Geodiversity of the Loch Lomond and The Trossachs National Park:

Statement of Significance and Identification of Opportunities

Geology and Landscape (Northern Britain) Programme

Open File Report OR/07/036

BRITISH GEOLOGICAL SURVEY

GEOLOGY AND LANDSCAPE (NORTHERN BRITAIN) PROGRAMME

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Front cover

Loch Lomond from Duncryne Hill, showing the contrasting landscapes across the Highland Border. BGS photo P001223.

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Contents

1 Introduction

The natural beauty and striking landscapes of the Loch Lomond and The Trossachs National Park are a direct product of its geological history. A major landscape feature within the Park is the Highland Border, which separates the rugged peaks and deep glens of the Highlands from the lower, rolling hills and broad straths of the Lowlands. This landscape feature follows a geological structure known as the Highland Boundary fault zone, which separates ancient Precambrian metamorphic rocks in the Highlands from younger, softer, sedimentary rocks to the south. These geological differences have been exploited over time by the erosive power of wind, water and ice to produce the present-day landscape of the National Park.

This report has been prepared for the Loch Lomond and The Trossachs National Park authority, to provide an overview of the park's geodiversity. Section 2 of the report describes the geological history of the National Park. Sections 3 and 4 pick out key localities of interest for their geology and geomorphology, and opportunities for management and interpretation of the park's geological heritage are discussed in sections 5 and 6.

2 Geological history of the National Park

The geological history of the Loch Lomond and The Trossachs National Park begins around 700 million years ago, in the Precambrian era. At that time, Scotland lay within a major supercontinent, which was positioned close to the South Pole. However, then as now, continents could move gradually across the Earth's surface through the process of plate tectonics. Such tectonic processes led to the crust of the supercontinent being gradually stretched and thinned, until eventually it split, and a new ocean began to grow. This is known as the Iapetus Ocean, and it separated Laurentia (a continent containing Scotland, Greenland and parts of North America) from the continent of Gondwana to the south. The continent of Laurentia moved northwards as the Iapetus Ocean widened. Around the margins of the continent, sediments were laid down on the ocean floor; these sediments would eventually become the rocks of the 'Highland' part of the Loch Lomond and The Trossachs National Park.

In Scotland, the rocks that were originally deposited in the developing Iapetus Ocean are known as the Dalradian Supergroup. They underlie the southern and central Highlands, extending from the Great Glen in the north to the Highland Border in the south. The oldest rocks in the National Park belong to the earlier part of the Dalradian Supergroup; most of them are part of a unit known as the Argyll Group. They occur along the park's northern margin, from Ben Lui to Killin, and they also stretch southwards along Glen Ogle to Loch Lubnaig. These rocks were originally formed as sands and muds, deposited on the sea-bed before 600 million years ago.

600 million years ago, sub-sea volcanic eruptions culminated in the development of new ocean floor and signalled the final split of Laurentia from Gondwana. Some of the volcanic rocks formed at this time are commonly associated with limestones, which were laid down in relatively shallow waters, and they form a marker unit that runs along the north side of Glen Dochart, then southwards towards Strathyre. This unit is known as the Loch Tay Limestone Formation. Associated with the volcanic activity were submarine hot springs, through which mineral-rich, heated fluids circulated to form mineral deposits within the older Argyll Group sedimentary layers on the sea-floor.

As the Iapetus Ocean began to widen, deep offshore basins developed. Mud, sand and rock fragments eroded from the continent were carried into the ocean, and cascaded down the continental slope to be laid down in these basins. At times, distant volcanic eruptions produced volcanic ash that was deposited along with the other sediments, forming distinctive rock units that are now known as the Green Beds. All these rocks make up the Southern Highland Group, the youngest part of the Dalradian Supergroup, and they underlie much of the National Park, from Glen Dochart south to the Highland Border.

