Chapter 1 Introduction

The deep valley of Glen Coe and the surrounding mountains together form one of the most spectacular natural landscapes in Britain. Glen Coe is in the south-western Grampian Highlands of Scotland (Plate 1) and descends westwards from the Rannoch Moor plateau at about 300 m above sea level to the sea at Loch Leven (Figure 1). The River Coe flows in the glen, over several waterfalls and through Loch Achtriochtan, entering Loch Leven at Glencoe village. The Three Sisters (Aonach Dubh, Geàrr Aonach and Beinn Fhada), great rocky buttresses separated by steep-sided hanging valleys, dominate the south side of the glen, extending north-eastwards from Bidean nam Bian (1150 m), which is the highest mountain in the Glencoe area. The northern wall of the glen rises steeply to the sharp, serrated edges of the Aonach Eagach and Am Bodach. At the eastern end of Glen Coe, the imposing bulk of Stob Dearg stands guard at the junction of Glen Coe and Glen Etive, while to the east of Glen Etive lie the remote peaks of Meall a' Bhùiridh, Creise and Clach Leathad. Farther to the east is Rannoch Moor, a wild expanse of peat bogs and lochans.

The Glencoe area is famous for its long and sometimes turbulent history, particularly the treacherous massacre there in 1692. Glen Coe was the home of the legendary Fingal, or Fionn MacCumhail, one of the great heroes of Celtic mythology; a cave high above Loch Achtriochtan is named after Fingal's son, the poet Ossian. Today, the glen is popular with visitors from all over the world who come to enjoy the dramatic mountain scenery. Many come to walk and climb; several Munros (Scottish mountains with summits over 3000 feet above sea level) rise above the glen and the numerous buttresses and rock faces afford spectacular routes for climbers. In winter the slopes of Meall a' Bhùiridh above the White Corries centre are used for skiing. A large part of the Glencoe area, including the Aonach Eagach, Bidean nam Bian, Buachaille Etive Beag, Stob na Bròige and Stob Dearg, is in the care of The National Trust for Scotland.

In this book, information is provided to enable the interested geologist to locate and examine key features in the field; a map and table of key field sites is provided (Appendix). Throughout the text, localities are given in square brackets as references to the UK Ordnance Survey National Grid; all refer to the 100 km square NN, which is omitted for brevity.

For those intending to visit the Glencoe area, it is stressed that:

- much of the terrain is very rugged and remote
- many localities and mapped lines are accessible only by rock climbing
- the weather can become extremely inclement with surprising rapidity
- some descent routes are not straightforward and can be arduous.

Most of the described locations are relatively accessible to the fit and experienced field geologist, weather permitting, and it is intended that they should be visited (*without* the use of a geological hammer). However, no site is perfectly safe and field safety is not indicated by the following descriptions that imply accessibility.

Outline of the geology

The Glencoe area exposes the roots of an ancient volcano that has been deeply dissected by the action of natural forces over millions of years, culminating in successive glaciations that ended only 11 000 years ago. It has been recognised as a classical area of British geology for almost a century. Meticulous fieldwork here by the Geological Survey in the early 1900s led to the first detailed analysis of the relationships between a volcano and its underlying intrusions, and hence between surface and subsurface magmatic processes. This early analysis was all the more remarkable for having been accomplished in terrain that is amongst the most rugged and physically demanding for fieldwork in Britain. The early interpretations of the Glencoe volcano profoundly influenced subsequent studies throughout the world, particularly of modern volcanoes where processes at depth could only be inferred indirectly. Now, the Glencoe Caldera-volcano Complex, as it is more formally named here, is renowned internationally both for its early influence in volcanology and for important new insights derived from a modern reappraisal. Detailed remapping of the entire volcanic succession at Glen Coe, utilising far richer volcanological understanding than was available nearly a century ago, has led to considerable modification of the original interpretations. This book, together with a new 1:25 000 scale geological map (British

Geological Survey, 2005), summarises the new discoveries; important technical terms, volcanic features and processes are explained in the next section.

The geology of the Glencoe area is dominated by an intra-caldera succession of silicic pyroclastic rocks, intermediate and silicic lavas and a wide variety of intrusions; unconformities with associated alluvial deposits are common in the sequence (Figure 2). This succession overlies a deeply eroded 'basement' of Neoproterozoic to early Palaeozoic metasedimentary rocks, as well as pre-caldera andesite sills with intervening sedimentary strata. Seven thick ignimbrites constitute most of the intra-caldera succession. These represent major caldera-forming explosive eruptions that were associated with volcanotectonic subsidence and piecemeal caldera collapse. The subsidence was incremental and involved the movement of numerous cross-cutting faults, many of which also formed the plumbing system that tapped the underlying magma chambers. Tectonic faulting continued during the periods between eruptions, causing changes in drainage and sedimentation that are recorded in the intercalated sedimentary rocks. A ring-fault system and associated intrusions formed after the early incremental caldera development, and these were succeeded by the emplacement of voluminous silicic magmas to form the Clach Leathad Pluton (new name; see p.98). This large intrusion formed during foundering of a considerable chunk of the caldera succession, which is thus largely obliterated in the south-east; it merges locally with the ring-fault intrusions and is truncated by the large Etive Pluton to the south (Figure 2); (Figure 3).

