# The Glencoe Volcano — An introduction to the GCR sites

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## Introduction

Glen Coe is famous worldwide as a classic example of cauldron subsidence — where a roughly cylindrical block of volcanic and basement rocks subsided into an underlying magma body. As this down-faulted inner block subsided, magma rose up around the margins and intruded the rocks outside in the form of a ring intrusion. A full wine bottle is a useful analogy: push down the cork (the down-faulted inner block) into the wine (underlying magma body), and as the cork is pushed in, wine will rise up (the ring intrusion) around the edges of the cork. One fortuitous outcome of cauldron subsidence is that the down-faulted rocks are preserved long after the surrounding volcanic products and features have been eroded away. In this part of Scotland, two spectacular and important examples of cauldron subsidence exist, at Glen Coe (five GCR sites) and Ben Nevis (one GCR site). Of these, Glen Coe contains the greater diversity of rock types and the greater structural complexity; spectacular erosion has revealed the original land surface of Dalradian metasedimentary rocks upon which the volcanic rocks were deposited, plus the three-dimensional shapes of many volcanic and intrusive units. These attributes have challenged geologists for over a century, and will continue to challenge the geologists of the future.

Cauldron subsidences are the subvolcanic expressions of volcanic calderas, where deeper erosion has revealed the rock types and structural features that accompanied surface caldera collapse and volcanism. The Glencoe volcanic rocks currently occupy an elliptical area approximately 16 x 8 km, with the long axis orientated WNW–ESE (Figure 9.8). This is certainly not the original shape of the volcano; the injection of innumerable NE–SW dykes from the Etive Dyke-Swarm, well after cauldron subsidence, resulted in major dilation along the WNW–ESE axis. However, even with a generous allowance for this dilation, the original shape of the volcano was probably slightly elliptical.

The first major investigations at Glen Coe were undertaken by C. T. Clough and his coworkers when they mapped the area for the Geological Survey. Many subsequent investigators have commented on both the detail and the accuracy of their mapping, and on their perceptive and precise observations. The paper summarizing this work (Clough *et al.,* 1909) and the minor modifications in later summaries (Bailey and Maufe, 1916; Bailey, 1960) are revered as classics. Here is a brief summary of their main findings.

1. All the volcanic and related rocks are contained within a ring fracture.
2. Marginal steepening of rocks within the inner block at the ring fracture.
3. Metasedimentary rocks within the ring fracture are of a lower grade than those outside.
4. Large-scale subsidence of a down-faulted inner block (cauldron subsidence).
5. Subdivision of volcanic (and related) rocks into seven groups.
6. General (regional) dip of rock units in a southerly direction (approximately 10–20°).
7. Well-preserved uneven palaeosurface of Dalradian metasedimentary rocks.
8. Early volcanic rocks are basalts to andesites; later rocks are rhyolites and andesites.
9. Lateral impersistence of all volcanic units.
10. Numerous sedimentary beds intercalated between volcanic units.
11. Presence of a ring intrusion outside the ring fracture.
12. Two generations of ring fractures and ring intrusions.
13. Presence of 'flinty-crush-rock' at contact of ring intrusion and ring fracture.
14. Igneous rocks show a calc-alkaline geochem-ical trend.
15. Recognition that the volcano had developed during the Early Devonian (fossil plant evidence — *Psilophyton* and *Pachytheca*).
16. Elliptical shape of volcano due largely to later dyke injection from adjacent igneous centre (Etive).

17. Later intrusion of Cruachan Granite into SE part of the volcano (after the cauldron subsidence).

Subsequently, various geologists looked at specific features of the volcano. The most pertinent publications are:

- Reynolds (1956): examined features of the ring fractures.
- Hardie (1963, 1968): investigated various breccia units.
- Roberts (1963, 1966a, 1966b, 1974): examined ring fracture and ring intrusion; recognized the presence of ignimbrites; recognized sub-groups within the major groups of Clough *et al.* (1909); developed a unifying model for the evolution of the volcano.
- Ferguson (1966): examined rhyolite flow structures.
- Taubeneck (1967): demonstrated overall inward-dip of ring fracture; recognized a major palaeoslope down to the west; and that abundant sedimentary rocks testified to incremental caldera collapse.
- Thirlwall (1979): analysed some Glen. Coe volcanic rocks as part of a regional geochemical survey.
- Garnham (1988): research on ring fractures and associated intrusions.
- Moore (1995), Moore and Kokelaar (1997, 1998): re-mapping of the volcano; detailed investigation of early volcanism; developed radical new model for the early evolution of the volcano.

