Ben Nevis and Glencoe : A landscape fashioned by geology

The area around Ben Nevis and Glencoe is one of the most popular in the Scottish Highlands. Easy road and rail access brings thousands of visitors to walk, climb, ski, cycle, sail, canoe, soak-up the turbulent history or just to marvel at the dramatic landscape. The shapely peaks of the Mamores, fashioned from 700 million year-old sandstones, contrast with the towering near-vertical cliffs of Glen Coe and the north face of Ben Nevis, which exhume the remains of 400 million year-old volcanoes. But the mountains, deep glens and sheltered sea-lochs that we see today were carved by glaciers in the last 2 million years, with many of the most obvious features only 12000 years old or less. It is an ideal place to ponder the vastness of geological time and the forces that have shaped the landscape.

Ben Nevis and Glencoe have been favourite tramping grounds of mine since I was a boy. My parents first met on the summit of the Ben, which gives it an extra significance for me. The whole area is redolent of history and intrigue as well as containing some of Scotland's finest landscapes, but I had never really thought about the geology that underpins it all until I read this fascinating booklet. Put a copy in your rucksack next time you go - it will make the outing even more interesting and worthwhile.

Andrew Thin, Chairman SNH

About the Authors

Kathryn Goodenough has worked as a field geologist in Scotland for ten years, first for Scottish Natural Heritage and now for the British Geological Survey. She is particularly interested in rocks formed in ancient volcanoes, both in Scotland and across the world. She spends much of her spare time walking and biking in the Scottish mountains.

David Stephenson has worked as a field geologist in Scotland for over twenty-seven years, concentrating mainly upon volcanic rocks of the Midland Valley and metamorphic rocks of the Grampian Highlands. In addition he has investigated igneous intrusions in Greenland, volcanic rocks in Burma and ancient oceanic crust in Arabia. He has climbed in Glen Coe in summer and winter and still enjoys walking the hills of the area; the Mamores are a particular favourite.

ISBN 978 1 85397 506 6
Price £4.95
Scottish Natural Heritage
www.snh.org.uk

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British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL
SCOTTISH NATURAL HERITAGE

ISBN 978 1 85397 506 6

A CIP record is held at the British Library
W3K0207

Acknowledgements
Authors: David Stephenson (BGS) and Kathryn Goodenough (BGS)
Series editor: Alan McKirdy (SNH)

Photography: **David Robertson/Alamy** 7; **Lorne Gill/SNH** front cover, frontispiece, 6, 9, 10, 16, 17, 18, 19 top, 19 bottom, 27 top, 27 bottom, 29, 30, 31; **Alex Gillespie Photography** 20; **Kathryn Goodenough/BGS** 12, 15 bottom; **John Gordon** 24, 26; **Peter Kokelaar/BGS** 15 top left, 15 top right; **Patricia & Angus Macdonald/SNH** 4, 25, 28; **US Geological Survey** 13; **Tom Pfeiffer/Volcano Discovery** 14 top; **Noel Williams** 8 top, 21 top, 21 bottom, 22, 23 top.

Illustrations: **Richard Bonson** 5; **Craig Ellery** 2, 3, 8 bottom, 11; **Clare Hewitt** 23 bottom; **Peter Kokelaar/BGS** 14; **Ian McIntosh** contents.

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The Publications Section,
Scottish Natural Heritage,
Battleby, Redgorton, Perth PH1 3EW
Tel: 01738 458530 Fax: 01738 458613
E-mail: pubs@snh.gov.uk
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Front cover image:
Cliffs of volcanic rock tower over lower Glen Coe
Back cover image:
Walkers in Glencoe

BEN NEVIS AND GLENCOE

A Landscape Fashioned by Geology

by

David Stephenson (BGS) and Kathryn Goodenough (BGS)

Composite landscape of Ben Nevis, the Mamores, Loch Leven and Glencoe

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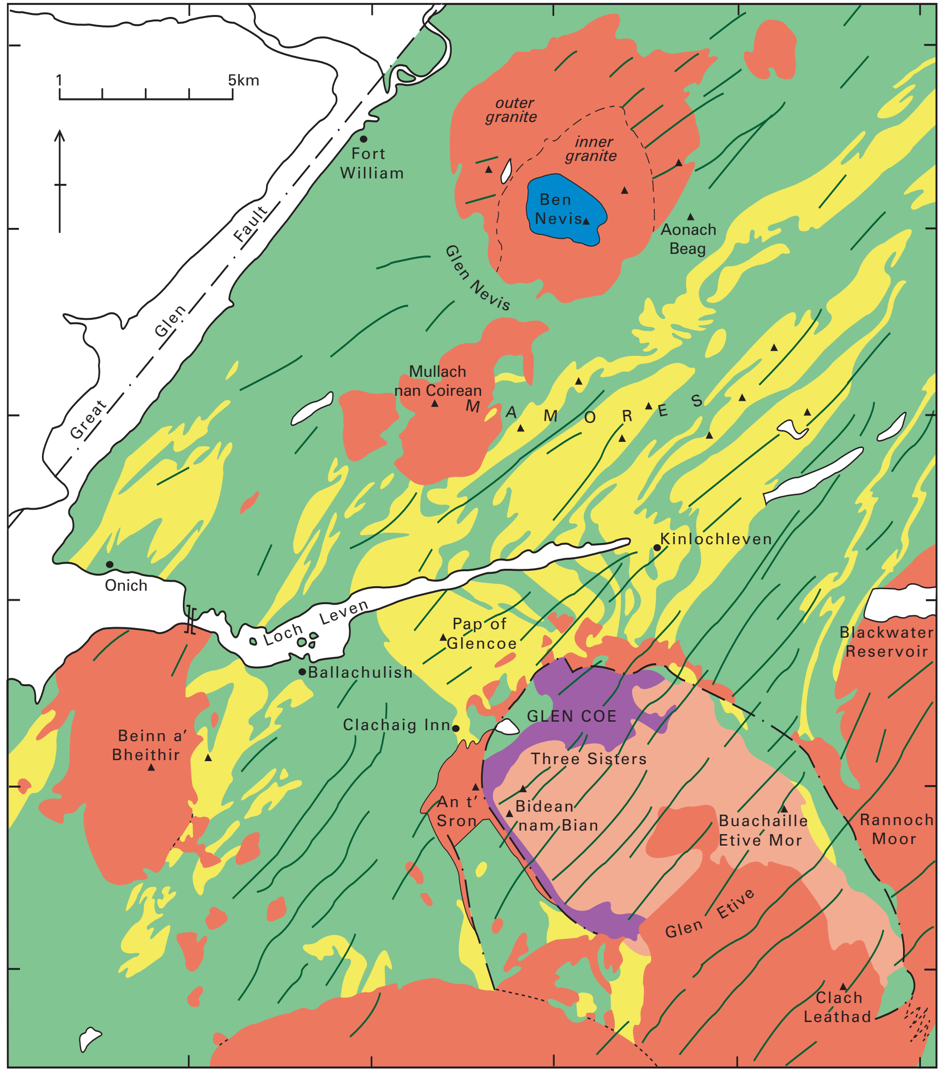
The Ben Nevis and Glen Coe area is one of the most mountainous regions of the British Isles, including Britain's highest peak. This rugged landscape is the product of a fascinating geological story that stretches back about 750 million years. The rocks of this area have formed in environments as diverse as ancient sea beds and the depths of great mountain chains. However, perhaps the most important features of the area, the peaks of Ben Nevis and around Glen Coe, were formed by volcanic activity just over 400 million years ago. Studies at Glen Coe and Ben Nevis, in the early twentieth century, led to some of the first simple models of how volcanoes work. The geological story culminates in the sculpting of the modern mountains by glaciers that finally melted around 11,500 years ago. However, more recent changes to the landscape have been largely due to the activities of man, including damming the glens for hydro-electric power schemes. Nowadays, much of the area is managed by organisations such as the National Trust for Scotland and the John Muir Trust, which aim to protect and conserve the wild landscapes. This book tells the story of how those landscapes were formed.