The Glencoe Caldera-volcano Complex forms part of an extensive magmatic province that is marked by numerous volcano remnants and plutons e.g. (Figure 3) and extends from Shetland in the north-east to Donegal (Ireland) in the south-west. The magmatic activity occurred during strike-slip faulting, uplift and erosion following the continental plate collision known as the Scandian Event of the Caledonian Orogeny, which is thought to have occurred 435 to 425 million years ago (Soper et al., 1992; Dewey and Strachan, 2003). At the time of the magmatism, the newly amalgamated continent was near southern tropical latitudes (Cocks and Torsvik, 2002) and climatic conditions in the region were semi-arid; rapidly eroding metamorphic and igneous massifs were flanked by alluvial plains characterised by flash floods and ephemeral lakes.

Isotopic dating suggests that the Glencoe volcano was active some 421 ± 4 million years ago (Thirlwall, 1988), in late Silurian times according to current time scales (e.g. Gradstein and Ogg, 1996; Tucker et al., 1998). However, plant remains and sporomorphs in pre-caldera strata indicate an earliest Devonian age (Kidston and Lang, 1924; Wellman, 1994) of around 415 million years (Lochkovian Stage). The apparent age contradiction, at least in part, reflects uncertainties attributable to the dating methods employed; it appears that the caldera-related volcanism may have lasted for no more than two or three million years (see p.104). Intrusions that cut the volcano complex, and thus postdate its activity, have yielded ages that suggest emplacement some 412 to 401 million years ago (Clayburn et al., 1983; Thirlwall, 1988), in early Devonian times (Pragian–Emsian ages).

What a caldera is, and why Glencoe caldera volcano is important

Catastrophic eruption of tens to thousands of cubic kilometres of magma from a chamber beneath a volcano typically leads to collapse of the chamber roof and consequent subsidence of the overlying volcanic pile. The subsidence forms a surface depression called a caldera (Figure 4). Calderas can be many tens of kilometres across and hundreds of metres deep: many become partially filled by lakes or form embayments of the sea. Well-known modern caldera volcanoes include Mount Mazama (Crater Lake) in the Cascades Range of the USA, Santorini in the Greek islands, and Toba in Sumatra (see Francis and Oppenheimer, 2004). Calderas form at long-lived volcanoes and they should not be confused with volcanic craters, which are relatively small depressions that form around vents by erosion during an explosive eruption or by build-up of ejecta.

Most caldera-forming eruptions are explosive (Figure 4)b; they involve sustained jets and gas-rich flows of vitric ash particles, pumice fragments and crystals, collectively called pyroclasts, usually with some included rock fragments called lithic clasts. Much of the erupted mixture is denser than atmosphere so that it falls to the ground, as in a fountain, and moves away from the vent as a pyroclastic density current (also known as a pyroclastic flow; see Branney and Kokelaar, 2002). The magma that erupts to form most medium-sized or large calderas is normally of intermediate or silicic composition, commonly dacite, rhyodacite or rhyolite, and its initial temperature is usually in the range 700° to 900°C.

Since the eruptive vents tend to lie within or around the periphery of calderas, pyroclastic material usually partially infills the topographical depression (Figure 4)b. Parts of both the eruptive fountain and the related pyroclastic density current (or currents) mix with and heat surrounding air and thus become buoyant, forming vigorously ascending plumes of pumice fragments and ash. Such plumes can be vast and can spread in the stratosphere so as to influence both regional and global climate, such as occurred with the caldera-forming eruptions of Mount Pinatubo (1991), Krakatau (1883), Tambora (1815) and Toba (about 74 000 years ago).

The deposits of the ground-hugging pyroclastic density currents that occur in caldera-forming eruptions are known as ignimbrites (synonymous with ash-flow tuffs). These normally are poorly sorted mixtures of ash, crystals, pumice fragments and lithic clasts, and tend to be thick within topographical depressions. Caldera-related ignimbrites can have volumes of up to thousands of cubic kilometres and can extend over tens of thousands of square kilometres. It is common for the fragmented magmatic material in ignimbrites initially to retain temperatures above 550° to 600°C, in which case the glassy constituents (vitric ash and pumice fragments) deform in a ductile manner and become fused together. Such ignimbrites are described as welded, and they typically show distinctive flattened pumice fragments, known as fiamme, and streakiness of the finer matrix to form eutaxitic texture (Plate 2a)(Plate 2b). Fallout from the buoyant plumes typically produces extensive blanket-like deposits of pumice or ash. Seven ignimbrites are now recognised in the Glencoe Caldera-volcano Complex; each is preserved within the caldera that formed during its eruption and accumulation, so that multiple subsidence is recorded. The total volume of material erupted in each case is unknown, because of incomplete preservation within the caldera and because an unknown proportion is likely to have escaped beyond the confines of the caldera during the eruption. Best estimates of the minimum volumes of magma erupted during formation of the most substantial preserved ignimbrites are in the order of ten cubic kilometres, which is a small volume by caldera volcano standards.