Deposition of sediments along the edge of the Iapetus Ocean continued through the Cambrian period and into the early part of the Ordovician period, around 480 million years ago. By now, the continental margin was more stable, and muds, sands, and lime-rich deposits were laid down in shallower waters. Early marine animals, such as trilobites, lived in the ocean waters, and their fossils have been found at two locations within the National Park. The rocks of this youngest part of the Dalradian Supergroup are now identified as the Trossachs Group.

Around 490 to 475 million years ago, the continuing deposition of oceanic sediments was violently disrupted by tectonic processes. A chain of volcanic islands, which had developed in the Iapetus Ocean, had been slowly moving towards the continental margin. Finally the island chain collided with the continent, causing a geological event known as the Grampian Orogeny. Large fragments of ocean floor were scraped up and thrust onto the continental margin, and remnants of this oceanic material can still be seen along the Highland Border today. However, much of the island chain was forced down beneath the continental margin. The combination of pressures from above and below meant that the sediments described above were buried and compressed, being squeezed into large-scale folds. As the external forces acting on these sediments changed, so new folds and structures were formed, with different shapes and orientations. At depth, the pressures and temperatures affecting the sediments increased, and so new minerals grew, in the process known as metamorphism. The resulting metamorphic rocks included psammites (formed from sandy sediments), slates and pelites (formed from muddy sediments), meta-limestones (formed from lime-rich sediments), and amphibolites (formed from sediments with a volcanic component). These are the rock-types that we see today across much of the Loch Lomond and The Trossachs National Park.

The compression of all these rocks thickened the continental crust, leading to uplift and the formation of a mountain chain, which was then rapidly eroded. Meanwhile, the Iapetus Ocean was gradually closing, as the ocean floor sank beneath the margin of the Laurentian continent at a subduction zone to the south of the previous collision zone. Eventually, around 430 million years ago, Laurentia collided with two other continental masses: Avalonia (England) and Baltica (Scandinavia). The effects of this collision were important in the rocks of the Northern Highlands, but may have been relatively limited in the Loch Lomond and Trossachs area. In the area of the National Park, deformation of the rocks around this time was largely restricted to displacement of blocks of rock along major fractures (faults) in the Earth’s crust. The most prominent of these structures is the Highland Boundary fault zone, which separates the older rocks of the Dalradian Supergroup from younger rocks to the south, and also forms a prominent landscape feature. However, it has always proved difficult to estimate how much movement actually occurred along this fault, and this is a debate that continues at the present day. Other faults, of similar age, run roughly north-east – south-west through Tyndrum and Inverarnan. It has been estimated that the blocks of rock on either side of these faults have moved several kilometres relative to each other.

Beneath the thickened crust on the continental margin, the sinking ocean floor began to melt, producing magma (molten rock). This hot, buoyant magma rose gradually upwards, through the Earth’s mantle and then through the crust. The faults described above, which probably extended down through the crust for several kilometres, provided conduits up which the magma could rise. Eventually, the magma reached a point at which, as it cooled, it was no longer less dense than the surrounding rocks, and so it ceased to rise. Magma from below continued to move up the fault, and then spread outwards, intruding into fractures in the surrounding rocks. Blocks of rock became surrounded by magma, and were themselves melted. The magma eventually cooled and crystallised, forming igneous rocks, which can now be seen on Garabal Hill above Inverarnan.

