Chapter 4 Volcanic history: Glencoe Volcanic Formation

In the following pages, the Glencoe Volcanic Formation is described in detail according to a modern understanding of volcanic processes. This understanding derives substantially from the study of relatively young volcanoes, knowledge of which was limited at the time of the original work in the early 1900s. The aim here is to establish the geological evolution in terms of volcanic, sedimentary and tectonic processes. There is emphasis on those features that characterise the Glencoe volcano as probably the world’s most instructively exposed, tectonically controlled, piecemeal, multi-subsidence caldera volcano. For detailed petrographical descriptions of the rocks the reader should refer to the original Geological Survey publications, especially Bailey (1960); many of the rocks have been horribly altered by hydrothermal activity.

Basal Andesite Sill-complex (Precaldera fluvial sedimentation and andesitic magmatism, followed by protracted erosion)

The Basal Andesite Sill-complex (Plate 3); (Plate 4) is a unit, up to about 500 m thick, composed of a stack of basalt, basaltic andesite and andesite sheets with intercalated sedimentary layers. The stack rests unconformably on deeply eroded metamorphic rocks and is mainly preserved north-west of the Queen’s Cairn Fault and along the south-west flank of the volcano remnant, as far as the vicinity of Dalness (Figure 8). The sheets in the western outcrops, previously interpreted as lavas (Group 1 of Clough et al., 1909; Roberts, 1974; (Table 2)), show evidence of having been intruded as shallow-level sills in unlithified wet sediments that occupied a small sedimentary basin. It is possible that some of the sheets near Dalness are lavas, but they are not sufficiently well exposed to establish this. The preserved extent of the sheets is strongly controlled by faults and the original extent was certainly greater before faulting and erosional planation; the top of the sill stack is marked by a major unconformity (see p.104). To the north and north-west, such as at Stob Coire Leith [NN 152 583], An t-Sròn [NN 1355 5526] and Stob Coire nam Beith [NN 1378 5461], the sill stack is truncated by the ring-fault; to the south, near Dalness, it is also cut by the Clach Leathad intrusion (Figure 8). It is absent farther east.

A succession of steep scarps with intervening ledges, well displayed on the north and north-west faces of Aonach Dubh above Loch Achtriochtan [NN 14 56], shows that the sill stack comprises approximately 17 sheets, a few of which terminate or bifurcate along the outcrop (Plate 3); (Plate 4). The separation into distinct sheets is largely due to (ledge-forming) sedimentary intercalations and associated breccia layers, which occur throughout the stack.

Layers and pockets of conglomerates with bedded sandstones and siltstones are preserved beneath as well as within the sill stack, and these display an asymmetrical distribution on either side of the valley in lower parts of the Pass of Glencoe. On the northern side, moderately sorted to well-sorted conglomerates partially infill both small V-shaped gullies and larger steep-sided palaeocanyons, up to 20 m deep and 300 m wide, incised into the metamorphic basement. The conglomerates comprise rounded pebbles, cobbles and boulders (some over a metre in diameter), mainly of basement quartzite and semipelite, with some of andesite, ‘biotite granite’, ‘quartz diorite’ and ‘basic plutonic rock resembling kentallenite’ (Bailey and Maufe, 1916). These features are well exposed on the south-facing slopes beneath the Aonach Eagach (Plate 5), in a prominent outcrop that extends south-eastwards along the base of steep cliffs from Coire Liath [NN 151 580] towards the farm buildings at Achtriochtan [NN 157 574]. Plant remains have been recovered from micaceous siltstones at the base of the sequence. Higher in the sill stack here, and on the opposite side of the valley, such as below Aonach Dubh e.g. [NN 1412 5608], impersistent thin-bedded, medium- to coarse-grained brown sandstones, commonly with normal grading and lobate basal surfaces, are interstratified with red fine-grained sandstones and siltstones.

The deep canyons on the north side of the present valley are interpreted as having been cut by a major north-west-trending river, from which the conglomerates were deposited. To the south, beneath Aonach Dubh, bedded sandstones and siltstones were deposited mainly from suspension during fluvial floods, probably in overbank areas. The river is thought to have formed part of an extensive drainage system and, although its flow direction cannot be proved from this occurrence, later rivers in the same vicinity (at stratigraphically higher levels) evidently did flow from south-east to north-west.

The sill stack is dominated by sheets of dark, blue-grey basaltic andesite and andesite, which are 20 to 30 m thick. The andesites are generally fine grained, lack phenocrysts (aphyric texture) and are nonvesicular, but varieties with sparse phenocrysts, mainly of pyroxene, and some with vesicles, also occur. The upper and lower margins of the sheets are marked by various red-to-purple breccias and peperite, which is a mixture of quenched magmatic particles and sediment. These features reflect brittle fragmentation of magma due to stresses imposed by flow and cooling-contraction, or explosive activity caused by interaction of magma with water in wet sediment, or both (see Kokelaar, 1986). The red coloration is due to oxidation of iron. Along the upper contacts of most sheets, peperites and vesicular sedimentary rocks, with evidence of sediment fluidisation by steam, are taken as diagnostic of intrusion into wet sediment (Kokelaar, 1982). Hence the sheets are sills and not extrusive lavas as was previously thought.

Good exposures of the key features of the sills are accessible around the top contact of a basaltic andesite sheet that lies close to the base of the stack and forms the lower waterfall of the Allt Coire nam Beithach [NN 1408 5594]. East of the stream, along the peperitic upper contact, irregular fingers of andesite extend upwards into homogenised and vesicular sandstones (Figure 9). The overlying bedded sandstones, exposed in the walls surrounding the uppermost plunge-pool of the waterfall and several metres thick, are intensely convoluted and locally overturned; in places they show discordance along low-angle reverse faults that formed before the sandstones were lithified. At the lobate irregular base of the succeeding sheet, peperite intrudes fractures that extend upwards for several metres into the andesite. These features are very similar to those of the andesitic sills in Ayrshire (Midland Valley of Scotland) that intruded similar sediments and are of similar age (see Kokelaar, 1982, pp.22–28), and contact relationships such as these persist throughout the stack of sills in Glen Coe. Near the top of the stack, spectacular examples of coarse andesitic breccia with peperite, up to 8 m thick, are exposed on extensive glacially smoothed surfaces near the uppermost waterfall where the stream drains out of Coire nam Beitheach [NN 139 551]. This breccia (Plate 6a)(Plate 6b) locally contains jigsaw-fitting andesite blocks surrounded by red siltstone and fine sandstone, which indicates in situ autobrecciation, due to break-up of the intrusion margins during emplacement. In the vicinity, squeeze-up structures record upward interstitial flow and moulding of fluid andesite around earlier-formed breccia-blocks.

The top of the sill stack is marked by an erosional unconformity (Plate 4); (Plate 7), the temporal significance of which has not previously been recognised; it records considerable erosional planation and hence indicates a substantial interval of time between the early andesitic magmatism and the later caldera-volcano activity. Nevertheless, the unconformity is cut into by ancient river canyons in virtually the same area as the palaeocanyons located beneath the sill stack, on the northern side of the Pass of Glencoe (Figure 8). The unconformity cuts metamorphic basement elsewhere in the volcano complex where the andesitic sheets are missing. Fluvial sedimentary rocks overlie the unconformity in places; conglomerates, invariably containing rounded fragments of andesite as well as Dalradian metamorphic basement, occur in the palaeocanyons and pass laterally into various bedded sandstones, which are mostly interpreted as overbank flood deposits. The most instructive and accessible section of these fluvial deposits is exposed at the foot of Stob Dearg, beneath the slab and overhang known as the Waterslide [NN 2285 5455]. Here there is a palaeotopographical depression in the quartzitic basement, the uppermost parts of which are widely brecciated and record development of a regolith. The depression, interpreted as a fluvial palaeocanyon, is partially filled by some 8 m of purple and green conglomerates mainly composed of subrounded to rounded fragments of semipelites and quartzite, with andesite and, according to Hardie (1968), a 15 cm subrounded clast of ‘granite’. These conglomerates are laterally variable and are locally intercalated with purple and green sandstones and siltstones, which also form an infiltrated matrix. Steep shear bands locally cut and deform the conglomerates and, as these bands are parallel to the strands of the Northeastern Graben Fault in this vicinity, they are interpreted as recording minor strain due to activity in that system. Overlying the conglomerates are a further 8 m of thin-bedded to laminated, red, purple and green sandstones and siltstones, which are interpreted as fluvial overbank deposits. It was within these siltstones that plant and algal remains were found during the early Geological Survey work (see Bailey and Maufe, 1916, p.98); these were thought to confirm a ‘Lower Old Red Sandstone’ correlation with the lavas of Lorn (but see Kidston and Lang, 1924; Bailey, 1960; Wellman, 1994). Similar coarse conglomerates with abundant andesite clasts occupy a palaeocanyon that exploited a strand of the Ossian Fault where it cut the Basal Andesite Sill-complex, as seen on Aonach Dubh (Plate 4).

Nearby, at Lorn and in the Midland Valley (Plate 1), piles of andesitic lavas many hundreds of metres thick overlie coeval sills that were intruded into unlithified sediments. These sills were emplaced in active-basin settings similar to that at Glen

Coe, and at more or less the same time (regarding the timing see Marshall, 1991; Wellman, 1994). By analogy with these nearby areas, it is inferred that andesite lavas originally covered the Basal Andesite Sill-complex at Glen Coe and that they were subsequently removed by erosion. An extensive early cover of lavas is suggested by the repeated fluvial supply of andesitic boulders from beyond the present limits of the volcano complex, especially from the east along with boulders from the unroofed Rannoch Moor Pluton (see pp.15; 40). The sills may represent the deeply eroded remnant of an andesitic volcano centred in the vicinity of Glen Coe, but no associated vent or conduit is recognised.

The evidence for fluvial systems below, between and above the sills, together with the thick stacking of the sills, reflects a strong tectonic control on basin development, sedimentation and andesite magmatism. The repeated incision by rivers in the same place indicates persistent tectonic control in a north-west-trending graben or half-graben. The preservation of the sill stack records a downthrow to the north-west of about 500 m on the Queen's Cairn Fault, and it is clear from the palaeocanyon that exploited the Ossian Fault (Plate 4) that this fault also was active after the sills were emplaced. Hence it is apparent that both north-west-trending and north-east-trending faults were active at Glen Coe prior to caldera development. This fault activity is thought to reflect regional transtension, a combination of normal extension and strike-slip displacement (Moore and Kokelaar, 1997; see also Dewey and Strachan, 2003). Given the large amount of tectonic downthrow and the apparently considerable erosion of the lavas and sill stack that is recorded in the unconformity on the sills, an interval of hundreds of thousands of years, or more, may separate the andesite magmatism from the following recorded volcanism (see p.104).

Kingshouse Breccias: tectonic subsidence and alluvial-fan sedimentation

Following prolonged erosion of the precaldera andesites and widespread accumulation of conglomerates and other fluvial sediments, several small alluvial fans formed in the vicinity of the Northeastern Graben Fault. The largest fan, which is the main element of the rather heterogeneous sedimentary association referred to as the Kingshouse Breccias (Table 2), is well exposed on the lower north-eastern flank of Stob Dearg [NN 22 54], part of the Buachaille Etive Mòr massif (Figure 10). The overlying silicic Kingshouse Tuffs constitute a remarkable record of the onset of explosive activity centred close to the Northeastern Graben Fault (see pp.40–46). The type localities of the two units are not far from the Waterslide [NN 2285 5455], where the basal fluvial sedimentary rocks are also well exposed (p.34). They are easily reached using one of the climbers' paths that lead from the main road, either from the car park at Altnafeadh [NN 2208 5630] to ascend gently, or, less pleasantly and including a river crossing, directly south-west from the road [NN 2368 5539].

The Kingshouse Breccias are up to 35 m thick and are well exposed between Central Buttress [NN 2282 5443] and Tulaich Buttress [NN 223 552], some 600 m to the north (Figure 10); (Plate 8a), (Plate 8b). They comprise thick-bedded breccias interstratified with cross-bedded sandstones and, towards the south-east, are topographically restricted in extent by two closely spaced fault scarps. These scarps are exposed on the eastern lower slopes of Central Buttress [NN 228 545], at the side of the rock slab that forms the Waterslide (Figure 10), (Plate 8). The faults show downthrow to the north-west and are orthogonal to the Northeastern Graben Fault. A small wedge of breccia at the foot of the upper scarp is talus buried by the alluvial deposits (Plate 8a), confirming the contemporaneity of the topographical barrier and the alluvial-fan sedimentation. The near-vertical fault scarp contacts exposed here, between the Kingshouse deposits and the psammite and quartzite of the metamorphic basement, were misinterpreted by Hardie (1968) as the walls of a vent infilled with explosion breccias (localities 5 and 6 on his figures 1 and 2).

The Kingshouse Breccias (Plate 8a), (Plate 8b) are characteristically very poorly sorted, with blocks up to 1 m in diameter predominantly of psammite, supported in a fine breccia to pebbly quartzose sandstone matrix. Most blocks are angular, but some rounded boulders also occur and rounded pebbles of vein quartz are common. Other clasts include angular fragments of porphyritic rhyolite, with rounded fragments of andesite and of granitic rock. Discontinuous lenses of poorly sorted thin-bedded sandstones, which mainly consist of well-rounded quartz grains, are intergradational with the breccias. Channels several metres wide and with steep margins are common in the breccias and these are mostly filled with cross-stratified sandstones. These features are impressively exposed on extensive glacially smoothed rock surfaces at and near the Waterslide [NN 2284 5454] (Plate 8b), but are most accessible at the foot of Great Gully Buttress [NN 2268 5486] (Figure 10)a, b.

Although the abundant angular blocks of psammite in the Kingshouse Breccias probably record development of talus and regolith from the metamorphic basement, the high degree of rounding of some boulders, and especially the rounding of quartz pebbles and granules in the sandstones, suggest considerable fluvial transport. Hence the alluvial-fan deposits are interpreted as recording incorporation of talus and regolith into a fluvial drainage system. The drainage was extensive enough to incorporate boulders and pebbles of volcanic and plutonic rocks that were exposed outside the Glencoe Caldera-volcano Complex. The chaotic organisation of the deposits suggests that they were deposited rapidly during flash floods. The granitic clasts, which probably derive from the Rannoch Moor Pluton (p.15), and possibly also the rounded andesite clasts, indicate provenance from the north-east or east, with dispersal generally towards the graben axis.

Another alluvial-fan deposit in the graben-bounding fault zone, at the same stratigraphical level as the Kingshouse Breccias described above, is exposed in the floor of Cam Ghleann in the south-east of the volcano complex [NN 2484 5181]. Here, unstratified conglomeratic breccias, dominated by boulders and subrounded blocks of Rannoch Moor granite (see petrographical analyses by Taubeneck, 1967, p.1301) and porphyritic andesite, grade generally south-westwards over 500 m into poorly sorted bedded breccias, in places with imbrication of coarse clasts indicating transport broadly from the north-east (Plate 9). The latter beds are intercalated with well-sorted sandstones that indicate subaqueous deposition. The andesitic clasts probably represent continued erosion of lavas remaining from an extensive volcanic field related to the Basal Andesite Sill-complex (pp.36; 38). The large size of the boulders, up to 60 cm, indicates steep drainage and substantial highlands nearby. It is conceivable that while there was more general uplift and erosion, for example causing unroofing of the Rannoch Moor Pluton, relative subsidence along the Glencoe Graben maintained steep slopes into it, as well as causing entrapment of the main fluvial drainage. The Rannoch Moor Pluton is exposed nearby, to the east and south-east of the Glencoe volcano complex. The common granitic clasts indicate that the pluton had been unroofed prior to development of the caldera volcano, and that the graben-axial river flowed from south-east to north-west.

Coarse breccias that rest upon more normal fluvial conglomerates and overbank siltstones, with a sharp contact, as at the Waterslide (see above), occur in several places at the same stratigraphical level along the Glencoe Graben. The breccias, which lack bed-thickening and coarsening-upwards trends and are coarse grained from the base, mark nearby onset of rapid fault-scarp growth with associated mass wasting. Such distinct switches, from relatively normal fluvial sedimentation to more catastrophic alluvial aggradation of sediment bearing abundant angular clasts, recurred throughout the subsequent history of the caldera volcano, commonly without any contemporary eruption and hence without any volcanotectonic subsidence (i.e. due to magma withdrawal). These switches of sedimentation without volcanism are regarded as a characteristic reflection of purely tectonic activity; in many cases, as described below, the switches were precursors to eruptions, which are thus considered as having been closely linked to the tectonic activity.

Kingshouse Tuffs: onset of explosive volcanism

Explosive volcanism at the Glencoe Caldera-volcano Complex began in the vicinity of Stob Dearg [NN 22 54] and is recorded by the Kingshouse Tuffs (Figure 11). Ascending rhyolitic magma interacted with groundwater in the Kingshouse Breccias, causing powerful phreatomagmatic explosions and eruption of abundant fine-grained ash. A tuff cone at least 2 km in diameter and possibly some 100 m high formed over the alluvial fan and is now superbly exposed in tangential section (Figure 10). Beyond the cone slopes the eruption formed a distinctive phreatomagmatic tuff layer, generally 1 to 2 m thick, which is preserved widely across the Glencoe volcano complex (Figure 11); Plate 10). On Aonach Dubh, near Ossian’s Cave (Plate 4), and on Dinner-Time Buttress [NN 146 559], canyon-filling ignimbrites up to 10 m thick beneath the tuff layer are interpreted as the result of channelling of pyroclastic currents some 7 km away from the vent. In this vicinity, the phreatomagmatic tuff layer forms the distinctive and more or less continuous overhang between the terraced and vegetated lower slopes formed by the Basal Andesite Sill-complex and the prominent upper buttresses of the Lower Etive Rhyolite (Plate 3); (Plate 4).

The Kingshouse Tuffs are thickest, at up to 70 m, on the lower slopes of North Buttress on Stob Dearg (Figure 10); 12a). They generally fine upwards from tuffaceous lithic breccias at the base (Figure 12)c to stratified and cross-stratified tuffs above (Figure 12)b. The deposits are interpreted as part of the outer flank of a low-profile tuff cone; there is no evidence of the extensive unconformities and slump structures that characterise the relatively steep inner slopes and vent areas of such cones (e.g. see Fisher and Schmincke, 1984). The lower tuffaceous breccias contain abundant blocks of psammite and smaller sandstone clasts derived from the underlying alluvial fan. Higher in the succession, thin-bedded tuffaceous breccias locally display bomb-impact sags that indicate ballistic trajectories from a vent that lay to the west or south-west (Plate 11a). Upper parts of the tuff-cone succession comprise planar-stratified and cross-stratified silicic tuffs with abundant accretionary lapilli formed by the aggregation of moist ash particles in an eruption plume.

Cross-stratified tuffs show long-wavelength (more than 1 m), low-amplitude (less than 40 cm) bedforms and low-angle scour surfaces (Figure 12)b; (Plate 11b). In places these are cut by steep south-west-facing scour surfaces, with original slopes at up to 45°, some of which are draped by steeply dipping laminated tuff that locally shows slump structures. These features are interpreted as scours that faced and were eroded by energetic pyroclastic currents, and were then plastered with wet ash. Excellent examples of the various stratified tuffs are exposed in the lower flanks of Great Gully [NN 2266 5479].

The tuff cone was constructed by both pyroclastic density currents and pyroclastic fallout during eruption from a vent that probably lay only a short distance south-west of Great Gully Buttress (no more than a few hundred metres into the hill). During early stages of the eruption, significant amounts of alluvium and interstitial water were incorporated in low eruption columns and these generated mostly high-concentration pyroclastic currents that rapidly deposited the mainly massive tuffaceous lithic-breccias. The fining-upward sequence reflects gradual clearing of debris from the vent, with progressive development of more efficient magma-water interaction and hence more explosive and higher eruption columns. The more energetic columns incorporated more ambient air and produced more dilute and more mobile currents that in turn deposited planar-stratified and cross-stratified silicic tuffs. The extensive scours within the succession (e.g. (Figure 12b); (Plate 11a), (Plate 11b)) mark periods when the pyroclastic currents were erosive. The regionally widespread accretionary lapilli-bearing tuff layer (Figure 11a; (Plate 10), which is a hybrid deposit formed by pyroclastic fallout and dilute pyroclastic currents, was deposited during construction of the upper parts of the tuff-cone succession.

On the north-east face of Sròn na Creise [NN 242 524], 2 km south-east of the tuff cone and vent, the correlative succession thickens abruptly to 40 m in a small fault-bounded basin (Figure 11); (Plate 12a), where it shows evidence of subaqueous deposition (Plate 12b). The strata here consist predominantly of tuffaceous sandstones with intergradational massive, graded, planar-laminated and cross-laminated divisions. These are turbidites, deposited from aqueous density currents, and they become thinner bedded and finer grained towards the south-east. Some tuffaceous sandstone beds show irregular downward loading into parallel-stratified tuffs. Liquefaction structures, such as convolute lamination and flame structures, are common (Plate 12b) and the strata show evidence of widespread sliding and slumping along low-angle detachment surfaces. This succession records syneruptive lacustrine (lake-bed) deposition from turbidity currents, with intermittent fallout of fine phreatomagmatic ash from suspension. It is inferred that the tuff cone grew across the Northeastern Graben Fault (zone) and the Glencoe Graben axis and dammed the graben-axial river, forming a lake to the south-east (Figure 11). South-east-directed pyroclastic currents apparently crossed the lake shoreline and formed turbidity currents, while sedimentation of ash from suspension formed the plane-parallel stratified tuffs (Plate 12b). Much of the ejecta that by-passed the cone’s south-eastern subaerial flank was trapped and deposited in the lake.

Lower Etive Rhyolite: large-volume rhyolitic eruption and graben-like caldera subsidence

Caldera subsidence was initiated with eruption of the first of the three enigmatic flow-laminated rhyolites that constitute the bulk of the Etive Rhyolite Member (Table 2). Earlier workers did not distinguish the three units, and, quite reasonably for the time, considered that the rhyolites originated as slowly extruded, viscous lavas. Now they are recognised as having formed from three discrete episodes of explosive eruptive fountaining, in which the fragments of magma remained sufficiently hot and fluid during pyroclastic dispersal to coalesce during deposition and only then form a lava-like flow (Moore and Kokelaar, 1998). The rhyolites differ from slowly extruded lavas in showing evidence for the combination of (1) explosive (pyroclastic) origins, (2) progressive deposition from the base upwards, and (3) rates of eruption sufficiently high to cause contemporary caldera subsidence and infilling. Such rocks are known from other volcanoes, both within and outside calderas. Examples occur in the USA (Ekren et al., 1984) and in England (Branney et al., 1992) and here they are referred to as lava-like ignimbrites (Moore and Kokelaar, 1998). The three lava-like ignimbrites at Glen Coe, now called the Lower, Middle and Upper Etive rhyolites, are each underlain by silicic tuffs: the Kingshouse Tuffs (see above), the Raven's Gully Tuffs and the Crowberry Ridge Tuffs, respectively. These tuffs constitute remnants of cones stacked in vertical succession in the position of Stob Dearg (Figure 10), with the intervening Etive lava-like ignimbrites recording increments of caldera subsidence. The repeated eruptions at this site reflect basement-fault control of the magmatic plumbing. The opening phreatomagmatic (tuff-cone) activity of each eruption was a consequence of eruption through wet alluvial sediments, the localisation of which also reflects the action of underlying faults. All three Etive rhyolites and their associated tuff cones are well exposed on Stob Dearg (Figure 10), but the Lower Etive Rhyolite has its type section in the north-west of the complex, on the north-west face of Aonach Dubh [NN 143 554].

The Lower Etive Rhyolite is exposed from Meall a' Bhùiridh [NN 257 501] in the far south-east of the Glencoe volcano complex to Stob Coire nam Beith [NN 139 548] in the far north-west. It is up to 110 m thick and has a low aspect ratio (thickness: lateral extent) of about 1:140. It shows ponding relationships against faults and flexures of both the Northeastern and the Southwestern graben faults and displays some substantial thickness changes across cross-graben faults (Figure 13). The rhyolite is generally crystal poor and dominantly flow laminated. Locally, especially towards the south-east, it contains several volume per cent of feldspar crystals and sparse small lithic clasts (Plate 13a), (Plate 13b). North-west of the Ossian Fault, stratified lithic tuffs occur at the base of the sheet. Autobreccias (brecciated rhyolite) are widely present along the top and also within the sheet.

In the north-west, the shape of the Lower Etive Rhyolite in cross-section between its bounding structures to the north-east and south-west suggests that it infilled a half-graben. On the north-west face of Stob Coire nam Beith [NN 139 547], close to Summit Gully, the sheet is ponded against the scarps of two closely spaced normal faults with combined downthrow of more than 80 m (Figure 14). These faults, which mark the Southwestern Graben Fault (Figure 13), have been rotated by at least 35° owing to later caldera-related subsidence, and the Lower Etive Rhyolite does not extend farther to the south-west. From this location, the rhyolite sheet can be traced across Glen Coe towards The Study [NN 180 564], where it wedges out across a steep flexure defined by an approximately 0.5 km-wide zone of steepening dips in the underlying Kingshouse Tuffs and Basal Andesite Sill-complex. The flexure marks the Northeastern Graben Fault (Figure 13) and is most clearly displayed south-east of the Meeting of Three Waters [NN 176 562].

North-west of the Ossian Fault, in the buttresses on the north-west face of Aonach Dubh [NN 14 55], the Lower Etive Rhyolite is not altogether lava-like and shows large-scale subparallel lithological stratification (Plate 3). This stratification is particularly striking when the buttresses are viewed from the north-west, with the summer sun low in the evening sky. The most south-westerly of the buttresses, G Buttress [NN 143 554], is the type section for the Lower Etive Rhyolite (Figure 15). Here, up to 20 m of stratified lithic-tuffs at the base of the sheet show alternations of lithic-rich and lithic-poor layers. The tuffs contain abundant blocks of flow-laminated rhyolite, with others of andesite and of quartzite, in a welded matrix with flattened pumice clasts (fiamme), especially in the lithic-poor layers. These features record pyroclastic deposition; the flow-laminated clasts could represent early-deposited lava-like ignimbrite shed from the Ossian Fault scarp as it grew during the eruption (see below). The stratified lithic tuffs grade upwards via crudely stratified tuffaceous breccias into rhyolite breccia, up to 20 m thick, which in turn passes upwards into coarsely flow-laminated (lava-like) rhyolite and further into finely flow-laminated rhyolite. The latter is up to 50 m thick and is characterised by intense flow-folding. Autobreccias gradationally and irregularly overlie the flow-folded rhyolite.

To the south-east, the lava-like ignimbrite buried a north-west-facing scarp of the Ossian Fault that was approximately 30 m high. The fault scarp is clearly exposed in cross-section on the north-east face of Aonach Dubh, a short distance to the east of Ossian's Cave [NN 157 563], where it offsets the top of the Basal Andesite Sill-complex (Plate 4). The basal stratified lithic tuffs of the type section are absent south-east of the Ossian Fault and the unit throughout much of the rest of the extensive outcrop is represented by finely flow-laminated rhyolite. In the far south-east of the volcano complex, the rhyolite shows abrupt thinning from 80 m to less than 30 m, which is inferred to register initial topographical restriction of the lava-like ignimbrite by the escarpment of the White Corries Fault (Figure 13).

On the flank of Stob Dearg, near Creag na h-Uamhaidh [NN 2202 5523], a short distance to the south-east of the path into Coire na Tulaich, the finely flow-laminated rhyolite locally includes metamorphic basement lithic fragments and sedimentary inclusions in more or less planar layers. The debris was apparently derived from unconsolidated Kingshouse Breccias and Kingshouse Tuffs. Autobreccia at the base comprises clasts of (nonvesicular) rhyolite in a matrix with relict pumice fragments from pyroclastic debris. Although no vent for the Lower Etive Rhyolite is exposed, the included clasts derived from the Kingshouse Breccias and Kingshouse Tuffs suggest that the vent, or a series of closely spaced vents, cut these deposits, probably within the Buachaille Etive Mòr–Stob Dearg massif in the vicinity of the vent of the Kingshouse Tuffs. This manifestly was the case for the Upper Etive Rhyolite (see p.54).

