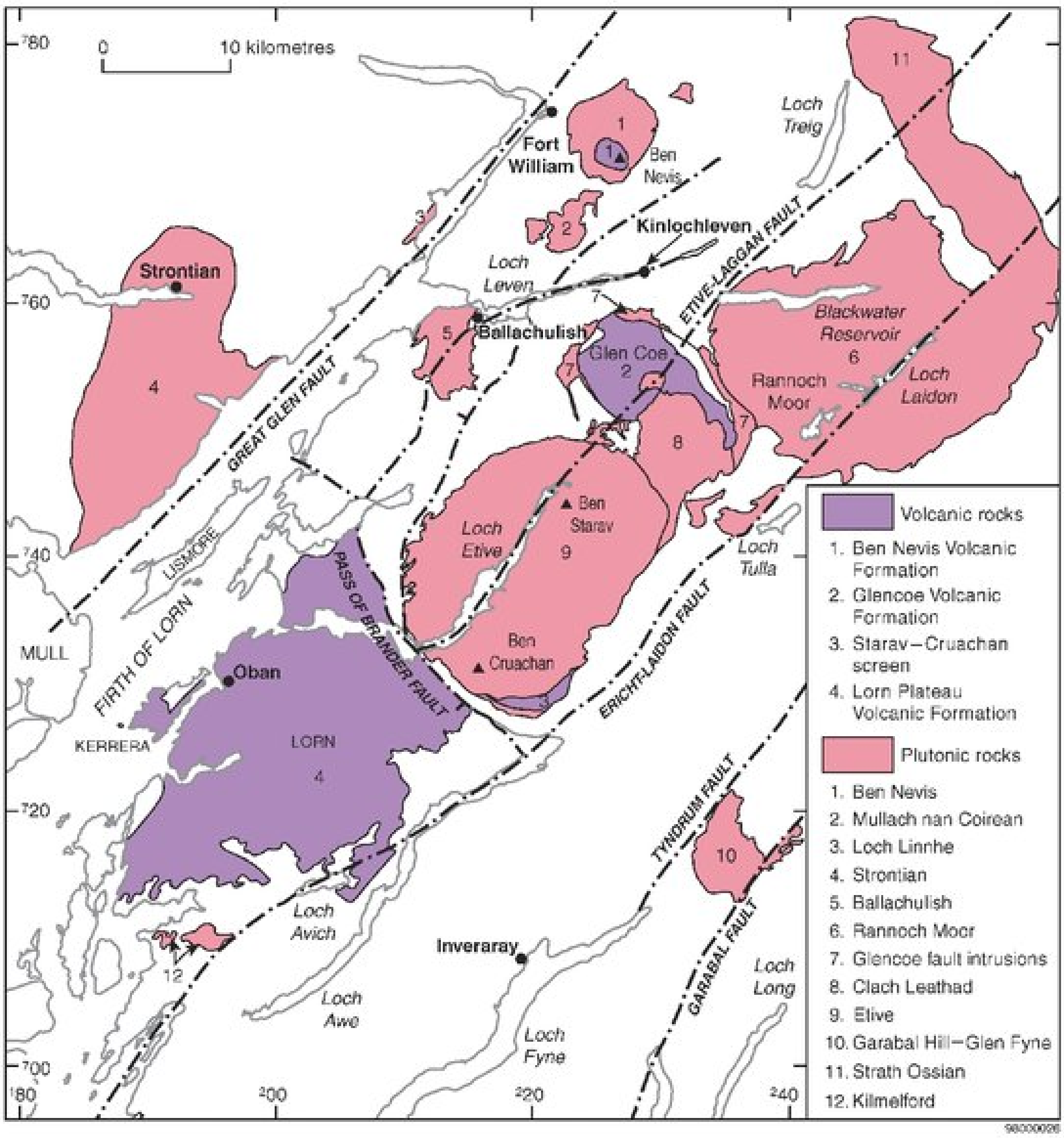
(Plate 1) A Satellite view showing the location of the Glencoe area in Scotland. BGS enhanced image © NERC, 2005. Grid lines in white show latitude and longitude; National Grid is indicated along the margin of the image.