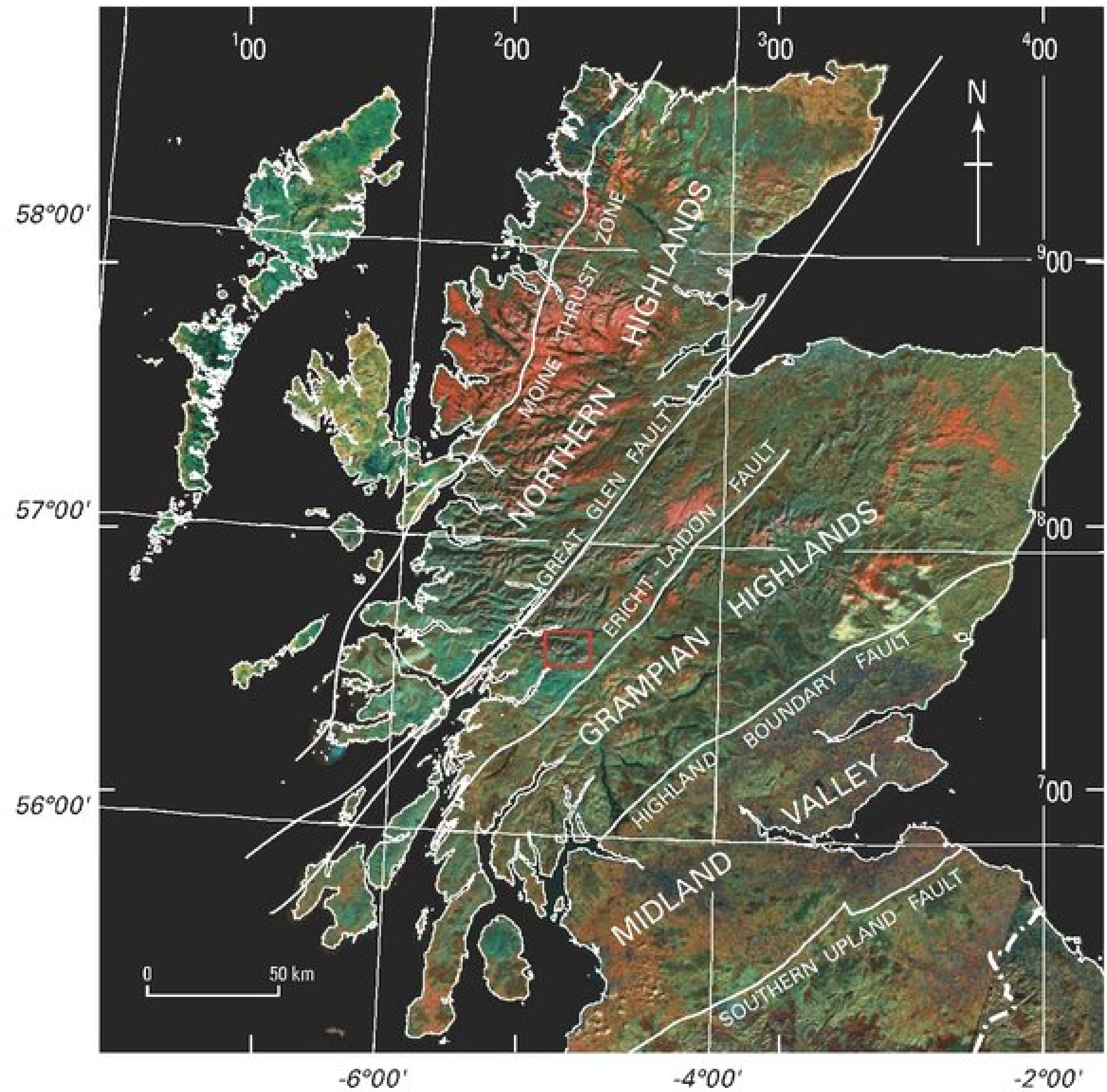
Because calderas are topographical depressions that are liable to become at least partially flooded with water, eruptions that occur within them commonly involve the interaction of magma and water. Such hydrovolcanic activity can be highly explosive, particularly where the interaction occurs beneath the ground surface, as in an aquifer, in which case it is referred to as phreatomagmatic explosivity. Phreatomagmatic explosions typically build low-profile tuff cones composed of erupted ash and fragments of the aquifer. Tuff cones normally include distinctive layers in which parallel- and cross-stratification record deposition from powerful ground-hugging ash clouds (another type of pyroclastic density current, commonly referred to as 'ash hurricane' or 'pyroclastic surge'), while bomb-sags register the impact of blocks hurled ballistically from the vent. Phreatomagmatic explosivity is now known to have punctuated the evolution of the Glencoe caldera volcano at least five times and, although not recognised until recently; extensive exposures of one pyroclastic cone with its underlying aquifer constitute a rare and exceptionally instructive section of a silicic hydrovolcano.

Calderas normally form within earlier-erupted, genetically related volcanic rocks. In many cases they are defined by steep and nearly circular, scalloped topographical margins with subannular arrangements of post-caldera intrusions, vents and lavas e.g. (Figure 4)a. Geologists have interpreted this ring-form as reflecting subsidence of a coherent, piston-like block of volcanic and crustal rocks into the magma chamber along a relatively simple bounding ring-fault (e.g. Smith and Bailey, 1968). The piston-subsidence model, however, did not originate from a modern volcano, but primarily from the early Geological Survey work on the ancient Glencoe volcano and associated intrusions (Clough et al., 1909), which was soon supplemented with perspectives from the nearby Ben Nevis volcano (Maufe, 1910). The subsided block and the associated intrusions that represent the contemporary magmatic plumbing system at these sites were originally referred to as 'cauldrons', emphasising the perceived fundamental role of ring-faults (Figure 5)a. It was as the archetypal piston-subsidence cauldron, with its excellent exposure and striking mountain setting, that Glen Coe and its environs became recognised as a classical area of British geology.