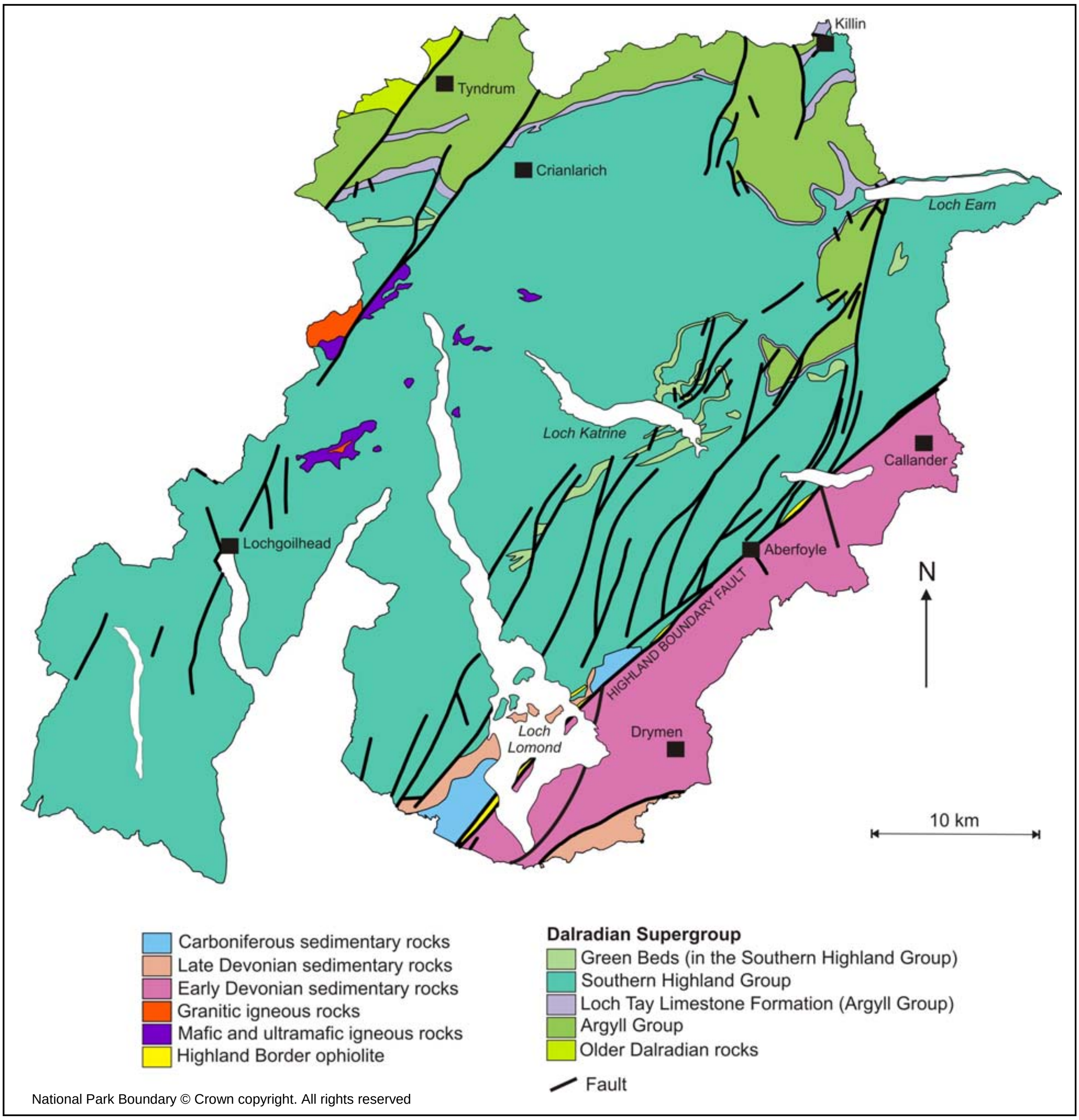

Figure 1: Simplified geological map of the Loch Lomond and The Trossachs National Park.

During the late Silurian into the Devonian period, from about 420 million years ago, Scotland lay to the south of the equator and was relatively arid. The Highland Boundary formed the dividing line between a chain of mountains to the north and an area of low-lying ground to the south. Seasonal rivers flowed down off the mountains, carrying with them sand and pebbles, which were then deposited on the lower-lying plains. Over time, this accumulated material became the red-coloured sandstones, mudstones and conglomerates that can be seen in the south-eastern part of the National Park. At that time, primitive plants were just beginning to colonise the land, and some plant fossils have been found within rocks just outside the park boundary. During the Devonian, volcanic eruptions also occurred, forming the rocks of the Ochil Hills, and some thin units of lava are preserved within the sedimentary succession inside the National Park.