Ben Nevis and Glencoe Through Time

QUATERNARY 2.6 million years ago to the present day	**11, 500 years ago to the present time.** As the climate warmed, loose rock cascaded down the steep valley sides as rockfalls. Glacial debris was redistributed by rivers. Eventually, vegetation recolonised the area and stabilised the slopes. **12, 500 to 11,500 years ago.** The last local glaciers of Scotland were particularly well developed around Ben Nevis and Glen Coe. They sculpted the peaks and glens into the shapes that we see today. **14, 700 to 12, 500 years ago.** A period of warmer climate, much like that of today, led to the melting of the glaciers. **29,000 to 14,700 years ago.** A thick ice sheet covered the whole of Scotland for the last time, with only the highest peaks protruding through the ice. **Before 29,000 years ago.** Several very cold glacial episodes were interspersed with warmer periods.
NEOGENE 23 to 2.6 million years ago	The high ground of the western Highlands was gradually eroded under warm, temperate conditions, cooling gradually until 2.6 million years ago when the ice age began.
PALAEOGENE 65 to 23 million years ago	About 60 million years ago, volcanoes began to erupt to the west of the Scottish Highlands, eventually leading to the opening of the North Atlantic Ocean.
CRETACEOUS 145 to 65 million years ago	Warm, shallow seas covered most of Scotland, which was now around 45 degrees north, but the Ben Nevis and Glen Coe area might have remained above sea level.
JURASSIC 200 to 145 million years ago	The area that is now the Scottish Highlands formed high ground on the margins of shallow seas, and dinosaurs roamed along the coast.
TRIASSIC 251 to 200 million years ago	Seasonal rivers flowed westwards across open plains, depositing wide spreads of silts, sands and pebbly gravels.
PERMIAN 299 to 251 million years ago	By this time Scotland had drifted 10 to 20 degrees north of the equator and was again hot and dry, with desert sands accumulating on lower ground
CARBONIFEROUS 359 to 299 million years ago	Scotland lay close to the equator and parts of the country were covered in tropical forests, from which the coal of central Scotland formed. Volcanoes were widespread in southern Scotland.
DEVONIAN 416 to 359 million years ago	Scotland had become part of a vast, arid continent. Magma continued to accumulate beneath the surface forming dykes and more granites.
SILURIAN 444 to 416 million years ago	The continents eventually collided and the land was uplifted to form a chain of mountains. The Ben Nevis and Glen Coe area lay about 15 degrees south of the Equator. It was dry and mountainous, with deep valleys that flooded during rare wet periods. Magma accumulated at depth, and cooled to form granites. It also rose up through the crust at Glen Coe, forming sills that spread out through river and lake sediments. Violent volcanic eruptions occurred later at both Glen Coe and Ben Nevis. The central parts of the volcanoes subsided to form calderas.
ORDOVICIAN 488 to 444 million years ago	As segments of the oceanic crust collided with Laurentia, the Dalradian sediments were compressed, heated and deformed into spectacular folds.
CAMBRIAN 542 to 488 million years ago	Sediments, now seen only in the North-west Highlands, continued to be deposited on the flanks of Laurentia, whilst other continental masses moved ever closer together, narrowing the intervening ocean.
PRECAMBRIAN Before 542 million years ago	The Dalradian sediments were laid down on the edge of a continent known as Laurentia.

Brown bars indicate periods of time represented by the rocks and loose sediments seen around Ben Nevis and Glen Coe.

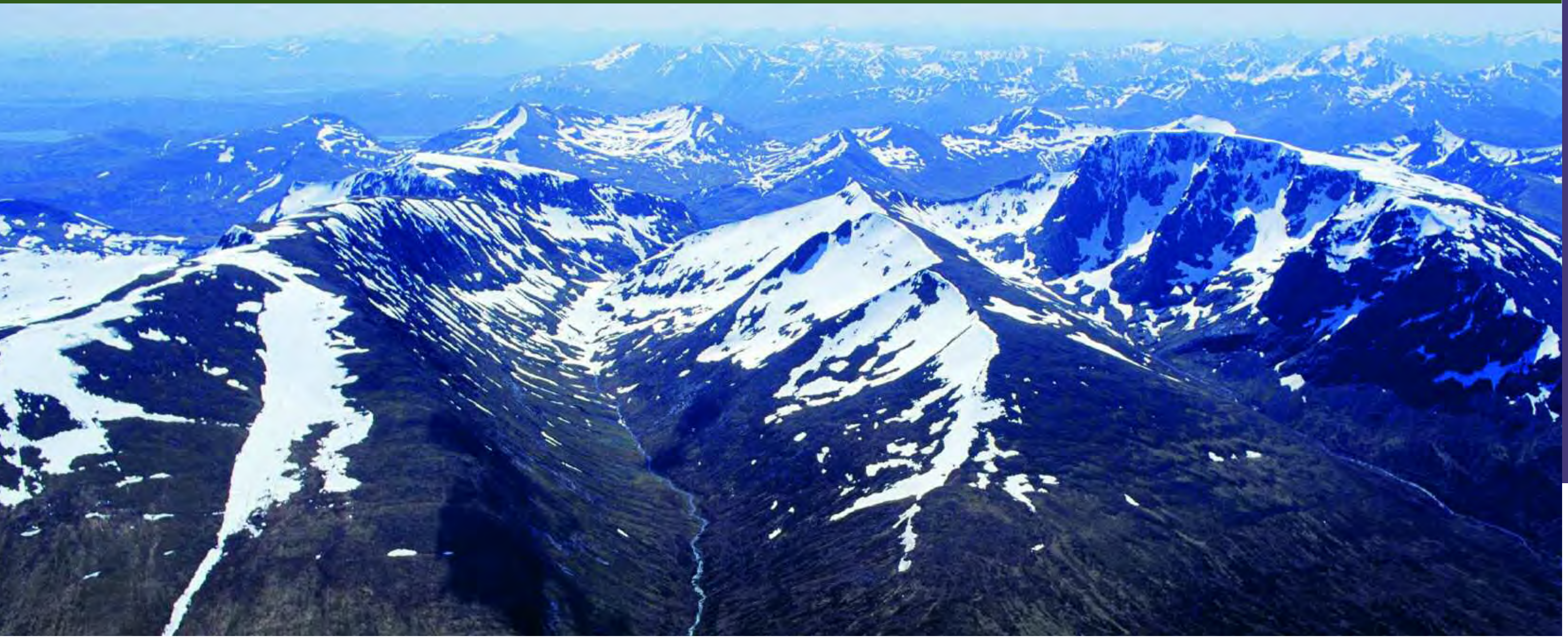
Geological Map of Ben Nevis and Glencoe



- Dykes (early Devonian)
- Granite and related rocks (late Silurian to early Devonian)
- Ben Nevis volcanic rocks and related sedimentary deposits (late Silurian to early Devonian)
- Later, explosive volcanic rocks and related sedimentary deposits of Glen Coe (late Silurian)
- Earlier subvolcanic rocks of Glen Coe (sills) (late Silurian)
- Dalradian metamorphosed sedimentary rocks (late Precambrian)
- Prominent quartzites within the Dalradian succession
- Faults

In the Beginning; the Birth of the Caledonian Mountains

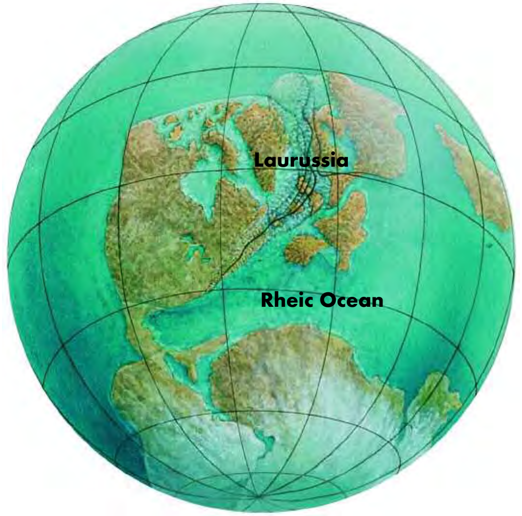
A view over the present-day Caledonian Mountains, with Aonach Mòr, Carn Mòr Dearg, and Ben Nevis in the foreground



The Scottish Highlands are just part of an ancient mountain range, comparable to the present day Alps or Himalaya, that extended for over five thousand kilometres. Today its eroded remnants are found in eastern North America, east Greenland, Ireland, Scotland and Norway, separated by the much younger North Atlantic Ocean. Throughout their length these are known as the Caledonian Mountains and the series of powerful earth movements that formed them is known as the Caledonian Orogeny.