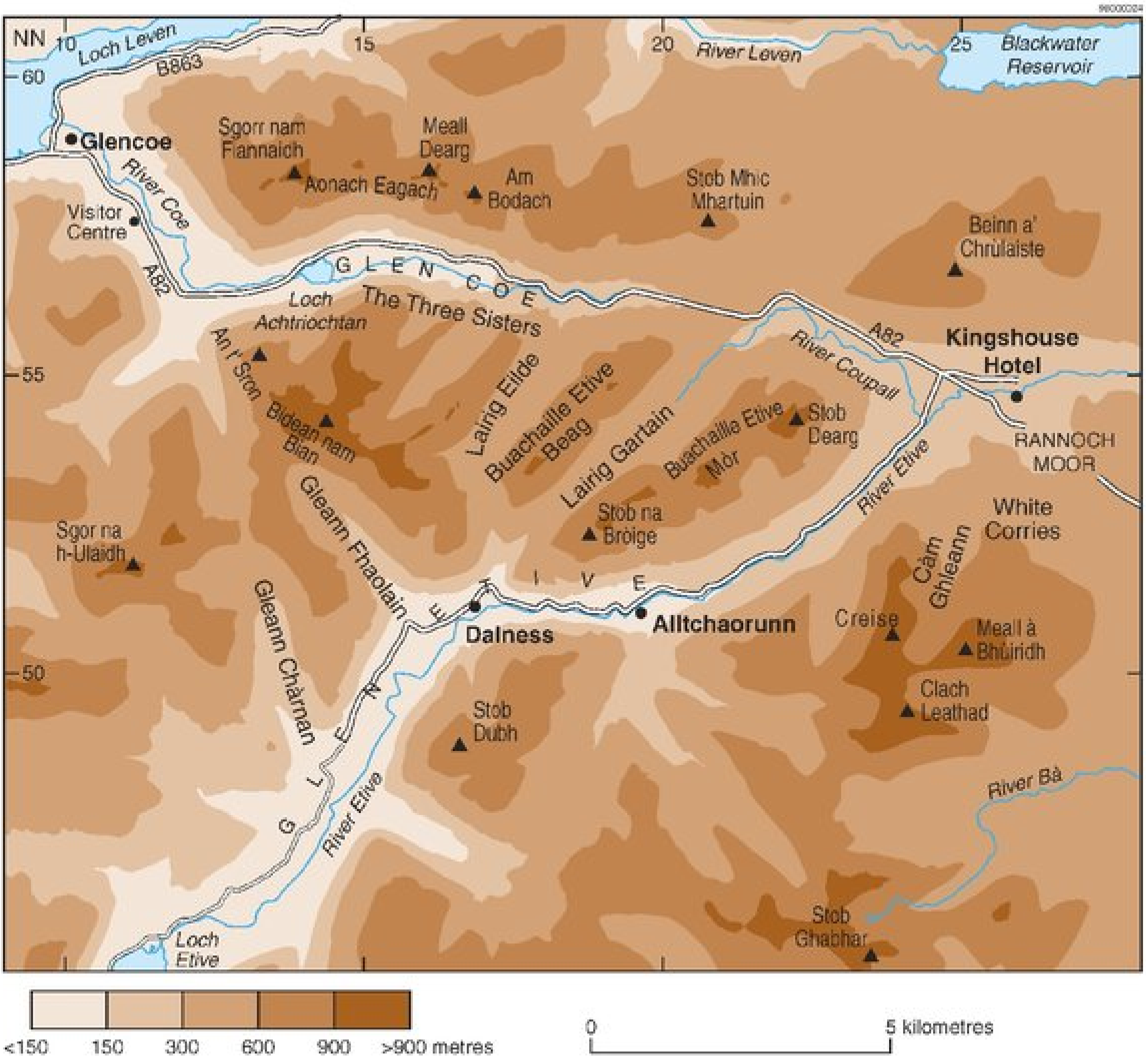
Although control of caldera subsidence by relatively simple ring-faults has often been inferred at volcanoes where there is little or no erosional dissection (e.g. the Valles caldera; (Figure 4)a, more complex and diverse structural processes are now known to be involved in many cases. These processes include downsag, which is flexural subsidence without development of a main controlling fault (Walker, 1984), although extensional structures around the edges of the depression are common. The latter include fractures that may be hundreds of metres deep and are referred to as crevasses, and in many cases also narrow graben or half-graben between tilted strata (Figure 4)b; Branney and Kokelaar, 1994; Branney, 1995; Moore and Kokelaar, 1998). Also, subsidence has been shown to develop incrementally, involving a succession of events and haphazard piecemeal movements of numerous caldera-floor fault-blocks (Figure 4)b; Branney and Kokelaar, 1994; Moore and Kokelaar, 1998). Controls on the structural evolution of multiple-subsidence calderas are complicated and difficult to determine precisely, because early-formed structures tend to be reactivated or cross-cut during later movements, or they are obliterated by later intrusions. Studies at the surface or at shallow levels of caldera volcanoes can overlook complexity that occurs at deeper levels, in the floors and early infilling deposits, mainly because early-formed features tend to be buried by later deposits. Thus, studies of ancient volcanoes that have been deeply dissected by erosion to expose their internal structure and stratigraphy are essential to complement any understanding derived from analysis of younger counterparts. The extremely rugged topography of the Glencoe Caldera-volcano Complex has provided excellent opportunities to examine the internal volcanic structure at various levels through to the underlying basement (see 1:25 000 scale geological map; British Geological Survey, 2005), with numerous valleys and intervening ridges virtually providing serial sections up to a kilometre high, and with extensive glacially scoured outcrops. It is because of this exceptional exposure that the Glencoe volcano is a world-class natural volcanological laboratory.