By the start of the Carboniferous period, around 350 million years ago, the Highlands had been eroded down to rolling hills. Scotland was moving progressively northwards towards the equator, and with this came increased levels of rainfall. Sands and muds continued to be laid down in lakes and shallow rivers along the edge of the hills, and seasonal drying-out of the lakes led to minerals such as gypsum being precipitated. Within the National Park, rocks formed at this time only occur in a small area around the southern end of Loch Lomond.

The youngest rocks in the National Park are dykes, mostly of Carboniferous to Permian age, although some younger dykes date from the opening of the North Atlantic around 60 million years ago. These features are called dykes because they often stand proud of the surrounding rocks and so resemble dry-stone walls. They formed by the crystallisation of relatively small amounts of magma that moved up fractures within the rocks, then cooled and crystallised within the fractures to form sheet-like bodies of igneous rock. They are scattered across the area, but are often only one or two metres wide and so can be difficult to find. In the Midland Valley, dykes like these fed volcanic eruptions during the Carboniferous and Permian periods. The erupted lavas now form hills such as the Campsie Fells, just outside the park boundaries; the only volcanic rocks of this age within the park are found on the small volcanic plug of Duncryne Hill.

Farther north, around Tyndrum, faults and fractures provided conduits not for magma, but for other fluids such as heated water, which carried dissolved minerals picked up from the rocks at depth. These dissolved minerals were re-deposited along the sides of the fractures as the water cooled. In the Tyndrum area, mineral veins formed in this way include sulphides of lead, iron and copper, but also gold and silver. Gold has been exploited at Cononish, and lead at Tyndrum.

From Carboniferous times onwards, the area of the Loch Lomond and The Trossachs National Park was a stable region, largely remaining as dry land even when much of central Scotland was covered by the sea. For that reason, there are no younger rocks within the park. The next important episode in the park's history began at the beginning of the Quaternary period some 2.6 million years ago, with the onset of the Ice Age.

During the Quaternary period northern Europe has been subjected to a series of climatic cycles, represented by alternating glacial and interglacial conditions. The glacial episodes are characterised by cold, unstable climate, and growth of large ice-sheets in the high and mid-latitudes. In contrast, interglacials (such as the current Holocene period which began approximately 11,500 years ago) experience a warmer, more stable climate, with more restricted ice cover.

Evidence for the earliest glaciation at mid-latitudes comes from deep-sea cores from the floor of the North Atlantic. Layers of debris dropped by icebergs indicate that calving glacier fronts were present around the north Atlantic region by 2.4 million years ago. Although no direct evidence has been found for glaciation of Scotland at this time, it remains possible that ice did build up, at least in highland areas. The first direct evidence for western Scotland being ice-covered comes from glacial sediments offshore, demonstrating that an extensive ice-sheet covered Scotland about 440,000 years ago, terminating at the margin of the continental shelf. The entire Loch Lomond and Trossachs area was probably overwhelmed by ice at that time.

There is some uncertainty as to when the most recent major glaciation in Britain (known as the Main Late Devensian) began. Organic deposits underlying glacially deposited material (till) have been identified to the south-east of the Loch Lomond and The Trossachs National Park in the Campsie Fells. These organic deposits are approximately 36,500 years old, suggesting that significant ice build-up in the area did not occur until after 36,500 years ago. The Main Late Devensian (MLD) ice sheet probably reached its maximum extent about 25,000 years ago, at which point even the highest mountain summits within the National Park area were submerged by ice.

