Chapter 5 Ring-fault system and fault-intrusions

The Glencoe volcano became internationally renowned for the striking occurrence of its thick succession of lavas and volcaniclastic deposits deep within metamorphic basement, with contacts along steep bounding faults that were described as a 'ring-fault'. It was considered by Clough et al. (1909), Bailey and Maufe (1916), Bailey (1960) and Roberts (1974) that a block of crust had subsided coherently along the ring-fault, and that the 'fault-intrusions' along the fault trace represent the complementary ascent of magma from an underlying chamber (Figure 5). However, Moore and Kokelaar (1997, 1998) showed that substantial displacements on the ring-fault system occurred only after formation of the lower parts of the volcanic succession. None of the five major silicic eruptions recorded by the Etive rhyolites and Three Sisters ignimbrites caused large-scale subsidence on the ring-fault, although the last one seems to have activated a section of it in the west, as is registered in the andesitic Church Door Buttress Breccias that overlie the Southwestern Graben Fault (Figure 22); (Figure 23). Similarly, the fault-intrusions have no known extrusive counterparts, except possibly the Bidean nam Bian Andesite Member, which could have been erupted via conduits now represented by the An t-Sròn composite intrusion (see pp.79; 92). Subsidence amounting to 700 m is known to have occurred along parts of the ring-fault system, but the timing of this and the associated intrusive activity remain poorly understood. In this book the descriptions of the ring-fault and associated fault-intrusions are derived substantially from earlier work (in particular Clough et al., 1909; Bailey and Maufe, 1916; Bailey, 1960; Roberts, 1966b; Taubeneck, 1967; Garnham, 1988), although new observations are added and the whole is placed in the modern context. For full petrographical details the reader should refer to Bailey (1960). The term 'ring-fault' is preserved here, for simplicity, but the previous connotations of a fault system continuously linked around a coherent block of crust should not be assumed.

Ring-fault system

The trace of the ring-fault system broadly outlines an incomplete and truncated ellipse, 14 km by 8 km (Figure 25), with major strands to the south of this; it is somewhat polygonal and not a continuous annular structure. Previous workers have emphasised the linkage of exposed fault strands to form a continuous dislocation ('ring'), which has formed the basis for the original piston-subsidence model (Clough et al., 1909; see (Figure 5)a and its successor, the asymmetrical or 'trapdoor' model (Roberts, 1974; see (Figure 5)b, but it is important to recognise now that the 'ring' is only a part of the system and that there was a southwards shift of the locus of subsidence such that south-western parts of the 'ring' did not delimit but lay in the floor of the later structure. In a modern review, Lipman (2000, p.656) expressed the opinion that the overall structure at Glen Coe 'seems reasonably interpreted as dominated by subsidence along the bounding ring faults, with smaller scale breakup of the floor largely preceding development of the ring-fault subsidence', but this is contrary to the observation that the maximum downthrow that can be determined on any strand of the ring-fault is *equal* to the downthrow that is known to have occurred within the Glencoe Graben. It is now too simplistic to view the caldera-volcano development as having been dominated by ring-fault controlled subsidence, and there is much to be learned from an objective reappraisal. The story that emerges involves migration and possible enlargement of successive caldera depocentres, with the various bounding rectilinear structures strongly influenced by a regional tectonic grain and active tectonism.

Long sections of the ring-fault system are poorly exposed, particularly in the north-east, and other parts are obliterated by intrusions, especially in the south by the Clach Leathad Pluton (Figure 25). Early Geological Survey geologists argued, with good reason, that in poorly exposed ground the existence of the fault could be inferred from the intrusions lying along the interpolated trace of the ring, even where the igneous contacts are not exposed. However, many well-exposed parts of the ring-fault system are distinctly polygonal rather than smoothly rounded, with sharply angular intersections of north-east- and north-west-trending fault planes, and with multiple subparallel branches and common bifurcations. There is abundant evidence that different fault strands were active, and were intruded by magma, at different times, and that some strands were reactivated. Thus in the poorly exposed ground in the north-east, between Stob Mhic Mhartuin and Cam Ghleann (Plate 23), the inferred trace of the ring-fault is probably a simplification. Tantalising glimpses here of the metamorphic basement within the mapped ring-fault show it to be considerably broken and locally to include minor intrusions interpreted as of the Early Fault-intrusion suite (Clough et al., 1909), suggesting that the fault system here is far more complicated than has been depicted.

The ring-fault is particularly well exposed in the accessible crag of Stob Mhic Mhartuin [NN 208 575], where there are two north-west-striking fault strands. The inner one, the ‘Main Fault’, is younger than the outer, ‘Early Fault’ (Clough et al., 1909), and both can be traced from Stob Mhic Mhartuin north-westwards as far as Coire Mhorair [NN 187 585]. These fault strands are planar, dip steeply outwards (towards the north-north-east) and include some right-angular fault-jogs. Farther north-west, Bailey (1934, 1960, p.157) located another outer fault strand, on the slopes of Meall Dearg [NN 165 589], but it is uncertain whether this might have been continuous with the outer fault at Stob Mhic Mhartuin, because it is cut by an intrusion. This strand, however, extends north-westwards for at least 1.5 km beyond the sharp angular change of strike of the inner fault, which forms the northernmost corner of the (closed) ring-fault system. This ‘corner’, in Coire Cam [NN 1583 5872], is the intersection of two planar faults, one striking nearly east–west and dipping north at 50° and the other striking north-east–south-west and dipping nearly vertically. In the vicinity of the classic view of the ring-fault (Plate 24), where it forms the deep gully known as The Chasm of An t-Sròn [NN 136 557] and crosses the An t-Sròn ridge towards Stob Coire nam Beith [NN 1355 5520], in the far west of the volcano complex, the fault has a vertical to steep inward dip (about 86°) through a vertical distance of approximately 1 km. However, as noted by Bailey (1960, p.77), this part of the ring-fault does not curve smoothly to the north-east across the floor of Glen Coe, but takes an angular deflection where the major downthrow was transferred from one steep fracture to another that intersected it. (Plate 24) shows the gully that marks the continuation of one fracture where it diverges from the ring-fault on the flank of An t-Sròn; a similar gully on the north side of the valley marks the continuation of the fracture that projects into the Chasm of An t-Sròn.

Inner and outer strands of the fault system are exposed in the far east of the volcano complex, in Coire an Easain [NN 257 490], but here the inner strand is the earlier one. These strands dip outwards and they both show abrupt, almost right-angled, changes in strike from north-east to north-west (see Bailey and Maufe, 1916, fig. 23; (Figure 25). Viewed from the summit region of Meall a’ Bhùiridh [NN 250 503], it is clear that the inner contact of the early fault-intrusion here is planar for more than 1 km across Coire an Easain [NN 25 49], and that it dips steeply outwards (towards the south-east) and intersects the Northeastern Graben Fault almost at a right angle. On the northern and western flanks of Beinn Ceitlein, south-east of Dalness [NN 180 503] and [NN 175 498], there are several subparallel fault strands, some of which are linked by faults almost at right angles (Clough et al., 1909). The fault that is part of the system in Gleann Fhaolain, between Bidean nam Bian [NN 139 540] and Dalness [NN 165 509], dips inwards (north-eastwards) at no less than 80° and is more or less straight and planar, while approximately 2 km to the south-west an outer, divergent strand, in Gleann Chàrnan [NN 13 51] (Figure 25), is also straight and is practically vertical. This latter structure displaces units in the Dalradian basement, throwing the Leven Schist Formation down to the east-north-east by more than 500 m, against the older Glen Coe Quartzite Member (Clough et al., 1909). This structure was considered by early workers also to be a boundary fault of the ‘cauldron subsidence’, linked with the faults on Beinn Ceitlein (Bailey, 1960, p.132, fig. 19). It has fault-intrusions along it and extends north-north-westwards into the An t-Sròn component of the ring-intrusion [NN 12 53]; it was probably active as a volcanotectonic fault at least by the time of emplacement of the Bidean nam Bian Andesite Member (see p.93).

The dips of the fault planes that constitute the ring-fault system evidently range from 50° outwards to no less than 80° inwards (Figure 25). Along northern and eastern sections the faults dip outwards, and elsewhere they are near vertical or dip steeply inwards (Clough et al., 1909; Bailey, 1960). There is no evidence for an upwards-flaring cone-fracture system as discussed by Taubeneck (1967) and Roberts (1974; see (Figure 5)b (see discussion on pp.14–15). Several previous authors interpreted the steepening of dips in volcanic strata near the ring-fault as evidence of shortening due to subsidence along inward-dipping faults (e.g. Taubeneck, 1967), and hence used this to confirm an upward-flaring ring-fault geometry. However, most of the inward dips of the strata at Glen Coe were caused by incremental (extensional) downsag before development of the ring-fault. The report by Clough et al. (1909) and Taubeneck (1967) of inverted strata in the north-west of the volcano complex, at Stob Coire nam Beith [NN 138 548], was a misinterpretation. The contacts concerned, with Etive rhyolite apparently overlain by the Basal Andesite Sill-complex, record top- inwards rotation, by at least 35°, of originally near-vertical fault scarps of the Southwestern Graben Fault see (Figure 14), rather than inversion with some 120º rotation of an originally horizontal, normal contact. Outward dips of strata immediately adjacent to the fault in the south-west of the volcano complex, on the south-western slopes of Stob Coire Sgreamhach

[NN 15 53] and Coire nan Easan [NN 15 52], probably register rotations due to listric faulting down to the north-east, or, alternatively, relatively late downsag towards the south-west.

Displacements on the ring-fault system are poorly constrained. The youngest part of the preserved volcanic succession, the Dalness Ignimbrite Member, is cut by the ring-fault system only in one area, approximately 1.5 km east-south-east of Dalness [NN 180 503], where the downthrow appears to be at least 600 m. From this point clockwise around the fault system towards the north at Coire Cam [NN 159 585], the metasedimentary rocks on the outside are mostly juxtaposed against the Basal Andesite Sill-complex and its metasedimentary substrate on the inside. In the west, a minimum downthrow of about 500 m can be deduced from the preservation of the greatest known thickness of the sill stack. However, 600 m or more (Clough et al., 1909, p.627) is apparent in the offset to the north-east within the fault system (to Coire Mhorair [NN 185 585]) of the south-dipping Ballachulish Limestone Formation, relative to its outcrop outside the fault system, high on the southern slopes of Sgorr nam Fiannaidh [NN 141 578] (see 1:25 000 scale geological map; British Geological Survey, 2005). Early Geological Survey geologists considered that in this western sector, near Loch Achtriochtan [NN 139 563], the ‘basement’ within the fault system (Leven Schist Formation; (Plate 24)) was of lower metamorphic grade than that outside, consistent with an origin for the inner rocks at significantly higher structural levels (e.g. Bailey, 1960, p.71; but see p.22). Locally, at Meall Dearg [NN 161 583] and Sròn Gharbh [NN 177 583], the fault system cuts the Lower Streaky Andesites, while towards the ridge of Sròn a’ Choire Odhair-bhig [NN 199 579] it cuts the Upper Streaky Andesites; here a minimum displacement of 400 to 500 m can be inferred (the Basal Andesite Sill-complex is thinner here). Continuing clockwise, the ring-fault system juxtaposes various Dalradian metasedimentary rocks, and, although the amount of displacement cannot be established, substantial downthrow can be inferred, because the Dalradian strata on either side of the fault system are lithologically and structurally different (e.g. at Stob Mhic Mhartuin [NN 208 575]). South-east of the River Etive, towards Coire Pollach [NN 256 512], metasedimentary rocks inside the volcano complex are faulted down against the Rannoch Moor Pluton, although elements of fault-intrusion intervene (Figure 25); (Plate 23). In this eastern part of the Glencoe volcano complex, the volcanic succession is cut by the ring-fault system only on the eastern slopes of Meall a’ Bhùiridh [NN 2578 5057]. Here the ring-fault merges into the margin of the ignimbrite-filled crevasse (Three Sisters Ignimbrite Member) that marks the Northeastern Graben Fault; it coincides with this feature for some 750 m and then cuts abruptly across it at [NN259 497], striking south-westwards.