The studies at Glencoe reported by Moore (1996) and by Moore and Kokelaar (1997, 1998) were undertaken with the knowledge that caldera volcanoes commonly form on major faults or fault zones (e.g. Smith and Luedke, 1984; Self et al., 1986; Kokelaar, 1988, 1992; Kokelaar et al., 1994; Milner et al., 2002; Manville and Wilson, 2003), and that crustal structure and active tectonism influence caldera form and evolution. When the Glencoe volcano developed, the regional tectonic regime was dominated by strike-slip and normal-slip movements on major crustal discontinuities such as the nearby Ericht–Laidon Fault, Great Glen Fault and Highland Boundary Fault (Figure 3); (Plate 1); Watson, 1984; Hutton, 1987; Treagus, 1991). The new studies found that the evolution of the volcano was far more complicated than previously thought, and that it was strongly influenced by the location and activity of underlying faults. Now the Glencoe volcano is considered as a different archetype; having once been the original piston-subsidence cauldron, it is now perhaps the prime example of a tectonically controlled, piecemeal, multiple-subsidence caldera volcano. The term ‘cauldron’ has been dropped, because of the recognition that much of the caldera subsidence was unrelated to any ring-fault. The new interpretations in this book largely derive from studies of the volcanic succession and structure within the ring-fault, but the intruded ring-fault system is also reappraised and interpreted within the new perspective. While there is now a far fuller understanding of the history of the volcano, much remains unknown; there is both need and scope for further research, particularly concerning the origins of the magmas and the relationships of the volcano to the nearby, broadly coeval plutons.