Unlike slowly extruded rhyolite lavas, which normally form domes flanked by blocky talus or have steep, free-standing brecciated flow margins, the Lower Etive Rhyolite has no such original upper surface. Its upper contact is generally more or less planar, while the sheet as a whole has a low aspect ratio of about 1:140. The restriction of the sheet against topographical barriers that developed in response to the eruption (i.e. by caldera subsidence), without brecciation at the contacts, indicates both fluid behaviour and high rates of eruption of a substantial volume of magma. The absence of vesicles and any larger cavities that were originally gas-filled (lithophysae) indicates that the rhyolite was substantially degassed by the time of its final emplacement. Hence it is inferred that the rhyolite formed from an efficiently degassing fountain of fluid pyroclastic particles, reflecting catastrophic venting. An explosive eruptive origin for the sheet is also suggested by the gradation from stratified eutaxitic tuffs containing diverse lithic clasts at the base of the sheet north-west of the Ossian Fault, and by other relict pumiceous textures, although these alone are not diagnostic. It is envisaged that a lava-like flow formed directly from the coalescence of fluid magma particles in lower parts of the pyroclastic fountain close to the vent. The parallel layers of lithic fragments within the laminated rhyolite probably represent periodic incorporation of clasts into the vent or conduit during the progressive build up of the flow. Much of the flow flooded into and was ponded within the actively subsiding Glencoe Graben. Large-scale stratification of the sheet in the north-west of the volcano complex proves progressive accumulation there. It is possible that, in the early stages of the eruption, erosion and nondeposition occurred close to the vent while accumulation occurred in the north-west of the graben, and that at a late-stage flow-laminated rhyolite was emplaced across most of the graben.

Raven’s Gully Tuffs, Middle Etive Rhyolite, Crowberry Ridge Tuffs and Upper Etive Rhyolite: further cycles of rhyolitic phreatomagmatic and magmatic activity with intervening fluvial incision

On Stob Dearg, at Broad Buttress [NN 2252 5485] and at Tulaich Buttress [NN 2232 5500] and [NN 2222 5507], there are remnants of a steep-sided palaeocanyon that was eroded up to 15 m deep into the Lower Etive Rhyolite and filled with breccias and boulders (Figure 10)b. This feature records re-establishment of the fluvial system on the north-east side of the Glencoe Graben. The silicic Raven’s Gully Tuffs overlie this palaeocanyon and its associated unconformity (Table 2), and, like the Kingshouse Tuffs, their outcrop on the north-east face of Stob Dearg [NN 22 54] represents a section through the outer flanks of a tuff cone (Figure 10). Abundant bomb-impact sags reveal that the vent, as in the earlier explosivity, lay to the west or south-west of the present outcrops. Deposits forming the low flanks of the cone pass laterally into a thin (1–2 m) phreatomagmatic tuff layer. North-west of the path leading into Coire na Tulaich, at Creag a’ Bhancair [NN 2188 5505], the tuff layer is locally interstratified with, and overlain by, lenses of tuffaceous breccia up to 10 m thick, derived from collapse of a fault scarp at or near the Devil’s Staircase Fault. Although there are no exposures of extensive sedimentary deposits formed by the re-established river, fragments of psammite within the Raven’s Gully Tuffs suggest that the eruption involved reworking of underlying alluvium. As with the Kingshouse Tuffs, the Raven’s Gully Tuffs phreatomagmatic eruption probably also resulted from the interaction of ascending magma with groundwater and surface water.

The overlying Middle Etive Rhyolite, known only on Stob Dearg (Figure 10), was topographically confined by the faults bounding the Glencoe Graben and by the cross-graben Glen Etive Fault and Devil’s Staircase Fault. The sheet is predominantly flow laminated and is thickest, at 100 m, near Central Buttress [NN 226 541]. To the south, along the eastern face of Stob Dearg [NN 22 53] (Figure 10)c, it thins progressively and wedges out in the vicinity of a series of closely spaced normal faults, referred to as The Chasm step-fault system (Figure 7). To the north-west, close to Creag na h-Uamhaidh [NN 2185 5502] and the path leading into Coire na Tulaich, the rhyolite thins to 30 m across a normal-fault scarp 850 m south-east of the Devil’s Staircase Fault. Although the termination of the Middle Etive Rhyolite is not exposed, it is considered that the scarp of the Devil’s Staircase Fault (indicated by breccias) formed its north-western limit. The rhyolite records a second major magmatic eruption from a vent in the vicinity of Buachaille Etive Mòr–Stob Dearg. As in the first cycle, there was an initial phreatomagmatic phase and collapse of fault scarps.

Following emplacement of the Middle Etive Rhyolite, the graben-axial river was re-established and another palaeocanyon was eroded close to the Northeastern Graben Fault. This palaeocanyon is well exposed north and north-east of the prominent rocky knoll known as The Study [NN 183 564] and farther north-west on the lower slopes of Am Bodach [NN 172 573], where the steep north-eastern wall of the canyon is overturned south-westwards owing to subsequent caldera downsag. Fluvial pebble-bearing red sandstones and siltstones, up to 3 m thick, occur in the palaeocanyon and also form overbank deposits elsewhere, such as at Creag Doire-bheith on the lower slopes of Beinn Fhada [NN 1782 5618]. However, the sedimentary deposits have been largely obliterated by intrusions of the Lower Streaky Andesites. Part of a deep topographical depression cut into the Lower Etive Rhyolite close to the Northeastern Graben Fault is also exposed on the north-east flank of Sròn na Creise [NN 242 521] (see (Plate 17)), but it remains unclear when the erosion was initiated here relative to the timing of emplacement of the Middle Etive Rhyolite. The feature has no fluvial infill and the geometry of the exposure suggests that the topography was cut across the trend of the main graben fault.

On Stob Dearg [NN 22 54], the silicic Crowberry Ridge Tuffs are part of a third tuff cone stacked above the two earlier cones (Figure 10). The tuffs take their name from Crowberry Ridge [NN 2255 5440], which is near the tuff-cone outcrop and is formed of rhyolite that cuts the cone centre. To the south-east and north-west of Stob Dearg, the tuff-cone succession is represented solely by an extensive accretionary lapilli-bearing phreatomagmatic tuff layer, 1 to 5 m thick, which can be traced for up to 6 km from the vent as far as the Ossian Fault in the north-west and some 4 km into Cam Ghleann [NN 2457 5146] in the south-east; it thickens into the base of the topographical depression exposed on Sròn na Creise (see above and (Plate 17)) and is missing on the south-east flank of this. The Crowberry Ridge Tuffs record a further phreatomagmatic eruption centred near the Northeastern Graben Fault and, although no sedimentary layer is exposed beneath the tuffs, groundwater or standing water must again have been involved with the ascending magma.

The overlying Upper Etive Rhyolite, up to 120 m thick, is an extensive flow-laminated lava-like ignimbrite ponded against graben and cross-graben faults and flexures. North-west of the Ossian Fault, in the north-west face of Aonach Dubh [NN 14 55], the ignimbrite is less than 30 m thick and overlies the autobrecciated top of the Lower Etive Rhyolite. To the south-east, it thickens within a few hundred metres to 120 m, across a steep flexure and fault at the position of the Ossian Fault (Plate 14a). The sense of downthrow is reversed relative to the subsidence that influenced the emplacement of the Lower Etive Rhyolite. South-east of the flexure, thick autobreccias occur at the base of the laminated rhyolite and, within the sheet, a large-scale fold of the lamination (with a wavelength of 500 m) is truncated by a major internal slump detachment. These features are well exposed at Guala Laidir, on the south-east face of Aonach Dubh [NN 1572 5592], and they suggest late-stage slumping away from the nearby flexure that developed over the Ossian Fault. On the northern side of the Pass of Glencoe, the lava-like ignimbrite is ponded, without brecciation, against a steep scarp of the Northeastern Graben Fault (Plate 14b). The fault scarp is well exposed in the south-west-facing crags of Am Bodach [NN 1665 5762], where they tower above the deep gully formed on the Ossian Fault. To the south-west, at the head of Coire Gabhail [NN 156 545], the ignimbrite thins dramatically across a flexure that defines the Southwestern Graben Fault zone. These relationships indicate that during the eruption of the Upper Etive Rhyolite the 4 km-wide volcanotectonic structure at Glen Coe had the form of a trapdoor-like half-graben, with asymmetry opposite to that of the half-graben that formed during the Lower Etive Rhyolite eruption. South-east of Glen Etive, the Upper Etive Rhyolite is about 100 m thick on Sròn na Creise [NN 240 522] and some 40 to 50 m thick in Cam Ghleann [NN 2454 5145], beyond which it is not found.

On Stob Dearg, in the conspicuous upper part of North Buttress [NN 2256 5455], a near-vertical and roughly cylindrical body of flow-laminated rhyolite is exposed in oblique section, cutting downwards for almost 200 m through the thickest sections of the Crowberry Ridge Tuffs, Middle Etive Rhyolite, and Raven’s Gully Tuffs (Figure 10). The flow laminations are steep and apparently continuous with those in the main part of the Upper Etive Rhyolite and the feature is interpreted as part of an infilled vent from which the lava-like ignimbrite was erupted. The eruption resulted in large-scale subsidence along the Glencoe Graben, within which flow was restricted by steep cross-graben flexures and fault scarps, notably the Ossian Fault in the north-west and, presumably, the White Corries Fault in the south-east (Figure 16).

Lower Streaky Andesites: extrusion and shallow intrusion of andesite followed by fluvial incision

Emplacement of the Etive rhyolites was followed by a phase of andesitic magmatism represented by the Lower Streaky Andesites (Table 2), which form sheets up to 100 m thick in northern parts of the volcano complex, on both sides of the lower reaches of the Pass of Glencoe. The pervasive streaky texture of the rocks is the result of mingling (incomplete mixing) of andesitic and rhyolitic magmas (Plate 15a). Andesite is volumetrically dominant, with the rhyolite forming 10 to 50 per cent of the rock; irregular bands of purple-grey andesite alternate with cream-coloured rhyolitic bands and in places there are bleb-like patches of the rhyolite.

Within the Glencoe Graben, mainly on the southern side of the present valley, the andesitic sheets were emplaced as sills along the unconformity surface between the Lower and Upper Etive rhyolites. They have peperitic lower and upper contacts, which, like those around the sheets in the Basal Andesite Sill-complex, record shallow-level interaction of the magma with wet sediments. The largest sill is spectacularly exposed in the steep north-eastern face of Gearr Aonach [NN 1675 5608], where it is approximately 100 m thick between the Lower and Upper Etive rhyolites (Plate 15b). Its rather abrupt south-westward termination is exposed in the south-eastern slopes of Gearr Aonach, towards the prominent rockfall boulder field in Coire Gabhail [NN 1676 5576]. Similar abrupt terminations are evident in the lower part of Coire nan Lochan, in the north-west face of Gearr Aonach [NN 1608 5584] and in the south-east face of Aonach Dubh [NN 1581 5593] (Plate 15b). Towards the north-east the sheet thins at Creag Doire-bheith [NN 1781 5617], on the gentle slopes north of Beinn Fhada. Where the unconformity surface between the Lower and Upper Etive rhyolites includes a deep palaeocanyon, as in the vicinity of The Study [NN 1820 5637], the intrusive andesite appears to have been restricted by the original canyon walls. Much of the steep palaeoscarp that follows the Northeastern Graben Fault, from the Allt Coire Meannarclach [NN 1879 5642]; near the large beehive-like cairn] north-westwards towards the lower slopes of Am Bodach [NN 1695 5750], also acted to confine the intrusive andesite (LSA-sill in (Plate 14b)). This originally near-vertical, south-west-facing scarp of Basal Andesite Sill-complex has been rotated, top south-westwards, by later caldera downsag, so that the older rocks now overlie the younger rocks originally restricted by the scarp (both Upper Etive Rhyolite and intrusive andesite). This distribution of the sill indicates that the andesitic intrusion was restricted between the Ossian Fault and the two faults that bound the Glencoe Graben, with distinct thickening (up to 100 m) towards the middle ground. Its emplacement evidently was at least partly facilitated by volcanotectonic subsidence, as the overlying strata were not pushed up so far as to accommodate the full thickness of the lenticular sheet. Some relatively minor uplift of the caldera floor probably did result from the sill intrusion, and this case constitutes one of the only two instances where uplift due to magma emplacement can be inferred fairly confidently at this volcano (see also p.74).

An extensive unit of andesites, over 3.5 km 2 in area and widely up to 50 m thick, is exposed on the ridges between Meall Dearg [NN 162 583], Am Bodach [NN 169 580] and Sròn Gharbh [NN 175 584] (Plate 14b), and extends towards A' Chailleach [NN 184 571]. This unit lies outside and to the north-east of the Glencoe Graben, where it was probably extruded as lavas. Its original extent is unknown; it is truncated to the north by the ring-fault system. Given that there was contemporary volcanotectonic subsidence within the Glencoe Graben, to accommodate the intruded andesite, it is probable that the lavas were erupted from one or more vents in the vicinity of the graben.

The Lower Streaky Andesites and other parts of the caldera-fill succession were eroded by rivers, which, like the earlier fluvial systems, formed a main canyon close to the Northeastern Graben Fault. This palaeocanyon can be traced for approximately 1 km between The Study [NN 1826 5647] and above the cottage at Allt-na-Ruigh [NN 1742 5690]. Like its predecessor, this palaeocanyon was subsequently intruded, in this case by magmas forming the Upper Streaky Andesites. Although the intrusion obliterated most of the record of sedimentary deposition within the palaeocanyon (thin pebble-bearing sandstones are preserved in places beneath the andesitic sheet), it did at least preserve the original canyon form. Between The Study and Allt-na-Ruigh [NN 176 567] it is possible to demonstrate that the later river incised more deeply than the one before; the later palaeo-canyon cuts through the floor of its predecessor.

Lower Three Sisters Ignimbrite: ignimbrite-forming eruption with graben-like caldera subsidence and downsag

The Three Sisters Ignimbrite Member consists predominantly of two welded (eutaxitic) ignimbrites: the Lower and Upper Three Sisters ignimbrites, up to 150 m and 200 m thick, respectively. These record major rhyodacitic explosive eruptions that were substantially different from the eruptions that produced the Etive rhyolites. They were accompanied by large-scale caldera subsidence and the ignimbrites are intercalated with coarse breccias. The Three Sisters Ignimbrite Member is thickest close to the Pass of Glencoe at Buachaille Etive Beag [NN 19 55] and [NN 20 55] and in the three prominent ridges known as the Three Sisters: Beinn Fhada [NN 17 55], Gearr Aonach [NN 16 55] and Aonach Dubh [NN 15 56]. The type section is at Stob nan Cabar [NN 19 55], at the north-eastern end of the Buachaille Etive Beag massif. The Lower Three Sisters Ignimbrite is underlain by fluvial sedimentary rocks and, in the far south-east of the complex, on Meall a' Bhùiridh [NN 25 50], it is sharply overlain by thick breccias (White Corries Breccias; (Table 2)). After emplacement, the Lower Three Sisters Ignimbrite was eroded by a drainage system that in places formed deep palaeocanyons, which, as on Stob nan Cabar [NN 19 55], are partially filled with alluvial-fan deposits referred to as the Queen's Cairn Conglomerates. On Stob nan Cabar these deposits are overlain by thick breccias and megabreccias, the Lower Queen's Cairn Breccias. During the last phases of emplacement of the Upper Three Sisters Ignimbrite, and for some time afterwards, breccias were shed locally from fault scarps around the caldera. Thick tuffaceous breccias exposed towards the summit of Stob nan Cabar are the Upper Queen's Cairn Breccias, and various other breccias and sandstones in the north-west of the volcano complex at and near this stratigraphical level are collectively referred to as the Church Door Buttress Breccias.

The Lower Three Sisters Ignimbrite consists mainly of massive strongly welded (eutaxitic) tuff (Plate 16a), (Plate 16b), but it also includes mesobreccias and, locally, megabreccias (breccias with clasts tens to hundreds of metres across). It filled an elongate volcanotectonic depression that can be traced from Loch an Easain [NN 25 49], in the extreme south-east of the volcano complex, as far as Ossian's Cave [NN 15 56] in the north-west (Figure 17). The ignimbrite is interpreted as the product of a single sustained eruption and it shows marked lateral changes in thickness and character that suggest it was emplaced over fault scarps, tilted strata, and, in places, deep open fractures (crevasses).

Between Loch an Easain [NN 2518 4960] and the slopes of Meall a' Bhùiridh above Cam Ghleann [NN 2532 5105], the ignimbrite is approximately 35 m thick and comprises thick but laterally impersistent mesobreccias and megabreccias, intercalated with thin layers of eutaxitic tuff. On the western side of Cam Ghleann, on the slopes of Stob a' Ghlais Choire [NN 2436 5178], the ignimbrite thickens considerably towards the south-west, and, farther north-westwards, on Buachaille Etive Mòr [NN 22 53] and Buachaille Etive Beag [NN 20 55], it is at least 150 m thick. The south-east face of Stob Dearg [NN 22 54] and [NN 22 53] shows spectacularly the great thickening of the ignimbrite away from the flanks of the Glencoe Graben, across three fault scarps of The Chasm step-fault system (Figure 10)c. Similar thickening relationships are exposed on the eastern slopes of Stob a' Ghlais Choire in Cam Ghleann [NN 24 51], where the upper parts of fault blocks of the Etive rhyolites in the step-fault system are cut by rotational slumps (Figure 18); (Plate 17). Mesobreccias at the base of the ignimbrite are ponded against palaeoscarps and slumps of The Chasm step-fault system 1 in (Figure 18), and, in places, megablocks of Etive rhyolite up to 40 m across are included. This suggests that fault scarps were initiated in the underlying rhyolites during early stages of the eruption, causing large blocks to be shed. Subsequently, emplacement of eutaxitic tuffs with lithic-breccia layers buried the basal breccias, fault scarps and slumps 2 in (Figure 18), and onlap with fanning dips of the internal layering demonstrates progressive downsag towards the south-west. The ignimbrite is strongly welded across the whole of the downsag area. For example, at Stob nan Cabar on Buachaille Etive Beag [NN 202 556], upper parts of the ignimbrite comprise monotonous, massive, intensely welded eutaxitic tuff over 100 m thick. The pronounced flattening fabrics show extreme pinching and moulding around lithic fragments and crystals, with aspect ratios of up to 1:20 in some fiamme.

The combination of step-faulting and downsag that deformed the caldera floor around Sròn na Creise and Buachaille Etive Mòr gave way to relatively simple downsag farther north-west. For example, where the Lower Three Sisters Ignimbrite is traced from north-east to south-west on the upper slopes of each of the Three Sisters — Beinn Fhada [NN 17 55] towards [NN 16 54], Gearr Aonach [NN 16 55] towards [NN 15 55] and Aonach Dubh [NN 15 56] to [NN 15 55] — it thins gradually and wedges out where a linear hinge separated untilted strata on the flanks of the Glencoe Graben from tilted (downsagged) strata within it (Plate 18). Close to this bounding structure, crevasse-like fissures up to 30 m deep and infilled with eutaxitic tuffs and breccias can be traced in Coire nan Lochan [NN 1547 5573], on the south-east flank of Gearr Aonach [NN 1578 5508] and onto the north-west flank of Beinn Fhada [NN 1627 5484].

The fault block north-west of the Ossian Fault apparently did not subside so much during eruption of the Lower Three Sisters Ignimbrite, if at all. In the steep cliffs at Ossian's Cave [NN 1537 5618], the ignimbrite, almost 40 m thick, is ponded against a fault scarp (Plate 14a) and farther north-west it is only exposed in a linear crevasse that extends over 1 km along the buttresses of the north-west face of Aonach Dubh. The most accessible exposures of the crevasse fill are near G Buttress [NN 1423 5525], where the crevasse tapers downwards for 40 m into the Etive Rhyolite Member and is partially filled with moderately welded lithic tuffs. The tuffs are themselves incised and overlain by cobble conglomerates, which suggests that a small energetic river exploited the crevasse. This crevasse system north-west of the contemporary subsidence area is considered to represent peripheral extension due to the major caldera downsag towards the south-east.

In the south-east of the Glencoe volcano complex, a crevasse system can be traced for approximately 2.5 km from Meall a' Bhùiridh [NN 259 497] towards Cam Ghleann [NN 251 516]. It lies along the Northeastern Graben Fault and separates Dalradian metasedimentary rocks to the north-east from strata of the Glencoe Volcanic Formation to the south-west 3 in (Figure 18); the volcanic strata are tilted at 40° to the south-west. On the north-eastern slopes of Meall a' Bhùiridh, strongly welded eutaxitic tuffs infill a crevasse-like fissure 5 to 20 m wide and at least 50 m deep. Both the inner and outer contacts of the tuffs in the crevasse are sharp and the eutaxitic fabrics have near-vertical or steep north-eastward (outward) dips. Although physical continuity is not preserved, the tuff is indistinguishable from the eutaxitic tuff of the Lower Three Sisters Ignimbrite, with which it is correlated. The crevasse fill is well exposed near the huts at the base of the upper ski tows above White Corries [NN 2558 5078]. Farther north-west, on the upper, north-west facing slopes of Cam Ghleann [NN 2508 5168], the crevasse is 200 m wide and contains megablocks, mesobreccia and tuff. It is approximately 500 m deep and tapers downwards to 20 m wide near the valley bottom [NN 2495 5200], in the subvolcanic basement 3 in (Figure 18). Locally, at deeper levels, mesobreccias with tuff matrix occur in sinuous north-west-trending dykes cutting metasedimentary rocks along strike in the fault zone. Locally, these breccia dykes contain irregularly shaped intrusions of rhyolite and are well exposed on the glacially smoothed lower slopes of Sròn na Creise and Stob a' Ghlais Choire e.g. [NN 2468 5210] and [NN 2449 5256] (Plate 17).

It seems likely that the tuff-filled and mesobreccia-filled crevasses exposed along the trace of the Northeastern Graben Fault in the south-east of the volcano complex, and the linear breccia dykes occurring at deeper levels, represent part of the vent and conduit system for the Lower Three Sisters Ignimbrite eruption. Repeated collapse of adjacent fault scarps periodically fed blocks into the pyroclastic density current, subsequently to be emplaced as breccias along successive surfaces as the ignimbrite progressively accumulated. This magmatic plumbing is in marked contrast to that of the more centrally located vents that supplied the three Etive rhyolites and initially produced tuff cones due to explosive magma-water interaction there (compare (Figure 16)a and b.

Following the Lower Three Sisters Ignimbrite eruption, catastrophic collapse of fault scarps in the extreme south-east of the volcano complex led to the accumulation of a wedge of breccias, the White Corries Breccias. These breccias sharply overlie the Lower Three Sisters Ignimbrite and contain blocks of Dalradian metasedimentary rocks up to 20 m across. They are well exposed and up to 35 m thick on the north-east flank of Meall a' Bhùiridh [NN 2557 5064], and they can be traced from the slopes above Loch an Easain [NN 2500 4980] almost as far as the south-eastern slopes of Cam Ghleann [NN 2525 5092].

Queen's Cairn Conglomerates: localised fluvial incision and alluvial sedimentation

On the crags of Stob nan Cabar at the north-eastern end of Buachaille Etive Beag, several steepsided palaeocanyons are incised up to 20 m deep into the Lower Three Sisters Ignimbrite e.g.[NN 2004 5564]. These are partially filled with poorly sorted boulder and pebble conglomerates, which are composed of rounded Dalradian metasedimentary clasts supported in a matrix of quartzose sandstone and reworked tuff. To the south-west, along the flanks of Buachaille Etive Beag [NN 1982 5495] and [NN 1875 2627], an extensive sedimentary layer, up to 2 m thick, comprises laterally variable conglomerates, sandstones and laminated siltstones. These deposits, collectively named the Queen's Cairn Conglomerates, together with the underlying erosion surface, reflect incision and sedimentation by a river system that originated beyond the site of the caldera volcano, entered the Glencoe Graben from the north-east, and was susceptible to flash floods. The widespread sedimentary layer is interpreted as recording short-lived braided streams and overbank areas of a small alluvial fan.

Lower Queen’s Cairn Breccias: tectonically induced collapse of scarps along the North-eastern Graben Fault

On the north-east-facing crags of Stob nan Cabar [NN 2006 5556], the Queen’s Cairn Conglomerates are sharply overlain by a 50 m-thick layer of breccias and megabreccias, the Lower Queen’s Cairn Breccias (Figure 17). These are crudely stratified, contain blocks of various metasedimentary rocks, with megablocks up to 30 m across, and they can be traced from Stob nan Cabar for 1 km to the south-west along both the south-east and north-west faces of Buachaille Etive Beag. They terminate sharply at Coire Raineach [NN 1921 5537]. The sparse matrix of the breccias apparently formed by breakage and abrasion of blocks during transport; in places, jigsaw-fitting clasts record the disintegration of blocks during late stages of their transport (Figure 19). Stratigraphically equivalent breccias are exposed on the relatively smooth rock slopes between A’ Chailleach and An t-Innean Mòr [NN 1875 5704], on the north side of the Pass of Glencoe, where they thicken abruptly to 60 m over a short distance towards the south and south-east. These breccias comprise blocks, typically 10 to 20 cm in diameter, almost exclusively derived from the Lower Streaky Andesites and Etive Rhyolite Member, which are exposed in this vicinity along the footwall of the Northeastern Graben Fault. The composition, geometry and position of these breccias, which lie north-west of the trace of the Queen’s Cairn Fault (Figure 17), suggest that they were banked against a south-east facing, degraded scarp of the Queen’s Cairn Fault (Figure 20)a. The Lower Queen’s Cairn Breccias represent catastrophic avalanching that followed alluvial-fan sedimentation and occurred without contemporaneous eruption, which implies that the recorded fault-scarp growth, with collapse, was tectonic in origin.

The Dalness Breccias, which rest unconformably upon the Basal Andesite Sill-complex along the south-western side of the volcano complex, from high on the flanks of Stob Coire Sgreamhach [NN 151 529] to the northern flanks of Beinn Ceitlein [NN 180 506], may include parts that formed during the tectonism that produced the Lower Queen’s Cairn Breccias. Like the latter breccias, the Dalness Breccias are overlain by the Upper Three Sisters Ignimbrite, but their full context is not known. They lie to the south-west of, or bury, the projected trace of the Southwestern Graben Fault (zone) and could relate to movements on strands of the ring-fault, as is registered in the uppermost Church Door Buttress Breccias, which succeed the Upper Three Sisters Ignimbrite (p.72).

Upper Three Sisters Ignimbrite: major ignimbrite- forming eruption with caldera subsidence

The Upper Three Sisters Ignimbrite, which is up to 200 m thick, is the most voluminous preserved pyroclastic unit at Glen Coe. It can be traced for 13 km from Meall a’ Bhùiridh [NN 25 50] in the south-east of the caldera-volcano complex to Stob Coire nam Beith [NN 14 54] in the north-west (Figure 17). It shows marked thickness changes across tilted strata and filled an elongate flexural volcanotectonic depression (downsag) between the major graben faults. Maximum subsidence was in the vicinity of Stob nan Cabar [NN 19 55] and [NN 20 55] on Buachaille Etive Beag. Here, the ignimbrite grades upwards from moderately to strongly welded lithic eutaxitic tuff, and includes several layers of tuffaceous mesobreccia. The strongly welded tuff is overlain by nonwelded bedded tuffs that in turn are overlain locally by laminated tuffs. The deposits characteristically contain a wide variety of lithic fragments, including metasedimentary rocks, Etive rhyolite, peperitic andesite and streaky andesite.