The maximum known cumulative subsidence of the metamorphic basement within the fault system, relative to a surface outside it, is the sum of the greatest subsidence within the Glencoe Graben, which is entirely within the ring-fault (about 700 m) plus the later downthrow on the ring-fault system (also about 700 m). Thus the maximum known cumulative subsidence is about 1400 m. It is possible that actual displacement on the ring-fault system exceeds the amount that can be simply determined, at least locally, so that the actual total could have been greater. This amount of subsidence is quite normal for caldera volcanoes, although such a piecemeal and multistage method of achieving it is either uncommon or has been overlooked and rarely recorded elsewhere (but see Branney and Kokelaar, 1994).

The manner in which faulting occurred on the ring-fault system is not clear. Because the basement of the Glencoe caldera volcano was cut by intersecting *regional* faults that were active before and during volcanism, and because, consequently, there was early fragmentation of the caldera floor, it is unlikely that the later ring-fault system ever formed a simple continuous dislocation such that there was large-scale piston-like or *en bloc* (coherent) subsidence within it. The upper members of the Glencoe Volcanic Formation appear to record depocentres that straddled the south-western elements of the main ring structure that lie between the general vicinity of Dalness [NN 17 51] and An t-Sròn [NN 13 55], and it is quite possible that the later volcanotectonic subsidence was bounded to the south-west by the outer strand of the ring-fault system, some 2 km to the south-west, in Gleann Chàrnan [NN 13 51]. The later subsidence that is recorded in the emplacement of the Clach Leathad Pluton (p.98), which partly obliterates and partly invades the Glencoe ring-fault system, possibly constitutes another shift or broadening of the influence of volcanotectonic activity; it is possible that some subsidence along north-eastern parts of the ring-fault system was related to early phases of emplacement of this monzogranitic intrusion.

Flinty crush-rock

The faults that constitute the ring-fault system are widely characterised by the presence of an extremely fine-grained black-to-brown rock, which Clough et al. (1909) called 'flinty crush-rock'. It occurs as a veneer along the fault planes, commonly at the margins of fault-intrusions, and also in veins that cut irregularly into adjacent (Dalradian) metamorphic rocks, various breccias and fault-intrusions. The flinty crush-rock is intimately associated with a dull pink to red porphyritic rhyolite originally referred to as 'red felsite' (Roberts, 1966b; Taubeneck, 1967; Garnham, 1988).

The type locality of the flinty crush-rock is at Stob Mhic Mhartuin [NN 208 575]. Here, the (inner) Main Fault is intruded by a sheet of porphyritic monzodiorite, up to about 30 m wide, which separates thick-bedded (Dalradian) quartzite, down thrown to the south-west, from flaggy quartzite and semipelite to the north-east. Along the planar south-western contact of the intrusion, the fault is represented in a zone, up to 1 m wide, which shows a gradation from undisturbed quartzite into brecciated quartzite, through a white fine-grained microbreccia and then a zone of banded micro-breccia with flinty crush-rock matrix, to flinty crush-rock, and then porphyritic rhyolite (Plate 25a), (Plate 25b). The flinty crush-rock is a band, 3 to 5 cm wide, of delicately laminated, black-to-brown, almost cryptocrystalline quartzofeldspathic material with various inclusions (Plate 26a), (Plate 26b). The most distinctive inclusions are abundant small (0.01–1 mm) quartz grains, many of which are obviously rounded. Locally, the flinty crush-rock encloses swarms of quartzite fragments and euhedral to subhedral (igneous) crystals of plagioclase, K-feldspar, chloritic relicts of amphibole and biotite, opaque oxides and zircon. The lamination is deflected around the included grains and is generally parallel to contacts (Plate 26a), (Plate 26b).

The moderately feldspar-phyric rhyolite ('red felsite') adjacent to the flinty crush-rock is locally up to 2 m thick and is of rather variable composition. Early workers thought that it was the chilled margin of the (monzodiorite) fault-intrusion (Clough et al., 1909; Bailey, 1960), but Roberts (1966b) and Garnham (1988) demonstrated that it is a separate intrusion, although in places the two are mingled. Thin veins of the rhyolite interfinger with the flinty crush-rock and various mingling relationships occur, ranging from bleb-like inclusions of rhyolite in crush-rock, through fine-scale swirling interlamination, to a thoroughly mixed hybrid rock (Plate 26a), (Plate 26b). Large crystals (phenocrysts) and clumps of crystals (glomerocrysts) in the rhyolite consist mainly of plagioclase and K-feldspar, with the plagioclase commonly occurring as fragments. Some of the feldspars in the flinty crush-rock are surrounded by a thin coating of rhyolite, showing that they are admixed phenocrysts from the rhyolite. However, other K-feldspars in the crush-rock, along with quartz grains, appear to be derived from a comminuted and partially melted metasedimentary protolith (K-feldspar is abundant in the metasedimentary rocks). Lithic fragments composed of granophyric intergrowths of quartz and K-feldspar in the rhyolite (Plate 26c) indicate a granitic derivation, conceivably from part of the Rannoch Moor Pluton extending at depth under this area. A xenolith of Rannoch Moor granite, 8 m in diameter, is enclosed nearby in the Main Fault-intrusion at Stob Mhic Mhartuin [NN 2090 5740] (see below).

Flinty crush-rock with rhyolite also occurs at the irregular (non-planar), outer contacts between the fault-intrusions and metasedimentary rocks (Roberts, 1966b; Taubeneck, 1967). In the vicinity of Stob Mhic Mhartuin, the quartzitic rocks along the outer contact of the Main Fault-intrusion are strongly fractured and, in contrast to the inner contact, tend to have sharp rather than transitional contacts with the flinty crush-rock. Irregular veins, up to 20 cm wide, of flinty crush-rock with cores of rhyolite, penetrate 2 to 3 m into the metasedimentary rocks, while fine stringers of the crush-rock alone extend several metres farther. In places, flinty crush-rock veins up to 5 cm wide penetrate the fault-intrusions; emplacement of one vein in the Main Fault-intrusion appears to have involved pushing aside of phenocrysts, suggesting that the vein penetrated an unconsolidated crystal mush. This vein locally shows that rhyolite melt entered first and it is interpreted as recording back-veining from the composite margin. Flinty crush-rock also invades interstices of sedimentary and volcaniclastic breccias adjacent to both the inner and the outer faults in this vicinity, and Taubeneck (1967) has identified volcanic rock fragments in the crush-rocks, thus confirming the incorporation of diverse extraneous igneous material into them.

Contact relationships similar to those at Stob Mhic Mhartuin occur elsewhere around the ring-fault system, notably near Loch Achtriochtan in the west [NN 139 566] and at Cam Ghleann in the east [NN 250 523], but in other places, for example in Gleann Fhaolain [NN 14 53] and at An t-Sròn [NN 13 55], the exposed downfaulted rocks are volcanic or sedimentary strata rather than metamorphic basement. Close to the faults, these nonmetamorphic strata show numerous dislocations and are brecciated, while along the faults the exposed fault rocks have loose rubbly or gouge-like textures. This is in marked contrast to the compact fault rocks that occur where the inner rocks are metasedimentary basement (e.g. (Plate 25a), (Plate 25b)). In Gleann Fhaolain, the relatively soft rocks along the fault plane have weathered out to form a pronounced hollow in the side of the valley, but in this case there is evidence of reactivation long after the Glencoe magmatism (see Bailey, 1960, p.155). Most previous workers have noted that wherever strands of the ring-fault juxtapose volcanic or sedimentary rocks on the inside against metasedimentary (Dalradian) rocks on the outside, neither flinty crush-rock nor rhyolite (‘red felsite’) is present. However, one exception has been recorded, south-east of Dalness [NN 178 505], where the inner rocks are Dalness ignimbrite.

Clough et al. (1909), Bailey and Maufe (1916) and Bailey (1960) considered that the flinty crush-rock was formed by frictional heating and partial fusion of the country rocks due to rapid movement on the ring-faults. Shand (1916) named this dark, almost vitreous-textured vein-rock ‘pseudotachylyte’ (synonymous with pseudotachylite), from its similarity to glassy basalt (tachylite). In the survey geologists’ interpretations of the Glencoe ‘cauldron subsidence’, the formation of the flinty crush-rock and emplacement of the fault-intrusion were considered as two stages in a single process. However, first Reynolds (1956) and then Roberts (1966b) disputed whether the contact relationships at Stob Mhic Mhartuin could result simply from intense mechanical brecciation and partial fusion along the ring-fault. Their main concern was that the material represented by the flinty crush-rock clearly had been injected to a considerable distance, at least 5 or 6 m, away from the fault plane on which it was supposed to have been generated. They doubted that a near-instantaneously produced friction-melt would be so mobile and that it could be injected so far into relatively cold rocks. From the published descriptions of the type locality, and rocks elsewhere, Reynolds (1956) postulated that the flinty crush-rock was produced from pyroclastic material that had been emplaced by fluidisation as magmatic gases escaped during or ahead of the ascent of the fault-intrusion magma. Roberts (1966b) reinvestigated details of the contact relationships around the (inner) Main Fault-intrusion at the type locality and, to an extent concurring with Reynolds, suggested that the flinty crush-rocks were produced primarily by the comminution of brecciated country rocks entrained in a (streaming) fluidised system, ahead of fragmenting magma. He suggested that the quartz grains were released from the fault plane during frictional sliding and that their distinctive roundness was caused by attrition in a fluidised system under high confining pressures. Roberts (1966b) went so far as to postulate that the main intrusion was also derived from a fluidised system, by coalescence of magma droplets, but its content of country rock (granite) xenoliths up to 8 m in diameter appears to preclude this. These problematic fault rocks are discussed further in following sections.

Fault-intrusions

The fault-intrusions include numerous and diverse bodies that occur extensively along and mostly outside the innermost trace of the ring-fault system (Figure 25). There is no simple ring-dyke. The intrusions are discontinuous and range from 1 m up to 2000 m wide; they generally have relatively planar inner contacts against the subsided rocks while outer margins are highly irregular (nonplanar). Country-rock xenoliths are abundant. The rocks are typically medium or coarse grained and range from gabbros, through diorites, tonalites and monzonites, to granites (52–72 weight per cent SiO_2; Garnham, 1988). Highly porphyritic varieties are common (phenocrysts 40–70 volume per cent), groundmass is microcrystalline to spherulitic, and chilled margins can be prominent. Distinctive, moderately porphyritic rhyolite occurs widely along intrusion contacts and was initially mistaken as representing chilled margins (‘red felsite’; see previous section). The intrusions occur either individually or in hybrid bodies, and, unlike the streaky andesites that occur in the volcanic succession, there are none that show abundant co-magmatic inclusions indicative of substantial in situ or shallow-level magma mingling. The paucity of exposure in many areas, together with marked lithological heterogeneity, confounds both estimation of the relative volumes of the different rock types and determination of their relative ages. The different types show no clear geometrical or temporal arrangement. According to Garnham (1988), the most abundant rock types are porphyritic diorites, tonalites and monzonites, which form most of the intrusions in Cam Ghleann [NN 249 525] and at An t-Sròn [NN 13 55] and [NN 13 54], as well as at Stob Mhic Mhartuin [NN 208 575]. Granitic rocks occur more commonly in the outer and earlier parts of the fault-intrusion system, notably in the west as sheets along bedding and joint planes in the metamorphic basement e.g. [NN 129 569]. Some of the silicic intrusions show clear evidence that they were emplaced earlier than other types, and these commonly record intense hydrothermal alteration. The altered rocks have numerous ramifying veinlets containing quartz or epidote, or both, or networks of fractures along which there is almost pervasive oxidation of iron-bearing minerals (reddening), and, in places, white mica and pyrite. Gabbroic rock types appear to be the least voluminous and least altered.