Subsequent climatic warming caused the ice sheet in Scotland to retreat westwards and northwards, towards source areas in the highlands. At that time a large proglacial lake was temporarily dammed by the retreating ice margin in the Endrick Valley, by the south-east corner of the National Park

The weight of the MLD ice sheet had depressed the earth's crust beneath it (a process known as isostatic depression). At the same time, global sea-level had been lowered by more than 100 m, due to a significant volume of water being locked up in continental ice sheets. As Scottish ice receded, rebound of the land surface failed at first to keep up with the worldwide (eustatic) rise in sea-level resulting from the melting of ice-sheets. Consequently, the Endrick and Blane valleys were inundated by the sea up to altitudes of 30 m above modern-day sea level, while Loch Lomond itself was temporarily turned into a sea loch. However, continued land uplift during this warmer period eventually equalled and exceeded the sea-level rise, allowing the net sea-level to finally begin to fall. Marine sediments deposited then are known as 'Clyde Beds', typically comprising clays and silts, and locally containing shells of cold water species.

A sharp, short-lived period of renewed cooling 12,700 to 11,500 years ago, known as the Loch Lomond Stadial, caused readvances of many glaciers in upland Britain. A large ice cap developed over the western Highlands, extending as far south as the southern edge of Loch Lomond – from where this cold period takes its name. Once more ice-dammed lakes formed in the Blane and Endrick valleys. At its maximum extent, the surface of the Loch Lomond Stadial ice cap reached 900 m in altitude near its centre over Rannoch Moor. In the Loch Lomond and Trossachs area, higher peaks such as Ben Lui, Beinn Ime and Ben Lomond protruded above the ice surface, as nunataks in Greenland do today. Following renewed warming, the ice cap gradually wasted and its outlet glaciers retreated towards a source area over Rannoch Moor. However, this retreat was not uninterrupted and many glaciers oscillated at their margins, depositing moraines which can be seen as bouldery mounds scattered over much of the National Park area today.

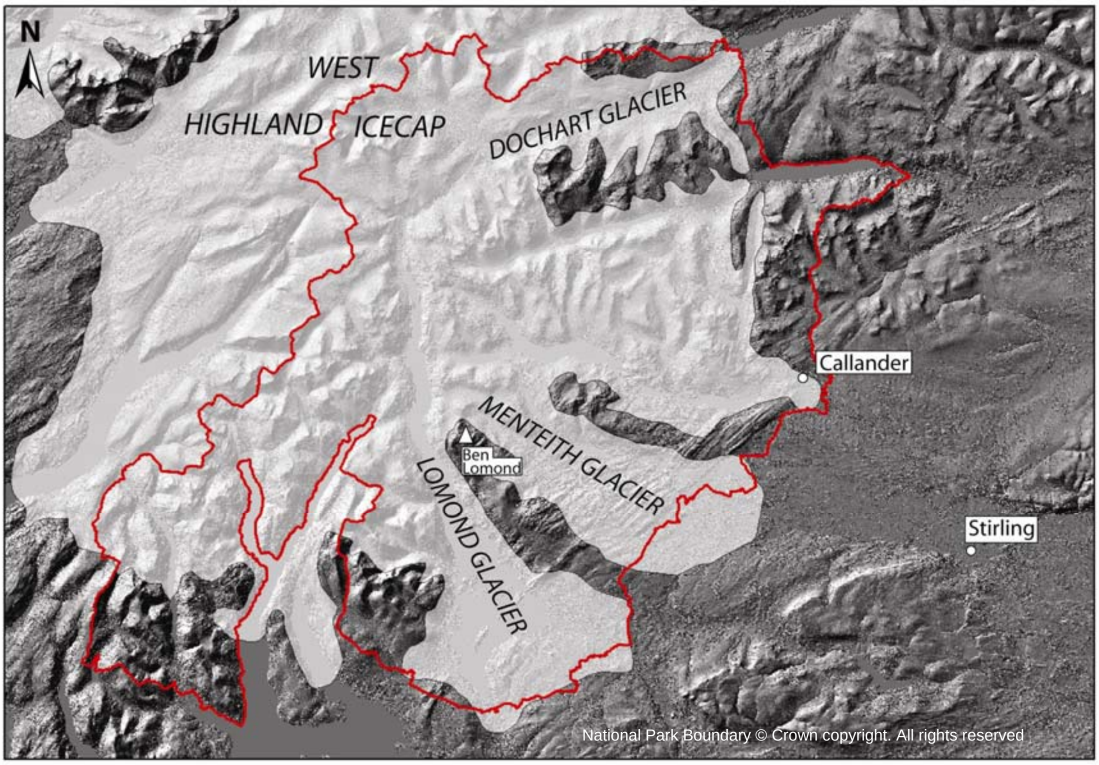

Figure 2: Reconstruction of the glaciers that existed within the National Park during the Loch Lomond Stadial, shown on a shaded relief model of the area.