The two most comprehensive studies after Clough *et al.,* (1909) were by Roberts (1966a, 1966b, 1974) and Moore (1995). Roberts (1974) presented a unifying model for the evolution of the volcano, with two episodes of subsidence of a down-faulted inner block along inward-dipping ring fractures generating ignimbrite eruptions at the ring fractures (see also Reynolds, 1956). The non-erupted magma became the ring intrusion. While this unifying model was a useful attempt at placing Glen Coe into a worldwide framework of caldera formation accompanied by ring-fracture ignimbrite eruptions (established by Smith and Bailey, 1968), the model lacked geochemical confirmation and was based on the assumption that the ignimbrites of the caldera fill were genetically related to the ring intrusions. Moore (1995) has demonstrated that this model is incorrect.

Thirlwall (1979) classified the volcanic rocks of the SW Highlands (including Glen Coe rocks) as high-K calc-alkaline, and noted their geochemical similarity to Andean-type volcanic arc rocks. He concluded that geochemical parameters (variations in large ion lithophile (LIL) and high field strength (HFS) elements, and concentrations of Ni, Sr, and Cr) do not support fractional crystallization as a key process linking together the different magma types. Instead, production of magmas in the mantle (via partial melting, mixing, and contamination) was considered more likely. While Thirlwall's study enabled some generalizations to be made about magmatism in the SW Highlands and provided some analyses of Glen Coe volcanic rocks, the likelihood of magma mixing in many Glen Coe eruptions (discussed later) requires caution in interpreting the geochemical data. Analyses of a comprehensive and well-characterized suite of samples are not available at present, and consequently any comments on magma sources and evolution at Glen Coe would be highly speculative at best.

The recent work of Moore (1995) has brought a modern volcanological perspective to Glen Coe. This work focused on the early evolution of the volcano (groups 1 to 3 of Clough *et al.,* 1909). He further subdivided these three groups, and convincingly demonstrated that the early volcanic and structural evolution of the volcano was controlled by a rectilinear fault system; a series of major graben faults/hinges (WNW–ESE) and cross-graben faults/hinges (NNE–SSW). Moore's work has shown that the unifying model of Roberts (1974) is incorrect. Piecemeal subsidence along a rectilinear graben/cross-graben fault system accommodated all of the early caldera subsidence, without the involvement of the ring fracture (Moore and Kokelaar, 1997, 1998). The probable role of the encircling ring fracture and ring intrusion is discussed later.

## Description

Clough *et al.* (1909) established seven volcano-stratigraphical units in the Glencoe volcano (groups 1 to 7). (Table 9.3) provides a comparison of the stratigraphy of Clough *et al.* (1909) and recent work by Moore (1995), plus approximate thicknesses.

## The original land surface

The basement is composed of Dalradian metasedimentary rocks, generally phyllites in the west (Leven Schist Formation) and quartzites and semipelites in the east. The land surface developed on these rocks was heavily eroded and uneven. Clough *et al.* (1909) recorded lenticular masses of conglomerates that they considered to be deposits from flash floods, and also noted that the terrain in the east of the volcano was much steeper than that in the west. Taubeneck (1967) recorded an input of elastic sediment from the east, and noted a 'marked downward slope to the west' which he considered to be 'as much as 2000 feet'. Moore (1995) developed these findings further and described canyons and other fluvial channels etched into the basement.