The rocks that underlie most of the Highlands southeast of the Great Glen are known as the Dalradian rocks. They originated as sediment laid down between 750 and 500 million years ago on vast coastal plains, in shallow seas and on an ocean margin on the flanks of an ancient continent known as Laurentia. Around 600 million years ago, this was separated by an ocean from the continent of Baltica, the foundations of Sweden, Finland and Russia, and from a smaller continent called Avalonia, on which the rocks of England and Wales were forming.

500 Million Years Ago
The continent of Laurentia lay in tropical latitudes on the north side of the Iapetus Ocean. The ocean was slowly closing, as the continents of Avalonia and Baltica moved north towards Laurentia.



430 Million Years Ago
Final closure of the Iapetus Ocean complete. Baltica has collided head-on with Laurentia, whereas Avalonia has 'docked' more gently to the south.

Some 500 million years ago, slow movement of the huge tectonic plates that form the outer layer of the Earth started to move the three continents closer together and gradually the ocean closed up. The rocks in front of the moving continents crumpled and folded, just as a tablecloth does if you slide it across a table top, and eventually, by about 430 million years ago, the continents collided and became welded into a single continent. By this process the Earth's crust along the weld became very much thicker than normal. The rocks that were deeply buried were heated and recrystallised, growing new minerals in the process that we know as metamorphism.

In extreme cases, the rocks melted to form magma, which accumulated in vast magma chambers, deep below the surface. Continental crust is less dense than the Earth's interior and hence it is buoyant and slowly rises. Crust that has been thickened rises higher than normal crust, just as a large iceberg rises to a greater height above sea-level than a smaller iceberg, and hence mountain ranges are formed; the Himalaya are still rising today at a rate of between one and four millimetres a year.

All of this contributes to mountain building, and we can see much of the evidence spectacularly displayed in the Ben Nevis and Glen Coe area.

Caledonian Foundations

Disused slate quarries at Ballachulish

The geological foundations on which the volcanoes of Ben Nevis and Glen Coe were built are the Dalradian rocks. These were deposited as sands, muds and limey deposits in shallow seas and on coastal plains around the Laurentian continent 750 to 650 million years ago. As these sediments were buried and compressed, they became sandstones, mudstones and limestones. During the Caledonian earth movements, 470 to 430 million years ago, these rocks were subjected to much greater stresses and high temperatures. The original sediment grains were recrystallised into new minerals and many of the rocks developed a new layering that reflected the crushing forces around them. Mudstones became schists and slates, sandstones became very hard, cream to white quartzites, and some of the limestones became beautifully patterned marbles. At the end of the orogeny these rocks were uplifted to form the young Caledonian Mountains.

Over millions of years, the original Caledonian Mountains have been worn down and carved into the hills that we see today. The slates, schists and limestones tend to form smooth, rounded slopes and hills and hence provide few distinctive natural landscape features, but the slates led to early industrial development in the region and are responsible for some impressive man-made features. At Ballachulish and to a lesser extent at North Ballachulish, they were quarried between 1693 and 1955 for roofing slates. These were exported throughout Scotland, England, Ireland and even to North America at one time. They can be easily distinguished on roofs to this day on account of the cubic crystals, a centimetre or more across, of shiny yellow pyrite (fool's gold) that they contain. The main quarry at Ballachulish has now been restored, with a visitor's trail.

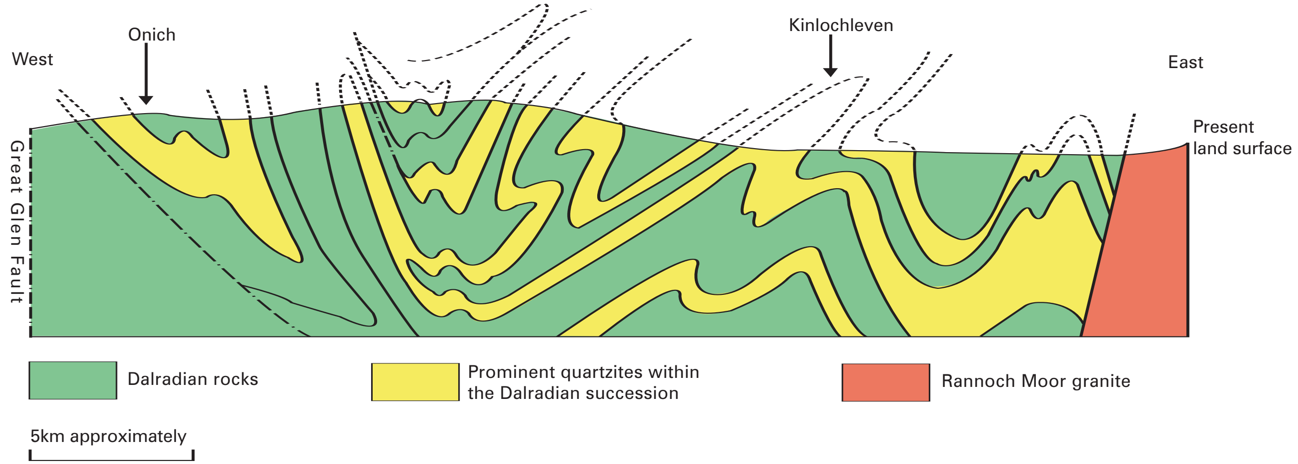
It is the quartzites that form the most obvious landscape features. Because of their hardness and resistance to erosion, they tend to form high peaks and ridges, especially in the Mamore range, between the Ben Nevis and Glen Coe areas. If you look up Glen Nevis on a clear summer's evening from near the visitor centre, the view is dominated by the glistening white peak of Sgurr a'Mhaim. It is easy to imagine this as an Alpine snow peak, but the upper part is composed almost entirely of quartzite.

View up Glen Nevis to the quartzite peak of Sgurr a'Mhaim

The quartzite peaks of the Mamore range, as seen from Ben Nevis

The main Mamore ridge consists of a series of quartzite peaks, including the shapely Stob Ban ('white peak') and the crowning top of Binnein Mor (1130 m). The summits are all made up of loose blocks of quartzite, shattered by the action of frost, but the flanks of the ridges often show the original sedimentary layering and this reveals spectacular geological and landscape features. The Caledonian earth movements have folded this layering into huge folds, several kilometres across in places. Geologists usually have to deduce the presence of such large structures from careful observations of smaller features that might be visible only in river beds. But in the Mamores, several amazing large fold structures can be seen on the hillsides, picked out by the layering in the quartzites. Visitors to the Alps will be used to seeing such a spectacle but this is the only place in Britain where folds can be seen on such a scale.

A cross-section (a vertical slice through the rocks) along the north side of Loch Leven, showing how the Dalradian rocks are folded

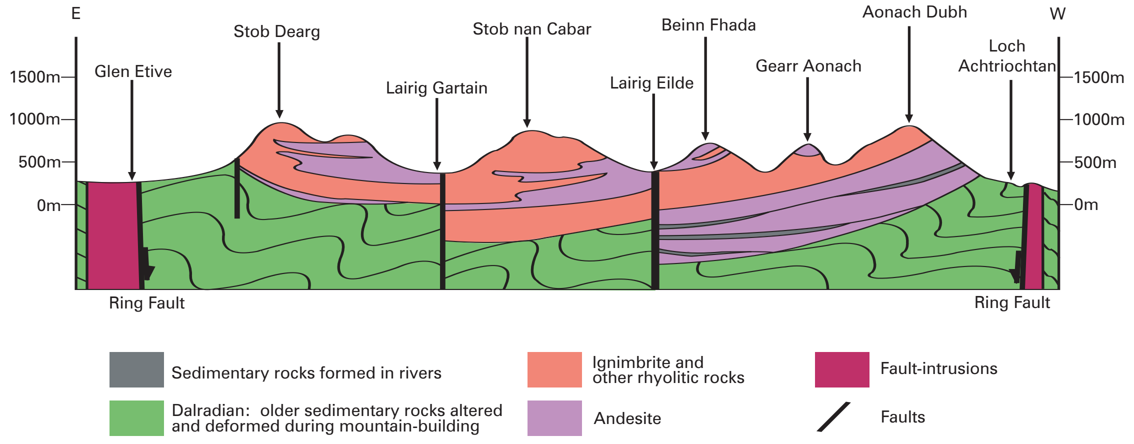


The Pap of Glencoe and the peak of Sgorr nam Fiannaidh are largely made of Dalradian quartzites

The Glencoe Volcano – early rumblings

The west face of Aonach Dubh shows a clear contrast between the dark-coloured andesitic sills that form the lower part of the face, and the pale pink cliffs above, formed from more silica-rich volcanic rocks

A cross-section through the rocks of the Glencoe volcano on the south side of Glen Coe



Towards the end of the Caledonian earth movements, that part of the Earth's crust that was to become Scotland lay south of the Equator at a latitude of about 20°. Then, as now, the climate in those latitudes was hot and dry. A few primitive plants existed, and indeed some fossilised remains have been found in rocks at the foot of the north-east face of Buachaille Etive Mor, but vegetation was sparse and there were no trees. Consequently, whenever it did rain, the run-off of water was rapid and violent. Thick deposits of cobbles and boulders accumulated with every flash flood and, as the water subsided, sand and mud settled out on the flanks of the main river channels.