The presence of chilled margins at intrusive contacts against the ring-fault, and the common lack of fault-related deformation of the intrusive rocks, led the survey geologists (e.g. Clough et al., 1909) to suggest that fault movement and intrusion were simultaneous. Some intrusions show evidence of having been emplaced before or at an early stage of development of the 'Main' ring-fault. In the far west of the volcano complex, the An t-Sròn composite intrusion [NN 13 55] and [NN 13 54], which is about 2 km wide, is the largest of this type (Figure 25). It is predominantly composed of varieties of diorite and tonalite, with branching granitic to rhyolitic ('felsitic') sheets towards the outer margin (Bussell, 1979; Garnham, 1988). The sharp inner contact against the ring-fault shows shear deformation and brecciation of a chilled margin, and there is no evidence of any substantial contact metamorphism in the Basal Andesite Sill-complex immediately east of the fault, in the downthrown block. In contrast, the outer intrusion margin is irregular and contains abundant xenoliths of Dalradian metasedimentary rocks. Garnham (1988) suggested that marked thermal metamorphism and partial melting of the metasedimentary rocks in the contact zone to the south-west are records of high heat flow due to substantial throughput of magma, and hence that the An t-Sròn intrusion represents the root (plumbing system) of a volcano. It is possible that the Bidean nam Bian andesite and dacite lavas are extrusive counterparts to the diorites and tonalites of this intrusion (see p.79). The lavas appear to have been deeply ponded by an escarpment in the vicinity of the ring-fault or farther south-west, or both, which would tie in with the relationships between the main An t-Sròn intrusion and two intruded ring-fault strands. Intrusive rocks continuous with the An t-Sròn body extend both along the main ring-fault trace trending south-eastwards on the high flanks of Gleann Fhaolain [NN 141 537], and along the outer, somewhat divergent strand of the fault system, approximately 2 km to the south-west and trending into Gleann Chàrnan [NN 132 517] (see (Figure 25)). In Gleann Fhaolain, from the south-western slopes of Bidean nam Bian towards Dalness, the fault-intrusion is in places as little as 10 m wide, is mainly composed of tonalite, and has relatively planar outer and inner contacts, like a dyke. The intrusion along the outer strand of the fault system in Gleann Chàrnan, with downthrow to the east-north-east of at least 500 m, is similar.

Cross-cutting relationships between strands of the ring-fault and early and late fault-intrusions are evident in the east of the volcano complex at Coire an Easain [NN 25 49], where there is an abrupt change in strike of both of the fault strands and of the later intrusion (see Bailey and Maufe, 1916, fig. 23). This later fault-intrusion element is continuous with the main body of the Clach Leathad Pluton (Figure 25), which was emplaced during foundering of a crustal block (see p.99), and early workers considered it to be the 'advance guard' of this large intrusion (e.g. Bailey, 1960). Along the north-east and south-west flanks of Creag Dhubh [NN 25 52] and north-west towards the River Etive [NN 24 54], the contacts of the fault-intrusion or intrusions are poorly exposed but seem to be broadly planar (Plate 23); farther north-west, however, the outer contacts are very irregular and the three-dimensional shape is evidently complicated.

At Stob Mhic Mhartuin [NN 208 575], where there are two parallel fault strands and associated intrusions of porphyritic monzodiorite, the Early Fault-intrusion is variably brecciated along the outer, Early Fault, which is supposed to have been reactivated (Bailey, 1960). Flinty crush-rock here penetrates the intrusion along brittle fractures. The inner, Main Fault-intrusion is not tectonised. Farther north-west, in Coire nan Lab [NN 175 589] and Coire Cam [NN 15 58], there are various cross-cutting intrusions. The outer margins of the intrusions here, and farther north-west on the slopes below Stob Coire Leith [NN 14 58] and Sgorr nam Fiannaidh [NN 13 57], are extremely irregular, and veins intrude the metasedimentary rock far beyond the main bodies.

Both Reynolds (1956) and Roberts (1966b) considered that the accommodation of fault-intrusions along the various strands of the ring-fault was problematic. They supposed that the controlling faults converged downwards, and then argued that, unless there was central uplift, space could not simply be made for intrusive magma. They questioned the survey geologists' proposal that the fault-intrusions worked their way upwards largely by magmatic stoping (bit-by-bit incorporation and removal of contact rocks in advancing magma) and suggested that gas-coring by fluidisation would have been a more effective mechanism for making space. With the more recent understanding that the caldera subsidence was piecemeal and substantially facilitated by tectonic dilatation (Moore and Kokelaar, 1997, 1998), and that the faults in fact do not converge downwards (see pp.85–86), neither stoping nor gas coring is required as a fundamental mechanism in accommodating the intrusions. However, that is not to say that they played no part. Given the heterogeneous, discontinuous and cross-cutting nature of the ring-fault intrusions, it is unlikely that there was a single climactic eruption involving large-scale subsidence along the entire system. Although large-scale displacements have taken place, the ring-fault system probably developed through several episodes of faulting and intrusion, over a long period of time.

The contrast between the irregular outer contacts and the planar inner contacts of the ring-fault intrusions (Figure 25) has not been understood. The outer contacts are extremely irregular and commonly include veins that penetrate the country rock extensively. Whereas the inner planar contacts are taken to represent an original fault-plane surface, the outer contacts appear to reflect one or more fault surfaces that have been substantially modified by magmatic stoping. Obviously, because of the great subsidence (order of hundreds of metres), the inner fault surfaces were formed at much shallower levels than the outer irregular contacts with which they are now juxtaposed (across the intrusions). One explanation of the contrasting features of the intrusion contacts could involve fault-plane dilatation and differences in the amount, pressure and temperature of groundwater or magmatic water, or both, present at different levels above the magma storage sites at the time of fault movement (Figure 26). Dilatation would be a natural consequence of subsidence on caldera-bounding faults that dip outwards, but can occur on any fault plane that is uneven, especially where there is slip that juxtaposes walls with differing curvatures. Rapid dilatation of a fault that transects a hydrothermal system will cause explosive transformation of liquid water to steam and vigorous expansion of vapour, with very steep local pressure gradients in fluid pathways around the cavity. The explosivity and fluid flow would effectively blast the hot-water-bearing country rock towards the dilating fault. On the other hand, the rock mass that subsided from shallower levels would not be so fragmented if it was relatively cool or essentially dry, and thus would present a planar fracture surface to the intrusion along its inner margin. This may explain the relationships around the Main Fault-intrusion at Stob Mhic Mhartuin, and the many similar relationships evident elsewhere. At Stob Mhic Mhartuin, the rocks around the Early Fault-intrusion clearly were affected by hydrothermal alteration in breccia zones that predated downthrow on the Main Fault. It is conceivable that dilatation on the Main Fault, following initial slip, caused the hydrothermal system to explode and disintegrate the (outer) fault wallrocks so that rising melts could penetrate and stope them quite easily e.g. (Figure 26).

How such an explosive system might have been linked with activity at the surface is unclear. Explosive fragmentation of the country rock may be recorded by abundant lithic blocks in pyroclastic deposits that formed from an eruption via such a dilated conduit, but the preserved volcanic succession mainly predates the ring-fault and intrusion system. However, the considerable lithicclast contents of the Three Sisters and Dalness ignimbrites (see previous sections) could at least in part reflect such a mechanism.

Substantial magmatically induced (resurgent) uplift is a common, but not ubiquitous, feature of modern caldera volcanoes (e.g. the central Redondo Peak dome and circle of rhyolitic lava vents of the Valles caldera; see (Figure 4)a. Cone-sheets or conical fractures that may indicate magma-chamber pressures sufficiently high to disrupt the overlying crust are unknown in the development of the Glencoe Caldera-volcano Complex. The preserved volcanic and sedimentary succession shows evidence of only limited magmatically induced (resurgent) uplift, in the form of some doming over the shallow-emplaced streaky andesite sills, and in these cases the magmatism was clearly associated with volcanotectonic subsidence. Perhaps the transtensional tectonic setting and graben-like developments of the volcano (Moore and Kokelaar, 1997, 1998) were not conducive to development of strong upward-directed magmatic pressures with attendant substantial uplift and intrusion of cone-sheets. On the contrary, it appears that the eruptions were facilitated by tectonism rather than having been caused by long-term build-up of magmatic pressure with eventual forceful releases of trapped magmas.