The Upper Three Sisters Ignimbrite is well exposed in the prominent upper crags of each of the Three Sisters — Beinn Fhada, Gearr Aonach and Aonach Dubh — and its three-dimensional geometry is well defined in the intervening Coire Gabhail [NN 16 55] and Coire nan Lochan [NN 15 55]. At the north-eastern end of each ridge, the ignimbrite grades upwards from moderately to strongly welded lithic eutaxitic tuff (e.g. on the north face of Aonach Dubh [NN 153 560]). However, to the south-west the ignimbrite thins rapidly (onlaps) onto underlying strata that were tilted during, and as a consequence of, the ignimbrite-forming eruption. The hinge separating tilted from nontilted strata coincides with the hinge that earlier confined the Lower Three Sisters Ignimbrite; both are well exposed towards the heads of Coire Gabhail (Plate 18) and Coire nan Lochan. The lower, moderately welded part of the Upper Three Sisters Ignimbrite thins south-westwards and wedges out some distance inside the hinge. The overlying strongly welded tuff thins similarly, but overlaps the moderately welded tuff and occurs extensively as a thin veneer over the flanks of the graben as far as the south-western slopes of Bidean nan Bian [NN 1448 5363] in Gleann Fhaolain.

In contrast, north-west of the Ossian Fault, the caldera floor subsided without flexural downsag. On the north-west face of Aonach Dubh [NN 14 55], the ignimbrite, 80 to 100 m thick, grades up from moderately welded to intensely welded tuff, but contains numerous thin intercalated mesobreccia-rich layers. Here, it forms pale outcrops in the upper parts of steep rock buttresses and to the south-west is ponded against the scarp of the Southwestern Graben Fault. These ponding relationships, schematically represented in (Figure 14), are well exposed in Coire nam Beitheach and on the lower slopes of Stob Coire nam Beith [NN 141 547]. The edge of the Upper Three Sisters Ignimbrite, where it pinches out against the steeply tilted Etive rhyolites, can be traced close to the summit of Stob Coire nam Beith [NN 1405 5468]. Away from the structural margin, thick tuffaceous mesobreccias at the base of the ignimbrite locally include megablocks, up to 50 m across, of Etive rhyolite (Figure 14). In places, as beside the Allt Coire nam Beithach [NN 1425 5486], these basal mesobreccias are crudely stratified and underlain by stratified tuff (Figure 21); (Plate 19a), (Plate 19b). Higher in the ignimbrite, mesobreccia lenses extend from Stob Coire nam Beith north-eastwards for up to 300 m across the floor of Coire nam Beitheach and show irregular basal contacts with the ignimbrite, recording loading-related foundering. It is inferred from evidence in overlying breccias (Church Door Buttress Breccias; p.71) that the ignimbrite in the north-western part of the volcano complex was also ponded against the Northeastern Graben Fault.

The Upper Three Sisters Ignimbrite is less well exposed in south-eastern parts of the caldera-volcano complex, but it can be traced more or less continuously around the ridges of Buachaille Etive Mòr [NN 21 54] and Stob a’ Ghlais Choire [NN 23 51]. On the south-eastern slopes of Buachaille Etive Mòr, in Coire Cloiche Finne [NN 21 53], the ignimbrite thickens progressively south-westwards away from the flanks of the Glencoe Graben, as identified in Stob Dearg (Figure 10)c. Here, it comprises moderately welded lithic tuff only, with mesobreccias interstratified at and near the base. In the extreme south-east of the volcano complex, on the slopes of Meall a’ Bhùiridh [NN 2533 5078], the ignimbrite is 40 m thick and includes breccias with blocks up to 2 m across.

It appears that the Upper Three Sisters Ignimbrite was deposited from a single sustained pyroclastic density current. Although no vent is exposed, the distinctive mixed lithic-clast population that occurs throughout the ignimbrite suggests a single source, which would have lain close to where the Queen’s Cairn and Devil’s Staircase faults intersect the Glencoe Graben (Figure 20)b; here, all of the distinctive rock types were available to supply clasts into the pyroclastic current. Layers of meso-breccia within the ignimbrite probably record repeated collapse of near-vent fault scarps during ignimbrite emplacement. The successive ponding of moderately welded tuff and then strongly welded tuff, with overlap onto tilted caldera-floor strata, indicates that during ignimbrite emplacement the pyroclastic density current became less topographically constrained by the downsag that developed.

Seemingly, strongly welded tuffs accumulated only in the vicinity and north-west of the Devil’s Staircase Fault. The laminated tuffs overlying the ignimbrite on Stob nan Cabar record fallout of ash suspended above the pyroclastic density current; they were preserved owing to the closely succeeding deposition of the Upper Queen’s Cairn Breccias.

Upper Queen’s Cairn Breccias fault-scarp degradation along the Northeastern Graben Fault

At Stob nan Cabar on Buachaille Etive Beag, the Upper Three Sisters Ignimbrite is overlain by thick-bedded tuffaceous breccias, named the Upper Queen’s Cairn Breccias (Figure 22). These have the form of a wedge that is thickest, at 60 m, in the north-east and thins south-westwards for 2.5 km. The relationships are well exposed from the summit of Stob nan Cabar [NN 2000 5546] south-westwards along Buachaille Etive Beag through Coire Raineach [NN 1918 5507] towards Coire Dubh [NN 1836 5455], where the breccias dip gently to the south-west. As with the Lower Queen’s Cairn Breccias, the clasts, which are mostly of psammite and streaky andesite, suggest that the talus was derived mainly from collapse along the footwall of the Northeastern Graben Fault where this extended between the Queen’s Cairn and Devil’s Staircase faults. Unlike the Lower Queen’s Cairn Breccias, however, pyroclastic debris in the matrix of these breccias indicates that the collapse accompanied or was closely followed by the final stages of emplacement of the Upper Three Sisters Ignimbrite; this suggests that the faulting in this instance was probably volcanotectonic in origin.

In the north-west of the Glencoe Caldera-volcano Complex, the Church Door Buttress Breccias (Figure 22); (Figure 23) comprise various layers of breccia, sandstone and tuff. These are exposed more or less continuously from their type section, around Church Door Buttress on the northern flank of Bidean nam Bian [NN 142 544], to Coire nan Lochan [NN

15 55]. They are also exposed on the south-west slopes of Bidean nam Bian in Gleann Fhaolain [NN 14 53]. The complex stacking geometry of the breccia layers (Figure 23) records successive failures of different fault scarps north-west of the Queen's Cairn Fault.

On the steep crags beneath the summit of Stob Coire nam Beith [NN 1410 5470], 12 m-thick stratified tuffaceous mesobreccias are intercalated with, and show loading into the top of, the Upper Three Sisters Ignimbrite (Figure 14). These mesobreccias, with clasts mainly of Basal Andesite Sill-complex rocks and Etive rhyolites, record an increment of collapse along the scarp of the Southwestern Graben Fault *during* the late stages of ignimbrite emplacement. Eutaxitic fabrics that are deflected around lithic blocks show that the loading occurred while the ignimbrite was sufficiently hot (more than 550°–600°C) for the glassy constituents to deform in a ductile manner. The mesobreccias thin gradually north-eastwards across the floor of Coire nam Beitheach (Figure 23) to beneath the scree-covered south-western slopes of Stob Coire nan Lochan [NN 1442 5493]. In Coire nan Lochan [NN 1508 5533] the Church Door Buttress Breccias overlying the ignimbrite are stratified and dominated by clasts of streaky andesite, and here the top of the underlying ignimbrite shows evidence of sedimentary reworking. The streaky andesite clasts are lithologically indistinuishable from the Lower Streaky Andesites, which crop out widely on the north-eastern flank of the Glencoe Graben (e.g. between Meall Dearg [NN 162 583] and Am Bodach [NN 169 580]).

Across the north-west face of Aonach Dubh [NN 14 55], the breccias dominated by streaky andesite thin south-westwards and overlap another breccia that thins in the opposite direction (Figure 23). This lower breccia thins north-eastwards from near G Buttress [NN 1437 5520] to B Buttress [NN 1475 5566] and rests with a sharp, slightly erosional contact on the Upper Three Sisters Ignimbrite. Like the tuffaceous breccias deposited during emplacement of the ignimbrite (see above), it is dominated by clasts from the Basal Andesite Sill-complex and Etive rhyolites. The two overlapping breccia layers mark successive collapses following ignimbrite deposition, first along the Southwestern Graben Fault and later on the Northeastern Graben Fault. From their long run-out distances they are inferred to record mainly catastrophic avalanching, as opposed to gradual accumulation of talus, but their upper and distal parts show some evidence of aqueous reworking and grade laterally into sandstones with scour-and-fill cross-stratification.

An uppermost breccia layer is well exposed at the head of Coire nam Beitheach. It is mainly non-stratified and is composed predominantly of angular blocks, 10 to 30 cm in diameter, which are derived from the Basal Andesite Sill-complex and set in a sparse matrix of comminuted andesite. It forms the 50 m-high Church Door Buttress [NN 1416 5437], where it overlies and effectively buries the Southwestern Graben Fault against which previous units were banked. The breccia layer thins gradually north-eastwards for approximately 1 km across Coire nam Beitheach and onto the south-western slopes of Stob Coire nan Lochan [NN 1440 5463], and it also thins south-eastwards across the southern slopes of Bidean nam Bian into Gleann Fhaolain [NN 1452 5364] (Figure 23). The significance of this breccia layer is that, unlike those beneath it, it marks large-scale failure of one or more fault scarps beyond the former south-west limit of the Glencoe Graben. The scarp or scarps that exposed the Basal Andesite Sill-complex may have been in the vicinity of, or beyond, the ring-fault mapped in this vicinity. The south-westward shift of the limit of subsidence that is recorded appears to anticipate later developments, wherein the former Southwestern Graben Fault became deeply buried *within* successive volcanotectonic centres of deposition (see p.82).

Upper Streaky Andesites: further phases of andesite intrusion and extrusion, with vent formation and fluvial incision

Emplacement of the Three Sisters ignimbrites and overlying collapse breccias was followed by a phase of andesitic magmatism represented by the Upper Streaky Andesites (Table 2). The andesites are extensively brecciated and contain bleb-like rhyolitic patches, locally forming a pervasive millimetre- to centimetre-scale streaky texture, which records magma mingling. Within the Glencoe Graben, the sheets occur as transgressive and locally bifurcating sills at shallow levels in or beneath the Three Sisters Ignimbrite Member, and variations in thickness of the sills mimic those of the ignimbrites. For example, on the south-east face of Buachaille Etive Mòr, on the lower slopes of Coire Cloiche Finne [NN 21 53], thick andesite sheets intrude lower parts of the Lower Three Sisters Ignimbrite and terminate against fault scarps that are part of The Chasm step-fault system [NN 2254 5326]. Similar relationships are evident on the north-west face of Buachaille Etive Mòr at Creag a' Bhancair [NN 2154 5504] and in Coire na Tulaich [NN 217 548], where andesitic sills densely intrude the Lower Three Sisters Ignimbrite and abut the same fault system. No correlative andesites are observed north-east of this fault system on Stob Dearg [NN 22 54]. In the north-west of the volcano complex, on Beinn Fhada [NN 17 55] and Gearr Aonach [NN 16 55], the andesitic intrusions occur at higher levels and cut the Upper Three Sisters Ignimbrite. Here, multiple and bifurcating sills thin rapidly and pinch out to the south-west in much the same manner as the enclosing ignimbrites (Plate 18). Where the cumulative thickness of andesitic sills is great, there is likely to have been some uplift of the caldera floor together with volcanotectonic subsidence, as seemed likely to have occurred with emplacement of sills of the Lower Streaky Andesites (see p.57).

Two conduits or infilled vents of the Upper Streaky Andesites have been identified. The more impressive example is well exposed on the north-eastern shoulder of Aonach Dubh [NN 157 561], less than 200 m east of Ossian's Cave (Plates 14a); (Plate 15b). Here, a near-cylindrical body of andesite, with steeply inclined streaky fabrics, cuts upwards through the Etive Rhyolite Member and into the Lower Three Sisters Ignimbrite. In places, thin veins of the streaky andesite interfinger with the latter ignimbrite and show that the intrusion caused reheating sufficient to allow ductile remobilisation of the tuff. Locally within the cross-cutting streaky andesite there are irregular bodies of agglomerate. These are rich in incorporated lithic fragments (Plate 20) and indicate explosive activity, possibly involving a vent at the contemporary surface. Another, larger cross-cutting intrusion occurs where the Upper Streaky Andesites crop out along the plane of the Queen's Cairn Fault. On the north side of the Pass of Glencoe, the contact between the streaky andesites and the Basal Andesite Sill-complex lies along the Allt Coire Meannarclach [NN 1905 5703]. From here the contact, against the Upper Etive Rhyolite, can be traced south-westwards through low ground across the road close to the large beehive-shaped cairn [NN 1872 5634], and some way into the Lairig Eilde [NN 1815 5550]. Here, and to the west, numerous ramifying sills of the andesite obscure the detail of the Three Sisters Ignimbrite Member. The intrusions record both mingling of magmas and emplacement associated with further volcanotectonic subsidence. The cross-cutting bodies interpreted as conduits or infilled vents are located close to where cross-graben faults intersect the Glencoe Graben axis, like the vents and associated tuff cones of the Etive rhyolites.

High on the north side of the Pass of Glencoe, streaky andesites, similar to those that are intrusive, are more than 200 m thick and overlie an unconformity that cuts intrusions of the Upper Streaky Andesites. Along the unconformity, which is poorly exposed on the north-west slope of Coire Mhorair [NN 1860 5795], there is a deep palaeocanyon partially filled with conglomerate and sandstone. Clough et al. (1909) recorded sedimentary intercalations within the overlying andesite succession. Although the stratigraphical relationships are somewhat obscure, it seems that fluvial incision and sedimentation occurred after emplacement of some of the Upper Streaky Andesites, and that andesite lavas were subsequently extruded across the sedimentary deposits while shallow-level sills were intruded within them.

Glas Choire Sandstone Member fluvial incision followed by alluvial-fan and lacustrine sedimentation

In the south-eastern part of the caldera-volcano complex, a canyon was cut into the Upper Three Sisters Ignimbrite; there is no evidence there for the extrusion of lavas of the Upper Streaky Andesites, although related intrusions occur at shallow depth and lavas may have been eroded away. At Glas Choire in Cam Ghleann [NN 241 514], the canyon is 300 m wide and up to 40 m deep (Figure 24); it trends north-west, as shown by counterpart exposures on the north-west flank of Stob a' Ghlais Choire [NN 237 518], and is exposed in a slightly oblique, north–south section. North-west of the Glen Etive Fault, the erosion surface is less deeply incised where it is exposed at Feadan Ban [NN 21 54], near the ridge of Buachaille Etive Mòr, and also on the slopes of Beinn Fhada [NN 17 55]. This change marks the opening of the palaeocanyon north-westwards onto a broad plain.

Deposits assigned to the Glas Choire Sandstone Member (Table 2) fill the palaeocanyon and extend laterally beyond its immediate confines; to the north-west they form an extensive layer on the broad fluvially reworked surface (Figure 22); (Figure 24). The sedimentary architecture of the palaeocanyon fill is well exposed at Glas Choire [NN 2416 5143], where undulose-stratified sandstones (Plate 21a) enclose poorly sorted conglomerates resting within broad (several tens of metres) asymmetrical scours. The conglomerates contain angular blocks as well as rounded boulders, both up to 1 m in diameter; numerous boulders are granitic and from the Rannoch Moor Pluton and large clasts of metamorphic basement are abundant, all in a matrix of pebbles, granules and rounded sand grains (Plate 21b). The lenticular conglomeratic units represent filled channels, and the deposits in the palaeocanyon contain at least four discrete groups of them, stacked with local overlap (Figure 24); they record the migration of successive stream channels during rapid aggradation and possibly formed during waxing and waning of only a few flash floods. Planar-bedded and laminated fine-grained sandstones and siltstones (Plate 21c), up to 10 m thick, overlie the main scour-and-fill succession and extend laterally beyond it. Although these are widely intruded and disrupted by sills related to the overlying Bidean nam Bian andesites, they clearly record deposition from aqueous suspension and from turbidity currents, and hence indicate standing water. The palaeocanyon and the sedimentary rocks within it record a switch from fluvial erosion to fluvial deposition, and the overlying strata record ensuing formation of a lake.

At Feadan Ban [NN 2108 5400], north-west of the River Etive, extensive parallel-stratified sheet-like pebbly sandstones, up to 25 m thick, are interpreted as alluvial plain deposits, downstream from the fluvial palaeocanyon. Farther north-west, distal correlative sandstones and siltstones are restricted and onlap against the earlier collapse-breccia wedges (Figure 22); (Figure 23). For example, in the vicinity of Coire Dubh on Buachaille Etive Beag [NN 1820 5446], planar-bedded sandstones and siltstones thin with onlap onto the south-western edge of the Upper Queen's Cairn Breccias, and, in Coire nan Lochan [NN 1550 5510], similar deposits thin onto the south-eastern edge of the Church Door Buttress Breccias. Farther north-west, on Aonach Dubh [NN 14 55], sandstones and siltstones, up to 5 m thick, accumulated in the topographical depression on the surface of the Church Door Buttress Breccias where the two contrasting breccia layers overlap (Figure 23). Some of these sandstones show normal grading, from medium- or fine-grained sand to silt and, where they rest on laminated siltstones, small load casts are common at their bases. Preferential recent erosion of the siltstones has formed the topographical feature on Aonach Dubh known as The Amphitheatre [NN 1456 5545].

It is inferred that a river draining from the east, with some catchment on the Rannoch Moor Pluton, initially caused substantial erosion in the east and then became dammed by changed topography so as to form a caldera lake. Damming of the river led to sedimentation across the broad eroded plain and back up into the topographical confines of the Glas Choire palaeocanyon. The planar-bedded and laminated strata that are prevalent towards the west and also form the upper part of the sequence in the east record lacustrine sedimentation in which the turbidity currents probably arose from periodic fluvial floods. The depth of the caldera lake is unknown; the existence of standing water and turbidite sedimentation at the site of the former palaeocanyon suggests development of a considerable topographical barrier, or dam, in the north-west. The lake may have been at least many tens of metres deep, possibly much deeper.

Bidean nam Bian Andesite Member: andesite and dacite extrusion with volcanotectonic ponding

Thick sheets of andesite and dacite overlie the Glas Choire sedimentary rocks and are collectively named the Bidean nam Bian Andesite Member (Table 2). They represent effusive eruptions of unusually large volume for magma of intermediate composition in an intracaldera setting. In the west of the volcano complex, a massive to extensively columnar jointed sheet forms the spectacular cliffs and pinnacles of Stob Coire nan Lochan (Plate 22a), (Plate 22b) and the peaks of Bidean nam Bian [NN 14 54], from which the member takes its name. These are the rocks from which Thirlwall (1988) obtained an age of 421 ± 4 million years. In the precipitous north-east face of Stob Coire nan Lochan [NN 148 550] and in the sheer walls around Central Gully and Diamond Buttress on Bidean nam Bian [NN 144 544], columnar jointing extends for more than 200 m, virtually from the top to the bottom, and there is no evidence of any internal flow-unit boundary. The unit is thickest, at 450 m, near the head of Coire Gabhail [NN 15 54], where it overlies the Southwestern Graben Fault, and from here it thins progressively for up to 4 km to the north-east, as seen along the ridges of Beinn Fhada [NN 16 54] and Buachaille Etive Beag [NN 18 54] and [NN 192 548]. Between Feadan Ban [NN 210 539] and the flanks of Stob na Doire [NN 207 533], on Buachaille Etive Mòr, the Bidean nam Bian member thickens dramatically south-westwards as the dip of the underlying pebbly sandstones steepens from a few degrees south-west to almost vertical. The unit thins to the south-east through Stob Coire Sgreamhach [NN 15 53] and Coire nan Easan [NN 160 518], becoming considerably thinner in the south-west slopes of Sròn an Fhorsair [NN 17 51], near Dalness.

South-east of the River Etive, Bidean nam Bian andesite and dacite, locally more than 200 m thick, forms the upper cliffs and summits of Stob a' Ghlais Choire, Creise [NN 24 51] (Plate 17) and Meall a' Bhùiridh [NN 25 50]. Here the columnar jointing is not as obviously continuous as elsewhere, but the rocks are monotonously uniform, dark blue and fine grained, and there is no sign of any internal flow-unit boundary. Around the high flanks of Stob a' Ghlais Choire [NN 2410 5176], one or more sills of the same rock type lie beneath the main unit, within the upper fine-grained sandstones and siltstones of the Glas Choire Sandstone Member (see previous section). These sills show pillowed and fragmental margins indicative of intrusion when the sediments were wet and unlithified. Elsewhere there are minor occurrences of autobreccia and peperite at basal contacts of the unit, as well as small-scale loading-related deformation of the underlying Glas Choire deposits, such as at Coire Dubh [NN 179 541]. The upper contact of the member is preserved only in the south-west of the volcano complex, where phreatomagmatic tuffs and ignimbrites lie unconformably upon it (see p.81). Upper parts of the unit are autobrecciated locally and in places the breccias show crude stratification, which may reflect some sedimentary reworking. These features of the upper contact suggest that the andesites and dacites were extrusively emplaced, as lavas, while the features of the basal contact indicate emplacement onto wet caldera-lake-floor sediments.

The Bidean nam Bian andesites and dacites are remarkably massive and homogeneous throughout their thickness, across the entire caldera volcano complex, with no well-defined internal contacts such as pronounced discontinuities of jointing, erosion or weathering surfaces, or sedimentary intercalations. In the north-west of the volcano complex, the andesites are distinctly porphyritic with well-formed (euhedral) phenocrysts of plagioclase and hornblende, typically 5 mm across, and plane-parallel flow lamination is common. Around the summit of Stob Coire nan Lochan [NN 148 548] this lamination occurs in domains with contrasting orientation, as if laminated material had been broken up in a brittle fashion and had then foundered into fluid. The andesites and dacites in the east are far less porphyritic than in the west, which may be interpreted as recording coexistence of two eruption centres, possibly tapping different parts of the same magma chamber.

Although the Bidean nam Bian andesites and dacites have many characteristics of lavas, the thick units lack features such as rubbly flow-unit boundaries and intercalated sedimentary detritus that would indicate accumulation from a series of eruptions over a long period of time. Instead, it seems that the andesites and dacites were emplaced in a short interval to form one or more deep lava ponds, and the implied rapid effusion rates and thick accumulation are likely to have been linked to volcanotectonic subsidence. Nevertheless, from the evidence for a pre-existing caldera lake (in uppermost Glas Choire sedimentary strata) it appears that there already was some form of basin at the time of onset of the eruption or eruptions; conceivably the first andesitic and dacitic magmas flowed into a lake. The limited preservation of overlying strata makes it difficult to establish details of the possible volcanotectonic subsidence, but the thickening of the unit to the south-west (up to 450 m) is most simply reconciled with asymmetrical or trapdoor-like subsidence primarily on volcanotectonic faults lying to the south-west of the Glencoe Graben, possibly involving the nearby strand of the ring-fault and the fault in Gleann Chàrnan see (Figure 7). The remarkable thickening of the unit along with steepening of substrate, on Buachaille Etive Mòr, is consistent with hinge-like subsidence towards the south-west. The original extent of the Bidean nam Bian Member across, and possibly outside, the Glencoe Caldera-volcano Complex is unknown, but a conservative *minimum* erupted magma volume of about 12 km^3 is estimated, which is unusually large for an intracaldera outpouring of andesite and dacite. The An t-Sròn composite intrusion [NN 13 54] has been interpreted as the root of an early andesitic central volcano (Bussell, 1979; Garnham, 1988; see pp.92–93), and its position in relation to the volcanotectonic faults makes it a likely source for the Bidean nam Bian member. The intrusion has branches that invaded the volcanotectonic faults, both along and south-west of the ring-fault; these include diorite and tonalite, which are the coarse-grained (intrusive) equivalents of andesite and dacite.

Coir Eilde Tuffs and Lower Dalness Ignimbrite: renewed phreatomagmatism and large-volume rhyolitic explosive eruption leading to caldera subsidence

The Dalness Ignimbrite Member comprises two welded (eutaxitic) tuffs, the Lower and Upper Dalness ignimbrites, which are at least 200 m and 100 m thick respectively. Each ignimbrite is underlain by extensive phreatomagmatic tuffs, the Coir Eilde Tuffs and the Coire nan Easan Tuffs, respectively. The sequence records further explosive eruptions that were associated with large-scale caldera subsidence. Unlike the previous major pyroclastic units, which have their thickest deposits and maximum subsidence in the vicinity of Buachaille Etive Mòr and the Three Sisters, on the Glencoe Graben axis, the Dalness ignimbrites are thickest (and have their type sections) towards Dalness in the south-west of the caldera-volcano complex. The ignimbrites are, however, not extensively preserved and their full original form is unknown.

The Coir Eilde Tuffs occur widely as a variably preserved layer, 1 to 2 m thick, of finely laminated porcellanous tuff with abundant accretionary lapilli, overlying the Bidean nam Bian Andesite

Member in the south-west of the volcano complex. They record phreatomagmatism similar to that which preceded eruption of each of the Etive rhyolites earlier in the volcanic history (Table 2).

The tuffs are best exposed at the type section in Coir Eilde, which is in the vicinity of the Southwestern Graben Fault, at the head of the Lairig Eilde. Here, north of the stream [NN 161 537], the tuff thickens to 25 m between palaeofault scarps that define a 200 m-wide basin in which there is evidence of subaqueous deposition. South of the stream [NN 1632 5347], the tuff thickens to 10 m.

The Coir Eilde Tuffs record a return to phreatomagmatic activity, but the location of the vent is uncertain. The extensive thin tuff layer records fallout of fine ash from dilute ash clouds, and the thickening of the sequence southwards to 10 m possibly represents the outer edge of a tuff cone. The fault-bounded aqueous basin probably acted to trap ash from pyroclastic currents during the eruption. The availability of water and evidence of contemporaneous faulting suggest that the Coir Eilde phreatomagmatism may have been influenced by movement or movements on the Southwestern Graben Fault and possibly also one or more intersecting cross-graben faults. The temporal shift of the magmatic plumbing towards the south or south-west, relative to the vents of the Etive rhyolites, would be consistent with the similar shift in the locus of maximum volcanotectonic subsidence evident from the Bidean nam Bian andesites (see p.78) and Dalness ignimbrites (see below).

The Lower Dalness Ignimbrite comprises strongly welded crystal-rich eutaxitic tuff and breccia, and it is ponded against tilted strata and within crevasse-like fissures. At its type section near Coir Eilde [NN 159 538], the ignimbrite is about 200 m thick and it appears to thicken south-eastwards towards Dalness and Stob na Bròige [NN 18 52], where, however, it is substantially altered owing to emplacement of the underlying Clach Leathad Pluton (see p.99); here most rocks are patchily or predominantly white weathering, recording remobilisation of silica and some recrystallisation. To the north-east along the ridge of Beinn Fhada [NN 16 54] and north-east along the upper slopes of Buachaille Etive Beag [NN 183 540], the ignimbrite thins with onlap onto tilted strata of the underlying Coir Eilde Tuffs. It is not possible to determine any original southern limit of the ignimbrite, because it is cut by the ring-fault system, on Beinn Ceitlein [NN 18 50], and is obliterated by the Clach Leathad intrusion.

North-eastwards from the Bealach Dearg [NN 151 537], along the ridge of Beinn Fhada, blocks derived from the Etive Rhyolite Member dominate mesobreccias at the base of the ignimbrite. Elsewhere at the base, blocks of plagioclase- and hornblende-phyric andesite similar to the Bidean nam Bian andesites are dominant. In Coir Eilde, the base of the ignimbrite shows loading into the thick sub-aqueous Coir Eilde Tuffs, and in places it includes clasts of the tuff. The upper part of the ignimbrite, which is up to 180 m thick, is massive and strongly welded crystal-rich eutaxitic tuff, containing whole and fragmented plagioclase phenocrysts with some phenocrysts of quartz, biotite and hornblende.