During the later uplift phase of the orogeny, the crust cooled and fractured, breaking up into rectangular blocks, hundreds to thousands of metres wide. These blocks moved up and down relative to each other along fractures (faults) and some down-faulted blocks created valleys at the surface, like the rift valleys of east Africa but on a much smaller scale. One such valley in the area that was to become Glen Coe contained a major northwest-flowing river system.

As the mountains were uplifted, rocks at depth melted to form magma, which moved upwards along the faults. The first magma to reach the surface in the Glen Coe area, about 420 million years ago, was andesitic – similar to that being erupted from volcanoes in the Andes today. But because it was not well charged with gasses and was much more dense than the sands and gravels that filled the valleys, it did not erupt explosively from a volcano. Instead it was injected sideways between the layers of sediment, where it crystallised to form horizontal sheets called sills. Geologists have recently become excited by the blobby edges to the sills and trails of gas bubbles in the sediments, which show that the sediments were still soft and wet at the time, so that the magma was rapidly chilled and the water vaporised into steam. If this magma did eventually erupt as lava somewhere in the Glen Coe area, those volcanoes are no longer preserved.

The sills and sedimentary rocks form the lower slopes around Loch Achtriochtan, and in the classic view of Aonach Dubh from near the Clachaig Inn they form the darker, entire lower half of the west face.

The Glencoe Volcano – forming a caldera

Outcrop of volcanic breccia, made up of many angular fragments of volcanic rock, on the slopes of Buachaille Etive Beag

The upper part of Aonach Dubh is distinctly different from the lower part. This is one of the most dramatic geological contrasts in the Highlands and it is well known to climbers. The dark lower slopes rise in short near-vertical steps formed by individual andesitic sills, which are separated by grassy banks developed on the sedimentary strata. But the pale pink upper cliffs soar with few natural weaknesses for 150 metres to form one of Britain's premier rock playgrounds. They are formed of silica-rich volcanic rocks that erupted during the most violent period in the history of the Glencoe volcano.

Some hundreds of thousands of years after the relatively gentle emplacement of the sills, a series of cataclysmic explosions heralded a whole new volcanic phase. Gas-charged magma rose along the bounding faults of the crustal blocks, exploding as it neared the surface and the pressure was released. (Shake up a bottle of fizzy drink and then take the top off to experience the same effect.) The surrounding rocks were shattered and the eruptive plumes that shot upwards for thousands of metres were a mixture of rapidly solidified frothy magma (pumice), crystals, rock fragments and ash particles. As the denser material fell to the ground it moved rapidly away from the site of the eruption (the vent) as billowing clouds of searingly hot particles known as pyroclastic flows. The flows, still at temperatures of about 600°C, hurtled down steep slopes at speeds of up to 200 kilometres per hour, obliterating anything in their path. Their deposits are called ignimbrites and they form most of the mountain tops on the south side of Glen Coe, including the Three Sisters.

A recent pyroclastic flow
Mount St Helens, Washington

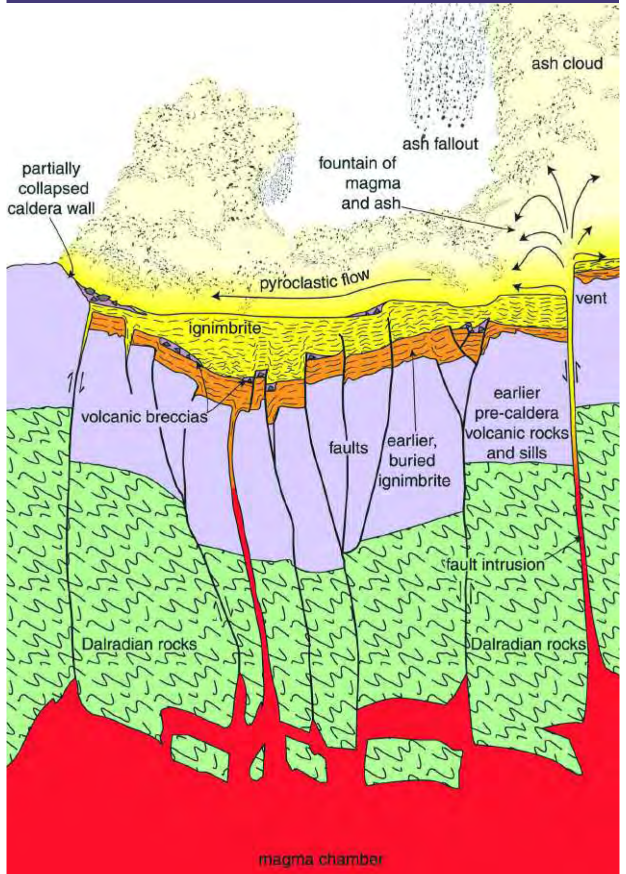
Today such flows are the most dangerous and destructive of all volcanic products and single eruptions have killed tens of thousands of people in eruptions such as those of Vesuvius (79 AD). In more recent times lives have undoubtedly been saved during such eruptions, as at Montserrat (1996-7), because of the better understanding that comes from studying both modern and ancient volcanoes.

A modern-day lava lake

Eruptions of large volumes of magma from a chamber beneath a volcano typically lead to collapse of the chamber roof and consequent subsidence of the overlying volcanic rocks. The subsidence forms a large surface depression called a caldera. These can be many tens of kilometres across and hundreds of metres deep; they should not be confused with volcanic craters, which are smaller features formed at the site of eruptions. The inner walls of a caldera are steep and unstable; they frequently collapse to add huge piles of volcanic debris to the caldera floor. At Glen Coe, the geological map clearly shows an oval outcrop of volcanic rocks that formed at the surface, entirely enclosed within rocks that originally formed the foundations to the volcano. The volcanic rocks have been dropped down along faults. This did not happen as a single event, and the individual fault-bounded blocks subsided at different times and at different rates, probably after each eruption. The overall effect is of a haphazard arrangement of blocks of volcanic rock within a broadly elliptical area, some 14 kilometres by 8 kilometres, that reflects the site of the caldera.

Each of the major explosive eruptions at Glen Coe might only have lasted for hours or days, but between the eruptions were long periods of inactivity that lasted for several thousand to tens of thousands of years. Rivers continued to redistribute volcanic debris, quite large lakes probably formed within the caldera and water accumulated in porous rocks underground. Consequently, at the start of each new eruption, the rising magma met with large volumes of water, resulting in particularly violent initial explosions and widespread deposits of volcanic ash, both as direct fall-out from the ensuing huge clouds of debris, and as pyroclastic flows.