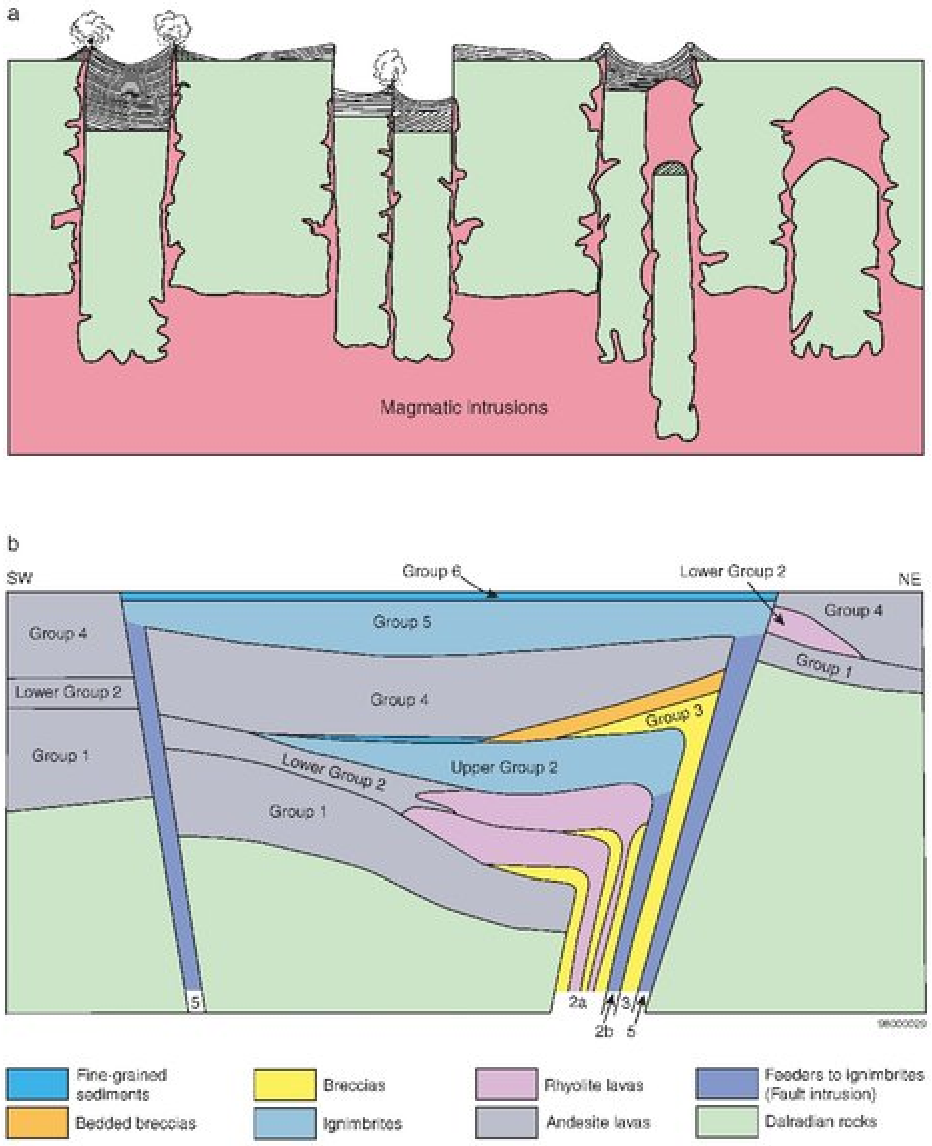
A unifying model

The arguments presented by Reynolds (1956) and Roberts (1966b) against the flinty crush-rock being a product of frictional melting (pseudotachylite; p.90) are not well founded. Firstly, there are no data on the mobility of friction-melts that form where fault movements amount to hundreds of metres over periods of hours or days, possibly involving substantial dilatation of fractures and even rocks that were significantly preheated. In thrust-fault systems, movement increments amount to only a few metres and pseudotachylite migrates only for distances of the order of tens of centimetres to occupy minor dilatational jogs (e.g. Camacho et al., 1995). In a volcanotectonic setting, substantial penetration of flinty crush-rock veins away from fault planes does not necessarily preclude an origin by frictional melting. Secondly, rounded grains are normal in melts formed in high-shear-rate experiments (and hence in pseudotachylites), where frictional melting follows inevitable initial comminution (cataclasis) (Spray, 1995). Hence, the small rounded quartz grains in the flinty crush-rock at Glen Coe are not proof of attrition in a particulate dispersion. Estimated rates of displacement on caldera-related (volcanotectonic) faults, in the range 0.1 to 10 cm per second, are sufficient to cause frictional melting to form pseudotachylite (Spray, 1995, 1997), and, consequently, it would be surprising if there was no pseudotachylite along such a well-exposed caldera-fault system. However, it would also be surprising if there were no intrusive (densely welded or coalesced) tuffs containing particles of cataclasite there too. Any melt that contains dissolved volatiles and ascends into an environment of relatively low pressure, such as into a rapidly dilating fracture, will transform into a foam or spray by explosive volatile exsolution. The resultant disrupted melt is likely to be entrained and swept by expanding gas into any opening spaces where, at high temperatures, it is likely to coalesce to a continuous fluid again, as the gas escapes by continued ascent or by diffusion (see Wolff, 1986). Glassy or cryptocrystalline material at the margins of the fault intrusions would represent the first veining by advancing melt, whether of friction-melting or magmatic origin.

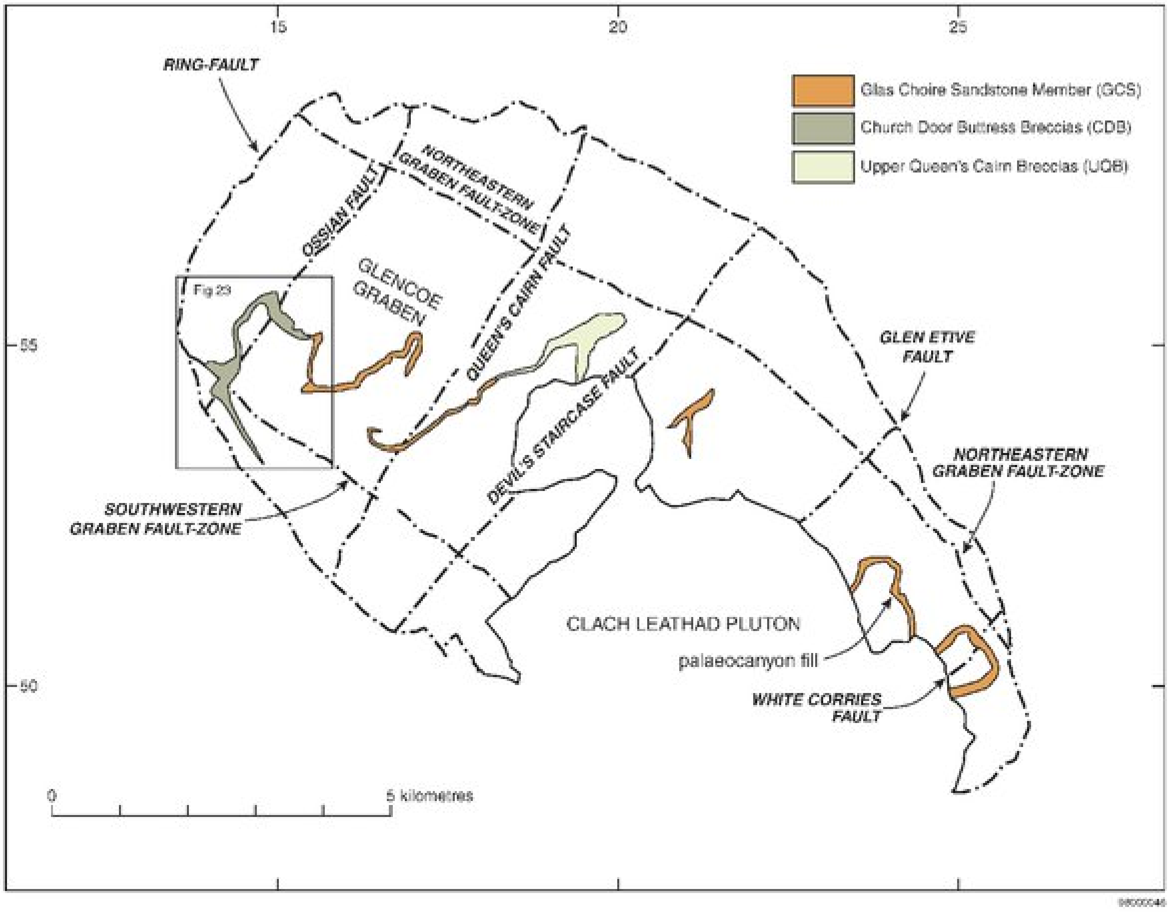
The model proposed here is that the flinty crush-rock (pure end-member) did originate by frictional melting, early during fault movement, and that both it and the rhyolite (‘red felsite’) were emplaced largely as fragmented fluids, like a spray, during dilatation of the fault and consequent catastrophic depressurisation of the accessible melts (see (Figure 26)c. That the flinty crush-rock represents an original melt with rheological properties like the magmatic rhyolite is indicated by the ubiquitously similar patterns of intimate mingling of the two components; they show virtually identical millimetre- and submillimetre-scale fine streaks, swirls and lobate interpenetrations, rather like two paints stirred together (Plate 26a), (Plate 26b). Furthermore an origin by frictional melting can readily explain the characteristic rounding of contained small quartz grains (see above), whereas rounding of small grains by gas streaming (as suggested by Roberts, 1966b) while larger grains remain angular seems unlikely. It is inferred that the rhyolite represents intrusive tuff that invaded the fault planes immediately after the first friction-melt was emplaced and shortly before emplacement of the main body of magma into the site to form the fault-intrusion. Such processes would account for the evident considerable mobility of the material that formed the crush-rock and rhyolite, and the sequence of events would readily produce the characteristic spatial succession of lithological units recognised at the type locality (Plate 25). The thorough cross-mixing of the solid constituents of the crush-rock and rhyolite (Plate 26a), (Plate 26b) is readily explained by the mixing of coexisting fragmented melts, while the considerable breakage of the feldspar phenocrysts is like that widely known to be a consequence of explosive magma fragmentation and particulate transport (e.g. Best and Christiansen, 1997; compare Allen and McPhie, 2003).

There is little doubt that the Main Fault at Stob Mhic Mhartuin cuts the Rannoch Moor Pluton at depth, since the Main Fault-intrusion encloses xenoliths, up to 8 m in diameter, of its (outer) distinctively foliated, quartz-rich biotite-granite facies. Without invoking some unlikely intrusive form for the pluton, the estimated minimum depth to the granite beneath Stob Mhic Mhartuin is some 300 to 400 m. It is most probable that the fragments of graphic quartz-feldspar intergrowths in the rhyolite at Stob Mhic Mhartuin were, like the xenoliths, also derived from the Rannoch Moor Pluton. This indicates a considerable mobility of the decompressed magma, which may have been blasted up the fault for several hundreds of metres, following and partly mixing with fragmental friction melt. Thus the mobility of friction melts formed by faulting may be far greater than ever previously conceived. However, cases of friction melt migration involving its fragmentation and transport for distances of tens to hundreds of metres may occur only in volcanotectonic settings.