Around the northern periphery where the ignimbrite thins against tilted substrata, the deposit infills irregular and steep-sided crevasses, up to 150 m deep, which opened in the Coir Eilde Tuffs and Bidean nam Bian Andesite Member. The crevasses are well displayed along Beinn Fhada; towards the head of Coire Gabhail, near the Bealach Dearg [NN 1542 5385], the main crevasse lies on the north-west side of the ridge, but, farther north-east, it is deflected round to the east, crosses the ridge of Beinn Fhada [NN 1656 5444], and is exposed in the Lairig Eilde [NN 1676 5452]. Originally, the fissures probably formed a more or less continuous, somewhat arcuate system from near or beyond the Southwestern Graben Fault generally north-eastwards towards the Glencoe Graben axis. It is possible that other related fissures occur farther to the south-east, on Buachaille Etive Beag, for example on the north and north-west flanks of Stob Dubh [NN 177 538], but they are not so clearly defined.

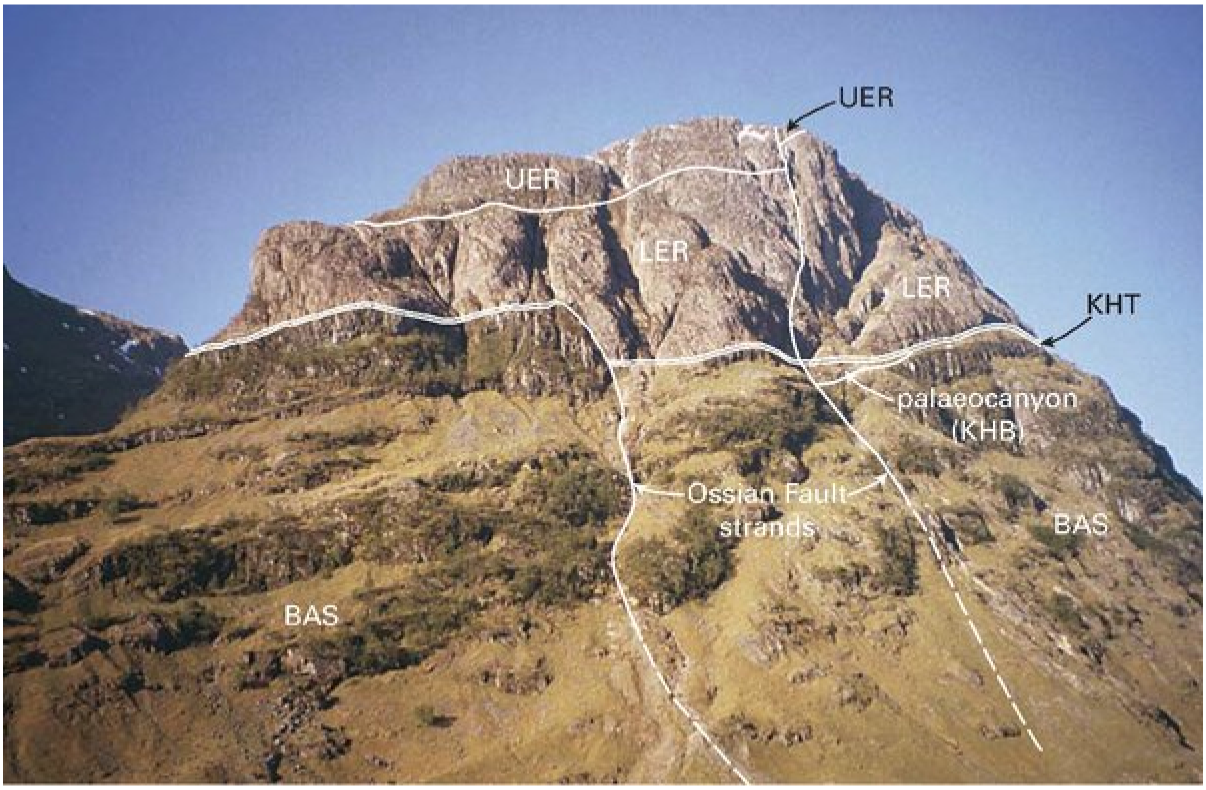
Although the Lower Dalness Ignimbrite is incompletely preserved, its distribution certainly marks a volcanotectonic centre of deposition south-west of those defined by the earlier ignimbrites and extending across the former bounding structure, the Southwestern Graben Fault. The crevasse-like fissure system represents extension bounding a major downsag, the centre of which lay to the south, near Dalness, but there is no evidence that the ignimbrite was erupted from the fissures. The abundant blocks of Etive rhyolite in the mesobreccias suggest that the rhyolite was exposed in the vicinity of the vent or vents, or along faults that were active during the eruption and associated subsidence.

Coire nan Easan Tuffs and Upper Dalness Ignimbrite: further phreatomagmatism and explosive rhyolitic eruption

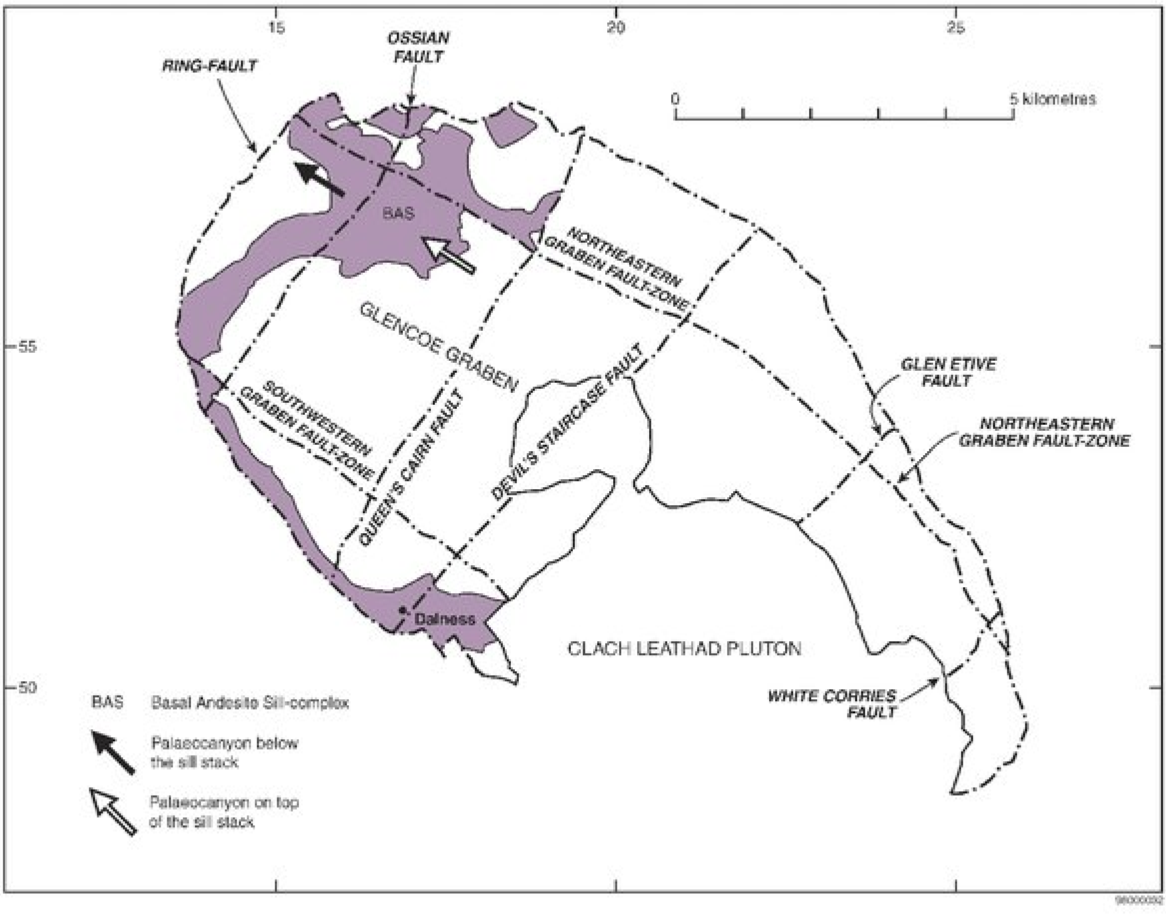
A layer of accretionary lapilli-bearing phreatomagmatic tuffs, the Coire nan Easan Tuffs, overlies the Lower Dalness Ignimbrite. Close to the peak of Stob Coire Sgreamhach [NN 1557 5356], bedded tuffaceous sandstone up to 10 m thick intervenes between the phreatomagmatic tuffs and the ignimbrite, but pinches out to the south-east, where the tuffs are finely laminated and porcellanous. These strata constitute the Group 6 'Shales and grits' of earlier workers (Table 2). Towards the top, the phreatomagmatic tuffs become interstratified with ignimbrite layers, and this sequence is overlain by stratified and then massive tuffs, which constitute the Upper Dalness Ignimbrite. This transition is well exposed on the south-facing slopes between Coire nan Easan and Dalness [NN 167 525]. In general, the Upper Dalness Ignimbrite is strongly welded and distinctly crystal-rich, similar to the Lower Dalness Ignimbrite. It is at least 100 m thick, but its original maximum thickness and extent are unknown. On Stob Dubh [NN 17 53] patchy to pervasive silicification and recrystallisation due to emplacement of the Clach Leathad Pluton inhibits discrimination of the Upper and Lower Dalness ignimbrites. Plagioclase- and hornblende-phyric andesites, texturally similar to the Bidean nam Bian andesites, intrude the Upper Dalness Ignimbrite locally with irregular and transgressive contacts; these too are altered in the vicinity of the pluton.

References

(Plate 3) Basal Andesite Sill-complex with overlying Kingshouse Tuffs and stratified Lower Etive Rhyolite, viewed looking east-south-east towards Aonach Dubh [NN 15 56]; the valley to the left is Glen Coe and the summit to the right is Stob Coire nan Lochan (P611767). BAS Basal Andesite Sill-complex; DA Dalradian metamorphic basement; KHT Kingshouse Tuffs; LER Lower Etive Rhyolite.



(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.



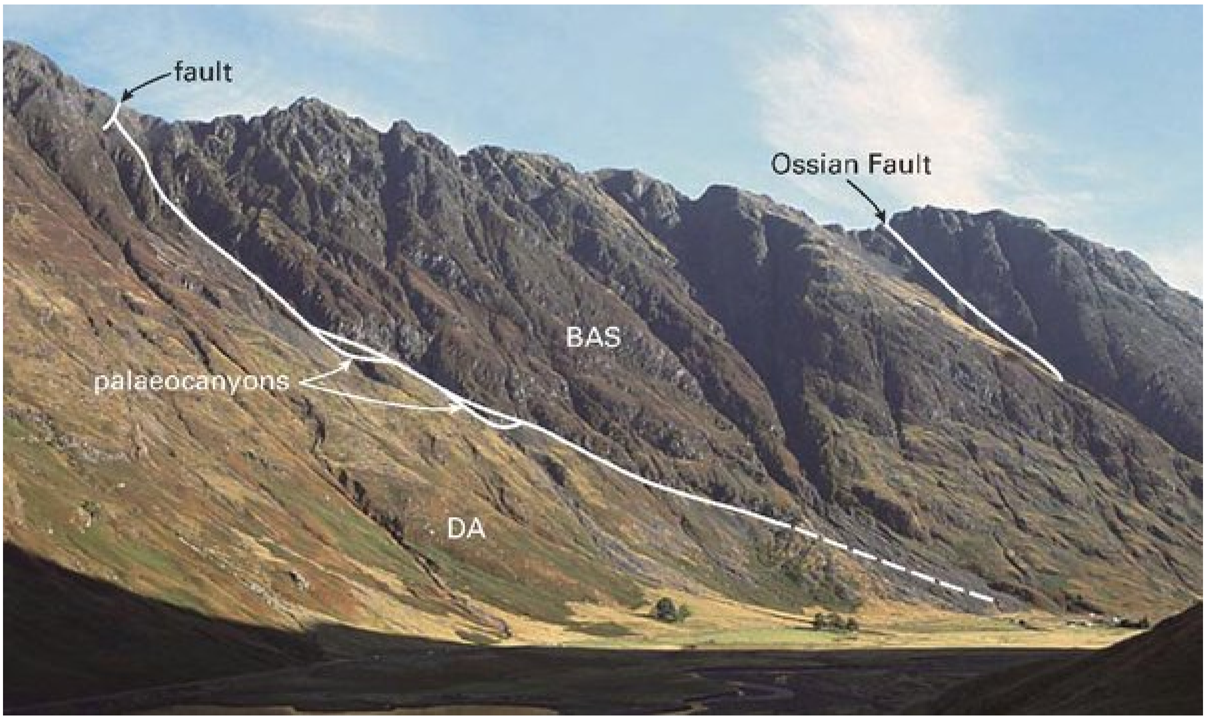
(Figure 8) Outcrop of the Basal Andesite Sill-complex relative to the structural framework.

Glencoe Volcanic Formation (this report)		Roberts (1974)	Clough et al. (1909)
Upper Dalness Ignimbrite	Dalness Ignimbrite Member	Group 7 Andesite and rhyolite lavas, with thin ignimbrite	Group 7 Andesites and rhyolites
Coire nan Easan Tuffs ↓		Group 6 Grits and shales	Group 6 Shales and grits
Lower Dalness Ignimbrite Coir Eilde Tuffs ↓		Group 5 Rhyodacitic ignimbrite	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	Three Sisters Ignimbrite Member		
Upper Three Sisters Ignimbrite		Upper Group 2 Rhyodacitic ignimbrite	Group 2 Rhyolites and andesites
Lower Queen's Cairn Breccias * Queen's Cairn Conglomerates ↓ White Corries Breccias Lower Three Sisters Ignimbrite ↓		Lower Group 2 Andesite and rhyolite lavas, with thin ignimbrite	
Lower Streaky Andesites			
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

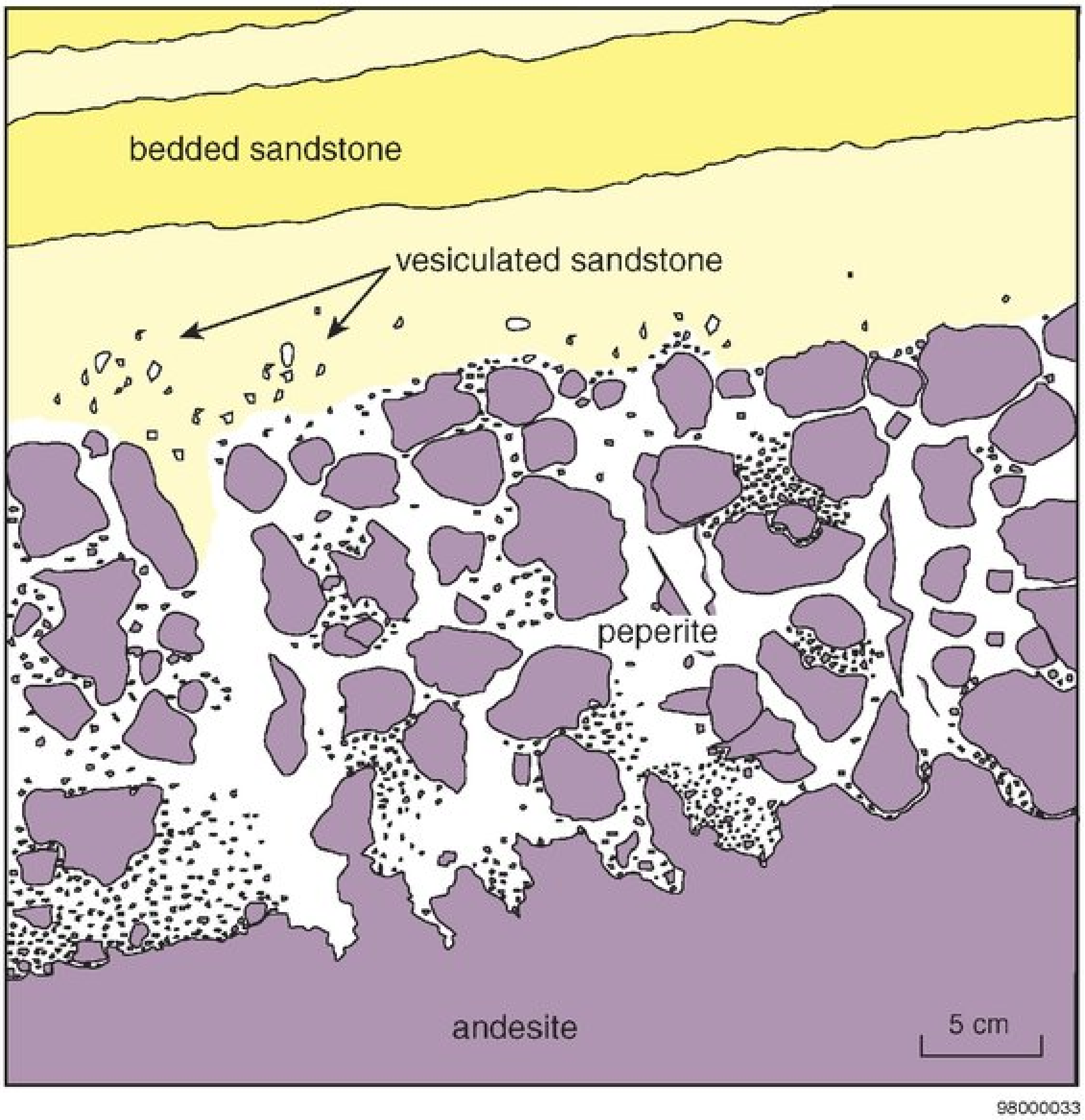
↓ *indicates unit that rests on fluvial sediments and an erosional unconformity*

* *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.



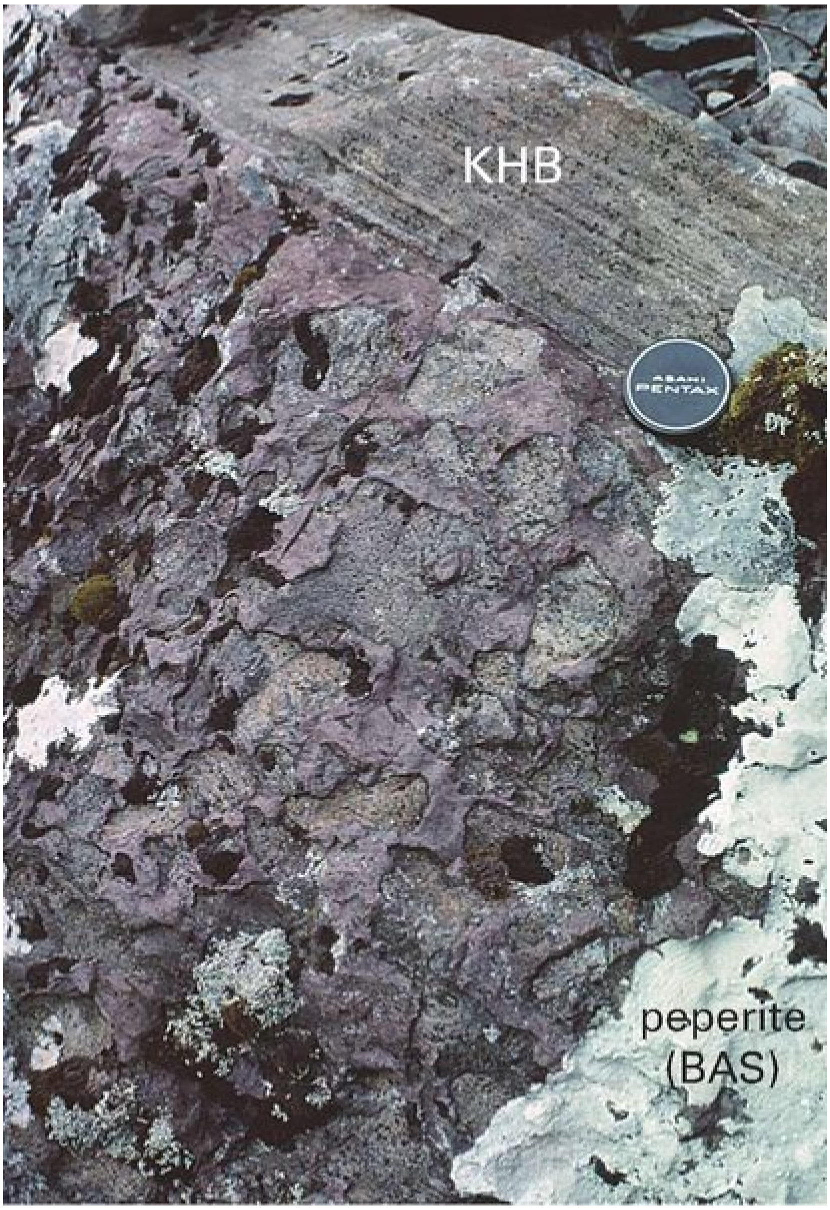
(Plate 5) Basal Andesite Sill-complex (BAS) and unconformity on Dalradian metamorphic basement (DA) including palaeocanyons on north side of Glen Coe [NN 15 57]. The sills and unconformity dip south- wards and are cut by a strand of the ring-fault system across the crest of the Aonach Eagach (serrated ridge at middle left) and beyond it on the north side. This dip away from the fault towards the inside of the caldera-volcano complex, and similar geometry elsewhere, was originally interpreted as due to subsidence between inward-dipping faults, but is now interpreted as early caldera downsag (see p.87) (P611769).



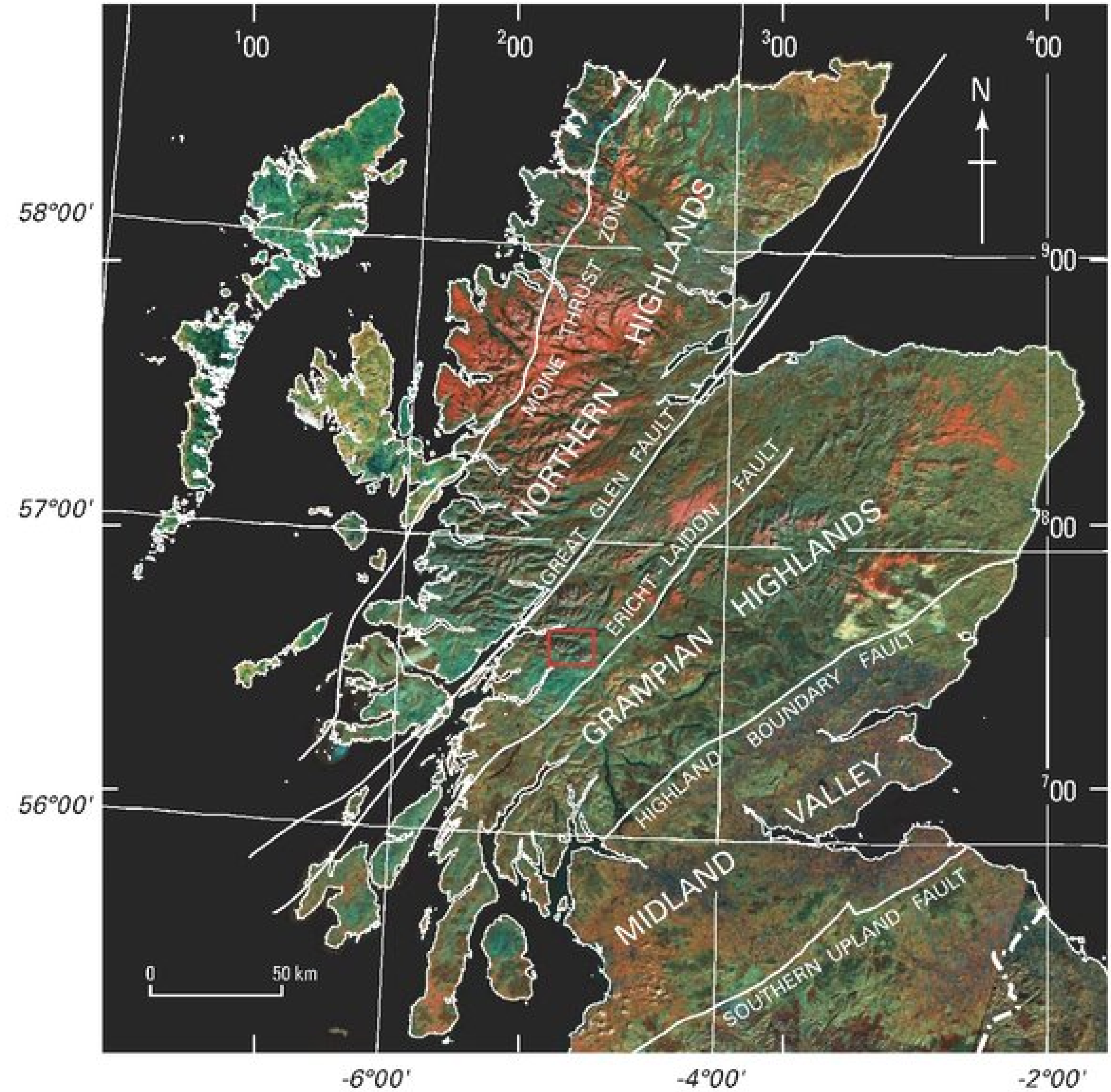
(Figure 9) Vertical section of the peperitic upper contact of one of the basal andesite sills, below Aonach Dubh [NN 1408 5594]. The vesicles were formed in the sandstone by gen- eration of steam in the original wet sediment, and, together with the in-situ swarms of andesite grains formed by magma-water interaction within the sedimentary host, are evidence that the magma was intrusive.

(Plate 6a) Basal Andesite Sill-complex in Coire nam Beitheach [NN 139 551]. a. Peperitic and autobrecciated top of a sill near the top of the sill stack (P611770).

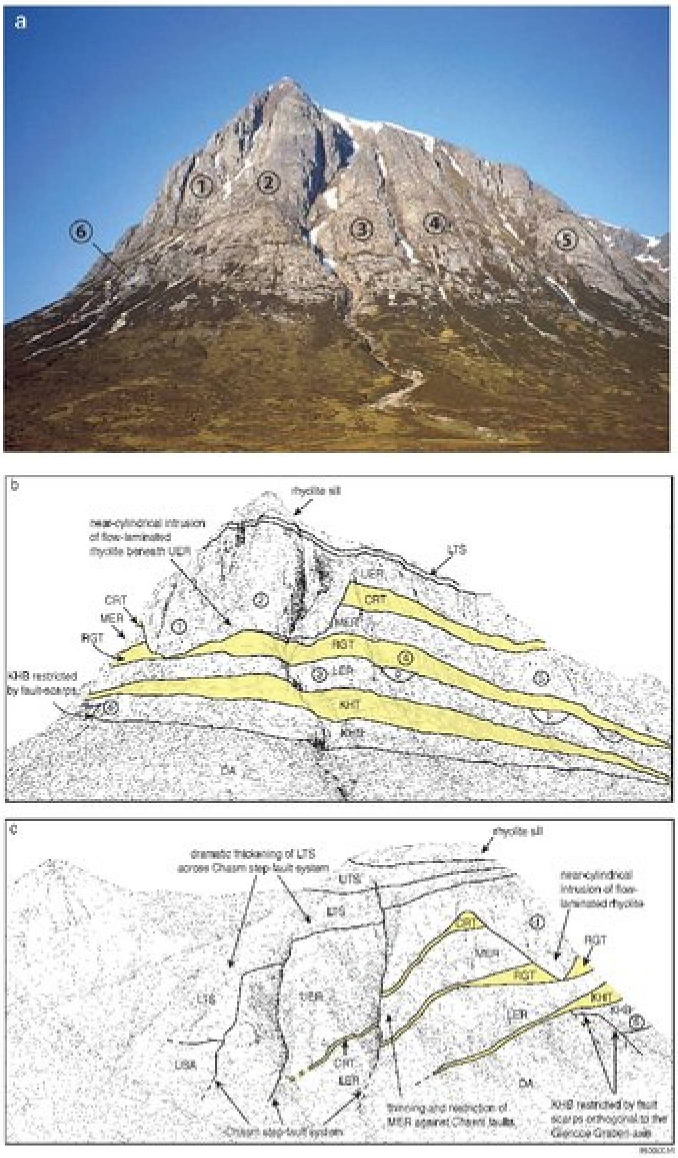
(Plate 6b) Basal Andesite Sill-complex in Coire nam Beitheach [NN 139 551]. b. Detail showing jigsaw fit of andesite fragments, due to in situ brecciation, within a purple, homogeneous fine-grained sandstone host. Drink can is 6 cm in diameter (P611771).