The development of the Glencoe caldera



Above left and above right: Spectacular columnar jointing in andesitic lava, Stob Coire nan Lochan

Below: Swirling bands in the rock preserve the syrupy flow of rhyolitic magma at the Queen's Cairn'

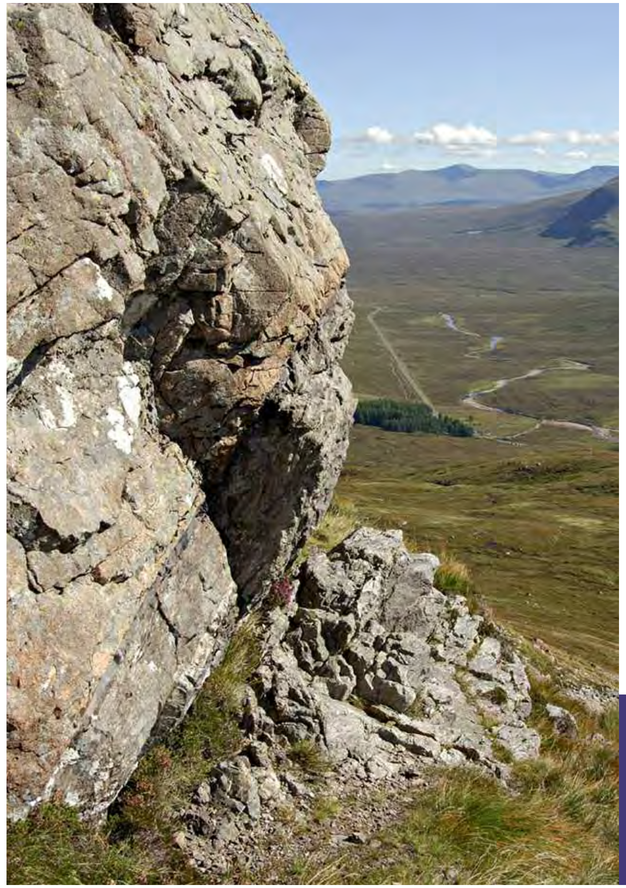
Ash fall-out and ash flows were not the only products of the caldera eruptions. In some eruptions, fountains of magma close to the vent released much of the trapped gas, so that when the hot, still fluid blobs fell to the ground they coalesced and flowed more like lava. If you look at the rock that the Queen's Cairn stands on, you can see swirls of banding and imagine it in a molten state, flowing like syrup.

The violent caldera eruptions all involved relatively silica-rich magma. Their products can be termed rhyolitic and are similar in composition to granite. Some of the later eruptions were of less silica-rich, andesitic magma, which was more fluid and contained less gas. Around the summits of Bidean nam Bian and Stob Coire nan Lochan are some unusually thick sheets of andesite, with spectacular cooling joints that form columns up to 200 metres high, far higher than any of the better known columns on Staffa, Mull or Skye. The magma probably erupted as fire fountains strung out along a fissure and then accumulated as a lake of molten lava hundreds of metres deep within part of the caldera.

The Glencoe Volcano – the final stages

The deep gully in the centre of the picture, known as the Chasm of An t-Sròn, has been eroded along a strand of the Glencoe ring-fault

We don't know the full story of the Glencoe volcano, because the products of its later eruptions have been removed by erosion over the past 400 million years. In fact we see its earlier deposits only because they have been dropped down by faults within the caldera and hence the level of erosion has only just reached them. The only possible clues to the nature of the later activity come from fault-intrusions, formed from magma that has risen along, and crystallised in, the many faults and fractures that cut the preserved volcanic sequence.



Outcrop on Stob Mhic Mhartuin, with pink fault-intrusion forming the upper part of the cliff. The band of dark rock below has been crushed in the ring-fault and melted by friction at the edges

Fault-intrusions occur along many of the faults bounding the rectangular crustal blocks that subsided into the caldera. But it is the ones that seem to encircle the volcanic rocks that are of the most interest. They follow what has become known as a ring-fault system, an interconnected set of faults that broadly define an ellipse marking the approximate position of the original caldera. The compositions of these intrusions are quite varied; some match the volcanic rocks that we still see today, but others do not and might represent the solidified feeders to the later eruptions whose products have long since been eroded away.

The margins of some of the fault-intrusions show clearly how they were related to movements on the faults and in some places, as on Stob Mhic Mhartuin near the Devil's Staircase, we can see rock that has been melted by friction along the fault plane. There, the line of the fault has been picked out by weathering and forms a ledge across the hillside. At the opposite end of Glen Coe the awesome Chasm of An t-Sròn, south of Loch Achtriochtan, marks another strand of the ring-fault system creating a remarkable landscape feature. The mountain of An t-Sròn is carved out of one of the largest of the Glencoe fault-intrusions, similar in composition to the andesite lavas nearby on Bidean nam Bian.

The Glencoe volcano could have been active for up to five million years, but that was not the end of the story, for magma continued to be injected into the crust throughout the Glen Coe and Ben Nevis area for another ten million years.

Magma at Depth: Dykes and Plutons

The volcano at Glen Coe was by no means the only one that existed towards the end of the Caledonian Orogeny in this area. The evidence for other volcanoes comes from igneous rocks formed by the cooling of magmas at depth. Beneath a volcano, magma is typically stored deep within the Earth's crust in a magma chamber, from which it can rise up to be erupted at the surface. When the eruption ends, the molten material in the magma chamber cools and crystallises slowly. The result is a large body (or pluton) of coarse-grained igneous rock such as granite, with crystals that are several millimetres to a few centimetres in size. Some of the magma begins its journey towards the surface, ascending up through fractures in the crust, but is never erupted. It cools in the cracks, forming vertical, sheet-like bodies of less coarse-grained igneous rocks called dykes.

The pink-weathering granite of Mullach nan Coirean contrasts with the grey-weathering quartzite ridge of Stob Ban in the middle distance

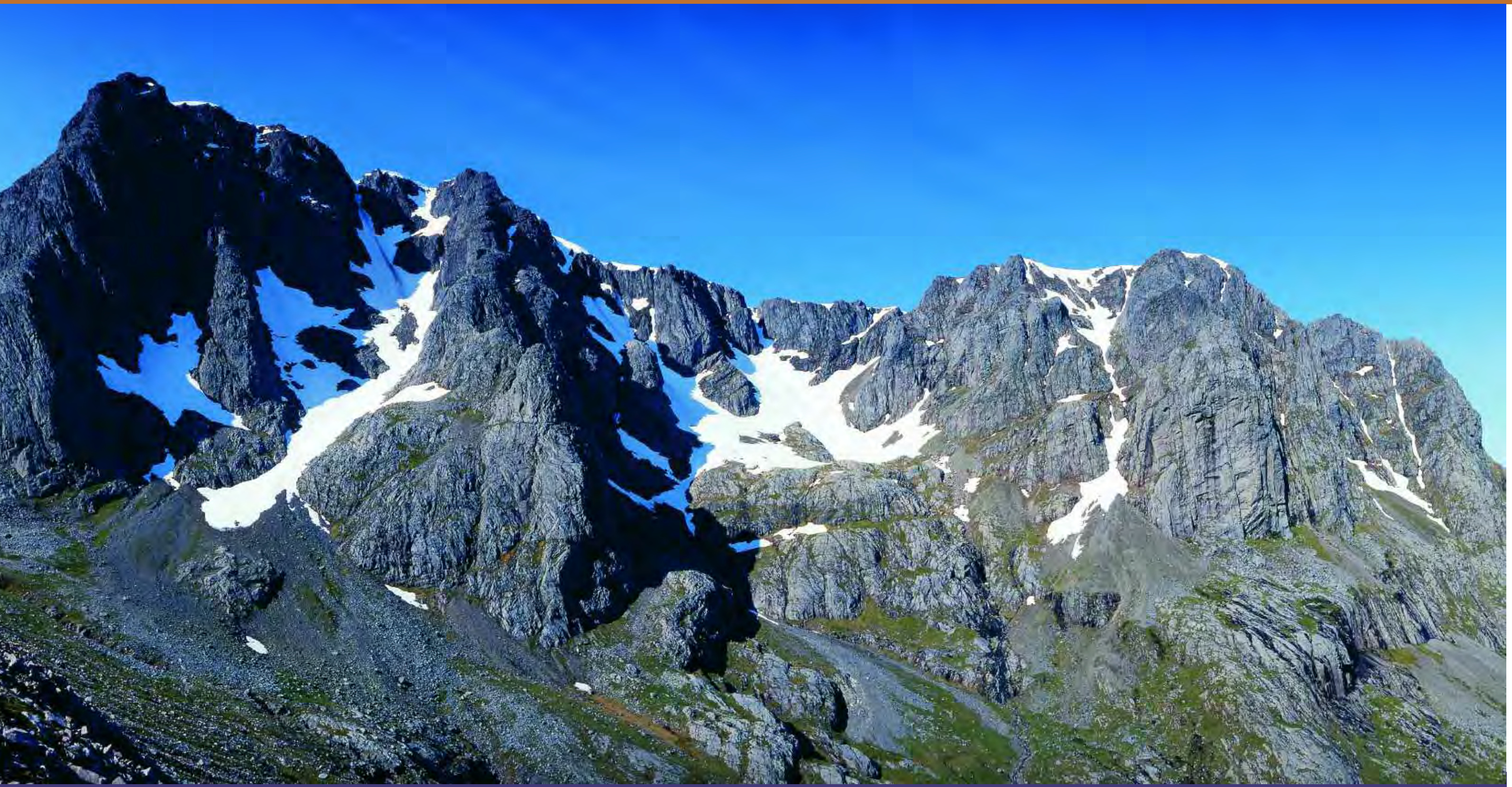
Pink granite in the River Etive

After the subsidence of the Glencoe volcanic rocks, magma continued to accumulate in a magma chamber, eventually forming a large granite body that cuts across the volcanic rocks of Glen Coe. This is the Clach Leathad Pluton, which forms the mountains of lower Glen Etive. The granite forms resistant cliffs and blocks in the River Etive, creating rapids that are a challenge for white-water canoeists. It is cut by a large number of dykes, which run from northeast to southwest and are known as the Etive Dyke Swarm. They cut across all the rocks of Glen Coe, forming prominent clefts and gullies on the hillsides.