Group	Subgroup	Formation	Member	Lithology
Appin	Ballachulish	Ballachulish Slate 400 m		Pelite, black; here mostly schistose in tectonic slices.
		Ballachulish Limestone 250 m		Dolomitic metalimestone, dark grey, impure schistose calcsilicate rock; intercalations of black pelite.
	Lochaber	Leven Schist 1500–3000 m		Upper part pelite and semipelite, grey-green, phyllitic to schistose; some calcareous strata near top. Lower part psammite and semi-pelite, dark, schistose, slightly graphitic; some quartzite; lower junction gradational.
		Loch Treig Schist and Quartzite	Glen Coe Quartzite 400 m	Very feldspathic, well-bedded, cross-bedded units up to 4 m thick, strongly slumped. Inter-calations of grey-green schist near top. Lower junction characterised by K-feldspar pebble beds and mud flakes.
			Binnein Schist 400 m	Semipelite and pelite, schistose, with rare metacarbonate, calcsilicate and graphitic beds; quartzite ribs at both junctions.
			Binnein Quartzite 300 m	Well-bedded, less feldspar but more muscovite than other quartzites; characteristically white weathering.
			Eilde Schist 400 m	Psammite and semipelite, schistose, distinct graded bedding, graphitic seams throughout. Quartzite ribs at both junctions.
			Eilde Quartzite 600 m	Feldspathic, well-bedded. Similar to Glencoe Quartzite, but thinner cross-bedded units and feldspar pebbles less conspicuous. Intercalated schists at top.
Grampian	Glen Spean	Eilde Flag 1350 m+		Feldspatic quartzite and psammite, micaceous, well-bedded, flaggy; minor schistose semipelite. Upper junction marked by 5 m of K-feldspar pebble beds and slump folding.

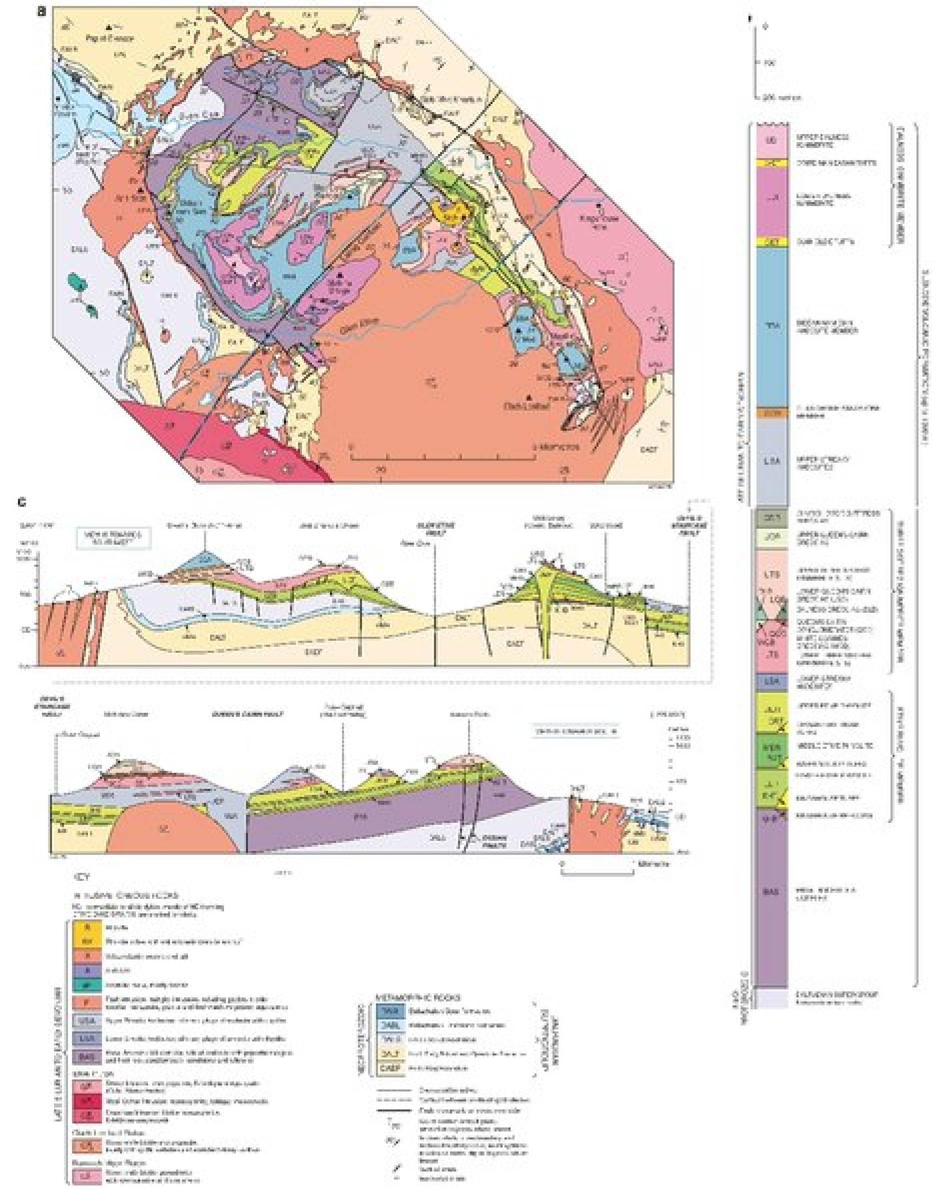
(Table 1] Stratigraphy of the Neoproterozoic Dalradian Supergroup in the area of Glen Coe (after Bailey, 1960; Treagus, 1974; Hickman, 1975). Thickness data, from Hickman, are maxima for the area.



(Figure 6) Structural cross-sections through Dalradian rocks along the classic Loch Leven section, just to the north of the Glencoe Caldera–volcano Complex. a. After Treagus (1974). b.After Hickman (1978). BSL Ballachulish Slide; BS Ballachulish Syncline; BWA Blackwater Antiform; BWS Blackwater Synform; KA Kinlochleven Anticline; MA Mamore Antiform; SBS Stob Ban Synform; TS Treig Syncline.