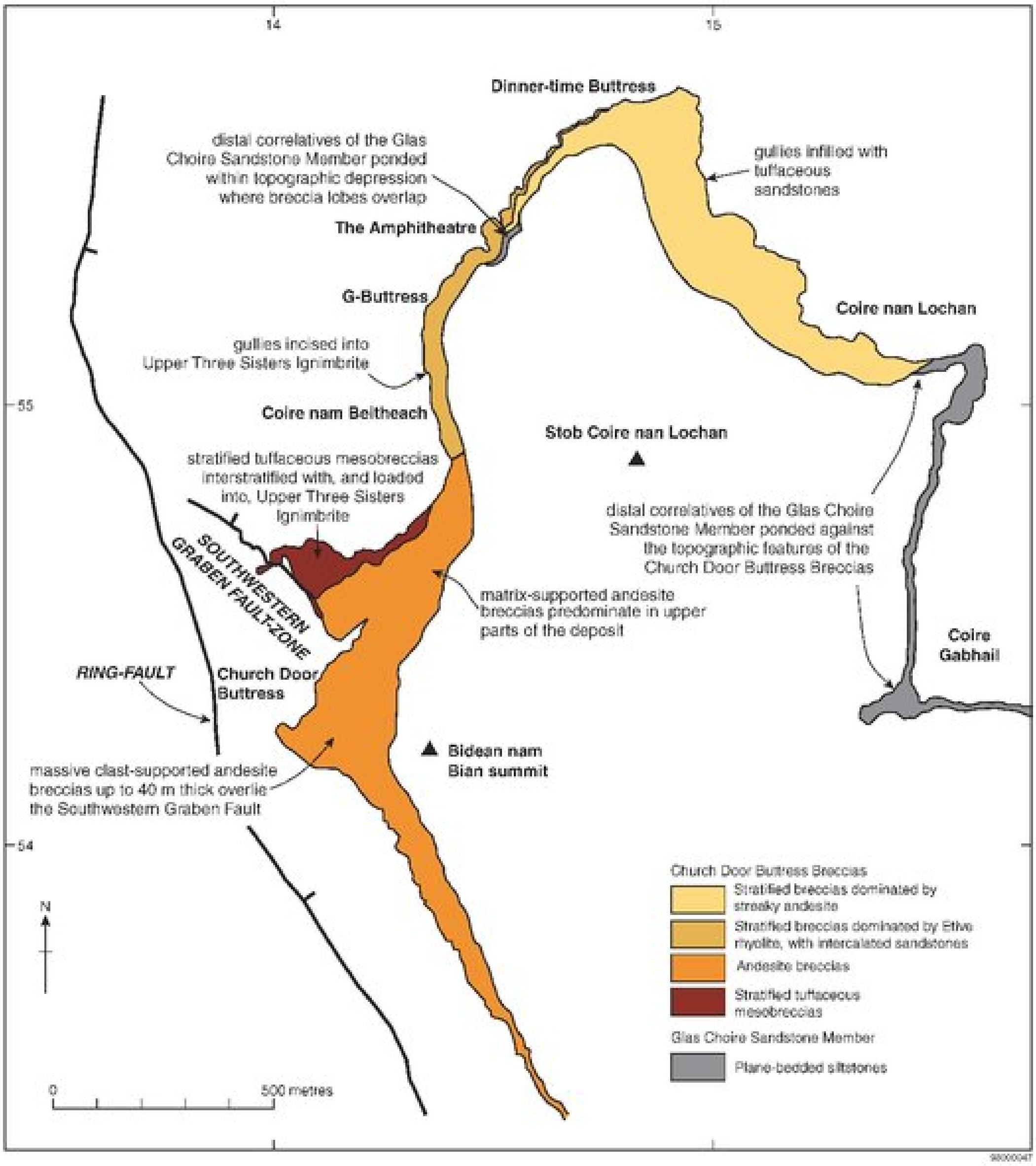
References



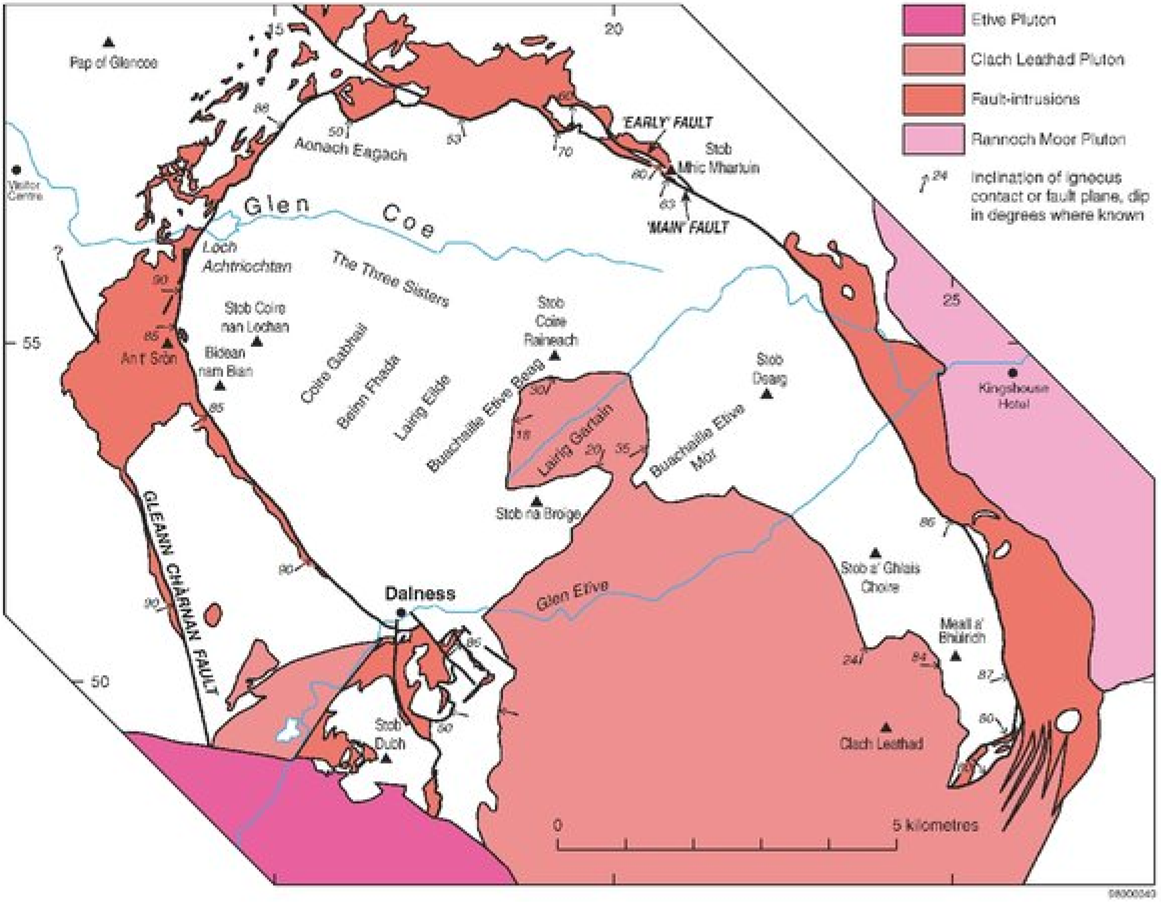
(Figure 5) Models of cauldron subsidence. a. The original models of cauldron subsidence derived from studies at Glen Coe (modified after Clough et al., 1909). b. Model of asymmetrical subsidence of a coherent caldera-floor block (after Roberts, 1974). Note the depiction of pronounced inward dip (downward convergence) of the bounding faults. This geometry is implausible for straightforward central-block subsidence and does not occur in reality.



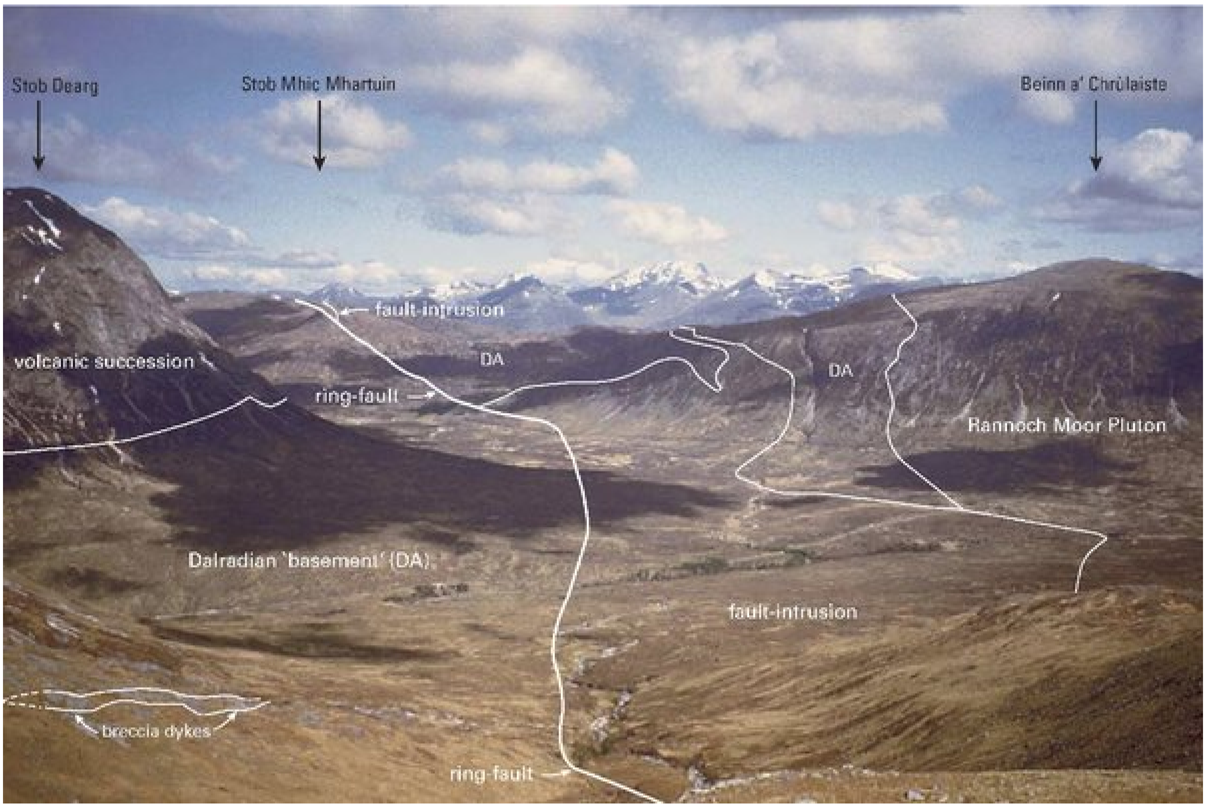
(Figure 22) Locations of outcrops of the Upper Queen's Cairn Breccias (UQB), the Church Door Buttress Breccias (CDB), and the diverse sedimentary rocks that infill the Glas Choire palaeocanyon and overlie a fluvially eroded surface to the north-west (Glas Choire Sandstone Member; GCS). The inset box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



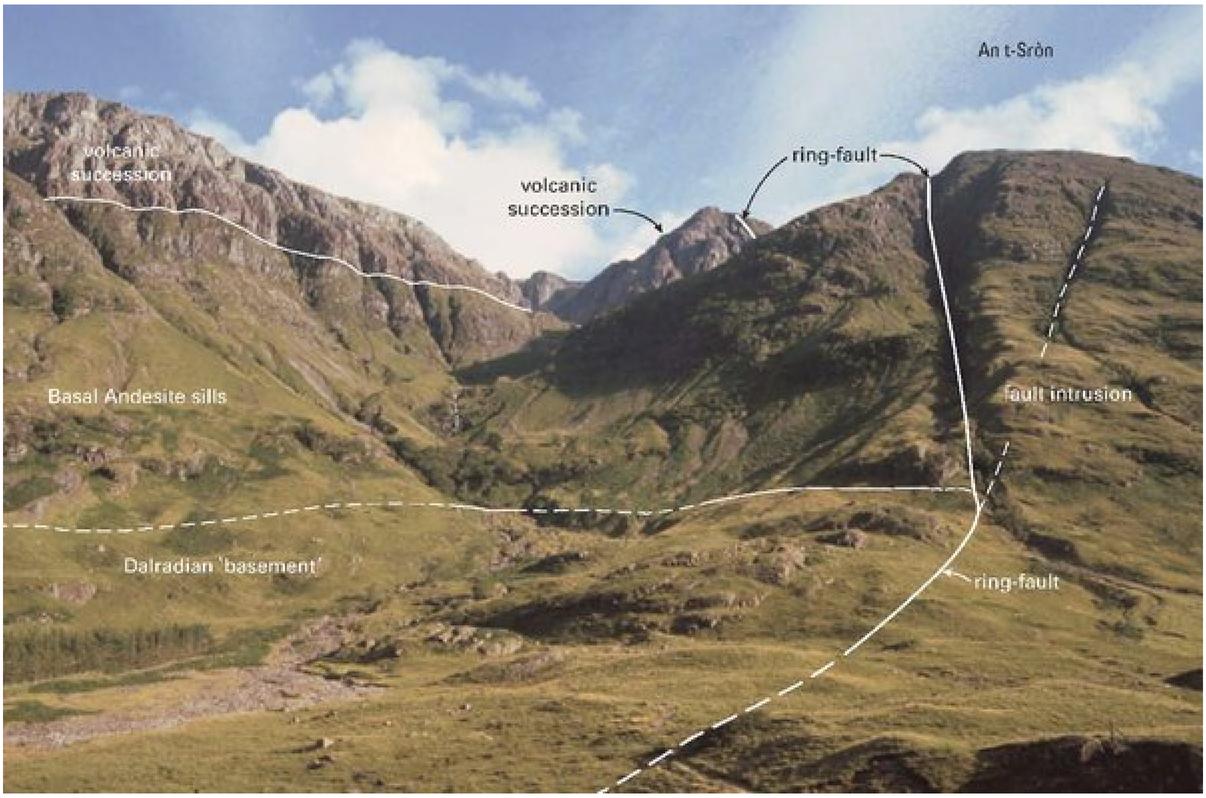
(Figure 23) Locations and key features of individual elements of the Church Door Buttress Breccias and of the distal Glas Choire alluvial deposits, in the north-west of the caldera-volcano complex see (Figure 14) and (Figure 22).