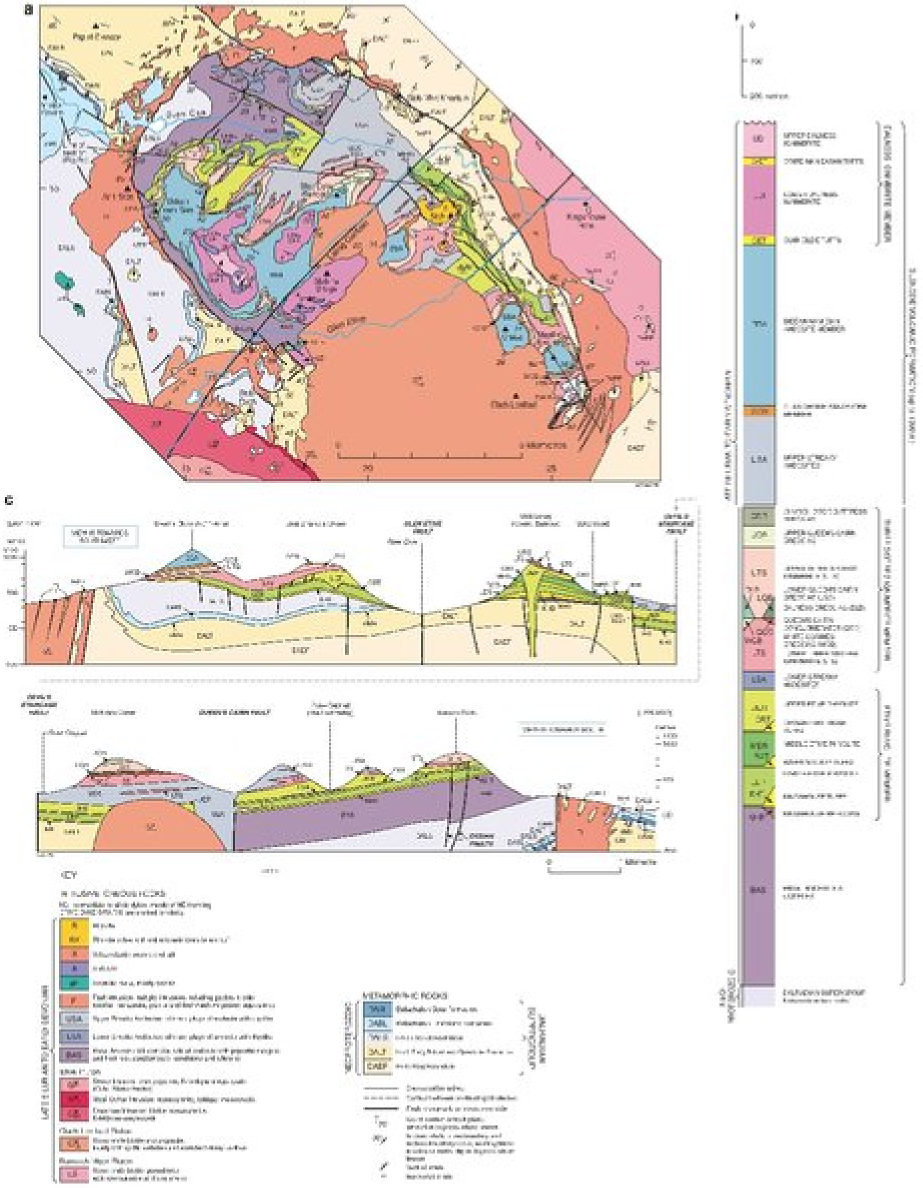
References



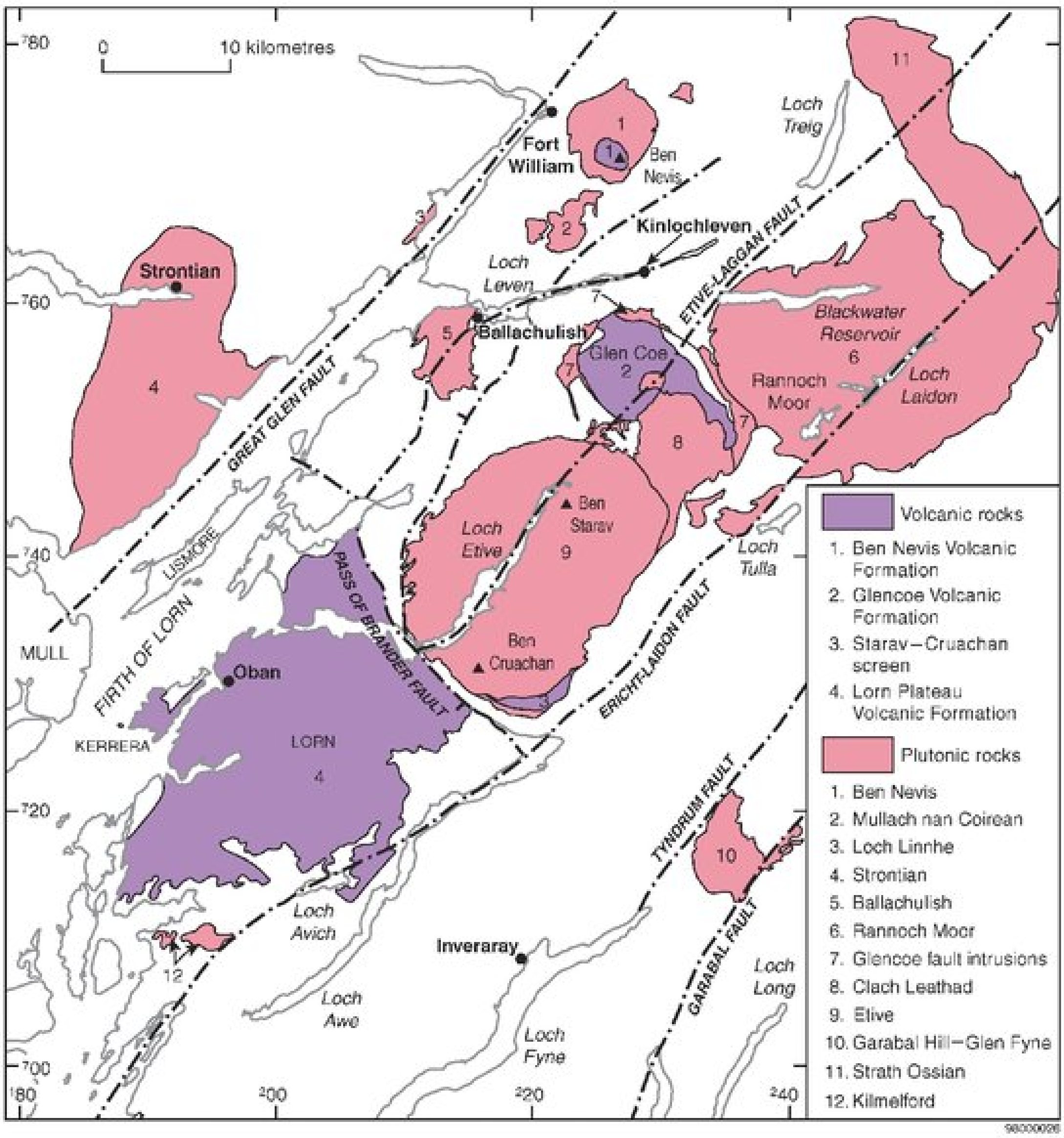
(Plate 1) A Satellite view showing the location of the Glencoe area in Scotland. BGS enhanced image © NERC, 2005. Grid lines in white show latitude and longitude; National Grid is indicated along the margin of the image.