(Figure 3) Distribution of Siluro-Devonian volcanic and plutonic rocks showing faults that were active during the magmatic activity.



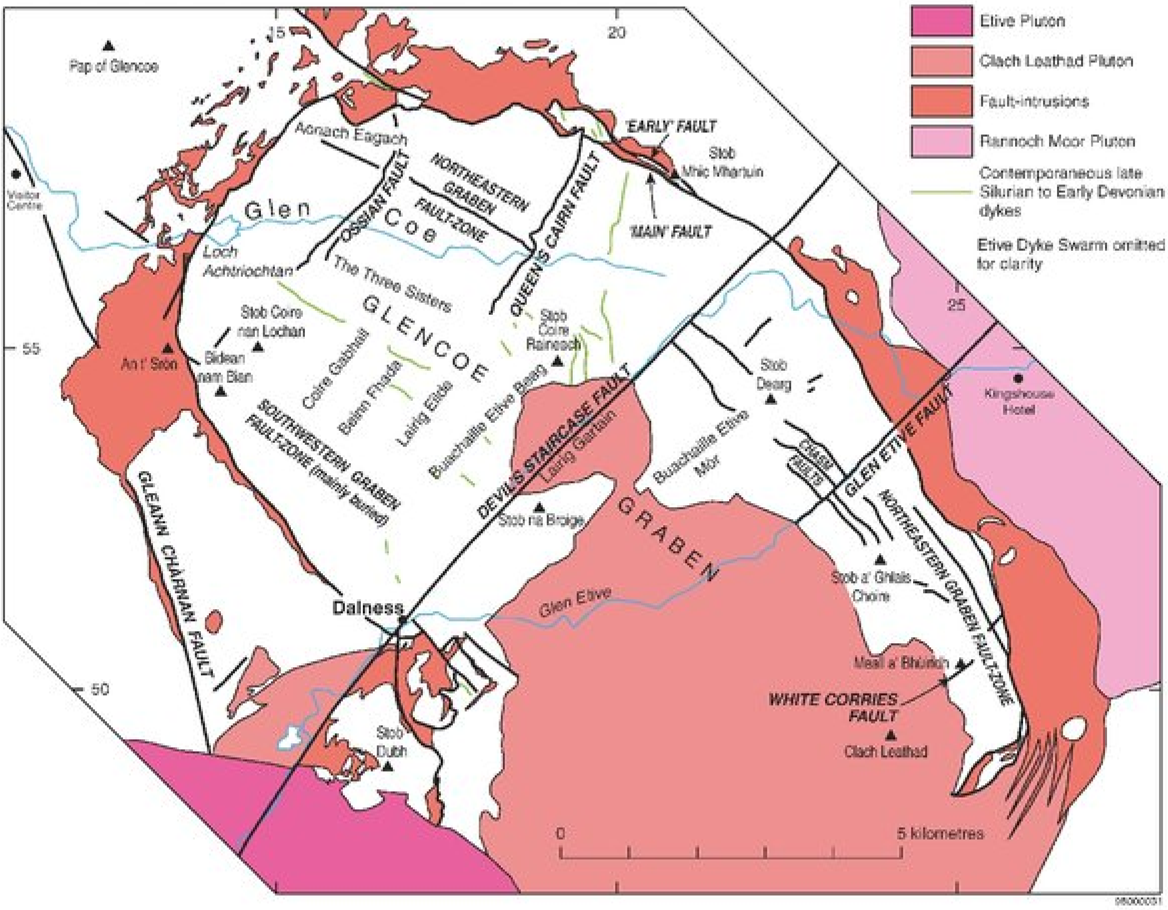
(Figure 2) Simplified map, generalised succession and cross-section showing the geology of the Glencoe area. The cross-section is drawn as if viewed looking towards the south, which is the view seen southwards from the main road (A82T) travelling west from the vicinity of the Kingshouse Hotel [NN 26 54] to the lower end of Glen Coe [NN 12 56]. See p.5 for key.

Glencoe Volcanic Formation (this report)		Roberts (1974)	Clough et al. (1909)
Upper Dalness Ignimbrite Coire nan Easan Tuffs ↓ Lower Dalness Ignimbrite Coir Eilde Tuffs ↓	Dalness Ignimbrite Member	Group 7 Andesite and rhyolite lavas, with thin ignimbrite Group 6 Grits and shales Group 5 Rhyodacitic ignimbrite	Group 7 Andesites and rhyolites Group 6 Shales and grits Group 5 Rhyolite
Bidean nam Bian andesites	Bidean nam Bian Andesite Member	Group 4 Hornblende-andesite lavas	Group 4 Hornblende-andesites
Glas Choire sandstones ↓	Glas Choire Sandstone Member	Group 3 Breccias, grits and shales	Group 3 Agglomerates and shales