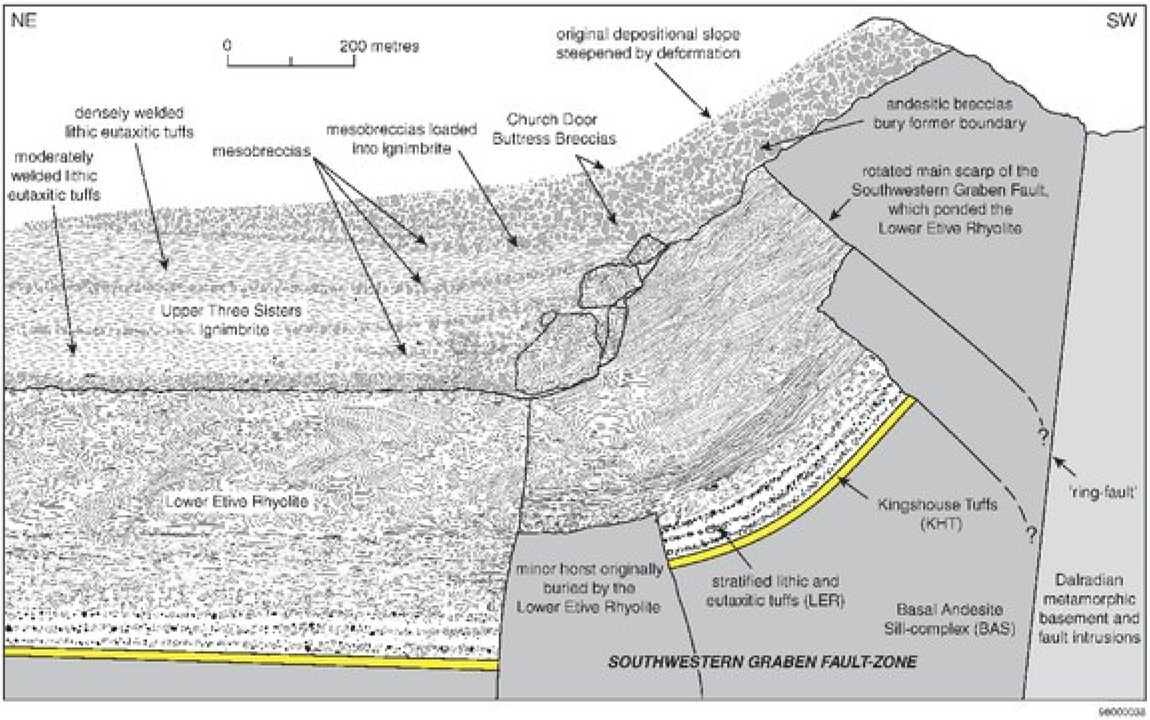
(Figure 25) Ring-fault system, associated fault-intrusions and the passively emplaced Clach Leathad Pluton.



(Plate 23) View (towards the north-west) illustrating the trace of the ring-fault and fault-intrusions between Cam Ghleann (foreground) and Stob Mhic Mhartuin. The western outcrop of the Rannoch Moor Pluton is also seen, and part of the Northeastern Graben Fault-zone is represented by the breccia dykes that cut the Dalradian metamorphic basement. Pleistocene till with patches of peat and alluvium cover much of the lower ground, which lies about 250 m above sea level (P611802).

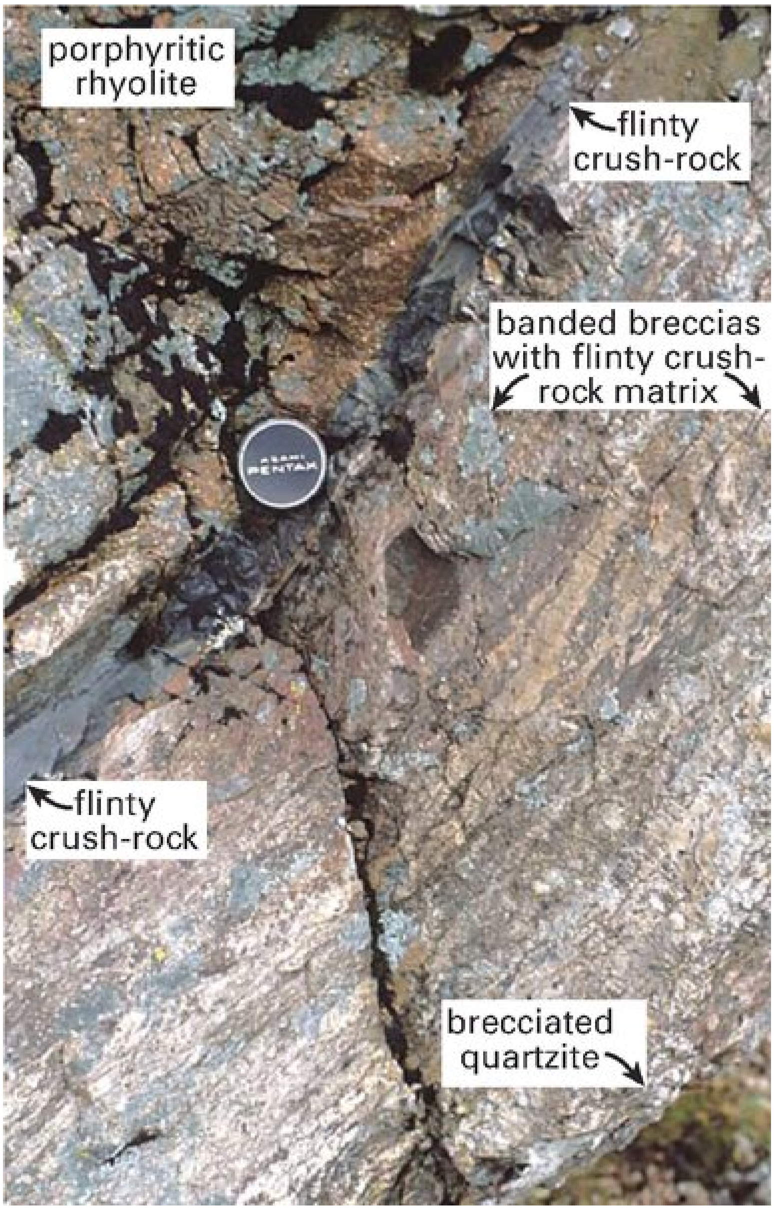


(Plate 24) The ring-fault at An t-Sròn and on Stob Coire nam Beith (background) (viewed towards the south) is traceable in 1 km of vertical relief and shows at least 500 m of vertical displacement of the volcanic succession and Basal Andesite Sill-complex. The deep gully formed along the fault is known as The Chasm of An t-Sròn; the other prominent gully to the right marks a related fracture that lies along a planar projection (dotted line) of the ring-fault plane that traces through the lower ground. (A complementary fracture that is a planar northwards continuation of ring-fault plane in An t-Sròn occurs on the valley side behind and to the right of the viewer) (P611803).

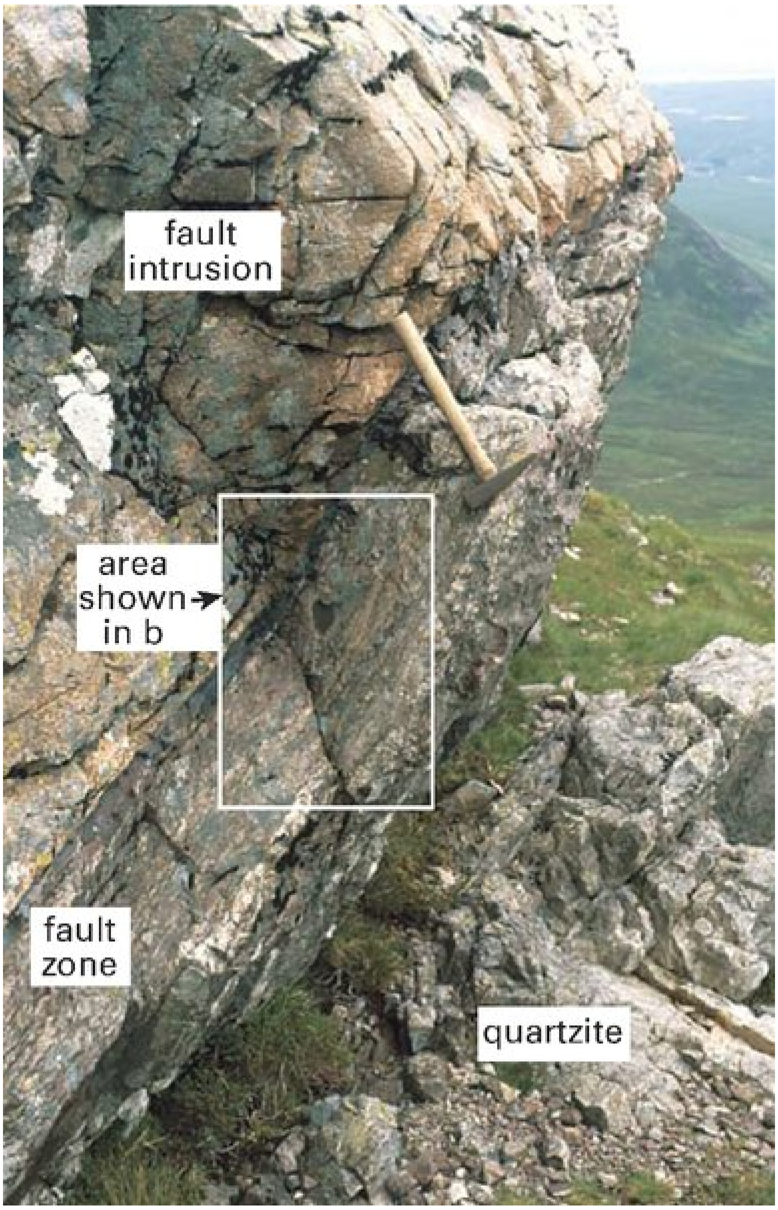


(Figure 14) Schematic cross-section illustrating ignimbrites and breccias restricted at and near the Southwestern Graben Fault (zone) in Coire nam Beitheach [NN 139 547], north-west of the Queen's Cairn Fault. Original near-vertical fault scarps that ponded the Lower Etive Rhyolite (LER) have been rotated by downsag towards the Glencoe Graben. Blocks and megablocks of Lower Etive Rhyolite have been incorporated at several horizons within the ponded Upper Three Sisters Ignimbrite. Overlying Church Door Buttress Breccias include mesobreccias that were shed from the Southwestern