During the Loch Lomond Stadial relative sea-level was still slightly higher than today, and a raised shoreline, known as the Main Lateglacial shoreline, was cut along many coastal areas of western Scotland. It is thought that intense periglacial activity brought about by the cold temperatures, coupled with increased storminess, enabled accelerated coastal erosion at that time.

The cumulative erosional impact of the Quaternary glaciations dramatically affected the landscape and influenced the pre-glacial drainage systems in the National Park area. Many river valleys were deepened and widened by glacier ice to form their present classic U-shaped form.

Loch Lomond itself was excavated through several glacial cycles, cutting across the regional geological structure and dissecting river valleys which originally ran west-east towards the Forth.

Following renewed warming and final deglaciation in Scotland, Loch Lomond once again existed as a fresh water loch. However, between about 7,000 and 5,500 years ago, sea-level again increased, due to melting of North American and Scandinavian ice sheets. Once more, Loch Lomond became a sea loch with shoreline features (known as the Main Postglacial shoreline) forming at heights up to 12 m above modern-day sea level. Continued isostatic rebound in Scotland has since elevated the land surface, restoring Loch Lomond to its current freshwater condition.

Preserved pollen in peat bogs and lake sediments show a typical vegetation succession for the southwest Scottish Highlands following disappearance of the last glaciers. Much of the National Park area would have, at first, been dominated by an open grassland environment, similar to parts of Scandinavia today. Taxa such as crowberry then became established, followed by juniper, birch and hazel and then pine. Some pollen evidence suggests that woodland development along the western sea-board may have been restricted, due to strong south-westerly winds. About 5000 years ago woodland began to decline throughout the south-west Highlands. An expansion of plants of wet blanket-mires occurred at the same time, suggesting that an increasingly wet climate was the cause.

3 Key bedrock features and localities in the National Park

3.1 THE DALRADIAN SUPERGROUP

The largest part of the Park, north of the Highland Border, is underlain by the metamorphosed sedimentary rocks of the Dalradian Supergroup. As discussed above, the rocks in most of the park belong to the youngest units of the Dalradian, the Southern Highland and Trossachs groups; but older Dalradian units, chiefly belonging to the Argyll Group, outcrop along the Park's northern boundary. Some of these older units contain volcanic layers (amphibolites) and mineralised layers, formed by hot springs associated with volcanic activity. A good example of one such mineralised layer is in the river above **Auchtertyre** [NN 354 291], south of Tyndrum. The rocks here are quartzites (quartz-rich sandstones) and they contain abundant sulphide minerals.

The Park contains some of the classic localities for study of both the structure and stratigraphy of the Southern Highland Group, in particular the areas around the **Bealach nam Bo** [NN 480 065] and **Duke's Pass** [NN 500 030] in the Trossachs. Both of these areas are Geological Conservation Review (GCR) sites (Table 1). The rocks in this area are chiefly metamorphosed sandstones, although slates are well-exposed at the abandoned quarries at **Aberfoyle** [NN 505 032] and **Luss** [NS 356 930]**.** Green Beds (sandstones containing some minerals derived from volcanic rocks) can be seen at Bealach nam Bo. The metamorphosed sandstones contain a variety of small-scale features that were formed as the sandstones were originally deposited: these include graded bedding, with coarser grains at the base of a sandstone layer; scours, formed by water flowing over the sediment; and rare ripple marks. By analogy with modern environments, geologists have used these features to show that these sediments were laid down on the ocean floor, over 500 million years ago, by sub-sea sand avalanches known as turbidity currents.