## Group 1: Basal Sill Complex

The lowest 'volcanic rocks' consist of approximately 17 separate sheets with an aggregate thickness of 450 m (Clough *et* al., 1909; Bailey, 1960). Although Clough *et al.* (1909) described extensive brecciation of the sheet margins and the presence of red sandstones and shales in the matrix, it is only recently that these features have been recognized as peperites, which formed when magmas intruded wet sediments (Moore, 1995). Analyses in Bailey (1960) show that these sheets are basalts, basaltic andesites, and andesites. The rocks are black to dark-grey when fresh, with small black phenocrysts of augite and pseudomorphs after olivine (Bailey, 1960). Moore (1995) noted that the sill complex is deeply incised and eroded (with an unknown thickness of material removed), and that extensive alluvial deposits overly this angular unconformity.

## Group 2: rhyolites

Clough *et al.* (1909) noted at least three separate rhyolite units in this group, and commented on their lack of lateral continuity; they also noted the presence of andesite sheets. After recognizing the presence of ignimbrites, Roberts (1966a, 1974) subdivided group 2 into the lower group 2 lavas and the upper group 2 ignimbrites, commenting on the striking variations in thickness of the rhyolite units.

Detailed mapping by Moore (1995) has enabled 11 sub-units to be identified (Table 9.3). These fall into two main units — the Etive Rhyolites and the Glencoe Ignimbrites — each of which represents a major eruptive cycle intimately related to graben-controlled caldera formation.

The first major eruptive cycle involved the eruption of three rhyolite lavas (producing the Lower, Middle, and Upper Etive rhyolites). Each began with a phreatomagmatic phase, which was followed by a flow-laminated rhyolite. A period of quiescence was marked by fluvial incision and sedimentation, and this sequence was repeated two further times. Each eruption was accompanied by subsidence (caldera collapse) of sufficient magnitude to enable fluvial systems to become re-established. Towards the end of this major eruptive cycle, andesite sheets (sills and possibly some lavas) were emplaced, which appear to be mixed magmas (with andesite dominant over rhyolite). Fluvial incision and sedimentation record further subsidence after andesite emplacement.

The second major eruptive cycle produced three ignimbrites (the Lower, Middle, and Upper Glencoe ignimbrites). Of these, the middle ignimbrite is the smallest and has a very limited outcrop, whereas the other two are larger in volume and are, more widespread. The first two eruptions were accompanied by irregular caldera collapse. More substantial caldera collapse accompanied the eruption of the third ignimbrite, and two syncaldera breccia deposits were produced — the Lower Queen's Cairn Breccias and Upper Queen's Cairn Breccias. After this second major eruptive cycle a further series of andesite sheets was emplaced.

**(Table 9.3) Stratigraphy of the volcanic and associated sedimentary rocks preserved in the Glencoe cauldron subsidence.**

| | **Group names of Clough *et al.* (1909)** | **Group names used in this account** | **Main units of Moore (1995)** | **Sub-units of Moore (1995)** |
|---|---|---|---|---|
| **Group** 7 c.100 m thick | Andesites and rhyolites | Andesites and rhyolites | — | — |

| | | | | |
|---|---|---|---|---|
| **Group 6** c.20 m thick | Shales and sandstones | Shales and sandstones | — | — |
| **Group 5** c.80 m thick | Rhyolites | Rhyolites | — | — |
| **Group** 4 c.280 m thick | Andesites | Andesites | — | — |
| **Group** 3 c.80 m thick | Agglomerates | Collapse breccias and alluvium | Collapse breccias and alluvial deposits | Glas Coire Alluvium |
| **Group 2** c.600 m thick | Rhyolites | Rhyolites | Glen Coe Ignimbrites | Church Door Buttress Breccias<br>Upper Queen's Cairn Breccias<br>Upper Glen Coe Ignimbrite<br>Lower Queen's Cairn Breccias<br>Queen's Cairn Fan<br>Middle Glen Coe Ignimbrite<br>Lower Glen Coe Ignimbrite |
| | | | Etive Rhyolites | Upper Etive Rhyolite<br>Crowberry Ridge Tuff<br>Middle Etive Rhyolite<br>Raven's Gully Tuff<br>Lower Etive Rhyolite<br>Kingshouse Tuff |
| **Group 1** c.500 m thick | Augite andesites and basalts | Basal Sill Complex | **Pre-caldera Basal Andesite Sill Complex | |