Upper Streaky andesites ↓			
Church Door Buttress Breccias Upper Queen's Cairn Breccias Upper Three Sisters Ignimbrite Lower Queen's Cairn Breccias * Queen's Cairn Conglomerates ↓ White Corries Breccias Lower Three Sisters Ignimbrite ↓	Three Sisters Ignimbrite Member	Upper Group 2 Rhyodacitic ignimbrite	Group 2 Rhyolites and andesites
Lower Streaky Andesites		Lower Group 2 Andesite and rhyolite lavas, with thin ignimbrite	
Upper Etive Rhyolite Crowberry Ridge Tuffs ↓ Middle Etive Rhyolite Raven's Gully Tuffs ↓ Lower Etive Rhyolite Kingshouse Tuffs Kingshouse Breccias ↓	Etive Rhyolite Member		
Basal Andesite Sill-complex ↓		Group 1 Basalts and pyroxene-andesite lavas	Group 1 Augite-andesites

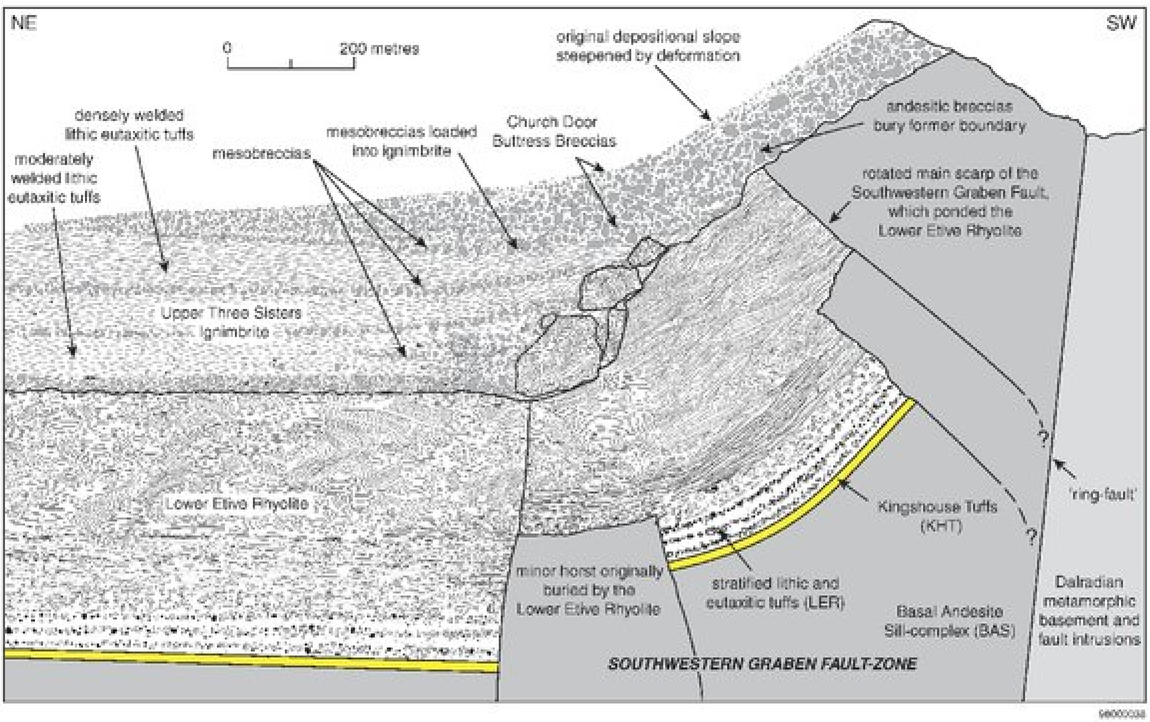
↓ *indicates unit that rests on fluvial sediments and an erosional unconformity*

* *The Dalness Breccias may, in part, correlate with the Lower Queen's Cairn Breccias. They are overlain by the Upper Three Sisters Ignimbrite, but rest upon the Basal Andesite Sill-complex and could have formed in part during development of the Etive Rhyolite Member*