Several other large bodies of granite in the area represent magma chambers that were almost certainly once part of volcanic systems. To the west of Glen Coe, the peaks of Beinn a'Bheithir – the Ballachulish Horseshoe – are formed of granitic rocks. Another distinctive granite forms the rounded, pinkish-weathering hill of Mullach nan Coirean at the western end of the Mamores, which contrasts strongly with the quartzite-capped mountains to the east. Outcrops of this very red granite can also be seen in the River Nevis above the Polldubh bridge. Granites commonly form high peaks, but an exception is the Rannoch Moor granite, which underlies the broad, topographically subdued area of Rannoch Moor. This is one of the oldest granite bodies in the area.

The broad, flat expanse of Rannoch Moor is underlain by a body of granite

Ben Nevis: Explosive Eruptions and Pyroclastic Flows



The towering North Face of Ben Nevis is largely composed of andesitic volcanic rocks

Volcanic rocks can also be seen on Ben Nevis, the highest mountain in the British Isles at 1344 m. From Fort William the mountain has a rather humped shape, but from the north and east the sheer cliffs of its north face can be appreciated. These contrasting sides of the mountain illustrate two quite different sides of its geology. The summit area of Ben Nevis, including the cliffs of the north face, consists of volcanic rocks that were erupted from a volcano, probably a few million years after the volcanic activity at Glen Coe. In contrast, the rocks of the lower slopes and surrounding hills are granite, formed in a magma chamber at depth.

Volcanic rocks form the North-east Buttress of the North Face of Ben Nevis

In the Allt a'Mhuillin, below the north face of Ben Nevis, are isolated outcrops of Dalradian rocks; just as at Glen Coe, these must have formed the land surface before eruption of the volcano. On top of these lie sedimentary rocks, mostly mudstones, formed in a lake. Above these, the lower parts of the north face are made up of volcanic breccias. These consist of fragments of volcanic rock of varying size, together with fine-grained particles of volcanic ash, all of which have been compressed together to form the rocks that we see today. These volcanic breccias were probably formed in pyroclastic flows and landslides that raced down the slopes of the exploding volcano.

The upper cliffs of Ben Nevis, and the summit plateau, are underlain by andesite lavas. These lavas were erupted from the volcano - possibly from a new, closer volcanic vent - and flowed out to cover the earlier breccias. The Ben Nevis andesites were thick and sticky, rather like treacle, and individual flows did not cover large areas of ground. Thus, there must have been a large number of separate eruptions to produce the thick pile of andesites that we see today.

Below: The ruined Observatory at the summit of Ben Nevis is built on frost-shattered blocks of andesitic lava

Ben Nevis: the Magma Chamber

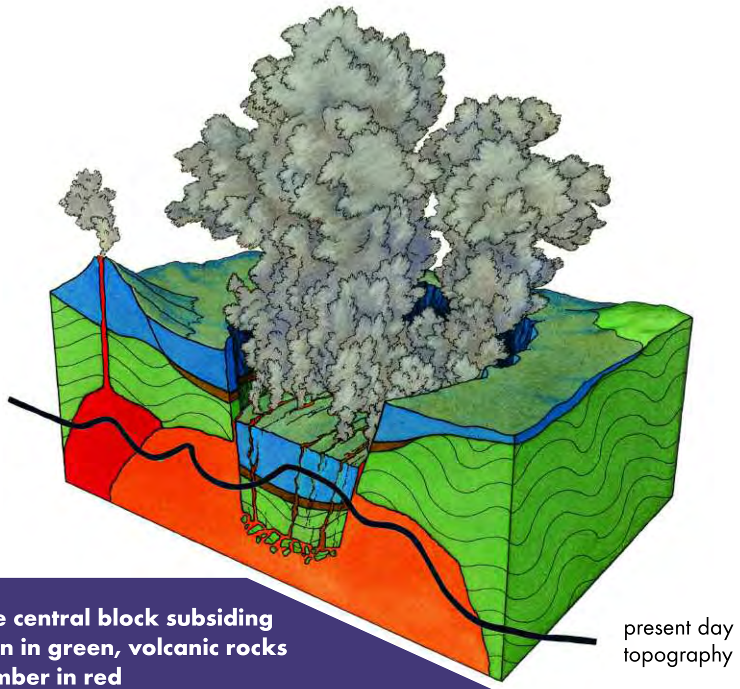
The peak of Carn Mòr Dearg is composed of pinkish grey granite

The smooth, pink granite slopes of Carn Mòr Dearg on the left contrast with the dark andesitic cliffs of Ben Nevis on the right

The lower slopes of Ben Nevis are carved from two different bodies of granite. The Outer Granite, which forms the hills of Meall an t-Suidhe and Aonach Mòr, was formed first. Most of it is pink in colour and coarse grained, with pink crystals of feldspar up to two centimetres in length. It is cut by abundant dykes of the Etive Dyke Swarm.

In contrast, the Inner Granite, seen on Carn Mòr Dearg, is finer grained and pink to grey in colour, and it is not cut by dykes. The Outer Granite had cooled and solidified, and the dykes had cut through it and cooled in turn, before the development of the Inner Granite magma chamber. These two granites were emplaced thousands, possibly millions, of years apart. Each magma chamber was probably associated with volcanic eruptions, but we do not know which of them, if either, was the source for the volcanic rocks of Ben Nevis.

We know that the volcanic rocks were formed at the surface, whereas the granites were formed at depths of a few kilometres. So how did they come to be adjacent to each other? The answer, as at Glen Coe, lies in volcanic subsidence. When an extremely powerful eruption occurred, large quantities of magma were removed from the magma chamber, and there was no longer enough support for the rocks above. A massive block of surface rock, containing the sediments and volcanic rocks that today form the summit of Ben Nevis, subsided downwards into the magma chamber. A caldera probably formed at the surface, but the upper parts of the volcano have all been eroded away, and only the rocks of the subsided block remain.



An illustration of the Ben Nevis volcano, showing the central block subsiding into the magma chamber. Dalradian rocks are shown in green, volcanic rocks in blue, and the granites forming in the magma chamber in red

Sculpting the Landscape

A modern-day ice sheet in Greenland, with only the peaks of the highest mountains protruding through the ice

By about 400 million years ago, the volcanic activity had ceased. Over hundreds of millions of years, this part of the Highlands was high ground, experiencing gradual erosion by wind and water. Eventually, almost all of the volcanic rocks of the area had been worn away, and only the subsided blocks at Ben Nevis and Glen Coe remained. Rocks that had formed deep within the Earth's crust were exposed at the surface, where we see them today. However, the final sculpting of the Highland mountains only occurred over the last two million years – during the Ice Age.

Parts of Scotland have been covered by glaciers for much of the last two million years, with warmer times between periods of glaciation. Glaciers have phenomenal erosive power; they pluck and scour away the underlying bedrock as the glacier grinds across the landscape. Each new glacial episode causes yet more erosion, which destroys much of the evidence for earlier glaciations. Thus, we only really know the details of the most recent glaciations in this area, which occurred between 29,000 and 11,500 years ago.