**Analyses in Bailey (1960) show that some of the sheets are in fact basalts and basaltic andesites.

### Group 3: collapse breccias and alluvium

Clough *et al.* (1909) noted that this group consists of a complex sequence of 'agglomerates', intercalated with various locally developed sedimentary units, all showing considerable thickness variations. They suggested that these 'agglomerates' might be detrital, and this view was shared by Roberts (1966a, 1974) and Taubeneck (1967), who considered them to be collapse breccias, fluvial deposits and lacustrine sediments. Moore (1995) concluded that there was widespread collapse of the caldera floor after eruption of the Upper Glencoe Ignimbrite, and that this subsidence is reflected in two contrasting types of deposit: fault-scarp collapse — the Church Door Buttress Breccias; and re-establishment of a fluvial system through the caldera, depositing alluvial and caldera lake sediments — the Glas Coire Alluvium.

### Group 4: andesites

These are described by Clough *et al.* (1909) and Bailey (1960) as greenish-grey to black andesites typically containing small hornblende and feldspar microphenocrysts set in a flow-banded matrix. A number of sheets are present, attaining an aggregate thickness approaching 300 m; they crop out across much of the volcano. Thin rhyolite units, which may be ignimbrites, and sandstone and shale beds (up to 10 m thick) are intercalated within the andesites (Roberts, 1974).

### Group 5: rhyolites

Clough *et al.* (1909) described this group as a black, vitreous, feldspar-phyric, flow-banded rhyolite up to 80 m thick, containing an abundance of lithic clasts (rhyolite, minor andesite, and infrequent quartzose schist) at its base. Both Roberts (1966a, 1974) and Taubeneck (1967) reinterpreted this sheet as an ignimbrite of rhyodacitic composition, and their descriptions hint at the presence of more than one eruptive unit. This rock may be a product of magma mixing, as

Roberts (1966a) described flattened (i.e. once molten) inclusions (up to 25 cm) of a dark, porphyritic rock within the rhyolite.

### Group 6: shales and sandstones

This group consists of a sequence of well-strati-fled greenish-grey shales and sandstones, of variable thickness up to a maximum of 20 m, which is exposed only around the southern shoulder of Beinn Fhada (Clough *et al.,* 1909). Taubeneck (1967) concluded that marked subsidence must have followed the eruption of the Group 5 ignimbrite(s) and attributed delicate lamination in the sediments to formation in a caldera lake.

### Group 7: andesites and rhyolites

These are the youngest volcanic units preserved within the volcano. They consist of rhyolites and hornblende andesites (and possibly a basaltic andesite) that have accumulated in an irregular fashion, to a maximum thickness of 100 m (Clough *et al.,* 1909). They are exposed only in impersistent outcrops around the southern shoulder of Beinn Fhada. Taubeneck (1967) reported the presence of a thin dacitic to rhyodacitic ignimbrite, containing numerous fragments of volcanic rocks and quartzose basement.

## Interpretation

The evolution of the Glencoe volcano can conveniently be divided into three phases: pre-caldera; graben-controlled caldera; and cauldron subsidence (ring-fracture-controlled caldera). Only the first two are represented in the preserved volcanic stratigraphy (Moore, 1995; Moore and Kokelaar, 1997, 1998).

### Pre-caldera phase

1. Uneven palaeosurface developed on Dalradian metasedimentary rocks, sloping down to the west.

2. Input of fluvial material from the east, with fluvial system traversing the putative Glencoe caldera, exiting to the west.

3. Localized subsidence in the west, leading to development of a small sedimentary basin (containing red sandstones and shales).

4. Group 1. Sills of basalt to andesite composition injected into the wet sediments (the Basal Sill Complex).

5. Major erosion of the Basal Sill Complex, and deposition of alluvial deposits.

### Graben-controlled caldera phase

6. Group 2. First cycle of rhyolitic volcanism (the Etive Rhyolites), with three subcycles of activity: each involving initial phreatomagmatic eruption, then rhyolite eruption, then caldera collapse, then re-established fluvial activity. First cycle culminated in eruption of andesite (mixed magma) sills and lavas.