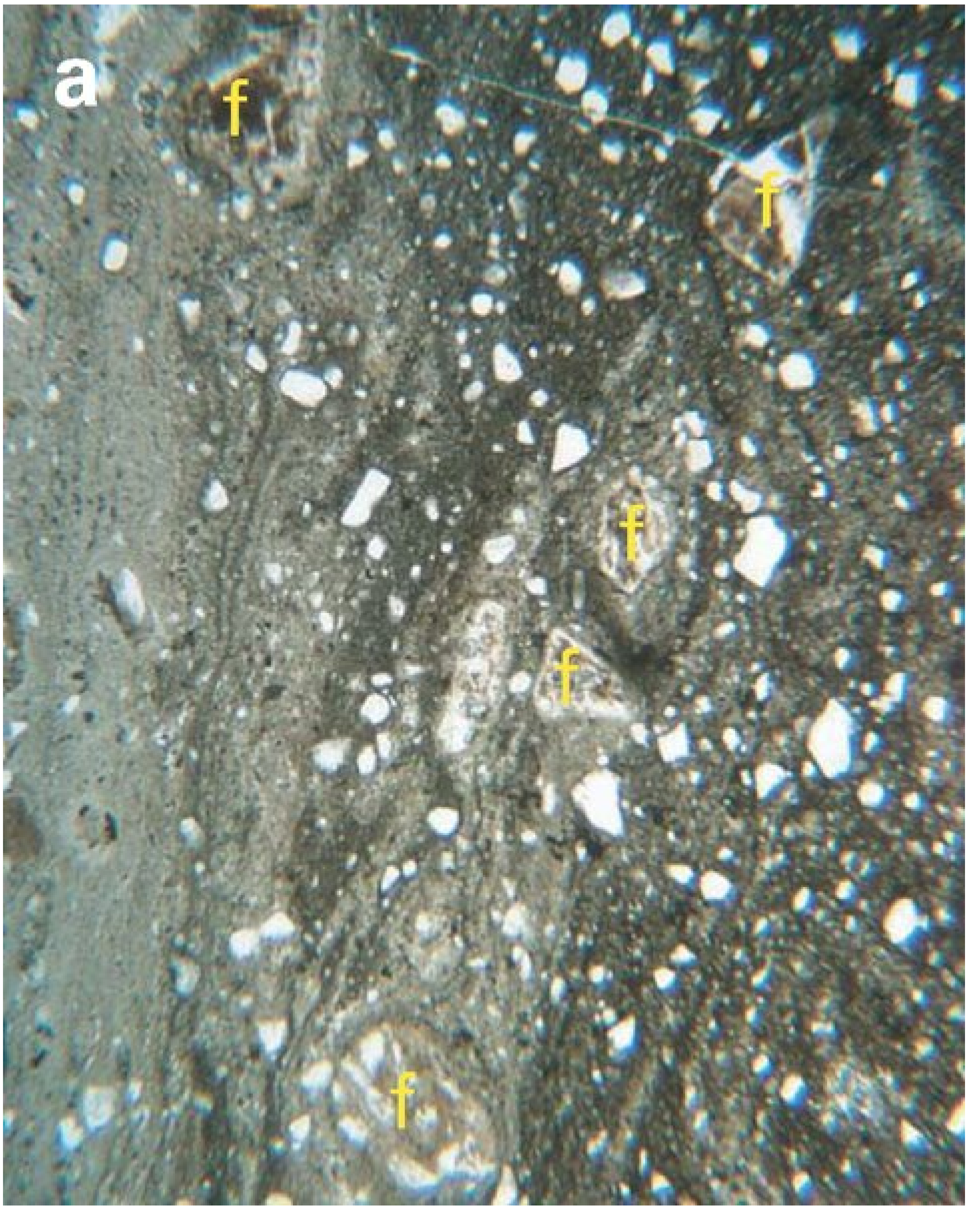
Graben Fault and show evidence of loading into hot ignimbrite; andesite-dominated breccias higher in the section were shed from scarps cutting the Basal Andesite Sill-complex farther to the south-west.



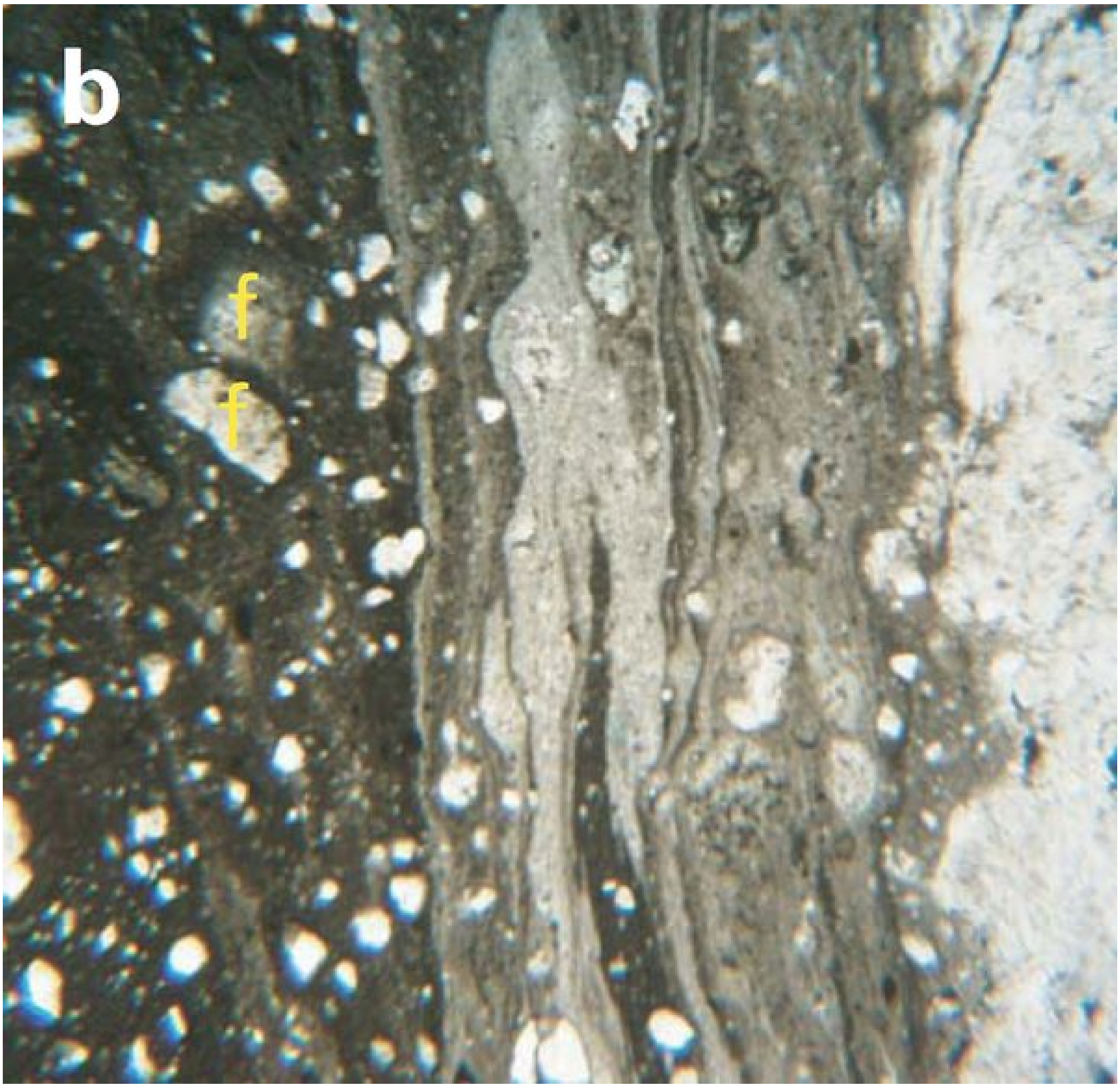
(Plate 25a) Main Fault at Stob Mhic Mhartuin [NN 2082 5742]. a The fault-plane exposed here dips outwards (away from the volcano complex) at about 63Â°; view is towards the south-east (P611804).



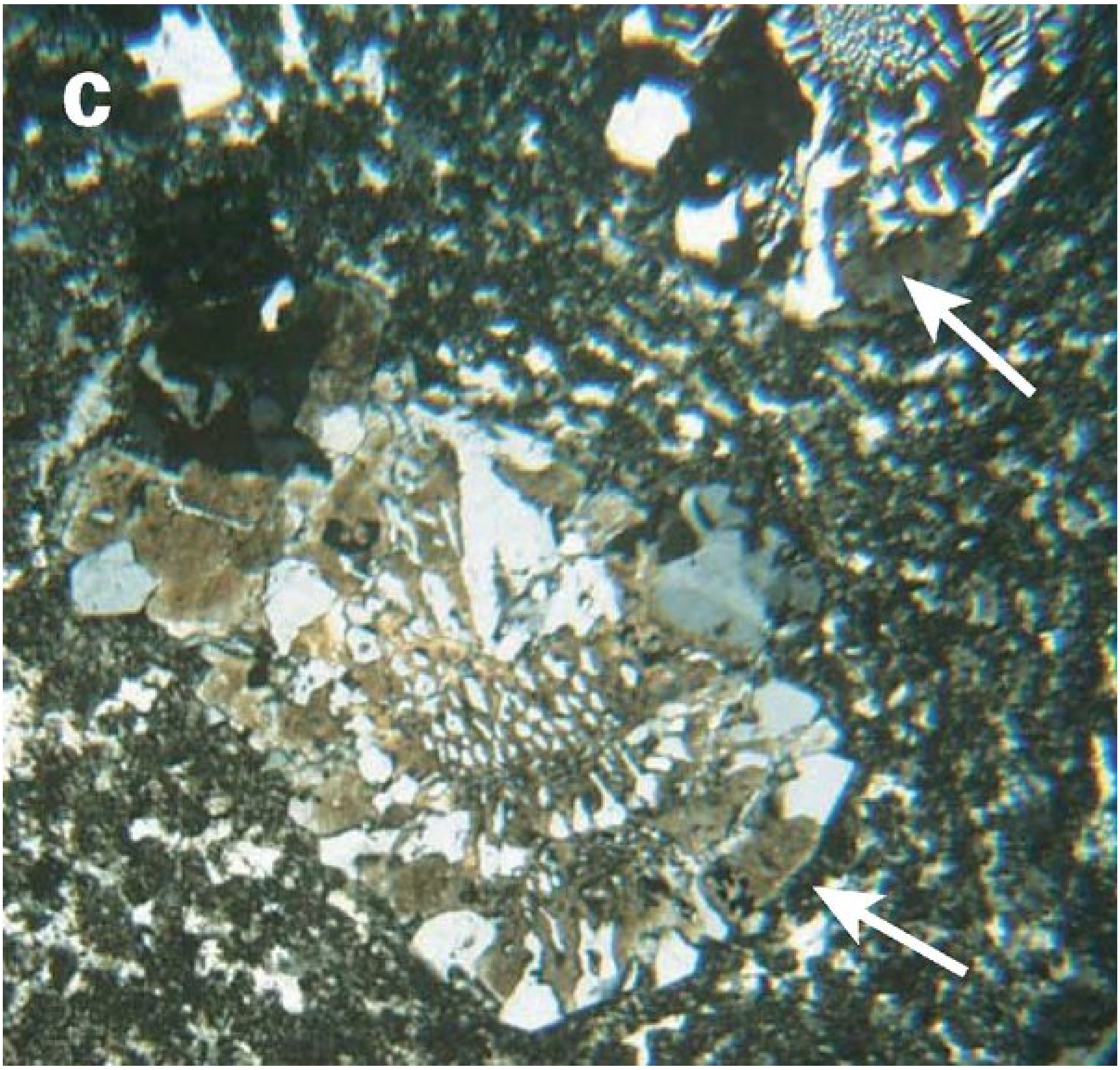
(Plate 25b) Main Fault at Stob Mhic Mhartuin [NN 2082 5742]. b Detail of the Main Fault zone (see a). The banded breccias are some 25 cm thick and show a general increase in microbrecciation and streaking with flinty crush-rock towards the main band of crush-rock and the porphyritic rhyolite. Despite the seemingly straightforward succession of zones, detailed study shows that there has been substantial mixing of components (P611805).