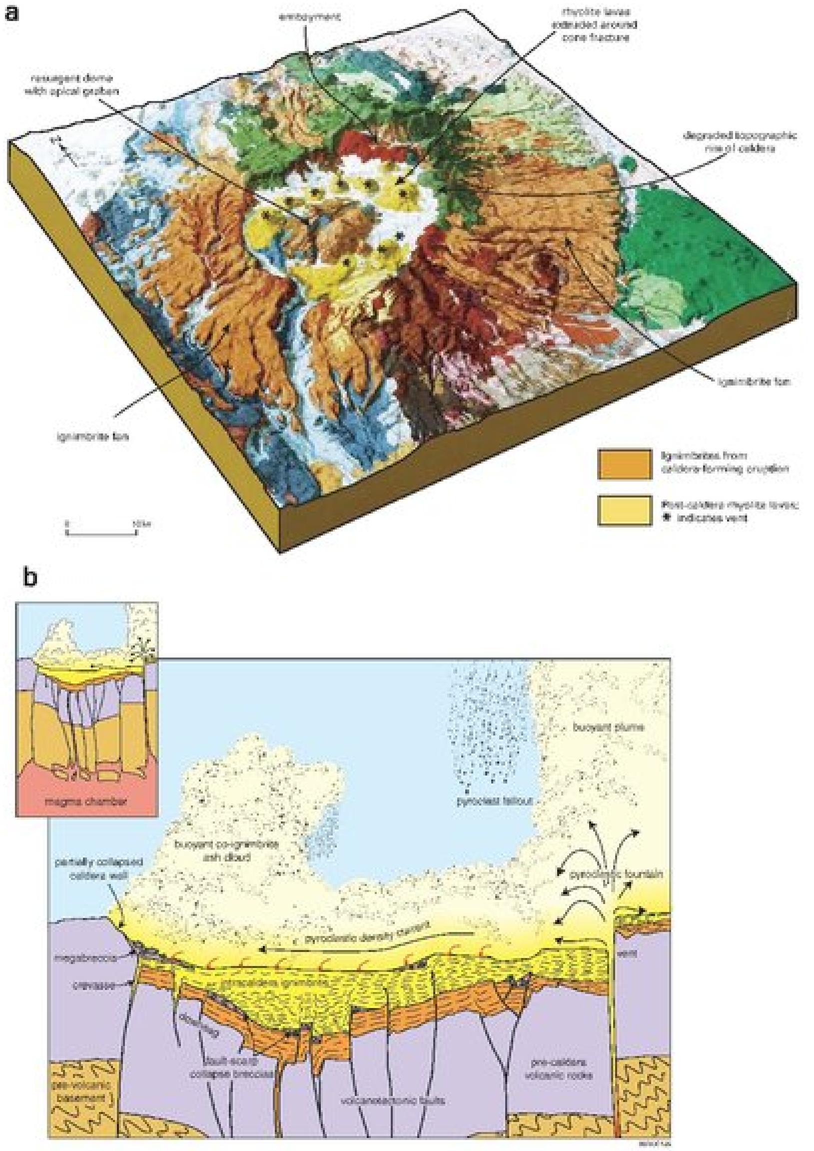
(Figure 1) Topography of the Glencoe area.