7. Group 2. Second cycle of rhyolitic volcanism (the Glencoe Ignimbrites), similar in pattern to the first cycle, but explosive eruptions generated ignimbrites instead of lavas, and major collapse accompanied eruption of the last ignimbrite. Second cycle also culminated in eruption of andesite (mixed magma) sills and lavas.

8. Group 3. Major fault-scam collapse generating breccias, alluvial deposits and lake sediments. Re-establishment of the fluvial system.

9. Group 4. Eruption of andesite sheets across the entire caldera. Presence of sedimentary beds and thin rhyolite units suggests periods of quiescence and collapse between eruptions. Thin rhyolite units may be ignimbrites.

10. Group 5. Ignimbrite eruption(s). Original lateral extent unknown. Caldera collapse. Erosion of upper parts of ignimbrite sheet.

11. Group 6. Establishment of caldera lake (and fluvial system?).

12. Group 7. Eruption of rhyolite and andesite, with at least one explosive rhyolite eruption producing an ignimbrite. Later eruptions of unknown volume and composition were subsequently removed by erosion (see 14 below).

### Cauldron subsidence phase (ring-fracture-controlled caldera)

13. Cauldron subsidence (i.e. cataclysmic caldera collapse along ring fractures), probably accompanied by major ignimbrite erup-tion(s). Emplacement of the ring intrusion — which chilled against the ring fractures. Fine-grained facies (flinty crush-rock) found at the margins of the ring intrusion is possibly an intrusive tuff emplaced during surface venting that generated syncaldera ignimbrites.

14. Removal of an unknown thickness of volcanic and sedimentary rocks from above the preserved Group 7 rocks.

This late-stage, large-scale down-faulting of a cauldron block along encircling ring fractures (i.e. major caldera collapse) contrasts strongly with the piecemeal, incremental graben-controlled caldera subsidence described by Moore (1995) during Group 2 to Group 3 time. It follows that a substantial volume of magma was vented some time after Group 7 time, when the major (sub-circular) caldera was formed. The syncaldera volcanic rocks, which would have filled the large (c. 8 km diameter) caldera during this event, have been completely removed by erosion and consequently the volcanic rocks that remain (i.e. groups 1 to 7) represent only the early (non-cataclysmic) magmatic and structural evolution of the Glencoe volcano.

It is instructive to compare the Glencoe and the Ben Nevis igneous centres (see the Ben Nevis and Allt a'Mhuilinn GCR site report), as these are the only two centres in the region where caldera-forming eruptions are known to have taken place and where down-faulted blocks have preserved the products of central volcanoes. The following similarities are apparent.