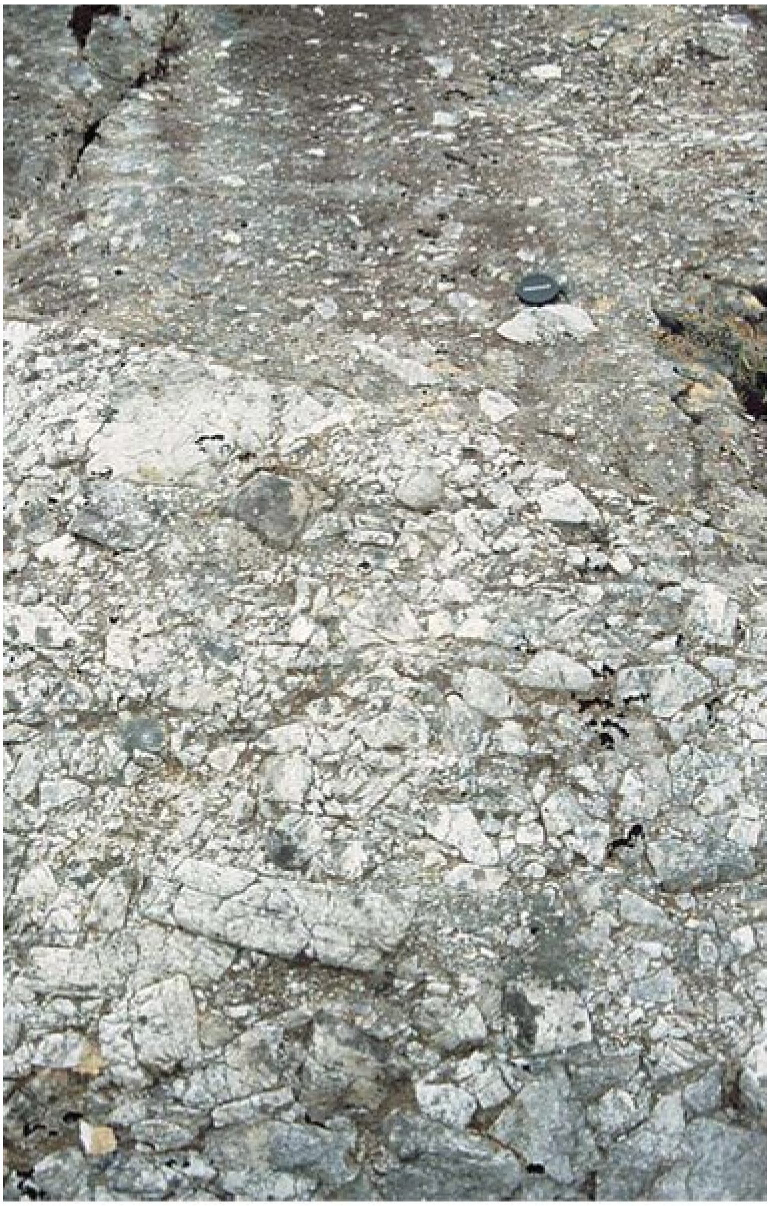
(Plate 7) Peperitic top of the uppermost sill of the Basal Andesite Sill-complex (BAS), unconformably overlain by thinly bedded sandstone (KHB) that locally forms the base of the Etive Rhyolite Member. This exposure, high on the very steep buttressed slopes north-east of Coire nam Beitheach [NN 142 554], estab- lishes the intrusive nature of the entire succession of andesitic sheets in this vicinity. The absence of coeval andesitic lavas here, together with several other lines of evidence (see text), is taken to indicate that the unconformity could represent a time break of the order of hundreds of thousands of years, or more (P611772).



(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.

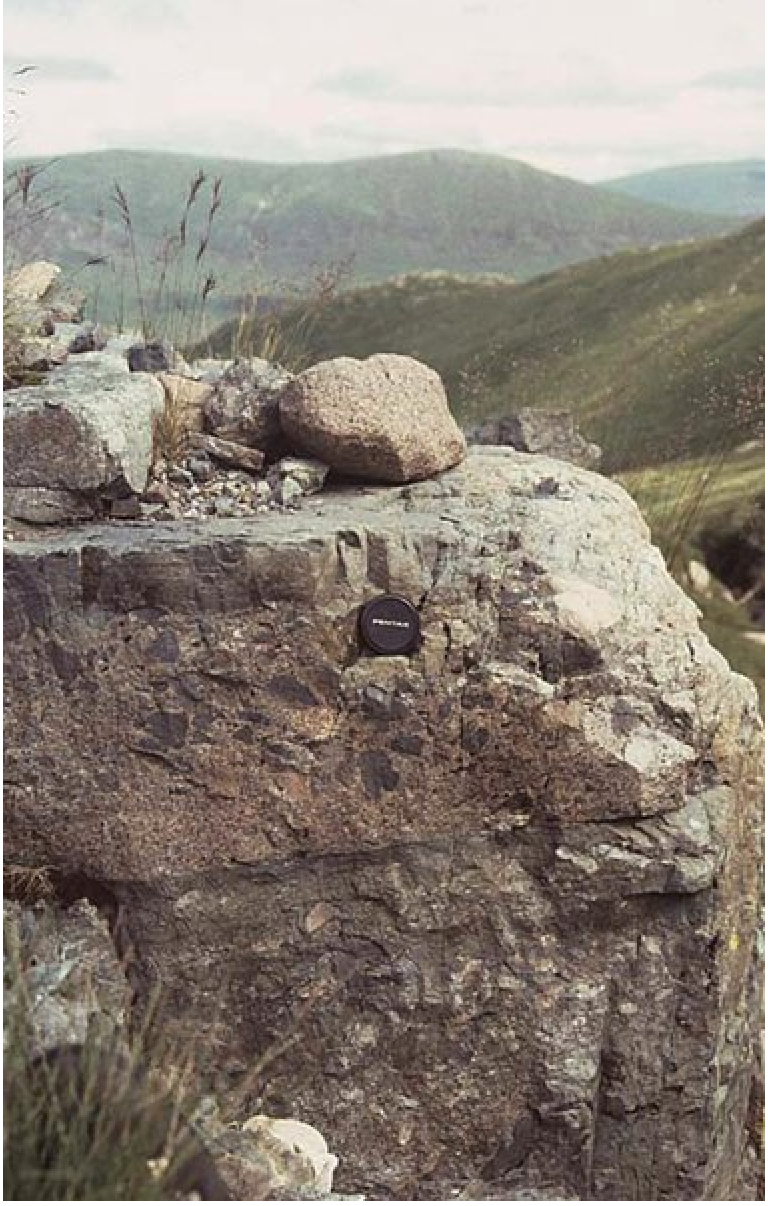


(Figure 10) (right) Stob Dearg [NN 22 54] (original drawings by K Lancaster) (P611773). a and b) Viewed towards the south-west, showing lower elements of the intracaldera stratigraphy and the cross-cutting rhyolite interpreted as infilling the vent from which the Upper Etive Rhyolite was erupted. c. Viewed towards the north-west, showing the rhyolite-filled vent of the Upper Etive Rhyolite and thickening of the Lower Three Sisters Ignimbrite across the Chasm step-fault system. Views b and c both show the restriction of the Kingshouse Breccias at palaeofault scarps that trend north-eastwards, at right angles to the Chasm step-fault system and Glencoe Graben. In view b, three broad V-shaped outcrops of breccia and conglomerate (labelled p) are remnants of a single infilled palaeocanyon that was cut into the Lower Etive Rhyolite parallel to the Glencoe Graben. The outcrops are remnants of the south- west side of the palaeocanyon, which must have trended north-westwards, parallel to the cliff faces (despite their appearance, they are not complete cross-sections of three separate features). 1 Central Buttress; 2 North Buttress; 3 Great Gully Buttress; 4 Broad Buttress; 5 Tulaich Buttress; 6 Waterslide; CRT Crowberry Ridge Tuffs; DA Dalradian metamorphic basement; KHB Kingshouse Breccias; KHT Kingshouse Tuffs; LER Lower Etive Rhyolite; LTS Lower Three Sisters Ignimbrite; MER Middle Etive Rhyolite; RGT Raven’s Gully Tuffs; UER Upper Etive Rhyolite; USA Upper Streaky Andesites; UTS Upper Three Sisters Ignimbrite.



(Plate 8a) Psammite breccias. a Psammite talus-breccia at the foot of a small fault scarp (out of view to left), overlain by poorly sorted psammite breccias of the Kingshouse Breccias, near the Waterslide on Central Buttress, Stob Dearg [NN 2282 5440] (P611774).

(Plate 8b) Psammite breccias. b Massive to weakly stratified psammite breccias with cross- stratified quartzose sandstone infilling a scour in the Kingshouse Breccias, at the Waterslide [NN 2284 5454] (P611775).



(Plate 9) Poorly sorted breccia and conglomerate (Kingshouse Breccias) dominated by clasts of andesite (purple) and of Rannoch Moor granite (pink), with interca- lated sandstones. These deposits, which show imbrication of the large clasts, form part of a small wedge mainly of unstratified breccia that extends south- westwards from the Northeastern Graben Fault in Cam Ghleann [NN 2484 5181] (P611776).

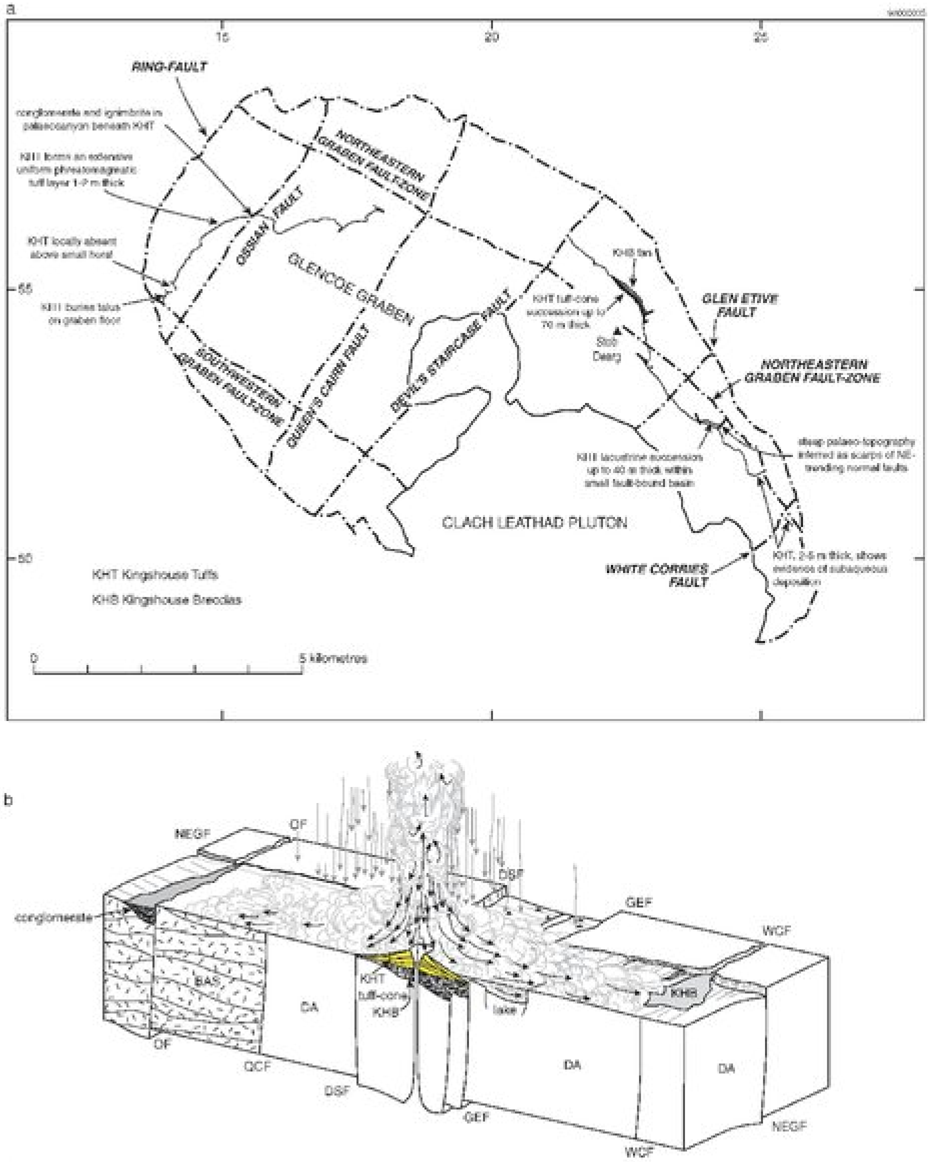
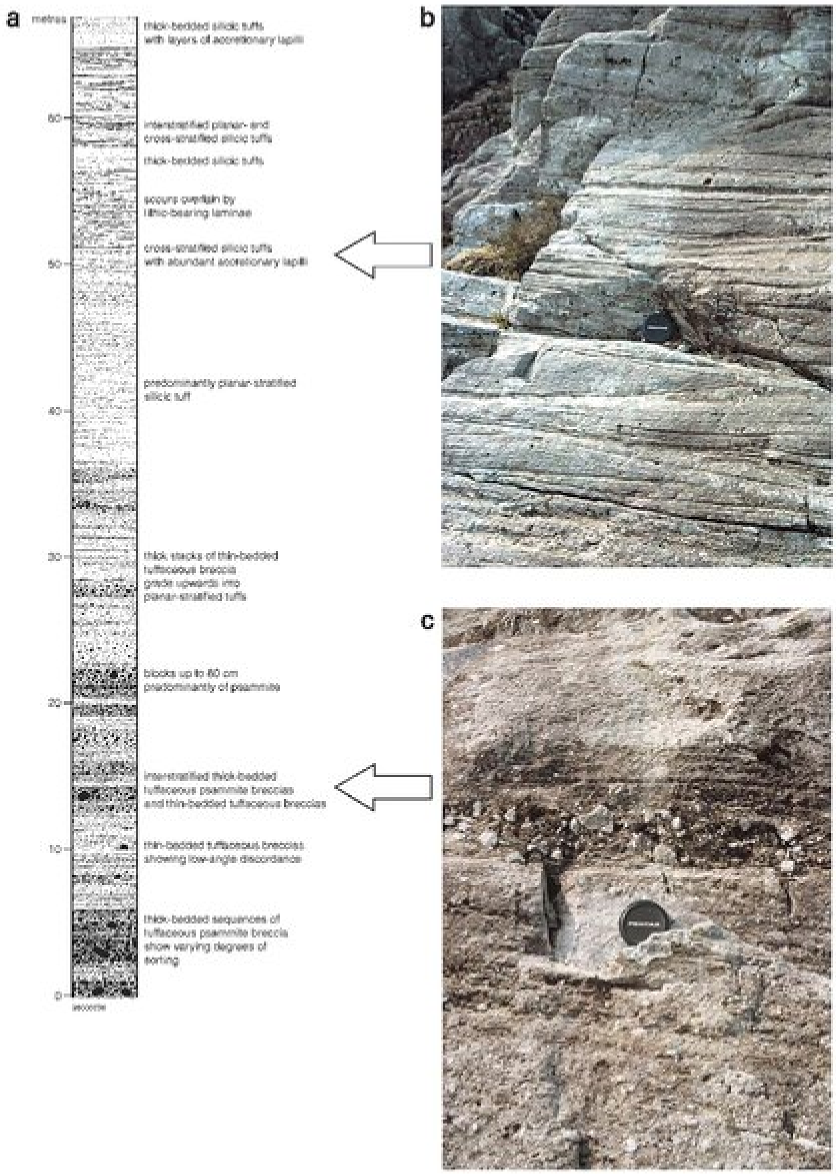
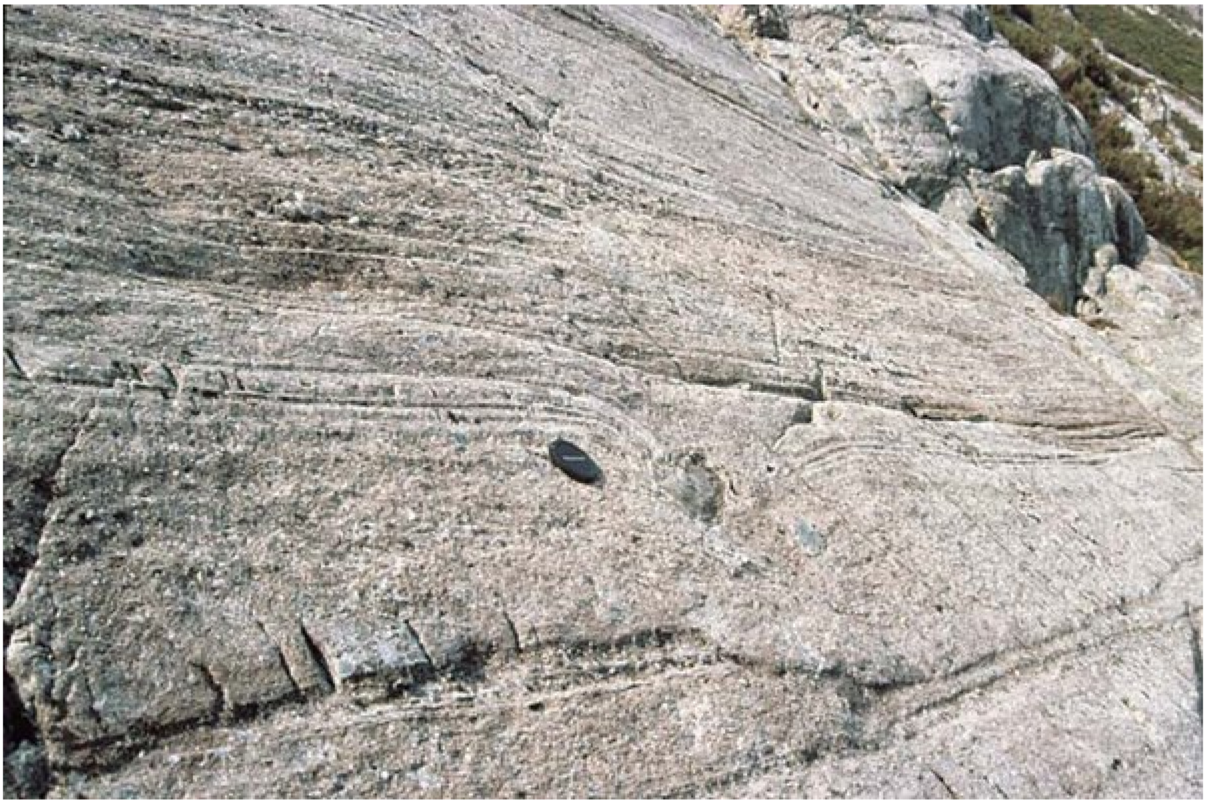


Figure 11 Kingshouse Tuffs (KHT).

(Figure 11) Kingshouse Tuffs (KHT). a Distribution. b Schematic diagram showing a north-west section parallel to the axis of the Glencoe Graben, and the setting of the Kingshouse Tuffs eruption and related deposits. This site was located at the intersection of the Glencoe Graben and a cross-graben between the Glen Etive Fault and the Devil's Staircase Fault; thus it was tectonically controlled, as were the alluvial fans of the Kingshouse Breccias (KHB). BAS Basal Andesite Sill-complex; DA Dalradian metamorphic basement; DSF Devil's Staircase Fault; GEF Glen Etive Fault; NEGF Northeastern Graben Fault; OF Ossian Fault; QCF Queen's Cairn Fault; WCF White Corries Fault.

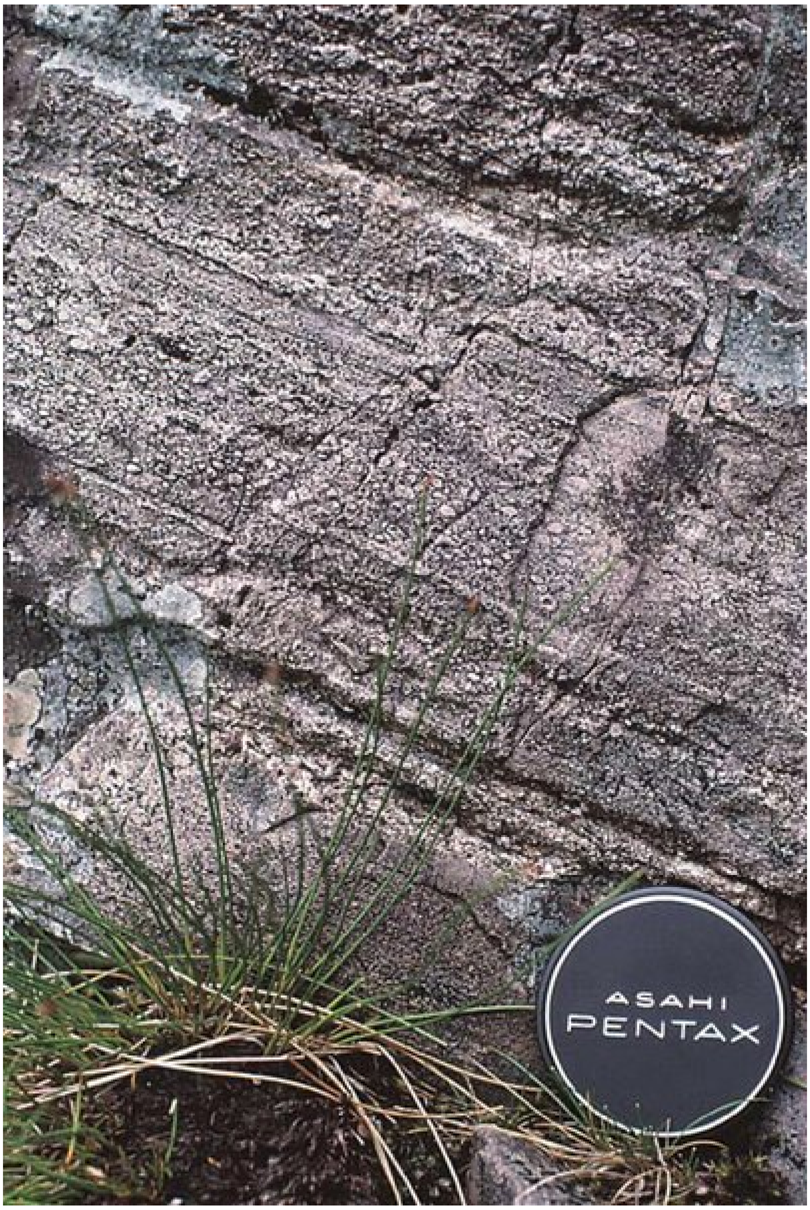


(Figure 12) (right) Kingshouse Tuffs (KHT) at North Buttress on Stob Dearg [NN 2270 5476]. a. Schematic log of the sequence that is part of the outer flank of a tuff cone. It shows an upward change from predominantly massive breccia with abundant lithic fragments to finer grained tuffs characterised by planar and low-angle cross-stratification with layers rich in accretionary lapilli. This section records phreatomagmatic activity transitional from early vent-clearing explosions to later development of a tall eruption column that produced energetic pyroclastic density currents and substantial ash fall. b Cross-stratified silicic tuffs showing low-amplitude bedforms and low-angle scour surfaces recording the passage of highly unsteady, energetic pyroclastic density currents (P611782). c Massive to weakly bedded tuffaceous lithic breccias and lithic-rich tuff formed from initial, vent-clearing, wet explosions; the lithic fragments are quartzite fragments from the underlying Kingshouse Breccias (P611783).



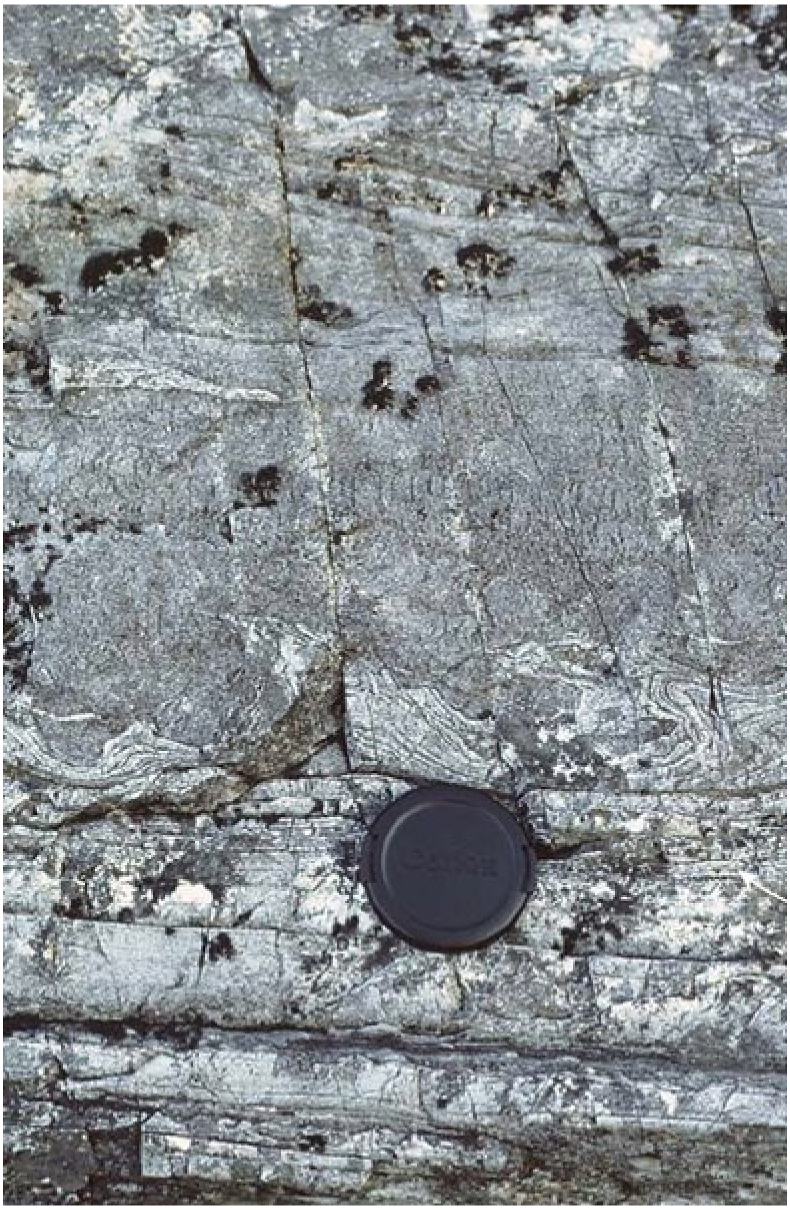
(Plate 11a) Indicators of the position of the vent of the Kingshouse Tuffs (KHT). a. Asymmetrical ballistic-bomb impact sag in bedded and cross-stratified silicic tuffs, indicating that the vent was located to the west or south-west (away from the viewer). The impacted beds lie on a surface scoured by the passage of one or more pyroclastic density currents; Great Gully Buttress, Stob Dearg [NN 226 548] (P611778).

(Plate 11b) Indicators of the position of the vent of the Kingshouse Tuffs (KHT). b. Cross-stratified silicic tuffs showing five scour (truncation) surfaces (indicated by arrows); the strata record deposition and migration of low-amplitude ash dunes down-current from the south-west (right to left), alternating with erosion. The uppermost scour surface is locally steep and here was plastered by damp ash, also indicating that the current direction was from the south-west. The dip of the beds, which is towards the south-west, resulted from caldera downsag; Broad Buttress, Stob Dearg [NN 225 549] (P611779).