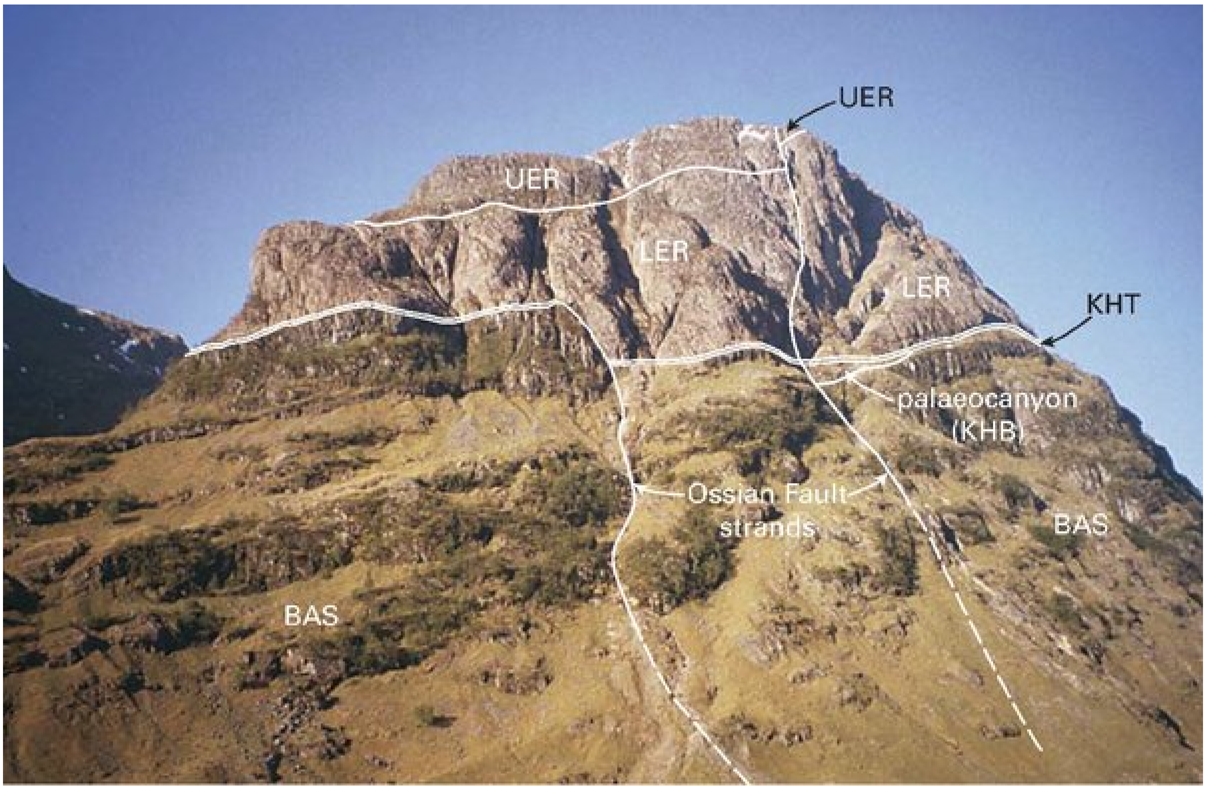
(Table 2] Lithostratigraphical and lithodemic nomenclature used in the Glencoe Caldera-volcano Complex.



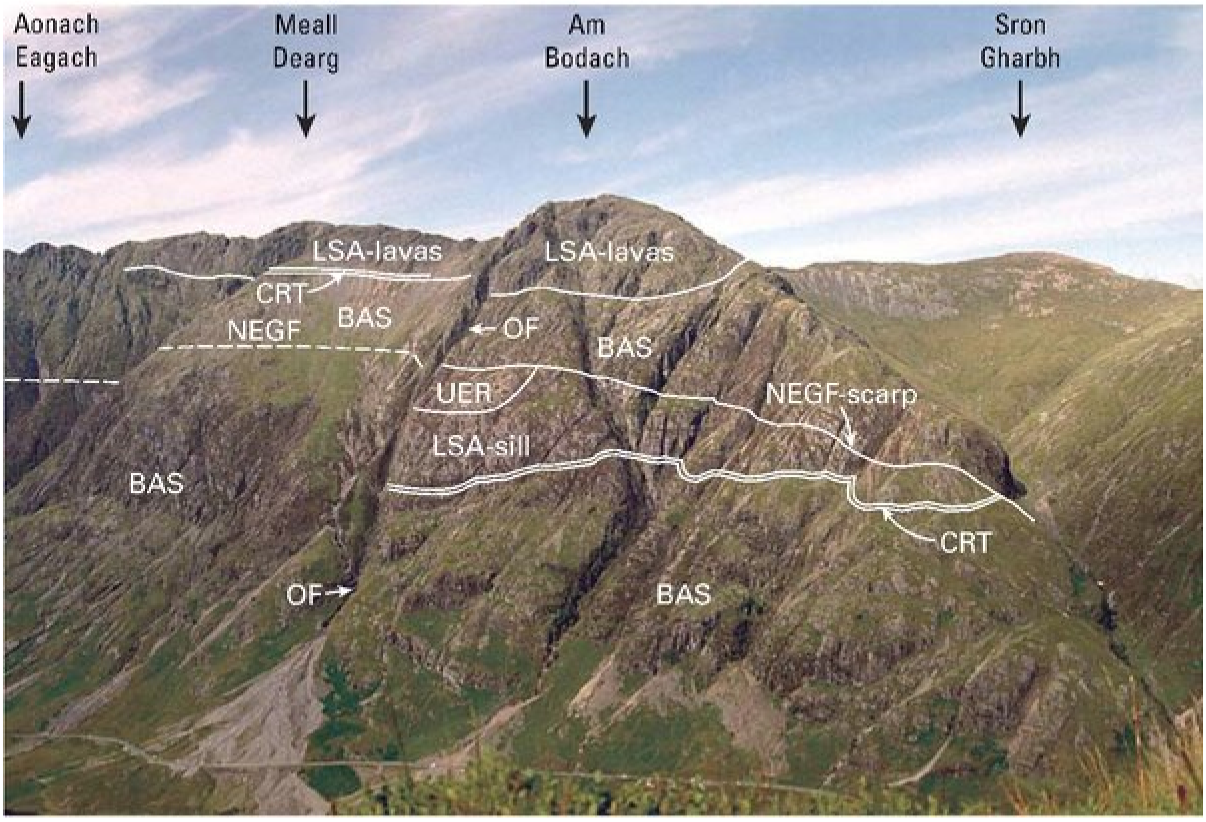
(Figure 7) Major structural features of the Glencoe Caldera-volcano Complex, highlighting intrusions and faults active during volcanism (Etive Dyke Swarm not shown).



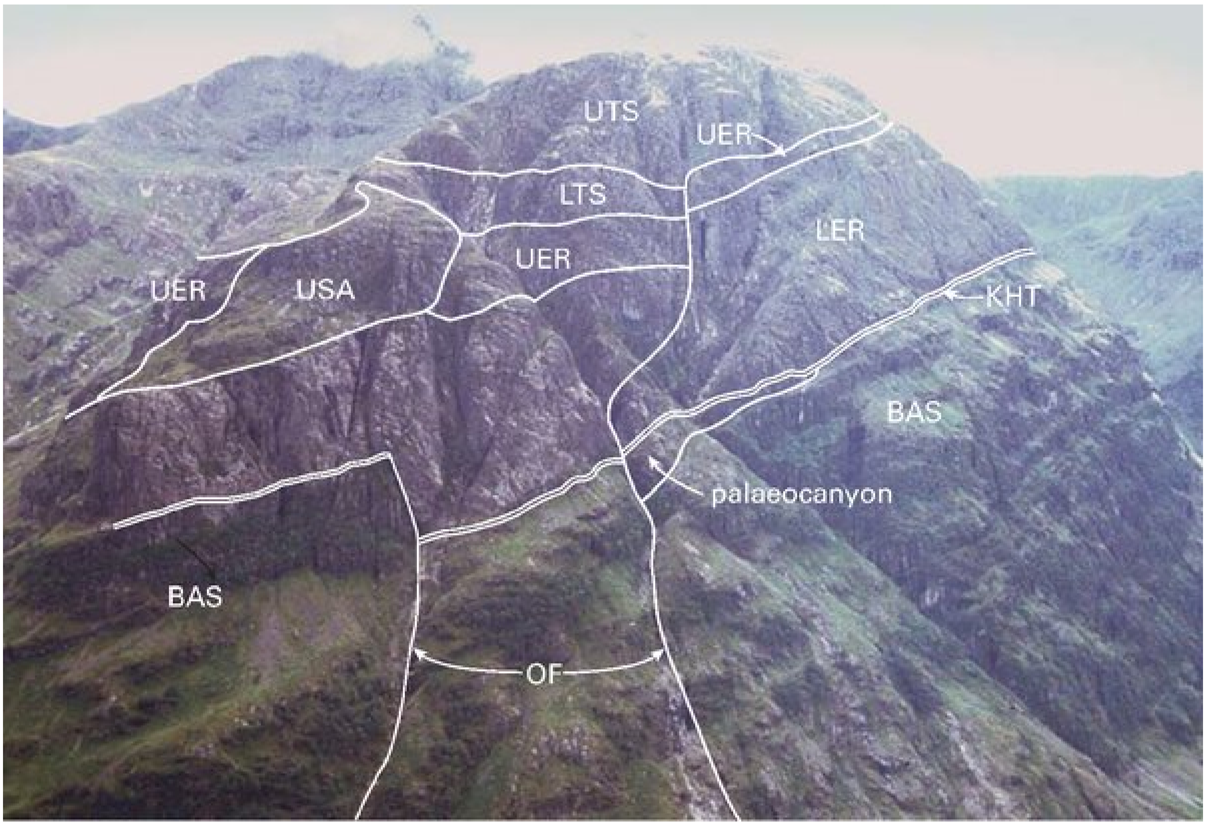
(Figure 14) Schematic cross-section illustrating ignimbrites and breccias restricted at and near the Southwestern Graben Fault (zone) in Coire nam Beitheach [NN 139 547], north-west of the Queen’s Cairn Fault. Original near-vertical fault scarps that ponded the Lower Etive Rhyolite (LER) have been rotated by downsag towards the Glencoe Graben. Blocks *and megablocks of Lower Etive Rhyolite have been incorporated at several horizons within the ponded Upper Three Sisters Ignimbrite. Overlying Church Door Buttress Breccias include mesobreccias that were shed from the Southwestern Graben Fault and show evidence of loading into hot ignimbrite; andesite-dominated breccias higher in the section were shed from scarps cutting the Basal Andesite Sill-complex farther to the south-west.*