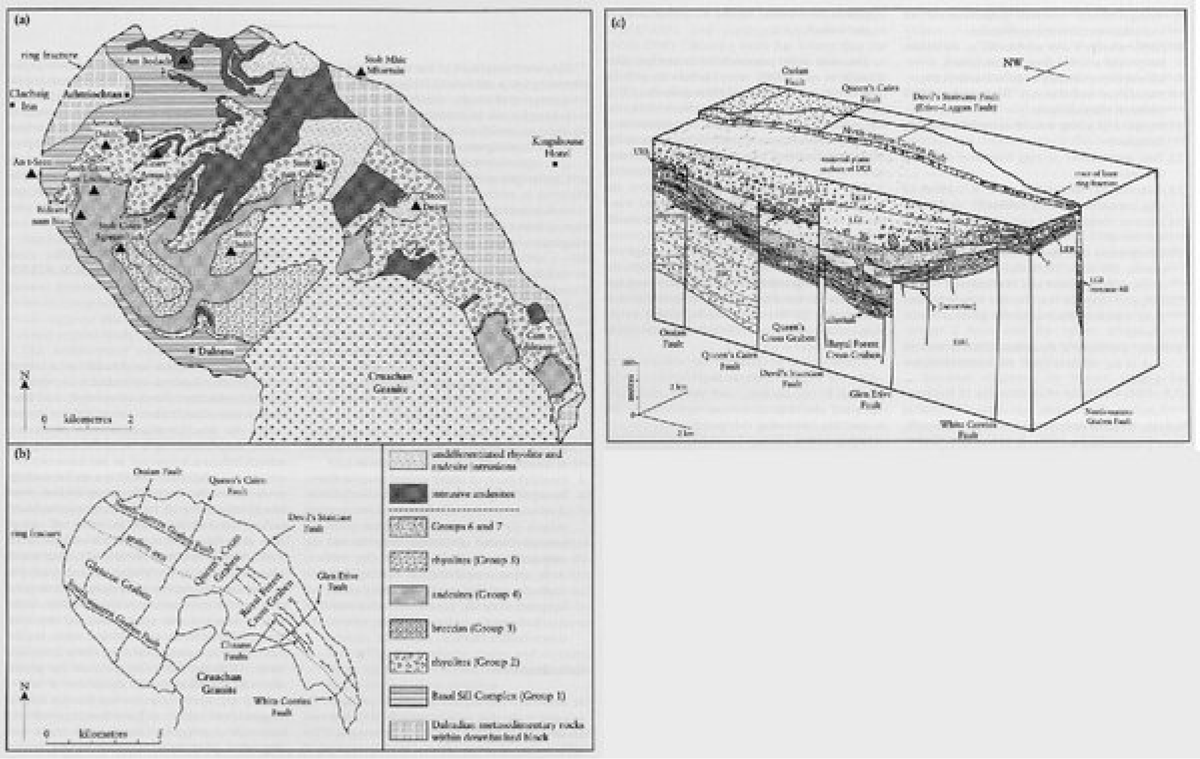
- both volcanic centres developed on Dalradian 'basement',
- early pre-caldera volcanic sequences at both volcanic centres are dominated by basalts and andesites,
- there was substantial subsidence, deposition of fine-grained sediments, and lacustrine conditions at both centres,
- both centres display a sharp contact between the down-faulted blocks and the encircling ring intrusions,
- a fine-grained variant of the ring intrusion (rhyolite plus flinty crush-rock) is found at the contact with both down-faulted blocks,
- late-stage volcanic products (including possible syncaldera ignimbrites) have been removed by erosion.

However, the downfaulted block at Ben Nevis is only *c.* 2.5 km in diameter whereas at Glen Coe it is *c.* 8 km. The sizes of blocks that subside during caldera-forming ignimbrite eruptions are intimately related to magma chamber diameter (Smith and Bailey, 1968; Smith, 1979), and from this it can be concluded that the Glencoe upper crustal magma chamber was probably the larger of the two. There is thus a greater likelihood that larger volumes of more evolved (silicic) magma were produced at Glen Coe than at Ben Nevis. Furthermore, it is apparent that intrusive rocks are dominant at Ben Nevis (*c.* 90% of the complex) whereas at Glen Coe they are subordinate and are concentrated at the discontinuous ring intrusion. It is likely that Glen Coe and Ben Nevis represent different erosion levels of broadly similar igneous centres, with Ben Nevis being more deeply eroded. The presence of major granite intrusions adjacent to Glen Coe (e.g. Starav, Etive, Cruachan, Moor of Rannoch) suggests that the Glencoe ring intrusion may be more extensive at depth, where it may look more like the Ben Nevis Inner Granite.

Two tectonic features may have an intimate association with the magmatism: (1) the major slides (Ballachulish and Sgurr a' Choise) that are cut by the volcanoes; and (2) the proximity of the Great Glen Fault. Jacques and Reavy (1994) commented on the possible influence of the Great Glen Fault on igneous centres that lie within 20 km of the fault. Moore (1995) recognized a system of main graben faults (and orthogonal cross-graben faults) at Glen Coe, with the cross-graben faults aligned parallel to the Great Glen Fault. Strike-slip movements on the Great Glen Fault could have developed localized transtension in the Glen Coe area (main graben faults), especially if a pre-existing crustal weakness or lineament was present. Evolved calc-alkaline magmatism in compressional regimes requires localized extension (see Pitcher, 1993), and localized transtension associated with movements of the Great Glen Fault is one possible mechanism for focusing and stimulating magmatism at Glen Coe.