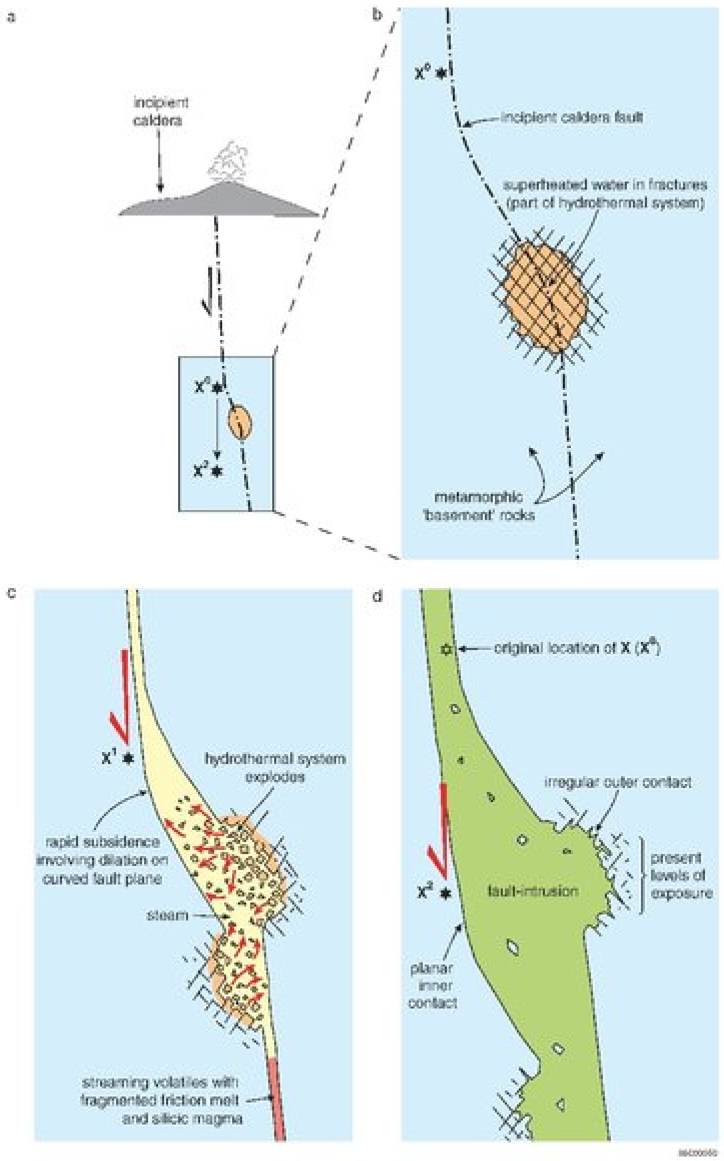
(Plate 26a) Photomicrographs of polished thin sections of flinty crush-rock and porphyritic rhyolite in the ring-fault zone at Stob Mhic Mhartuin [NN 2082 5742]. Fragments of quartz appear white and feldspar phenocrysts (f) are indicated. a. Textures recording intimate fluid-state interlamination and cross-mixing of solids between melts that formed flinty crush-rock (dark and prevalent on right-hand side) and porphyritic rhyolite (pale and prevalent on left-hand side). Fragments of quartz, appearing white and with smaller grains showing rounding, occur mainly in the crush-rock component but are also embedded in the rhyolite (far left). Feldspar phenocrysts of the rhyolite are heavily altered and broken; an original cluster appears to have been attenuated into the flinty crush-rock by laminar flow (middle). Field of view is 3 mm wide: plane-polarised light (P612385).



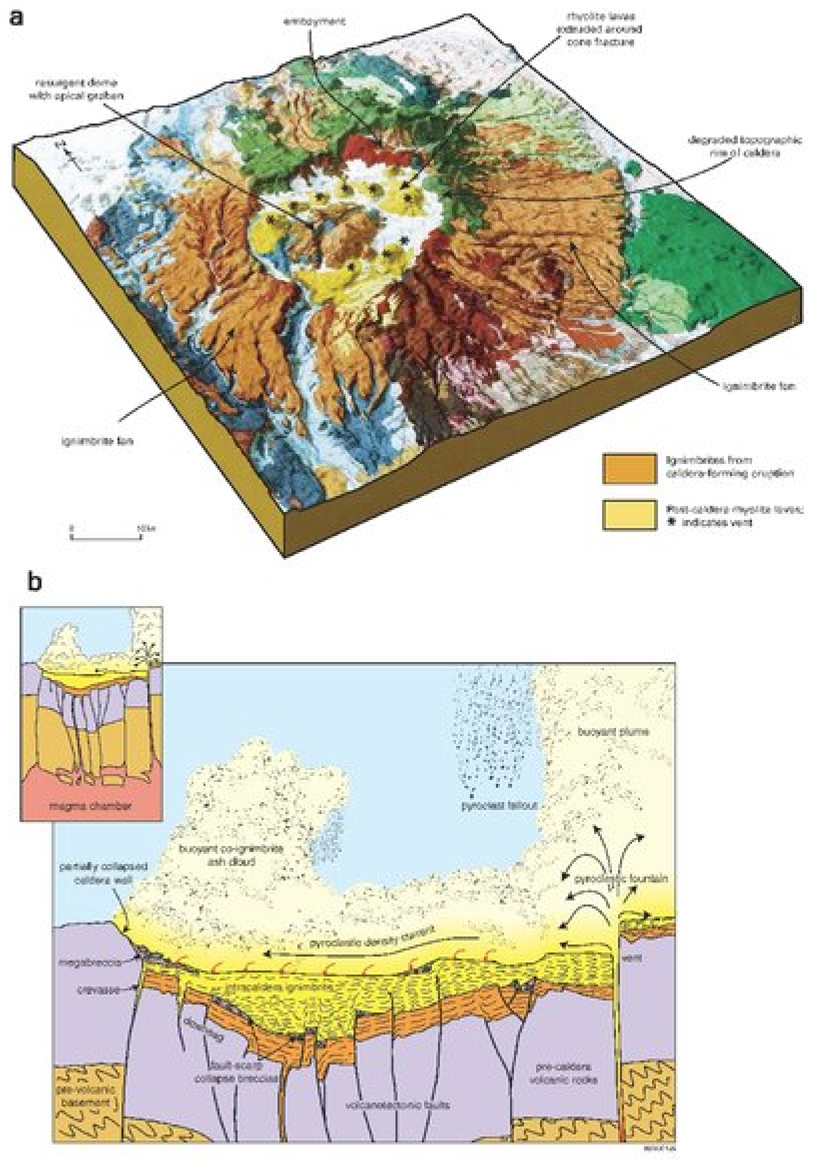
(Plate 26b) Photomicrographs of polished thin sections of flinty crush-rock and porphyritic rhyolite in the ring-fault zone at Stob Mhic Mhartuin [NN 2082 5742]. Fragments of quartz appear white and feldspar phenocrysts (f) are indicated. b. Textures recording various degrees of mingling of original melts. The flinty crush-rock component predominates on the left-hand side (dark with numerous quartz fragments appearing white) and contains isolated feldspar crystals of uncertain origin. Rhyolite forms the pale streak in the middle, which is flanked by intimately mingled (finely interlaminated) rhyolite and crush-rock. Fragmented quartzite forms the bright band on the right-hand side. Field of view is 3 mm wide: plane-polarised light (P612386).



(Plate 26c) Photomicrographs of polished thin sections of flinty crush-rock and porphyritic rhyolite in the ring-fault zone at Stob Mhic Mhartuin [NN 2082 5742]. Fragments of quartz appear white and feldspar phenocrysts (f) are indicated. c Two lithic fragments (arrowed) of granophyric quartzâ€"K-feldspar intergrowths contained in groundmass of (porphyritic) rhyolite; closely similar granophyric textures occur in a nearby xenolith of granite enclosed in the fault-intrusion. Field of view is 3 mm wide: cross-polarised light (P612387).



(Figure 26) Simplified conceptual model proposed to explain occurrences at Glen Coe of fault-intrusions with planar inner (caldera-side) contacts and extremely irregular outer contacts (see text). a. This shows the setting of a hypothetical hydrothermal system at considerable depths (at least several hundreds of metres) where it will be intersected by a dilating caldera-fault plane. The figure shows a potential releasing bend in the incipient fault plane, although in reality dilatation may be more general where the fault dips outwards or where it is more irregularly curved and juxtaposes parts with different curvatures. The depicted isolation of the hydrothermal system is a diagrammatic simplification. b. The hydrothermal system is shown here as a localised network of fractures containing superheated water under high confining pressure. In reality such a hydrothermal reservoir would probably have greater vertical extent and be connected to both meteoric and magmatic water sources at depth, and to fumaroles at the surface. X0 is an arbitrary reference point in the block that subsides. c. The proposed immediate effect of rapid subsidence on the caldera fault (X0 to X1): rapid dilatation causes the hydrothermal system to explode, via transformation of superheated liquid water to vapour and vigorous expansion of vapour. Such processes would most probably be followed rapidly by ascent of fragmented melts from depth, these too having been disrupted by volatile exsolution and expansion due to pressure relief. d. The final form of the opposed contacts of the fault-intrusion, as seen at outcrop at Glen Coe: the overall shape and relative dimensions of the intrusion are hypothetical. The vertical distance moved by the reference point (X0 to X2) would be of the order of several hundreds of metres and the duration of that subsidence a matter of only hours or a few days.



(Figure 4) (right) Main features of calderas, caldera-forming eruptions and the associated phenomena. a. Valles caldera, Jemez Mountains, New Mexico, USA (image generated by H P Foote; geology from USGS map I-571, 1970). The main topographical depression in the summit of the volcano is the caldera. This formed via two large-scale explosive eruptions between 1 and 1.5 million years ago. The entire volcano records some 13 million years of activity. The caldera wall shows degradation by collapse, with a typically scalloped form and with wedges of collapse breccia forming part of the caldera fill. Ignimbrites emplaced during the caldera-forming eruptions form fans on the outer flanks of the volcano and a large part of the fill in the caldera. Post-caldera resurgence of magma into the volcano has caused the intracaldera ignimbrites to be forced upwards, forming a central resurgent dome, with an extensional graben across its apex, and a discontinuous ring of vents with lava flows. b. Sketch illustrating eruption within a multi-subsidence, piecemeal caldera. Hypothetical volcano illustrating a large-scale eruption with associated progressive deposition of ignimbrite from the base of the pyroclastic current and collapse of developing volcanotectonic fault scarps. Downsag with related extensional opening of crevasses is depicted for the ongoing eruption. The diagram illustrates how the complexity of an early stage of caldera collapse, represented by the lower of the two intracaldera ignimbrites, can by obscured by burial. The Glencoe Caldera-volcano Complex records seven caldera-forming eruptions with deposition of intracaldera ignimbrites; most involved both downsag and piecemeal volcanotectonic faulting.