20,000 years ago, Scotland would have looked more like parts of Greenland do today. A large ice-sheet, over a kilometre thick, covered Rannoch Moor. Glaciers flowed westwards from the ice sheet, gouging out and steepening valleys such as Glen Coe, Glen Nevis and the trough of Loch Leven. Rock outcrops in the valleys were abraded and smoothed into whalebacks by the action of the ice.

The Lairig Eilde in Glen Coe; a classic U-shaped valley

Individual fragments of rock in the base of the glaciers scraped grooves known as glacial striae into the bedrock, some of which have been found at heights of over 900 m on the peaks of Glen Coe and on Aonach Beag. Blocks of granite, frozen into the ice on Rannoch Moor, were dropped by the glaciers on the peaks of Buachaille Etive Mòr and the Aonach Eagach. These are known as 'erratics' – blocks of rock that have been carried far from where they were formed. The presence of erratics and striae on the high peaks tells us that the glaciers overtopped almost all the mountains in the area.

The Last Glaciers

The Marinet Glacier, France, a modern-day corrie glacier

From about 18,000 years ago, the glaciers began to retreat, and may eventually have disappeared completely. However, another cold period began about 13,000 years ago, and glaciers re-formed in the area. Once again, an ice cap formed on Rannoch Moor, with glaciers flowing out down the glens.

These valley glaciers were up to about 600 metres thick, and many of the highest peaks remained ice-free. Smaller, subsidiary glaciers formed in the high corries, sculpting the classic glaciated ridges we see today. On the exposed peaks, arctic conditions prevailed. Water in cracks repeatedly froze and thawed, shattering the rocks to produce loose angular blocks.

A roche moutonnée in Glen Nevis

This last period of glaciation did not last long, as the climate rapidly warmed again and the ice retreated. By about 11,500 years ago, the glaciers had disappeared, leaving behind them moraines – piles of rock debris dumped from the melting ice. Many of the moraines around Glen Coe and Ben Nevis were deposited from stagnant, slowly melting ice. These form hundreds of hummocks spread out over a wide area; very good examples can be seen from the road across Rannoch Moor. Well-defined end moraines, which mark the past extent of glaciers, are only found in a few places, for example at the mouth of the Lairig Gartain.

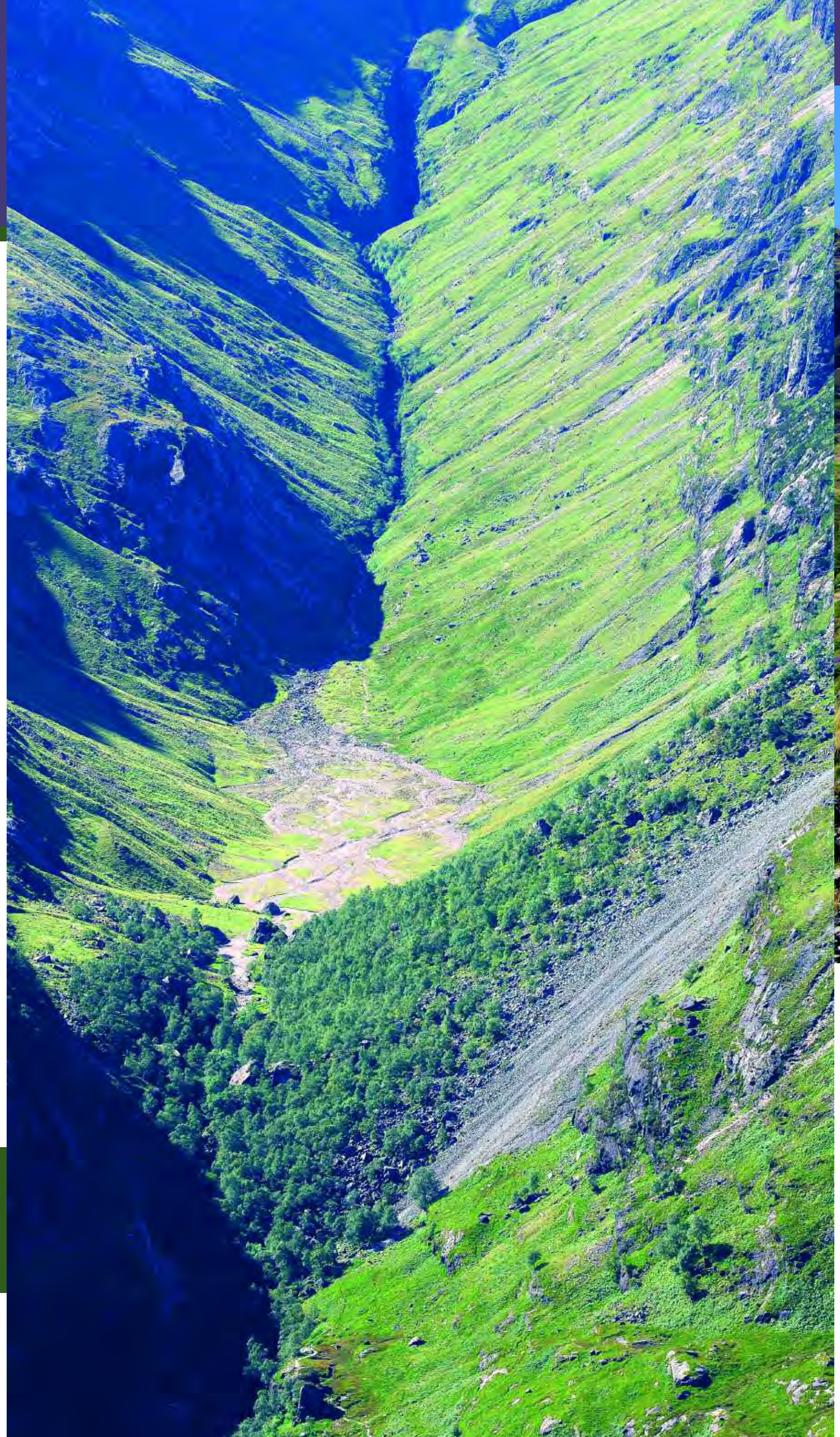
Over time, the large weight of ice locked up in the glaciers had depressed the Earth's crust. Although sea level rose initially as the glaciers melted, once this weight of ice was removed, the land slowly began to rise (or 'rebound'). Coastal features such as beaches, which had formed during the glacial period, were thus steadily raised above sea level. Today, excellent examples of 'raised beaches' can be seen around the shores of Loch Leven and Loch Linnhe, about eight metres above sea level. Indeed, the modern road actually runs along one such raised beach near Ballachulish.

Coire nan Lochan, in Glen Coe, would have held a glacier around 12,000 years ago

Rivers and rockfalls

As the glaciers melted away, freeze-thaw processes shattered the bedrock of the mountains, which became very unstable. The loose blocks tumbled down the steep slopes to form screes. In places, whole cliffs collapsed to produce rockfalls. By far the most spectacular rockfall occurred close to the mouth of Coire Gabhail, in Glen Coe, where boulders the size of houses lie scattered across the narrow glen between towering cliffs. This catastrophic event formed the largest single rockfall feature in the whole of Great Britain. The fallen boulders blocked the mouth of the valley, so that the stream that flowed through it could no longer carry its cargo of pebbles down to the River Coe. Behind this natural dam, the 'Lost Valley' has a completely flat floor where sand and pebbles have built up as they were deposited from the blocked stream.

Glacial meltwater, carrying large amounts of loose rock, led to rapid erosion along the lines of faults and dykes, forming deep gullies. Such features can be seen in Glen Coe around the 'Meeting of Three Waters', where gorges eroded along two separate dykes meet.



The tree-covered Coire Gabhail landslide, with the flat plain of the 'Lost Valley' behind

A major debris cone in Glen Coe

Rock debris piled up at the bottom of steep gullies, forming debris cones that are still growing today, and occasionally even bury the roads. Some of the debris cones in Glen Coe and Glen Etive are among the most spectacular in Britain. Rivers flowing down the glens redistribute some of the rock debris to form wide, flat gravel plains in the lower parts of the glens.

Study of pollen, preserved in peat bogs in the area, has given us a picture of how the landscape looked after the glaciers retreated. At first, the glens and moors were covered in moss and juniper scrub, whilst the mountains remained bare. Gradually, the lower slopes became covered in birch woodland, with the later arrival of other trees such as hazel, oak and pine. The native forests were important features of the Highland landscape until around 5000 years ago, when increasing numbers of people began cutting timber for fuel and clearing spaces for agriculture. Protecting and regenerating what remains of these native forests is an important part of managing the landscape of this area today.