The Bealach nam Bo and Duke's Pass areas are also important localities for understanding the structures formed during the Grampian Orogeny, around 470 million years ago. In this area, geologists have unravelled complex fold structures in the rocks to recognise several different phases of deformation, which in turn can be related to larger-scale tectonic processes.

The very youngest rocks associated with the Dalradian Supergroup (the Trossachs Group) are well-exposed in the **Keltie Water** [NN 645 125], near Callander, in the nearby **Leny Quarry** [NN 615 098], and in **Lime Craig Quarry** [NN 533 018] and **Bofrishlie Burn** [NS 498 988] near Aberfoyle. The first three of these localities are also GCR sites. Limestones from both Leny and Lime Craig quarries contain fossils, including trilobites, that date from the Cambrian and early Ordovician periods. These rocks have been the source of much debate. Some geologists have suggested that they are part of the Dalradian succession, and thus provide evidence that sediments were being deposited along the Laurentian margin right up until the collision that caused the Grampian Orogeny; others have suggested that these rocks are 'exotic' – that is, they were brought into contact with the Dalradian Supergroup by tectonic processes. The most recent work has supported the former theory, but research in this area continues.

3.2 THE HIGHLAND BORDER

The southern margin of the Highlands is marked almost everywhere by the Highland Boundary fault zone, and along this fault zone are several slivers of rocks that are interpreted as part of an ophiolite – a slab of ocean floor that has been thrust up onto the continental margin. Elsewhere in the world – in Cyprus and Oman, for example – much larger, undeformed ophiolites can be seen and these have allowed geologists to understand much about how the ocean floor is formed. These large ophiolites typically consist of a certain assemblage of rocks. Some of these rock-types can be seen in the Highland Border ophiolite, although it is worth noting that many of the characteristic parts of the ophiolite assemblage are missing.

Within the National Park, rocks of the Highland Border ophiolite are best seen in the GCR site around **Arrochymore Point** [NS 419 915], on Loch Lomond near Balmaha. Outcrops of a rock-type called serpentinite can be seen on the slopes just above Arrochymore Point. Serpentinite is formed by the alteration of very iron- and magnesium-rich 'ultramafic' rocks, which are common in ophiolites around the world; these rocks come from the uppermost part of the Earth's mantle. Associated with the serpentinites are conglomerates, consisting of pebbles of serpentinite and other ophiolitic rock-types enclosed within limestone. These conglomerates can be seen on the south-western flanks of **Conic Hill** [NS 415 914] and on the island of **Inchcailloch** [NS 410 907]. Similar rock-types can be seen at Lime Craig Quarry near Aberfoyle.

The Highland Boundary fault zone forms a major landscape feature, best seen in the view across Loch Lomond from Conic Hill, but the individual faults within the zone are not easily studied in detail within the Park, and debate continues about the nature of the movements in this fault zone.

Figure 3: View from Conic Hill along the Highland Boundary fault zone. BGS photo P221039

3.3 MINERALISATION

The main sites of mineralogical interest lie in the northern part of the Park, around Tyndrum. There are three GCR sites in this area: the **Tyndrum Main Mine** [NN 320 305], **Crom Allt** [NN 333 320], and **Ben Oss** [NN 291 265]. The workings of Tyndrum Main Mine form a distinctive scar on the landscape, easily viewed from the A85. This mine was worked for lead in the 17th, 18th and early 19th centuries, and indeed the village of Tyndrum began life as a miner's village. Several other localities around Tyndrum were also worked on a smaller scale, such as the vein in the Crom Allt just north of Tyndrum. The mineralisation in the area takes the form of mineral veins, which have formed along networks of fractures associated with the Tyndrum Fault. All these veins contain quartz, with associated sulphides of lead, zinc, iron and copper, as well as native gold and silver around **Cononish** [NN 300 285]**.** Localities where the veins can be studied in detail include the Tyndrum Main Mine itself, the currently inactive **Eas Anie** adit west of Cononish [NN 292 287], and in the Crom Allt stream north of Tyndrum. In the gully of the Allt Coire Chruinn, on the north side of Ben Oss, there are excellent exposures of a splay of the Tyndrum Fault; this is one of the best localities for the study of structures associated with faulting in the Park.