(Plate 4) Basal Andesite Sill-complex, Kingshouse Tuffs and Lower Etive Rhyolite cut by strands of the Ossian Fault in the north face of Aonach Dubh [NN 15 56]. A palaeocanyon filled with conglomerate overlain by ignimbrite is located on the trace of the right-hand fault strand and is part of the extensive unconformity surface that cuts the sill-complex. The Lower Etive Rhyolite thickens considerably to the right (north-west) across both fault strands; the right-hand strand shows reactivation in the opposite sense (down to the south-east) (P611768). BAS Basal Andesite Sill-complex; KHB Kingshouse Breccias; KHT Kingshouse Tuffs; LER Lower Etive Rhyolite; UER Upper Etive Rhyolite.



(Plate 14a) North face of Aonach Dubh [NN 15 56] and northern side of Glen Coe [NN 16 57]. a. The Upper Etive Rhyolite (UER) becomes thicker across one strand of the Ossian Fault (OF) due to syn-eruptive down-to-the-south-east (to the left) movement; this is opposite to the offset that formed during eruption of the Lower Etive Rhyolite (LER). Ponding of the Lower Three Sisters Ignimbrite (LTS) and thickness change of the Upper Three Sisters Ignimbrite (UTS) are also evident across this fault strand (P611786). BAS Basal Andesite Sill-complex; KHT Kingshouse Tuffs; USA Upper Streaky Andesites .



(Plate 14b) North face of Aonach Dubh [NN 15 56] and northern side of Glen Coe [NN 16 57]. b. Traces of the Northeastern Graben Fault (NEGF) and its footwall scarp along the north side of the Pass of Glencoe [NN 16 57]. The scarp, composed of Basal Andesite Sill-complex (BAS), formed a volcanotectonic topographical barrier during *emplacement of the Upper Etive Rhyolite (UER), which is ponded against it, as well as forming a subterranean barrier during intrusion of the Lower Streaky Andesites sill (LSA-sill) within the Glencoe Graben. Lower Streaky Andesites lavas, which form much of the ridge crest from Am Bodach to the Aonach Eagach, were extruded onto the footwall block outside of the graben. The talus cone in the lower left of the view is the largest and most active in the vicinity (P611787). CRT Crowberry Ridge Tuffs; OF Ossian Fault.*