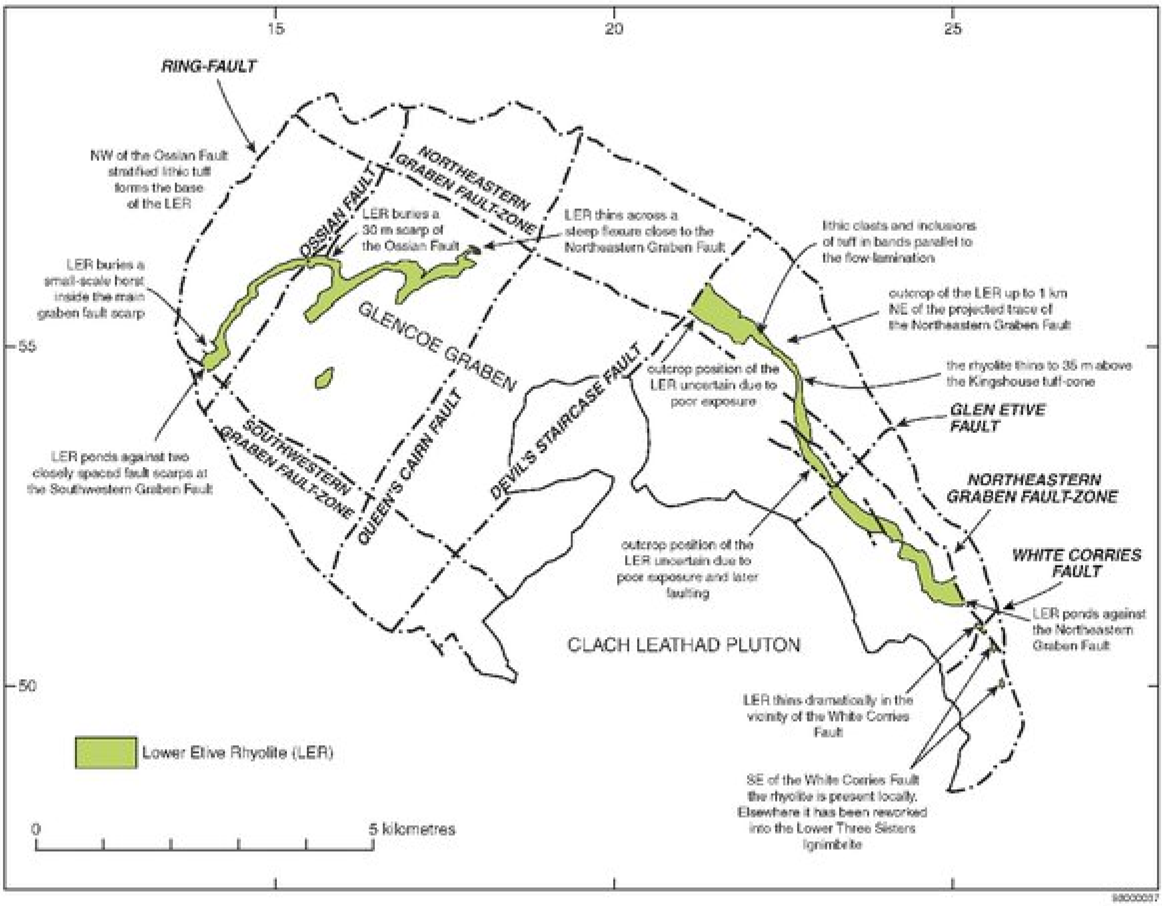


(Plate 10) Parallel-bedded distal Kingshouse Tuffs, 7 km from the vent, showing layers rich in small accretionary lapilli (centre); F Buttress on Aonach Dubh [NN 1432 5550] (P611777).

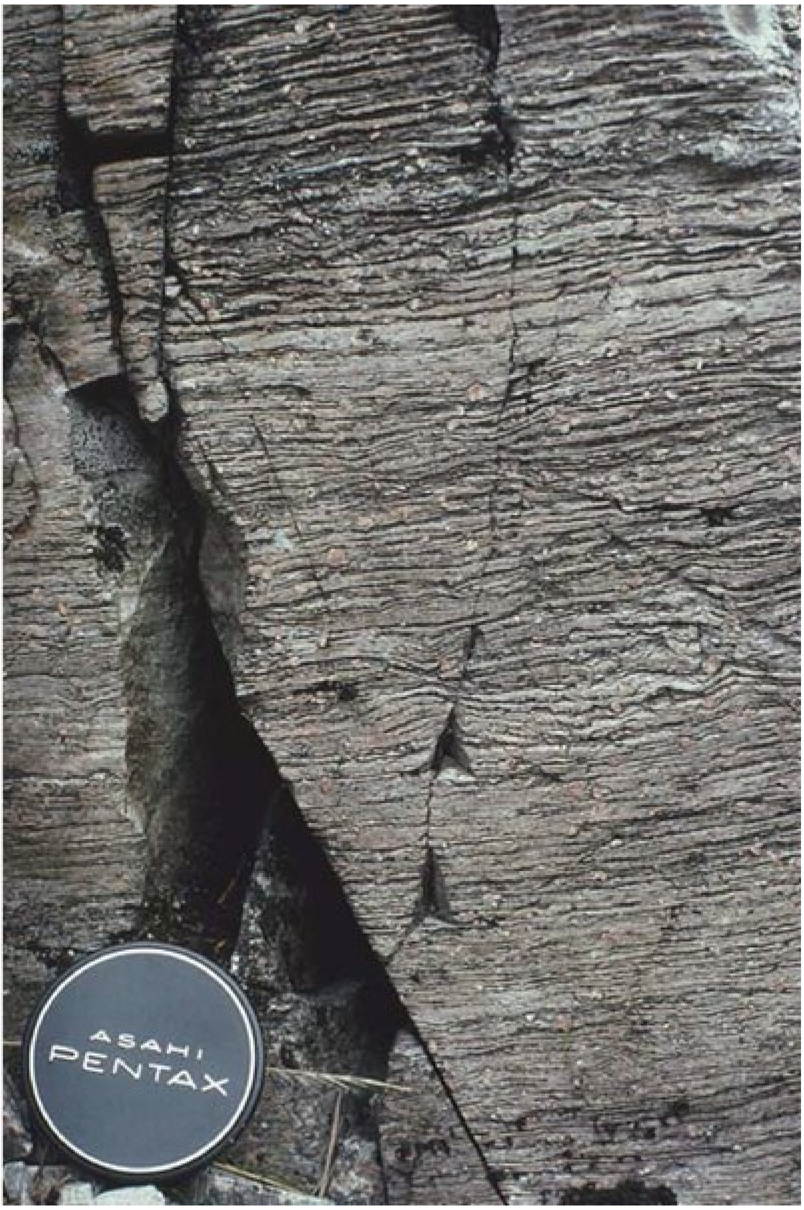
(Plate 12a) Aqueous litho- facies of the Kingshouse Tuffs. a. View towards the south-west showing the flanks of Sròn na Creise (buttress on right hand side) and Stob a' Ghlais Choire (middle summit) with an extensive outcrop of the Kingshouse Tuffs, including the thick lacustrine succession formed in a small fault-bounded basin (P611780).



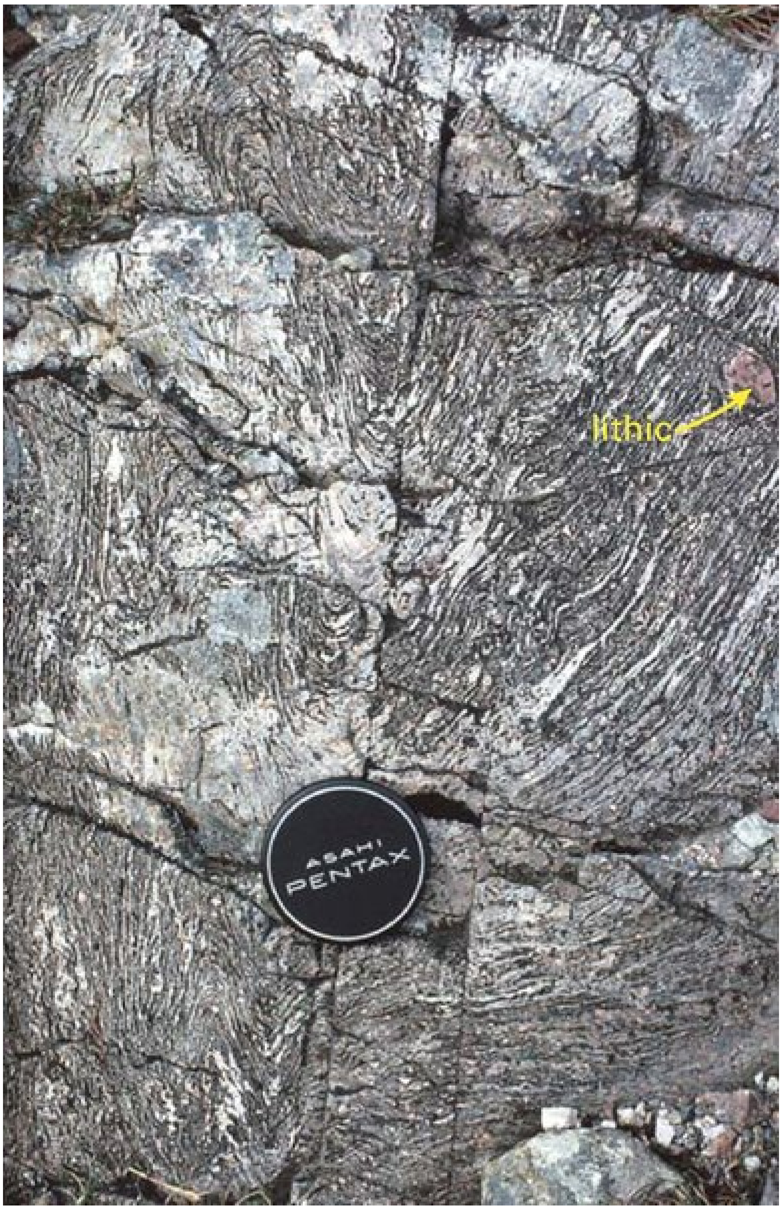
(Plate 12b) Aqueous litho- facies of the Kingshouse Tuffs. b. Flame structures and convolute laminations in silicic tuffs deposited from aqueous suspension (parallel-stratified tuffs) and by turbidity currents (mainly massive division showing near-vertical water-escape structures near its middle); Sròn na Creise [NN 241 525] (P611781).



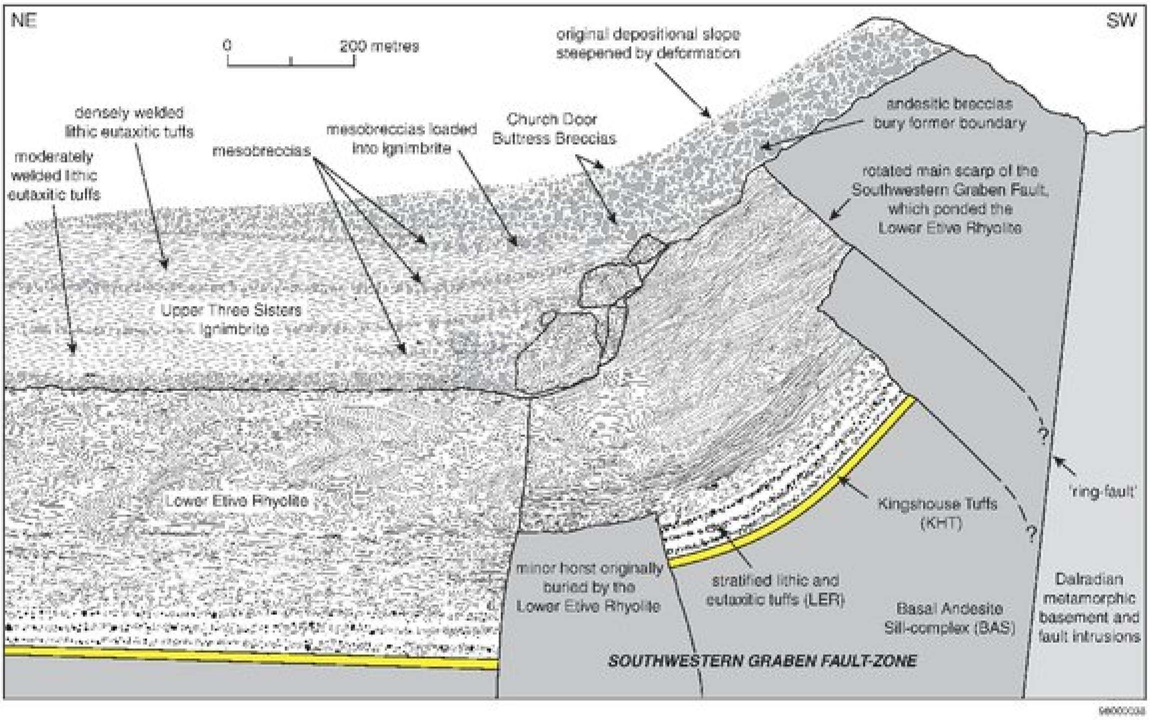
(Figure 13) Lower Etive Rhyolite distribution and key features.



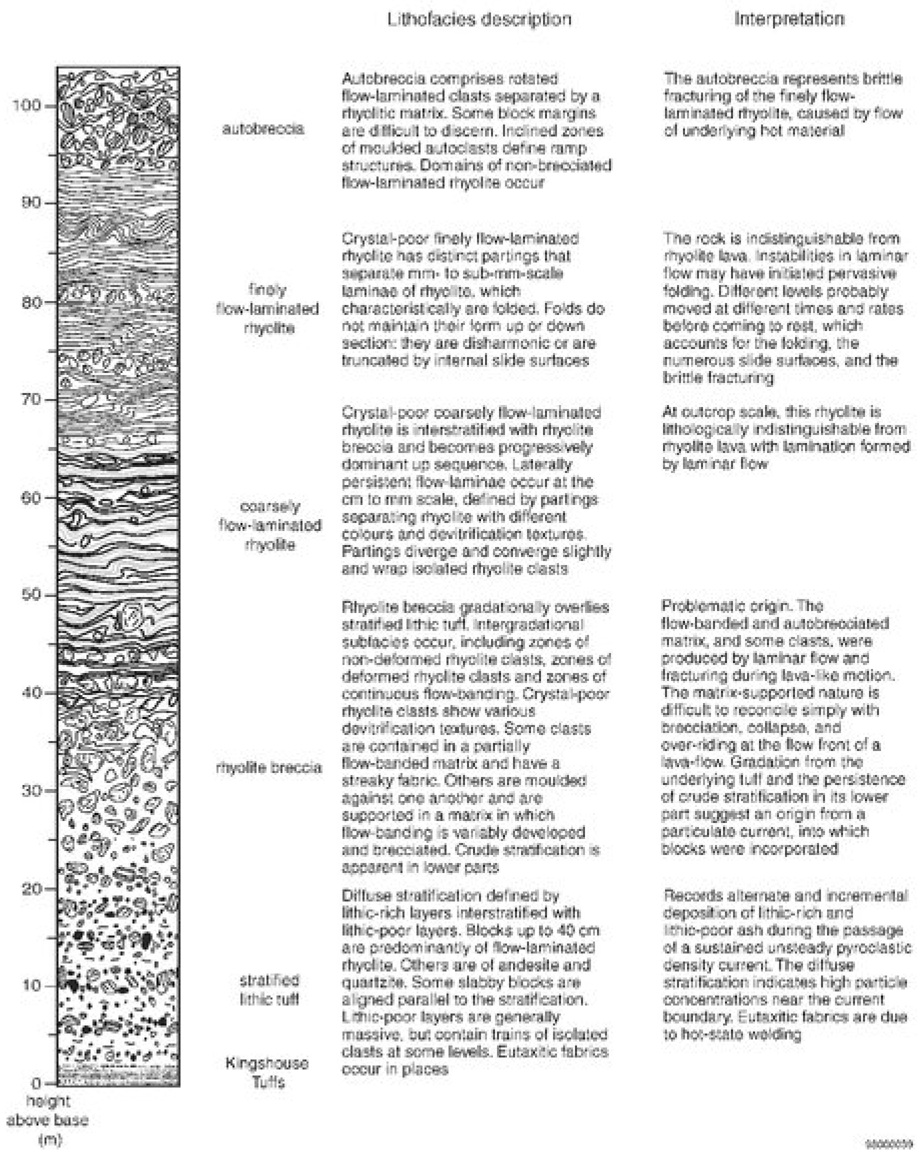
(Plate 13a) Lower Etive Rhyolite with sparse feldspar crystals; Stob Dearg [NN 220 552]. Although texturally similar to rhyolite lava at outcrop, the overall field relationships indicate an explosive, pyroclastic origin, so that the rock is referred to as lava-like ignimbrite. a Fine parallel flow-lamination (P611784).



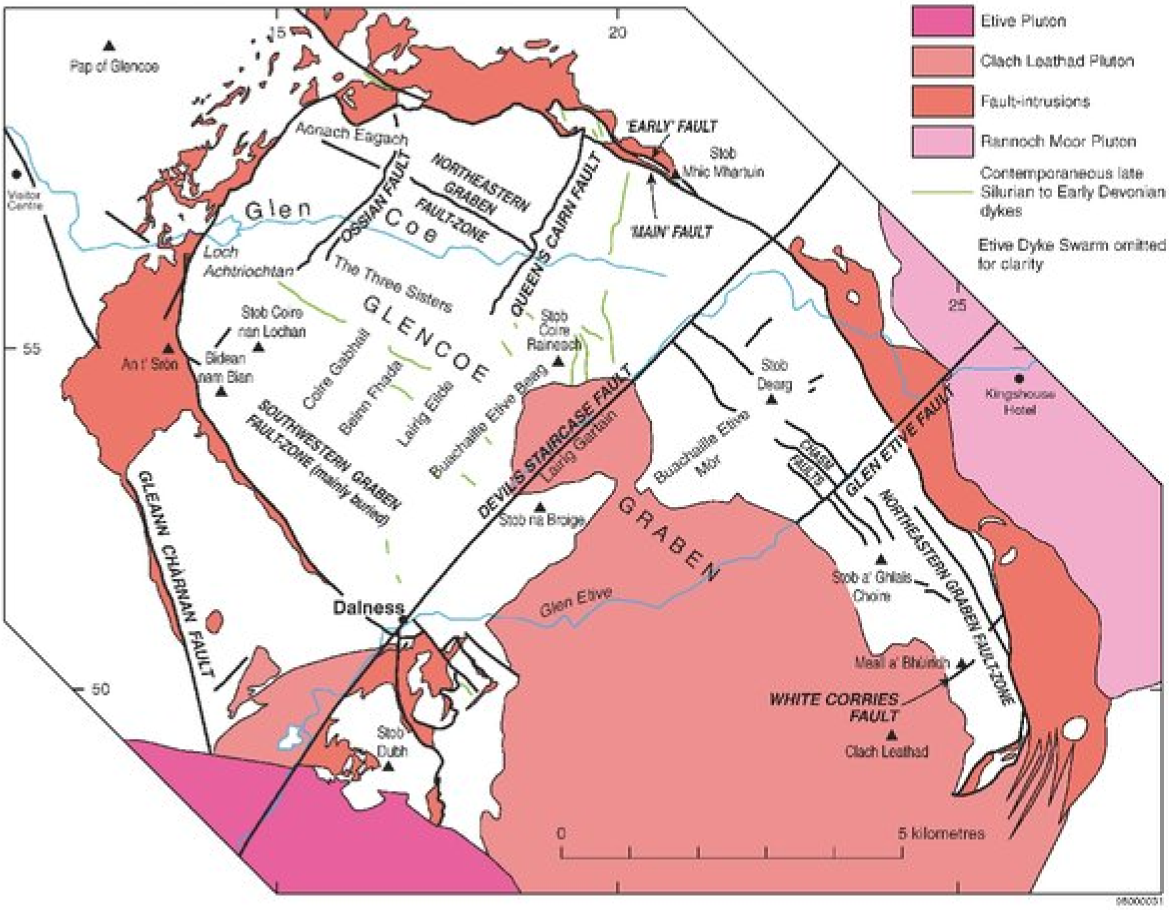
(Plate 13b) Lower Etive Rhyolite with sparse feldspar crystals; Stob Dearg [NN 220 552]. Although texturally similar to rhyolite lava at outcrop, the overall field relationships indicate an explosive, pyroclastic origin, so that the rock is referred to as lava-like ignimbrite. a Fine parallel flow-lamination (P611784). b Convolute flow-lamination and a rare lithic fragment (arrow) (P611785).



(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.

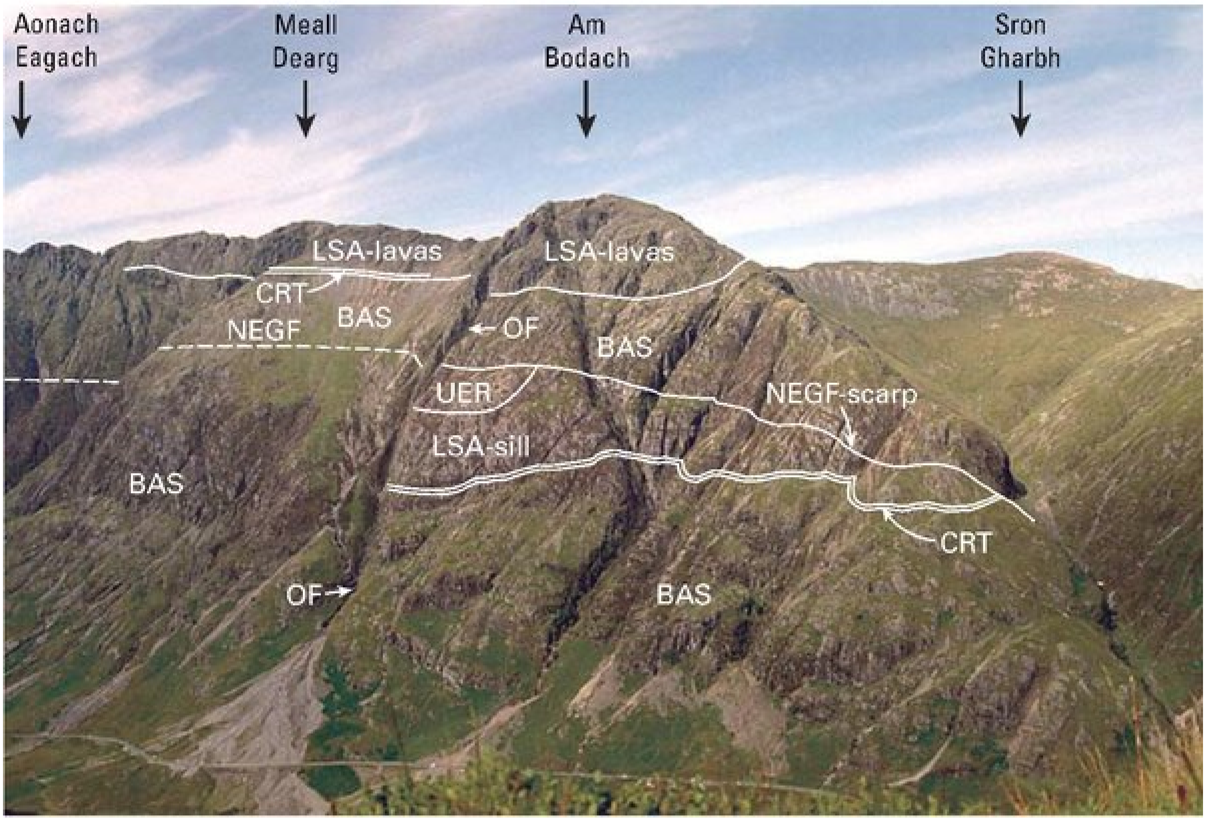


(Figure 15) Vertical section through the Kingshouse Tuffs and Lower Etive Rhyolite, north-west of the Ossian Fault, on G-Buttress, Aonach Dubh [NN 143 554].

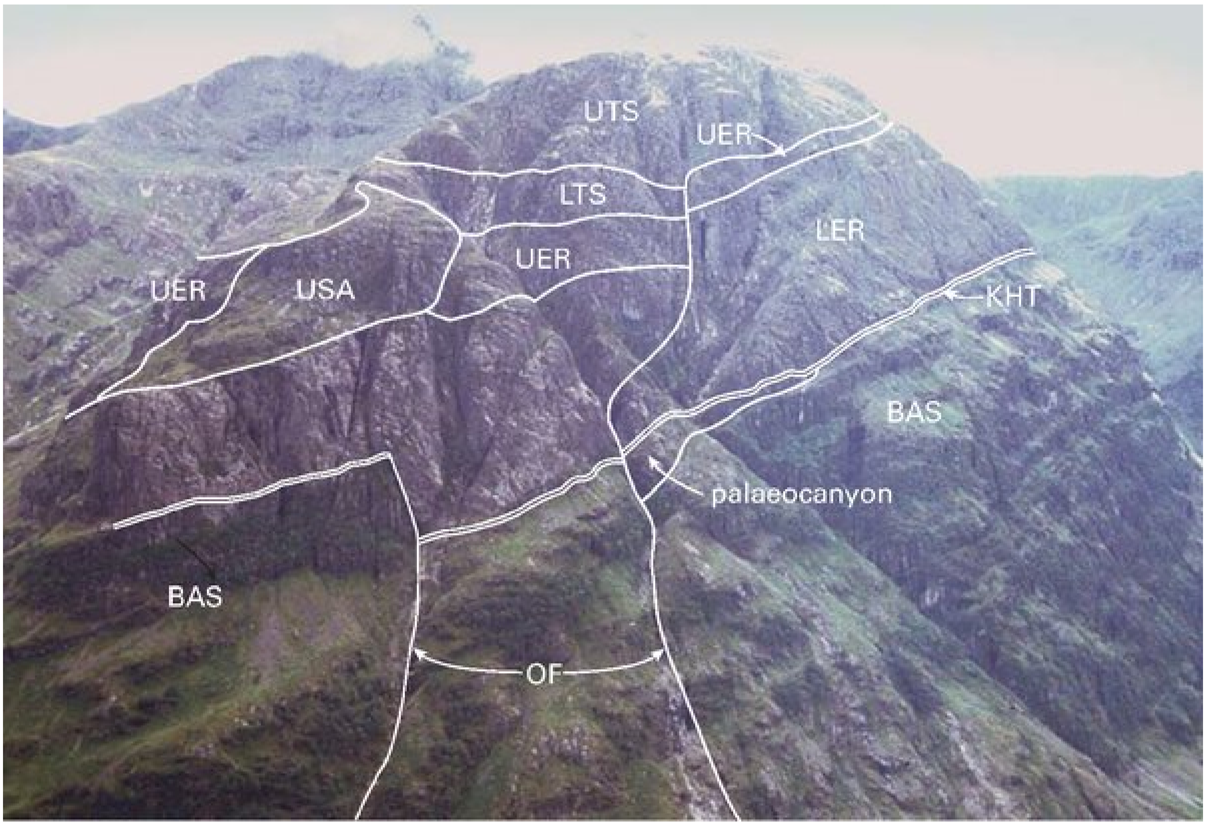


(Figure 7) Major structural features of the Glencoe Caldera-volcano Complex, highlighting intrusions and faults active during volcanism (Etive Dyke Swarm not shown).