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

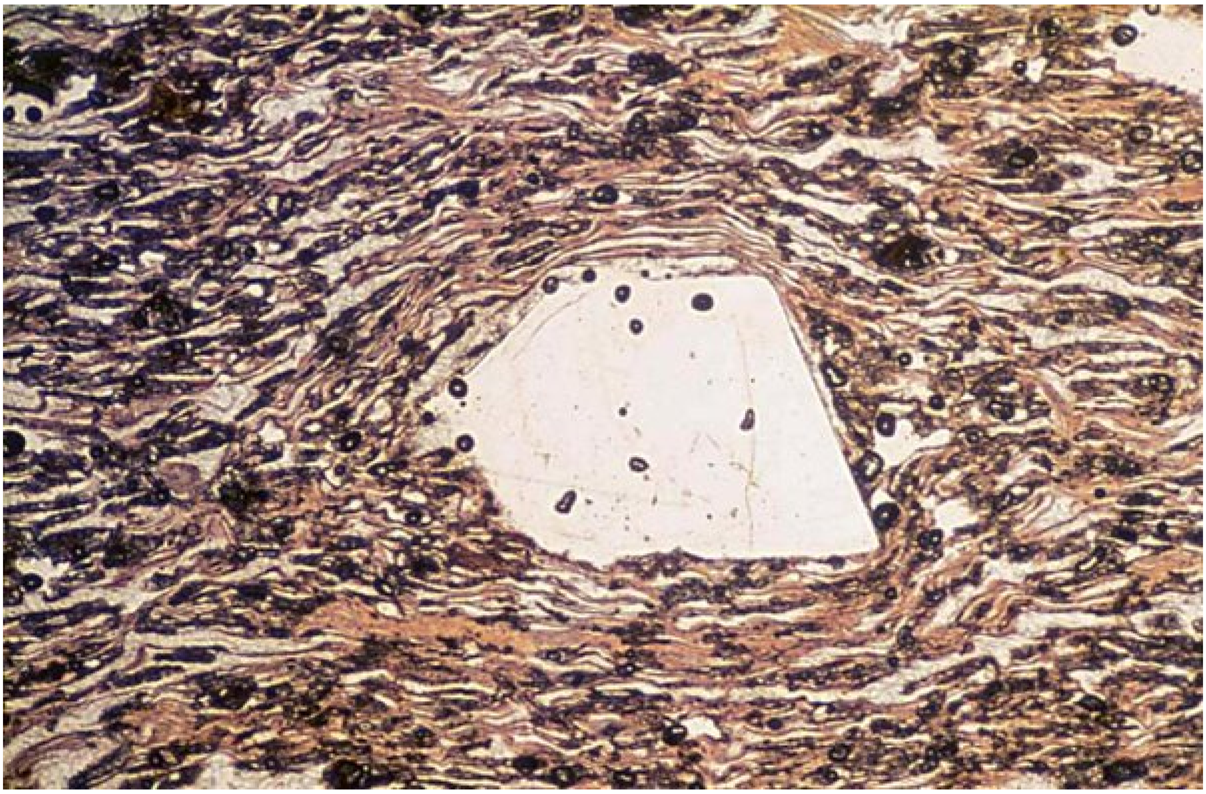


(Figure 3) Distribution of Siluro-Devonian volcanic and plutonic rocks showing faults that were active during the magmatic activity.

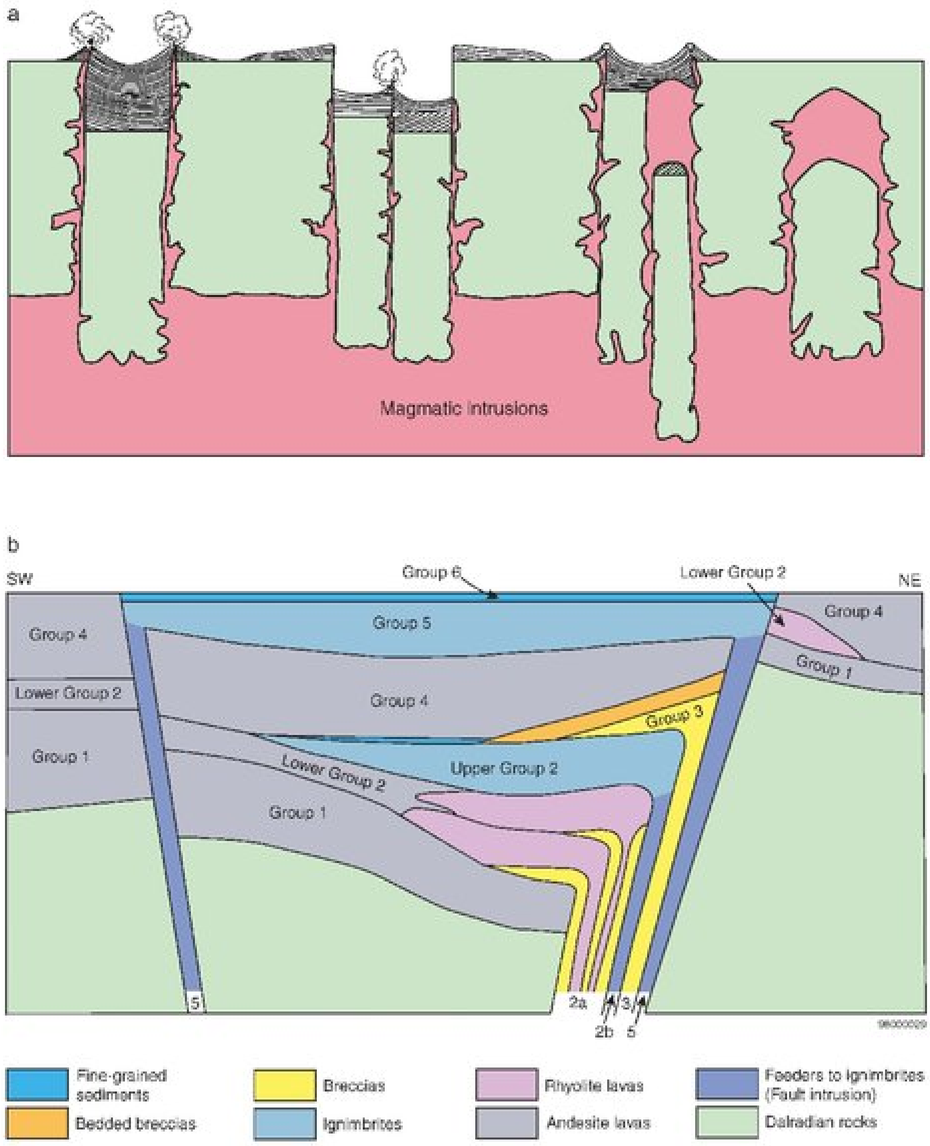


(Figure 4) (right) Main features of calderas, caldera-forming eruptions and the associated phenomena. a. Valles caldera, Jemez Mountains, New Mexico, USA (image generated by H P Foote; geology from USGS map I-571, 1970). The main topographical depression in the summit of the volcano is the caldera. This 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.

(Plate 2a) Welded ignimbrite. a. At outcrop: the black lenticular fiamme represent pumice fragments that collapsed within the hot- state compacted ash matrix. Locally the flattening fabric is wrapped around a rock fragment (just below centre) that was rigid (P611765).



(Plate 2b) Welded ignimbrite. b. Under the microscope: a eutaxitic texture can be seen. Brown to colourless glass shards are strongly flattened and wrapped in a ductile fashion around a rigid crystal of quartz (centre). Field of view is 4 mm wide: plane-polarised light (P611766).



(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.