The Landscape Today

The Blackwater Reservoir dominates an upland area now stripped of trees by man's activities

The landscape that we see today is by no means a natural one, mainly because of the removal of extensive tracts of native woodland that once cloaked the lower slopes. Attractive remnants remain, for example around Kinlochleven and in middle Glen Nevis, but the commercial plantations that have taken their place impart a very different character and are arguably man's biggest impact upon the present landscape.

Industry too has left its mark. The hydro-electric pipes that descend the lower slopes of Ben Nevis at Fort William are only too obvious and the Blackwater Reservoir, by far the largest man-made feature of the area, certainly cannot be ignored. However, most of the small defunct quarries, such as those at Ballachulish, are being assimilated back into the landscape, with a little help from restoration projects, and the large working limestone quarry at Torlundy, north of Fort William, is well screened by forest from most viewpoints.

Glen Coe forms part of a major communications corridor through the Highlands and hence cannot avoid being dominated by the A82 trunk road. Other roads, mainly along the coast and commonly following raised beaches, link small settlements to the urban conurbation of Fort William and Corpach. Sadly, the picturesque ferry across Loch Leven has been replaced by a bridge, which, although essentially functional, has become a feature of the modern landscape.

Older routes have less impact; the military road from Rannoch Moor over the Devil's Staircase and through to Fort William is barely visible from a distance and yet forms a major section of the West Highland Way long-distance path. The latter has revitalised the village of Kinlochleven, once an industrial centre dominated by its aluminium smelter and now full of outdoor activity-related businesses and a focal point in the surrounding landscape.

Recreation has had an impact, most notably through the ski facilities at White Corries, south of Glen Coe and Aonach Mor, north of Ben Nevis. And increased erosion by the feet of hillwalkers has necessitated the construction of paved footpaths, as in Coire nam Beith, in Glen Coe and on the old pony track leading to the summit of Ben Nevis.

Native woodland still cloaks the lower slopes above Loch Leven, hiding the coastal road

Scottish Natural Heritage and the British Geological Survey

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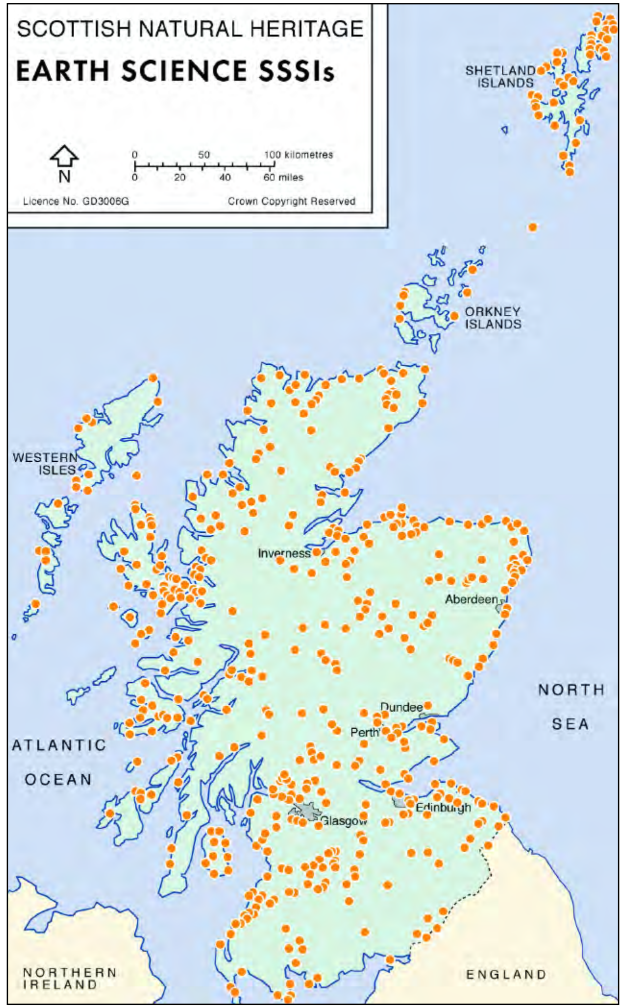

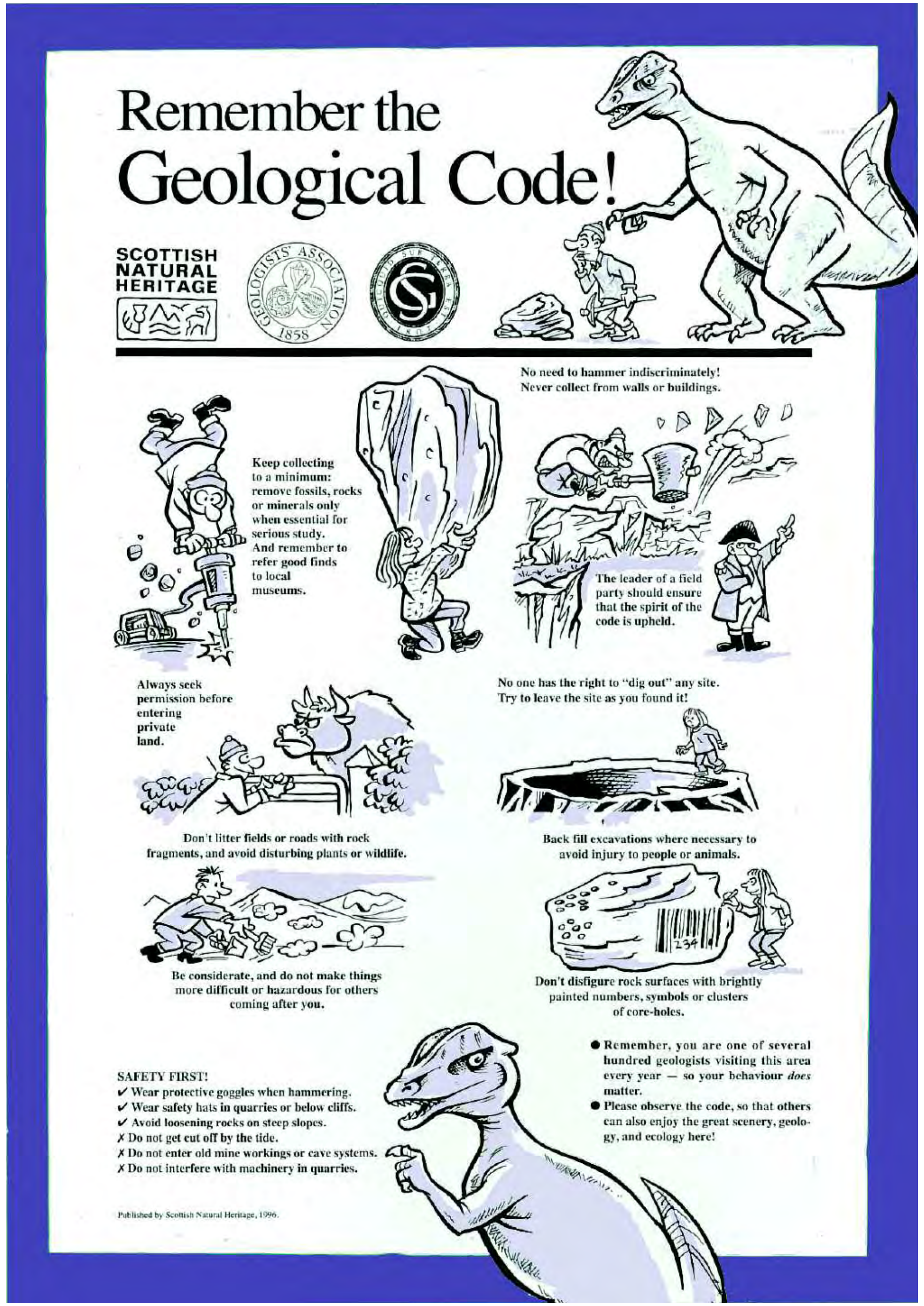

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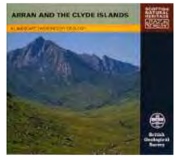

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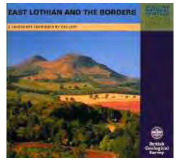

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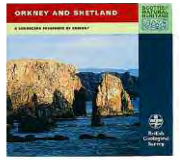

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