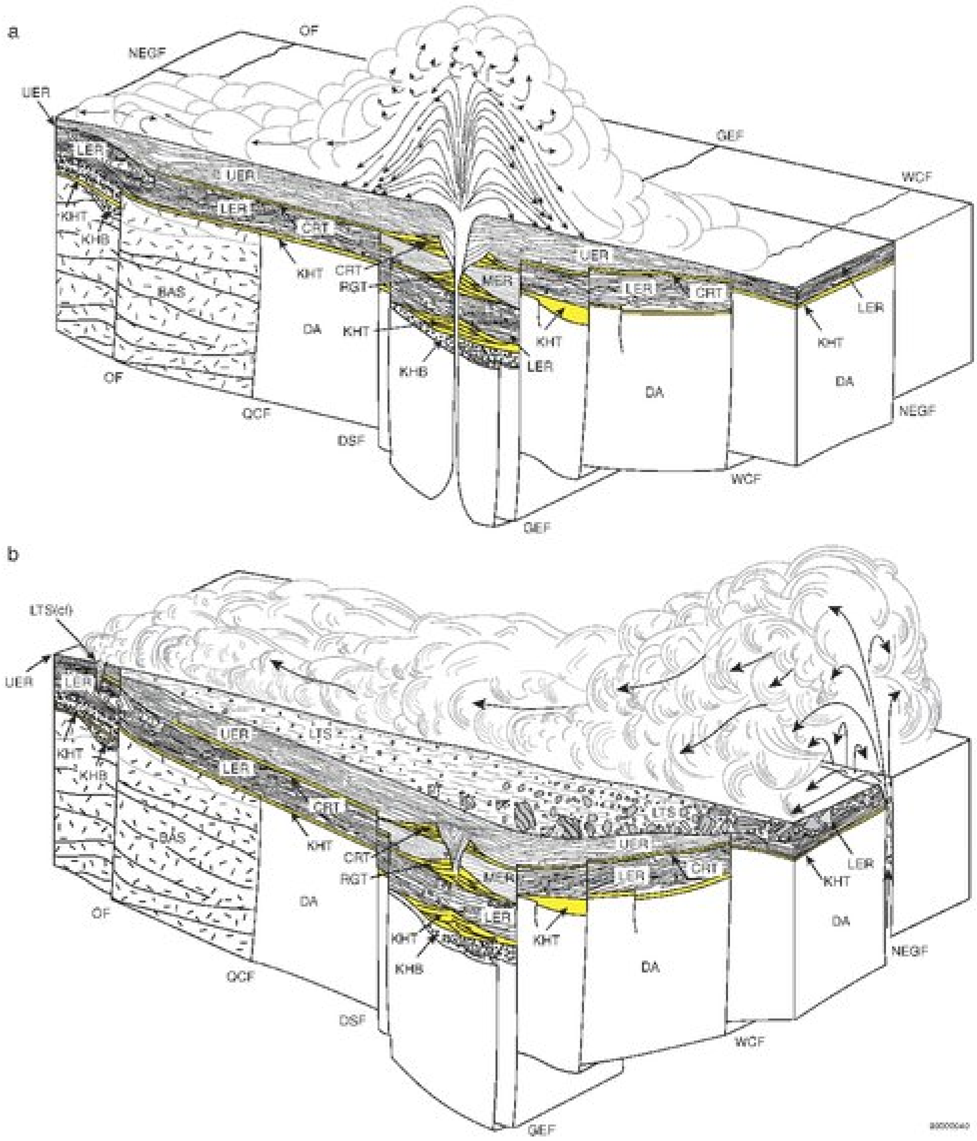
(Plate 17) East flanks of Sròn na Creise and Stob a’ Ghlais Choire showing slumping of the Upper Etive Rhyolite (UER) towards the Chasm step-fault system and related thickening of the Lower Three Sisters Ignimbrite (LTS) towards the axis of the Glencoe Graben. Also shown are breccia dykes in the Dalradian metamorphic basement (DA) along the trace of Northeastern Graben Fault, the faulted margin of the lacustrine facies of the Kingshouse Tuffs (KHT; extreme right), a topographical depression eroded deeply into Lower Etive Rhyolite (LER) and partially draped by Crowberry Ridge Tuffs (CRT), the Glas Choire Sandstone Member (GCS) in the vicinity of its type locality, and the overlying Bidean nam Bian Andesite Member (BBA) (P611792).



(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 .

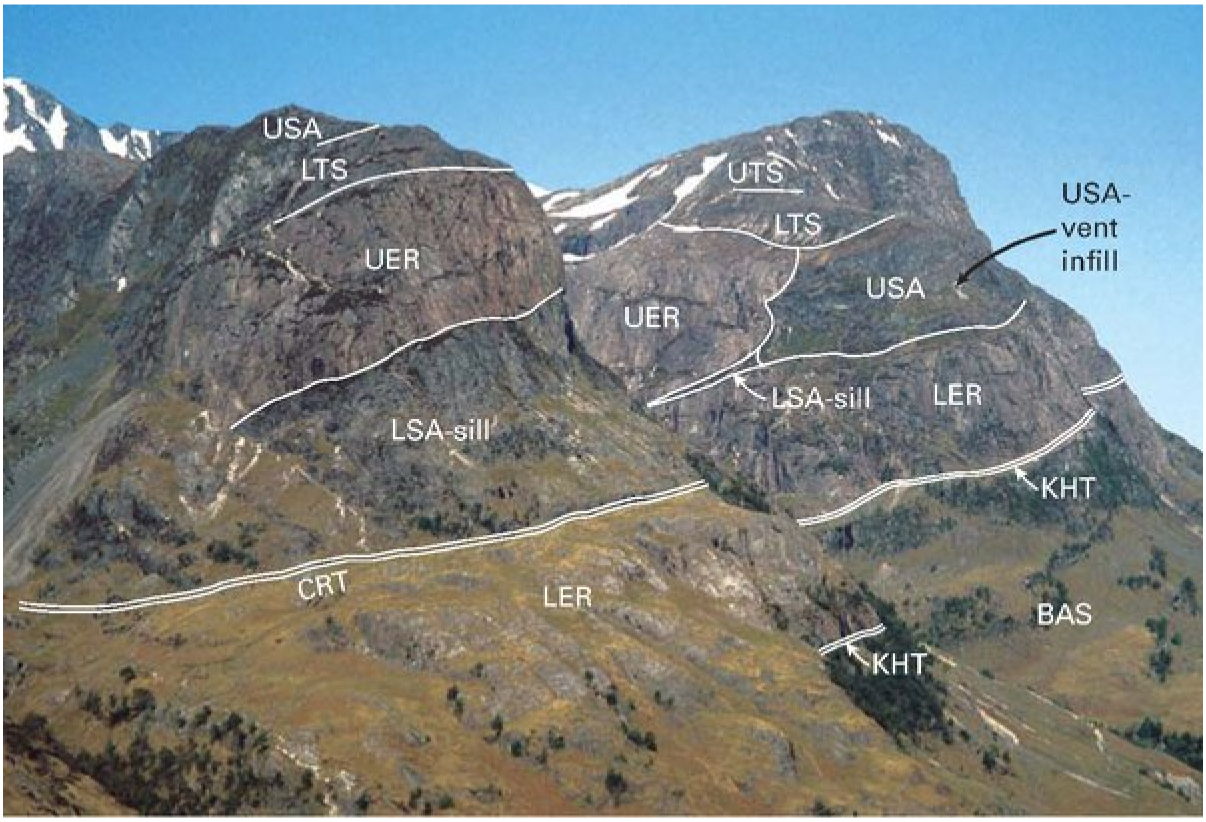


(Plate 14b) North face of Aonach Dubh [NN 15 56] and northern side of Glen Coe [NN 16 57]. b. Traces of the Northeastern Graben Fault (NEGF) and its footwall scarp along the north side of the Pass of Glencoe [NN 16 57]. The scarp, composed of Basal Andesite Sill-complex (BAS), formed a volcanotectonic 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.*



(Figure 16) (left) Glencoe Graben: schematic diagrams showing a north-west to south-east section parallel to the axis of the graben and the contrasting eruptions of the Upper Etive Rhyolite and Lower Three Sisters Ignimbrite. a. The three Etive rhyolite eruptions formed mainly lava-like ignimbrites from pyroclastic fountains at the sites of tuff-cones that were active during the initial phreatomagmatic explosivity. The vents were located centrally, at the intersection of the Glencoe Graben and the cross-graben bounded by the Devil's Staircase and Glen Etive faults. They probably formed in or close to the Chasm Fault system, on the north-east side of the main graben. b. The Lower Three Sisters Ignimbrite appears to have been erupted from the Northeastern Graben Fault (zone) at a location towards the south-east of the volcano complex; its emplacement involved both volcanotectonic faulting and downsag. Buoyant-convective ash plumes that would have risen above both the vent and the pyroclastic currents are omitted for clarity. BAS Basal Andesite Sill-complex; CRT Crowberry Ridge Tuffs; DA Dalradian metamorphic basement; DSF Devil's Staircase Fault; GEF Glen Etive Fault; KHB Kingshouse Breccias; KHT Kingshouse Tuffs; LER Lower Etive Rhyolite; LTS Lower Three Sisters Ignimbrite; NEGF Northeastern Graben Fault; OF Ossian Fault; QCF Queen's Cairn Fault; RGT Raven's Gully Tuffs; UER Upper Etive Rhyolite; WCF White Corries Fault.

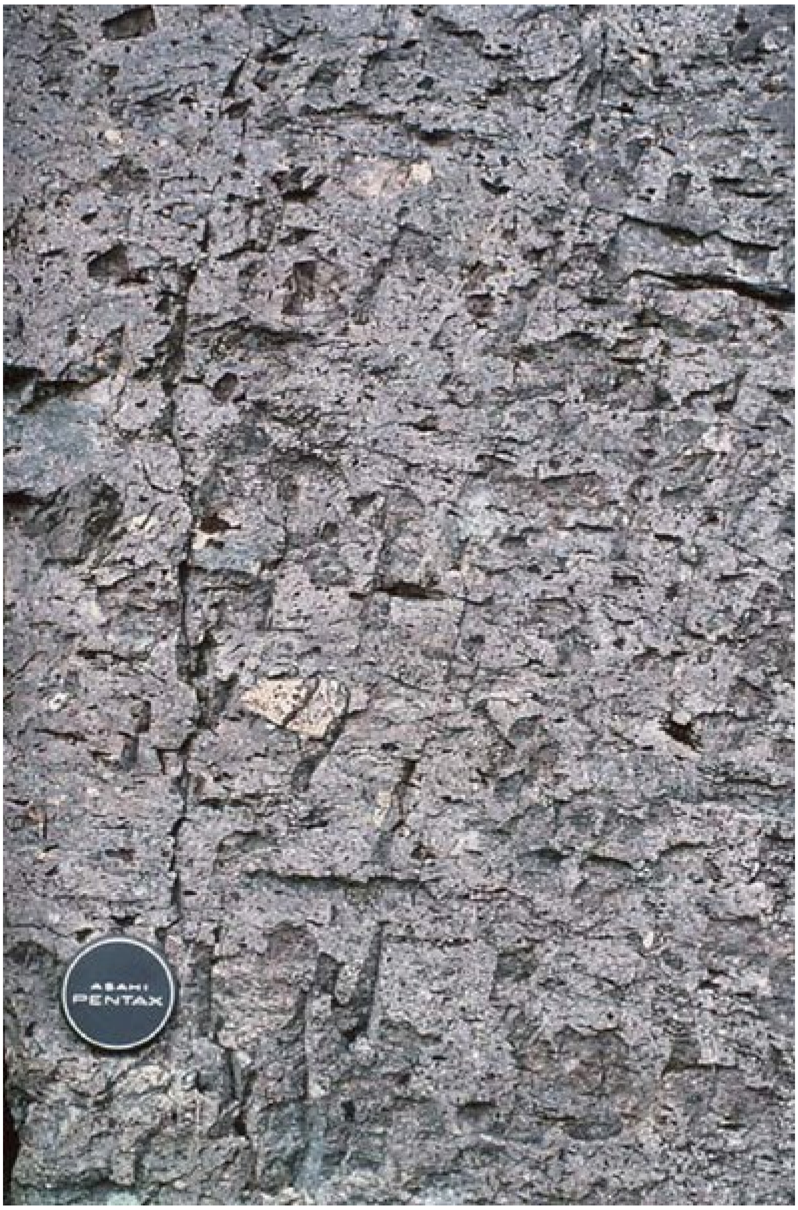
(Plate 15a) Lower Streaky Andesites on Gearr Aonach and Aonach Dubh. A. Typical exposure of the Lower Streaky Andesites showing purple andesite streaked with rhyolite. Both rock types contain up to 5 per cent of plagioclase phenocrysts; Gearr Aonach [NN 167 561] (P611788).



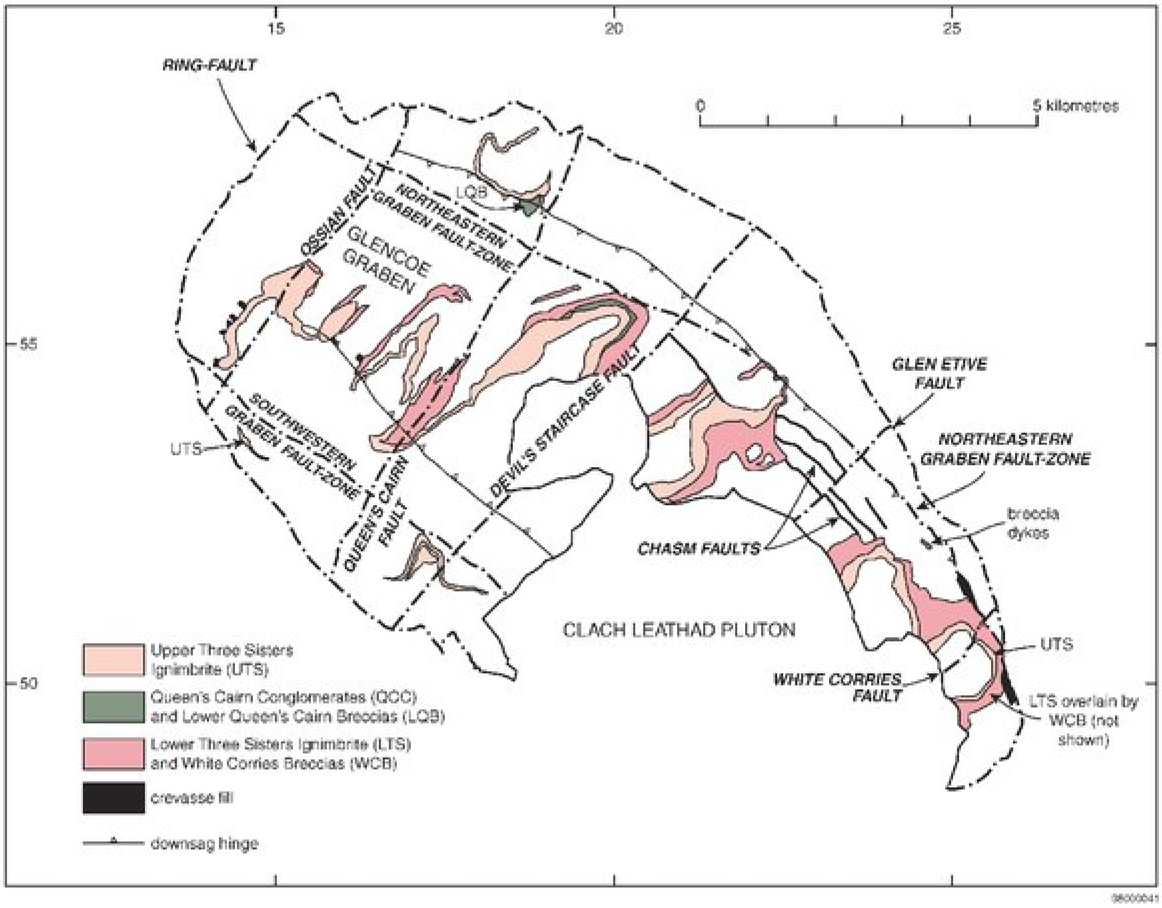
(Plate 15b) Lower Streaky Andesites on Gearr Aonach and Aonach Dubh. b. Two of the Three Sisters, Gearr Aonach (left) and Aonach Dubh (right) showing dramatic thickness variation of a Lower Streaky Andesites sill: viewed towards the west. The sill is about 100 m thick on Gearr Aonach and thins to only a few metres over a distance of less than 750 m away from the viewer, adjacent to the Upper Streaky Andesites vent on Aonach Dubh. The sill is the same intrusion as seen in Plate 14b (P611789). BAS Basal Andesite Sill-complex; CRT Crowberry Ridge Tuffs; KHT Kingshouse Tuffs; LER Lower Etive Rhyolite; LSA Lower Streaky Andesites; LTS Lower Three Sisters Ignimbrite; UER Upper Etive

Rhyolite; USA Upper Streaky Andesites; UTS Upper Three Sisters Ignimbrite.

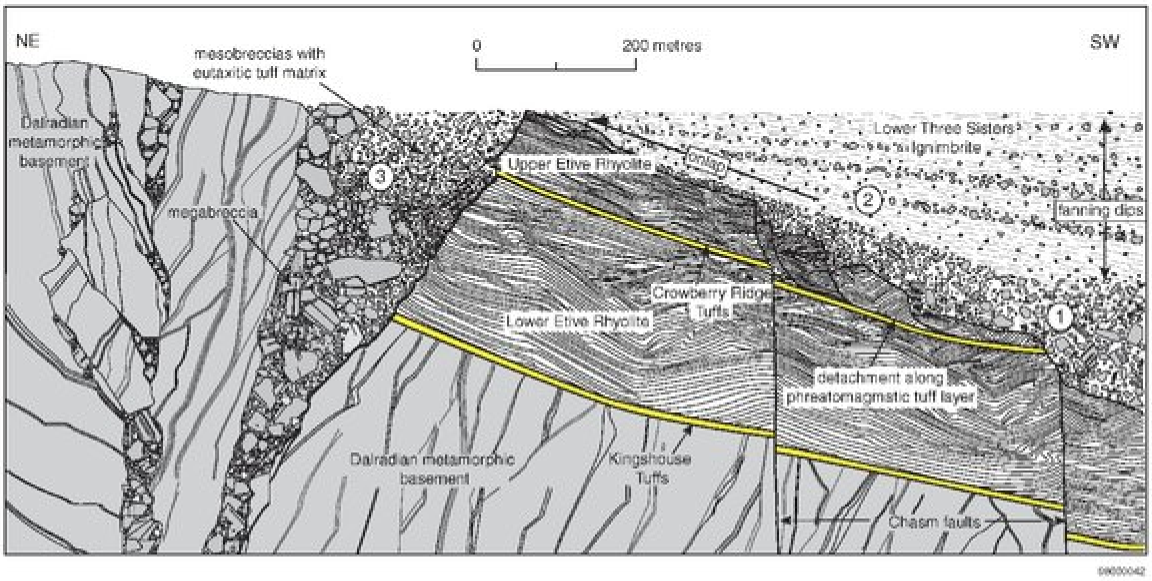
(Plate 16a) Lower Three Sisters Ignimbrite showing well-developed eutaxitic texture (welding), with moderately abundant fiamme and small lithic clasts. The contrast between the non-silicified matrix (a) and the silicified matrix (P611790) .



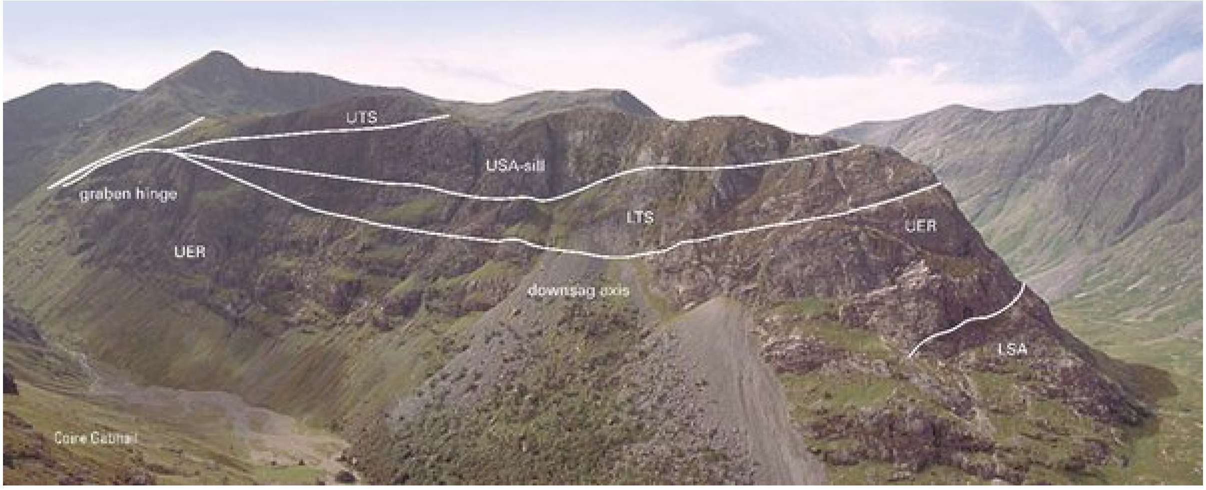
(Plate 16b) Lower Three Sisters Ignimbrite showing well-developed eutaxitic texture (welding), with moderately abundant fiamme and small lithic clasts. The contrast between the non-silicified matrix (b) records variable hydrothermal alteration; Sròn na Creise [NN 239 521] (P611791).



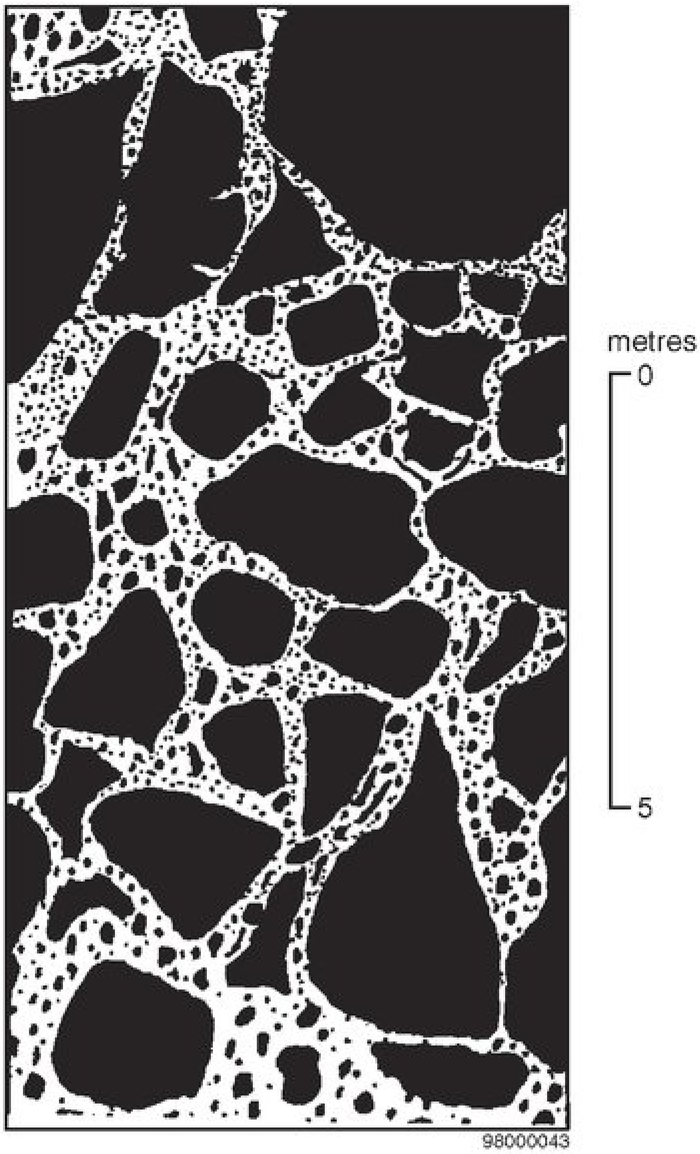
(Figure 17) Distribution of the Three Sisters ignimbrites, associated sedimentary rocks and contemporary volcanotectonic features. LQB Lower Queen's Cairn Breccias; LTS Lower Three Sisters Ignimbrite; QCC Queen's Cairn Conglomerates; UTS Upper Three Sisters Ignimbrite.



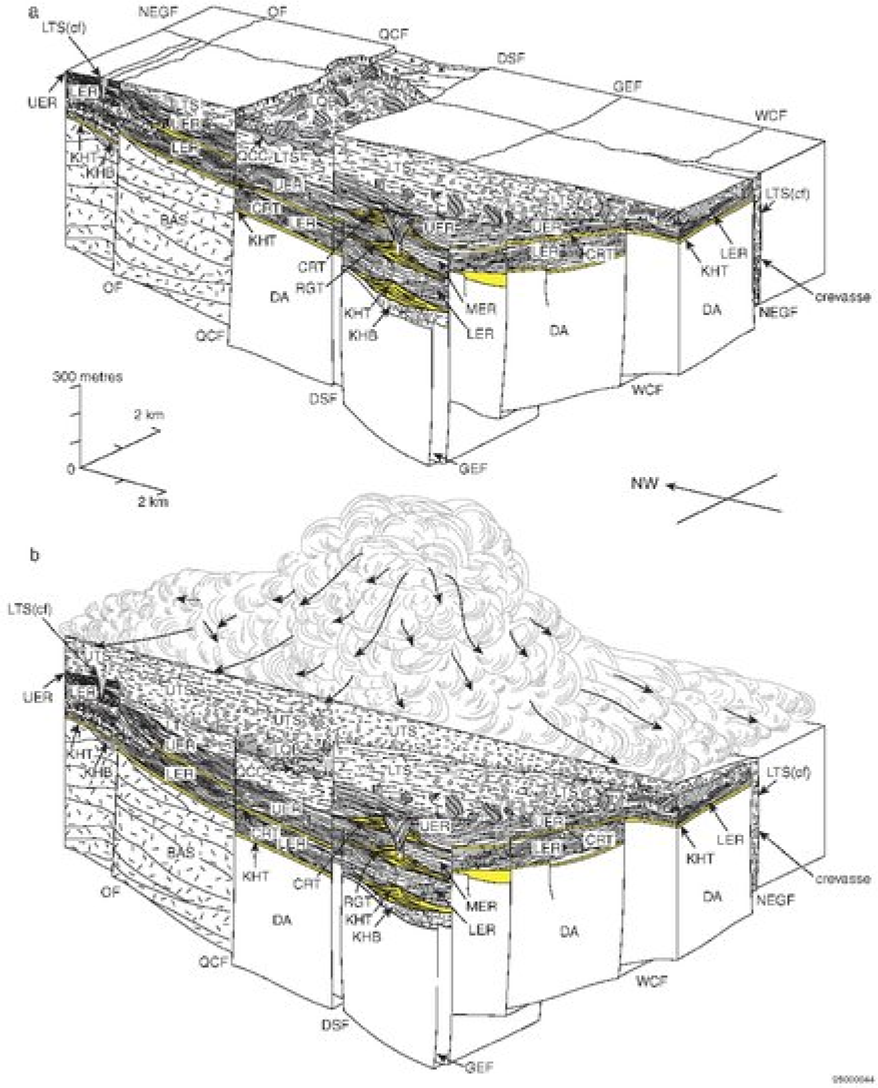
(Figure 18) Schematic cross-section of the Lower Three Sisters Ignimbrite and its contact relationships transverse to the Glencoe Graben, south-east of the Glen Etive Fault. 1 Mesobreccias and megabreccias shed from fault scarps of the Etive rhyolites during early phases of caldera subsidence in the course of the Lower Three Sisters eruption. 2 Eutaxitic tuff with mesobreccia layers showing onlap and fanning dips that respectively record progressive aggradation of the ignimbrite and progressive downsag during the course of the eruption. 3 Extensional crevasse formed along the Northeastern Graben Fault to accommodate the downsag towards the south-west.