It is apparent that, despite being a classic area of the geology of Great Britain, there are still numerous gaps in our understanding of the Glen Coe magmatism. At the time of writing no modern study has been made of groups 4 to 7, and it is not known how much material has been removed by erosion from above Group 7. Furthermore, it is possible that neighbouring igneous centres (e.g. Etive, Cruachan) supported flourishing volcanic systems (now removed by erosion), that could have contributed caldera fill material to Glen Coe, and that some of the rocks preserved could be from these sources. Other aspects needing further investigation include: how the volcano evolved geochemically; the role of magma mixing; eruption mechanisms of the rhyolites; why there is such extensive sill emplacement; relationships between local and regional magmatism; relationships between local and regional tectonics (especially the nearby Great Glen Fault system); the precise mechanism of cauldron subsidence; and emplacement of the ring intrusion.

## References



*(Figure 9.8) (a) Map of Glen Coe showing rocks enclosed by the ring fracture (i.e. within the down-faulted block); Dalradian metasedimentary 'basement'; groups 1 to 7 (with groups 6 and 7 shown together); and undifferentiated intrusive rocks (rhyolite and andesite). Group 3 rocks are sandwiched between groups 2 and 4 rocks throughout most of the area, and only substantial group 3 outcrops are shown. The Etive Dyke-Swarm, minor intrusions, and small outcrops are omitted. The ring intrusion is not shown (see the Stob Mhic Mhartuin GCR site report). Note the incursion of the younger Cruachan granite into the cauldron block from the south. Redrawn after Clough et al. (1909), Roberts (1966a), Roberts (1974), and Moore (1995). (b) Map of the Glencoe cross-graben fault system preserved within the ring fracture (after Moore and Kokelaar, 1997). Figure 9.8(c) Block diagram showing the 3D structure of the Glencoe caldera as interpreted by Moore and Kokelaar (1997). The sections have been restored to a horizontal plane surface presumed to have been formed by the eruption of the 'Upper Glencoe Ignimbrite' (top of Group 2). Thin deposits from this eruption extended north of the North-eastern Graben Fault, but are not shown. The long axis of the block diagram lies along the axis of the Glencoe Graben. DAL, Dalradian metasedimentary rocks; BSC, Basal Sill Complex; LER, MER and UER, Lower, Middle and Upper Etive rhyolites (lower Group 2); LGI and UGI, Lower and Upper Glencoe ignimbrites (upper Group 2); p, phreatomagmatic tuff.*

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| | Group names of Clough *et al.* (1909) | Group names used in this account | Main units of Moore (1995) | Sub-units of Moore (1995) |
|---|---|---|---|---|
| **Group 7** *c*.100 m thick | Andesites and rhyolites | Andesites and rhyolites | – | – |
| **Group 6** *c*.20 m thick | Shales and sandstones | Shales and sandstones | – | – |
| **Group 5** *c*.80 m thick | Rhyolites | Rhyolites | – | – |
| **Group 4** *c*.280 m thick | Andesites | Andesites | – | – |
| **Group 3** *c*.80 m thick | Agglomerates | Collapse breccias and alluvium | Collapse breccias and alluvial deposits | Glas Coire Alluvium<br>Church Door Buttress Breccias<br>Upper Queen's Cairn Breccias |
| **Group 2** *c*.600 m thick | Rhyolites | Rhyolites | Glen Coe Ignimbrites | Upper Glen Coe Ignimbrite<br>Lower Queen's Cairn Breccias<br>Queen's Cairn Fan<br>Middle Glen Coe Ignimbrite<br>Lower Glen Coe Ignimbrite |
| | | | Etive Rhyolites | Upper Etive Rhyolite<br>Crowberry Ridge Tuff<br>Middle Etive Rhyolite<br>Raven's Gully Tuff<br>Lower Etive Rhyolite<br>Kingshouse Tuff |
| **Group 1** *c*.500 m thick | Augite andesites and basalts | Basal Sill Complex | **Pre-caldera Basal Andesite Sill Complex | |

**Analyses in Bailey (1960) show that some of the sheets are in fact basalts and basaltic andesites.