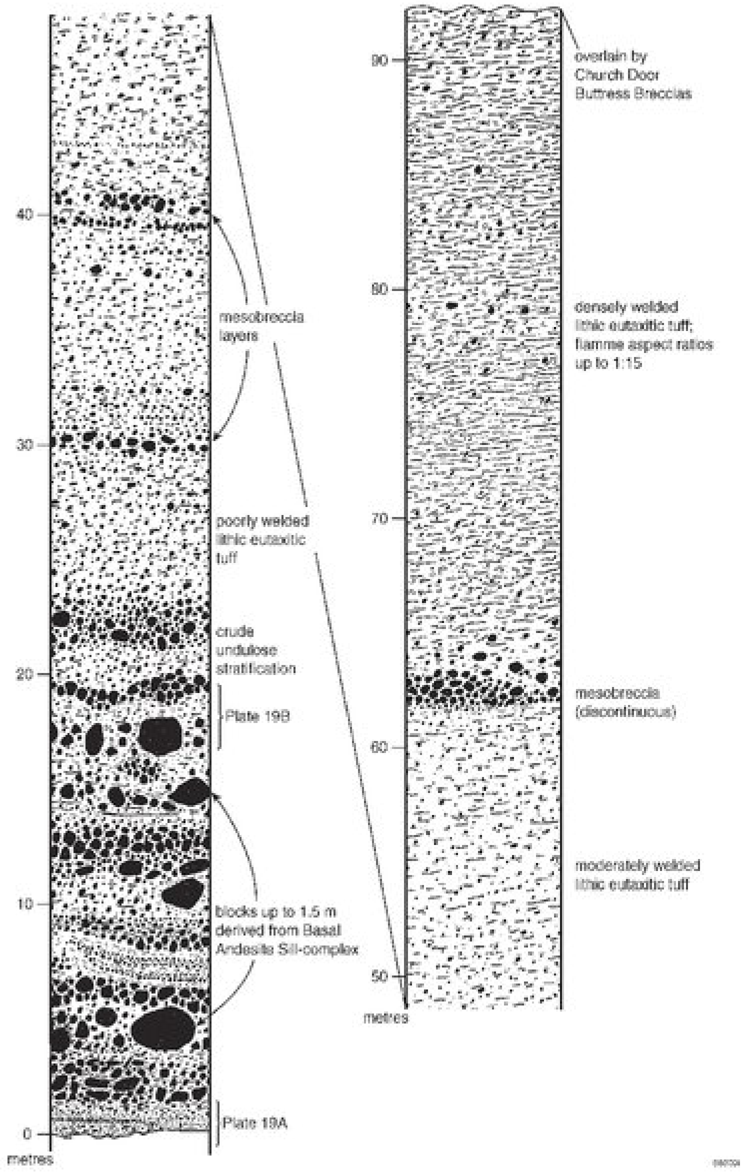
(Plate 18) Gearr Aonach viewed from the east across Coire Gabhail [NN 16 55] showing ponding of the Lower Three Sisters Ignimbrite (LTS) within a downsag north-west of the Queen's Cairn Fault. The ignimbrite is up to 50 m thick along the downsag axis (which trends north-west along the Glencoe Graben) and it thins progressively towards the south-western graben hinge, as does the overlying sill of the Upper Streaky Andesites (USA). The Upper Three Sisters Ignimbrite (UTS) shows similar thinning relationships, but overlaps the hinge line. The large composite debris cone in the foreground was formed by catastrophic rockfall following deglaciation (see p.109) (P611793). LSA Lower Streaky Andesites; UER Upper Etive Rhyolite.



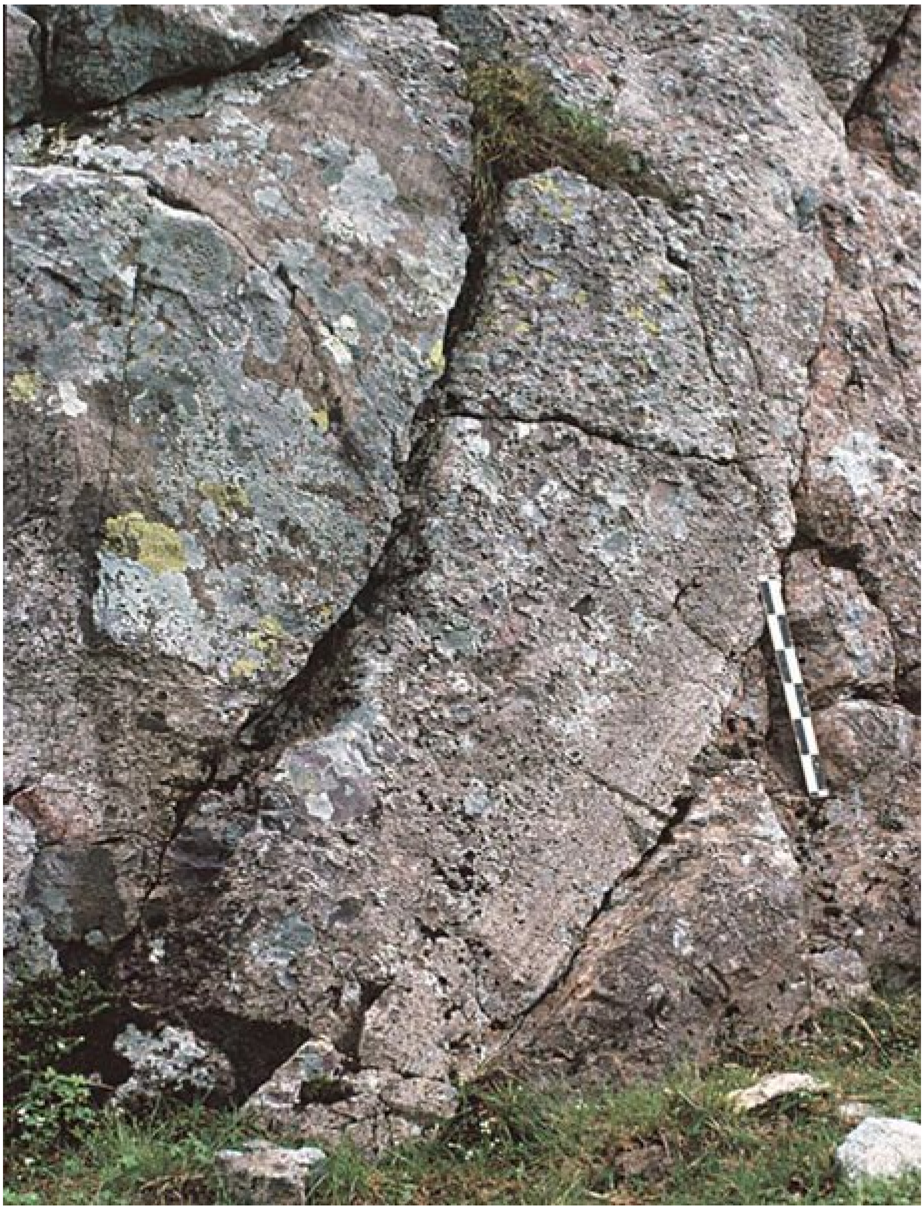
(Figure 19) Texture of coarse-grained lithofacies of the Lower Queen's Cairn Breccias showing near jigsaw-fitting of clasts and sparse matrix of similar material, which together indicate fragmentation at a late stage of transport. Such textures in sedimentary deposits are characteristically formed in debris avalanches.



(Figure 20) (right) Schematic sections north-west to south-east parallel to the axis of the Glencoe Graben. a. The tectonic development that led to emplacement of the Lower Queen's Cairn Breccias (LQB). The breccias are banked against a retrogressively degraded scarp of the Queen's Cairn Fault and spread to the south and south-east across the alluvial surface formed of Queen's Cairn conglomerates, sandstones, and siltstones (QCC).b. The ensuing eruption that formed the Upper Three Sisters Ignimbrite (UTS) and led to volcano-tectonic subsidence involving both faulting and downsag. Buoyant-convective ash plumes that would have risen above both the vent and the pyroclastic currents are omitted for clarity.BAS Basal Andesite Sill-complex; CRT Crowberry Ridge Tuffs; DA Dalradian metamorphic basement; DSF Devil's Staircase Fault; GEF Glen Etive Fault; KHB Kingshouse Breccias; KHT Kingshouse Tuffs; LER Lower Etive Rhyolite; LTS Lower Three Sisters Ignimbrite; NEGF Northeastern Graben Fault; OF Ossian Fault; QCF Queen's Cairn Fault; RGT Raven's Gully Tuffs; UER Upper Etive Rhyolite; UTS Upper Three Sisters Ignimbrite; WCF White Corries Fault.

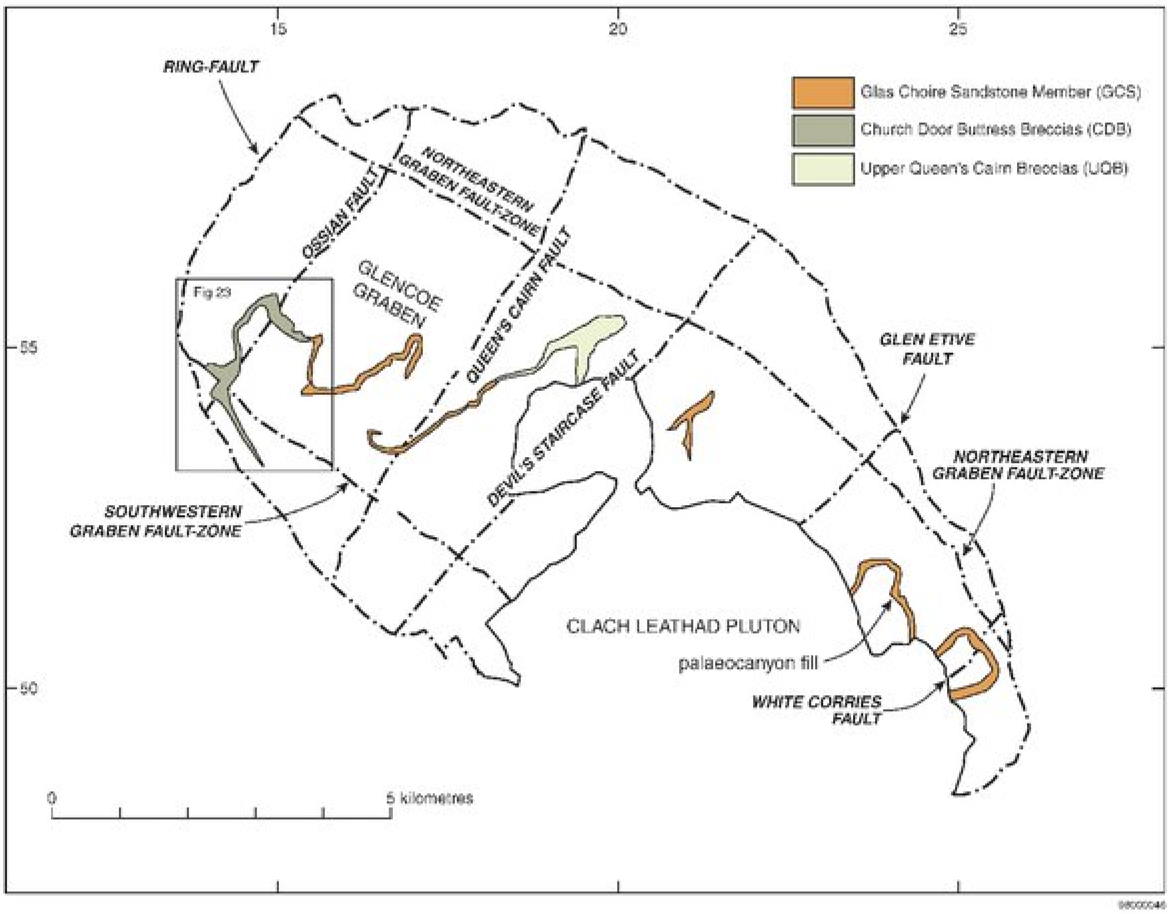


(Figure 21) Schematic log of the Upper Three Sisters Ignimbrite in Coire nam Beitheach [NN 1414 5473] showing stratified mesobreccias towards the base and, at around 65 m, the characteristic increase from moderate to dense welding picked out by intensification of the eutaxitic fabric (flattening of fiamme). The stratigraphical levels of the ignimbrite shown in Plate 19 are also located.

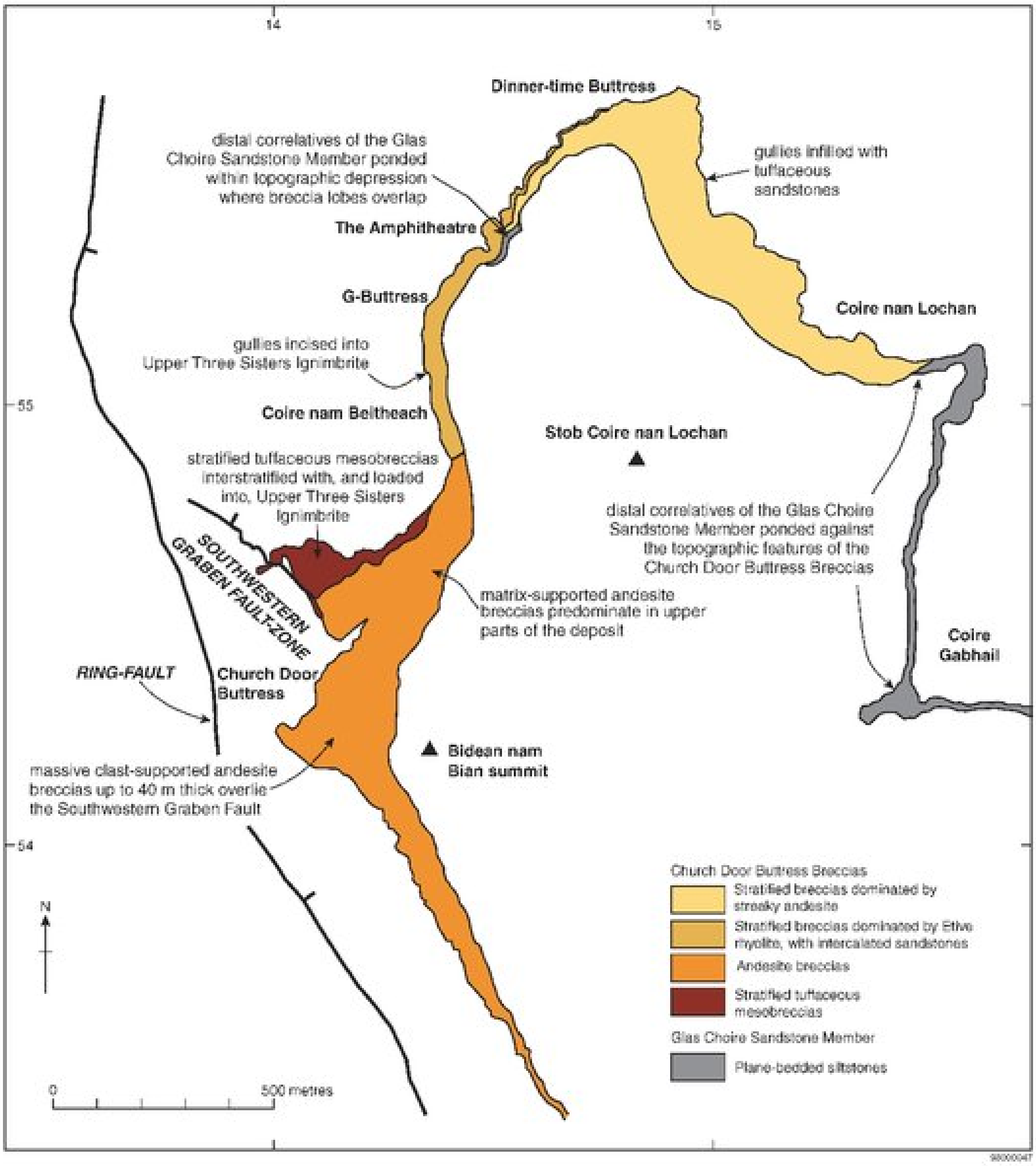


(Plate 19a) Upper Three Sisters Ignimbrite in Coire nam Beitheach [NN 142 548]. a. Stratification and inverse grading of lithic tuff at the base of the ignimbrite; the substrate is Lower Etive Rhyolite (right-hand side). Scale intervals are 5 cm (P611794).

(Plate 19b) Upper Three Sisters Ignimbrite in Coire nam Beitheach [NN 142 548]. b. Mesobreccia layer including large matrix-supported blocks derived from the Basal Andesite Sill- complex (located with arrows) and Lower Etive Rhyolite. (See also (Figure 14) and (Figure 21)) (P611795).

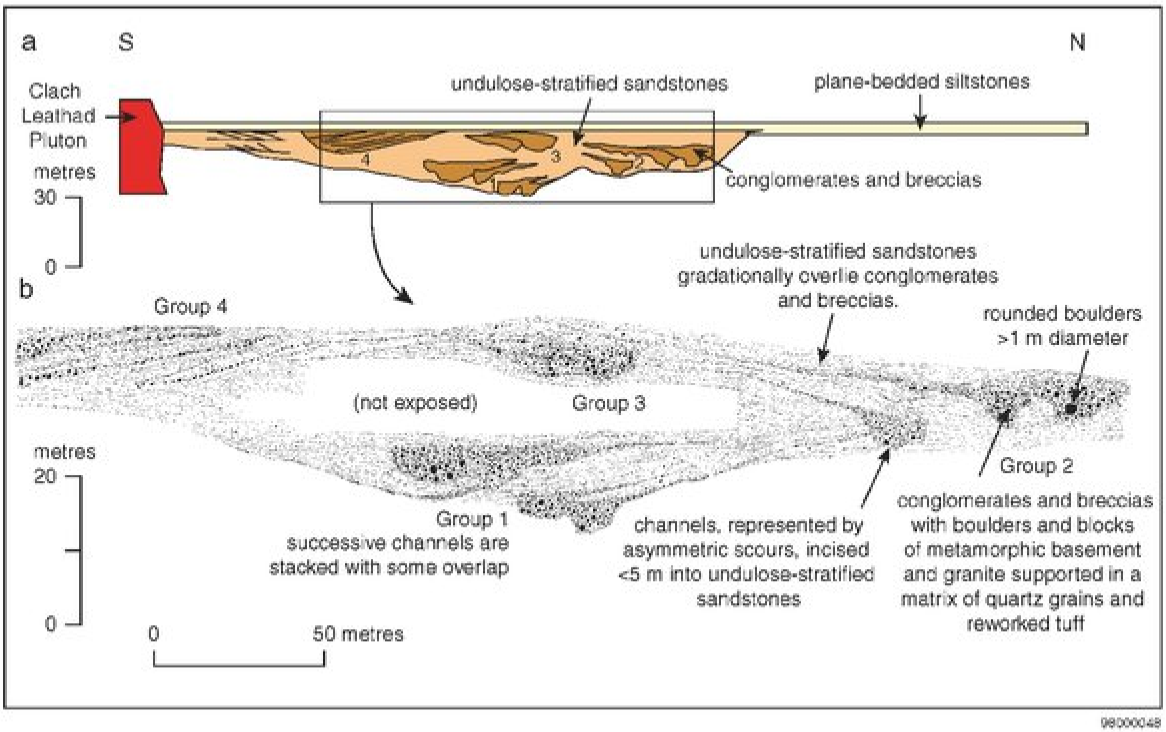


(Figure 22) Locations of outcrops of the Upper Queen’s Cairn Breccias (UQB), the Church Door Buttress Breccias (CDB), and the diverse sedimentary rocks that infill the Glas Choire palaeocanyon and overlie a fluvially eroded surface to the *north-west (Glas Choire Sandstone Member; GCS). The inset box shows the location of the detail provided in (Figure 23).*



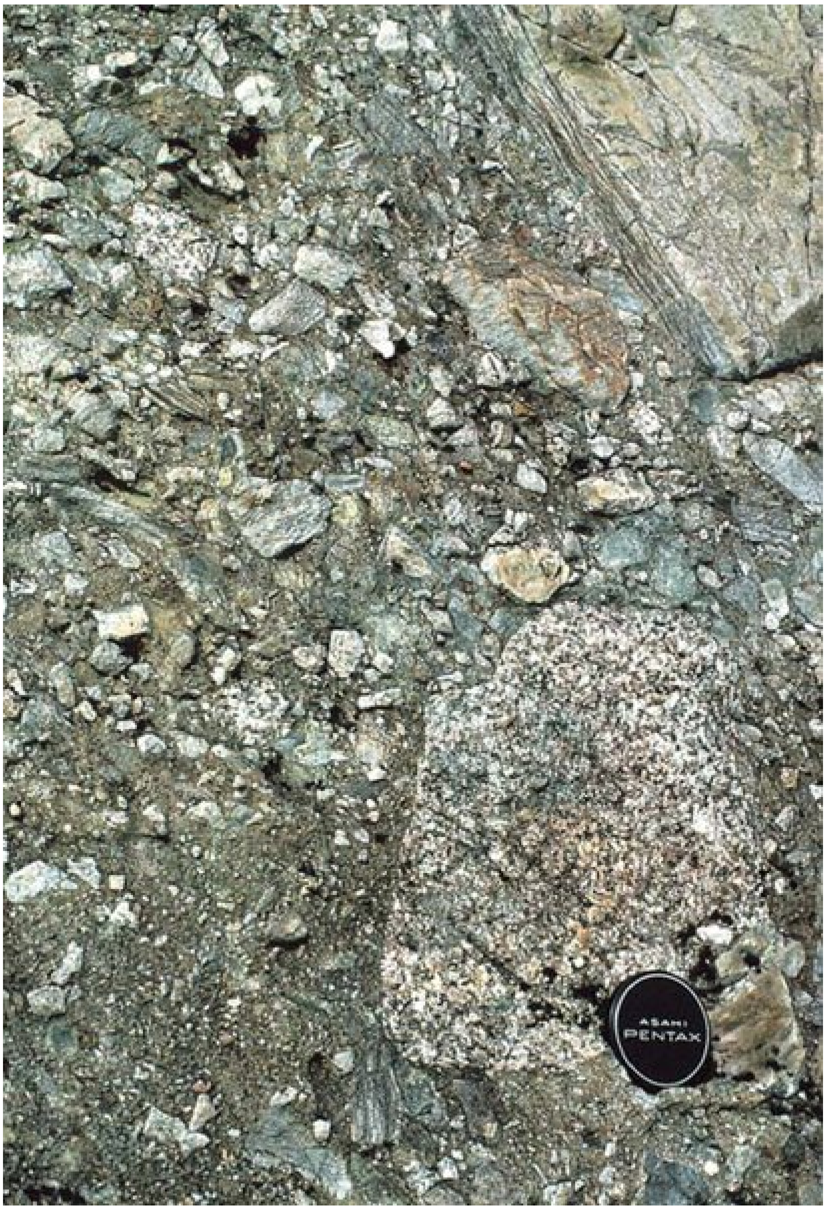
(Figure 23) Locations and key features of individual elements of the Church Door Buttress Breccias and of the distal Glas Choire alluvial deposits, in the north-west of the caldera-volcano complex see (Figure 14) and (Figure 22).

(Plate 20) Upper Streaky Andesites agglomerate forming part of the infill of the vent exposed in the north-eastern shoulder of Aonach Dubh (see Plates 14a and 15b). The various angular lithic fragments are intensely altered (P611796).



(Figure 24) Alluvial architecture of the fill within the Glas Choire palaeocanyon.a. Schematic section of the Glas Choire palaeocanyon fill, showing four groups of stacked and infilled channels, with overbank siltstone that lies on the shoulder of the palaeocanyon. The uppermost siltstones are lacustrine in origin. b. Detail of the alluvial architecture: vertical scale is approximately 2 the horizontal scale.

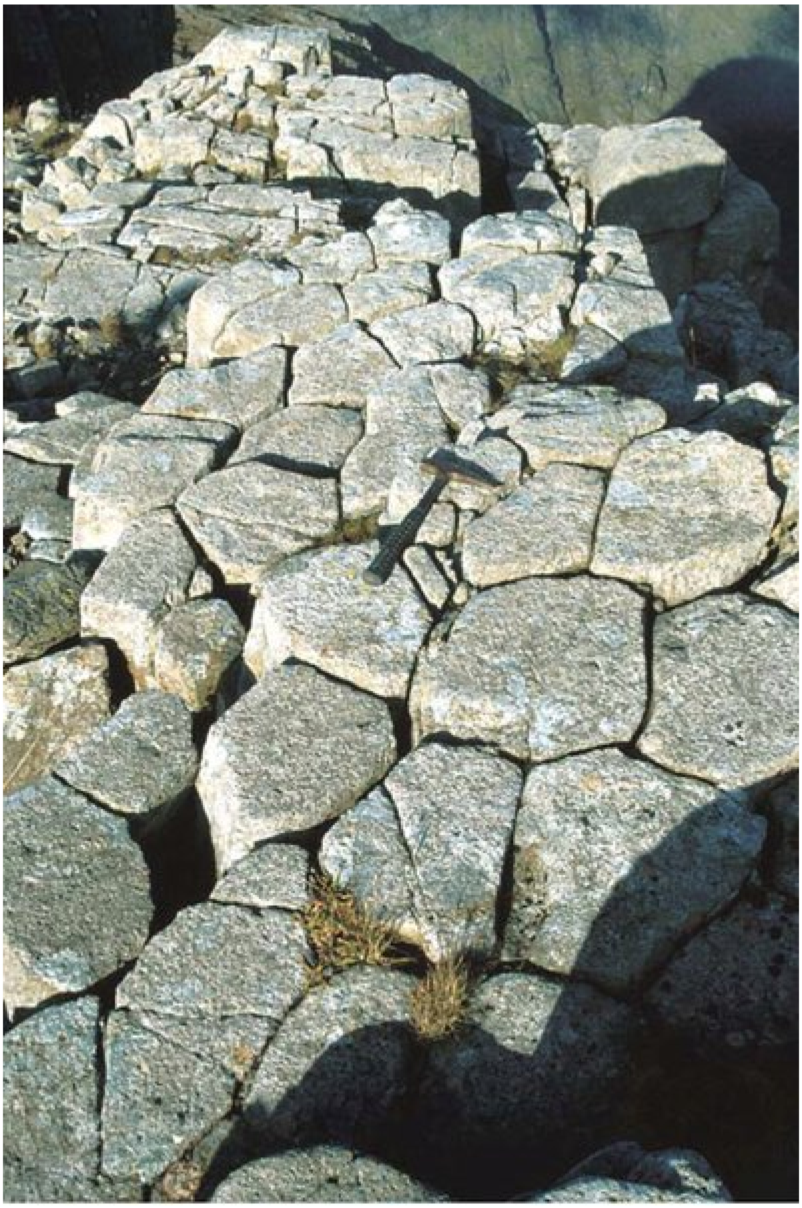
(Plate 21a) Glas Choire palaeocanyon, infills of sandstone and conglomerate, with overbank siltstones. a Undulose-stratified pebbly sandstone within the palaeocanyon [NN 241 514] (P611797).



(Plate 21b) Glas Choire palaeocanyon, infills of sandstone and conglomerate, with overbank siltstones. b Cobbles and boulders of metamorphic basement and Rannoch Moor granite in poorly sorted conglomerate that infills channels within the palaeocanyon [NN 241 514] (P611798).

(Plate 21c) Glas Choire palaeocanyon, infills of sandstone and conglomerate, with overbank siltstones. c Planar-bedded and laminated siltstone and fine-grained sandstone showing normal grading and loading-related soft-sediment deformation, interpreted as overbank deposits; Stob a' Ghlais Choire [NN 2418 5168] (P611799).

(Plate 22) a and b Bidean nam Bian Andesite Member at Stob Coire nan Lochan [NN 148 549]; this columnar jointing persists through more than 200 m thickness with no apparent discontinuity, so that the sheet appears to be a single cooling unit (P611800) and (P611801).



(Plate 22) a and b Bidean nam Bian Andesite Member at Stob Coire nan Lochan [NN 148 549]; this columnar jointing persists through more than 200 m thickness with no apparent discontinuity, so that the sheet appears to be a single cooling unit (P611800) and (P611801).