3.4 IGNEOUS ROCKS

As described above, many igneous rocks (rocks formed by the cooling and crystallisation of magma) were intruded into the crust of Scotland following continental collision some 430 million years ago. The most important examples of igneous rocks in the Loch Lomond and The Trossachs National Park occur at the northern end of Loch Lomond, on **Garabal Hill** [NN 305 175] and **Meall Breac** [NN 260 160]. These intrusions, known as the Garabal Hill – Glen Fyne igneous complex, are important because they include igneous rocks of a wide range of chemical compositions, from very iron- and magnesium-rich 'ultramafic' rocks to more silica-rich rocks such as granite. The ultramafic compositions, in particular, are virtually unique among igneous rocks of this age in the British Isles. This igneous complex has been the subject of research into how magmas of different compositions form since the end of the 19th century, and work in the area has continued into recent years.

Igneous rocks of Permo-Carboniferous age are generally not a distinctive feature of the National Park; the exception is the small volcanic plug of **Duncryne Hill** [NS 435 859] at the south end of Loch Lomond.

3.5 DEVONIAN SEDIMENTARY ROCKS

Sedimentary rocks of Devonian age, belonging to the Arbuthnott-Garvock and Strathmore groups, underlie the south-eastern part of the National Park. They are well exposed around the town of Callander, particularly at the popular walking spots of **Callander Craig** [NN 630 088] and **Bracklinn Falls** [NN 645 085], and also on **Ben Gullipen** [NN 595 045] in the Menteith Hills. These rocks include conglomerates (composed of rounded pebbles held together by a finer-grained groundmass) and sandstone, deposited in rivers flowing off the high ground to the north. Some layers of mudstone also occur, and were probably deposited on the floodplains of the rivers.

4 Key geomorphological features and localities in the National Park

Much of the mountainous area in the National Park bears evidence of its glacial history. Preglacial V-shaped river valleys were widened to form classic U-shaped valleys, such as **Glen Dochart** and **Glen Cononish**. In many cases, valleys were also deepened through several cycles of glacial erosion, and are now occupied by deep lochs including **Loch Lomond**, **Loch Katrine** and **Loch Voil**. Excellent examples of glacially carved corries exist on the north-eastern sides of **Ben Lui** [NN 266 263] and **Ben Lomond** [NN 366 028]. Receiving more shading from sunlight, and being positioned to capture snow blown by strong westerly winds, these NE-facing corries would have provided ideal sites for glacier growth at the beginning of the cold climatic stages.

As the ice flowed over the landscape, debris carried at its base scoured and smoothed the rock surface below (a process known as abrasion). Excellent examples of glacially smoothed bedrock surfaces can be seen by the **Rowardennan** car park [NS 359 988]. Here, bedrock undulations have been smoothed to form ‘whalebacks’.

When the Loch Lomond Stadial ice cap grew to its maximum extent, ice filled the valleys in the northern part of the National Park. The surface of the ice cap reached up to 900 metres in altitude, with peaks such as **Ben Lui**, **Ben More** [NN 433 245] and **Ben Oss** [NN 287 253] protruding above the ice. Due to the intensely cold conditions, rocks on these exposed peaks were subjected to considerable frost-shattering. Today, the angular blocky debris on the high summits contrasts with the glacially smoothed landscape in the valleys below. During their final retreat, glaciers throughout northern and central parts of the National Park deposited suites of moraines at their margins. Although now more subdued, these landforms can be observed as ridges and hummocks scattered along valley floors, with particularly good examples occurring in **Glen Cononish** [NN 331 286].

Figure 4: Hummocky moraines at the mouth of Glen Cononish. BGS photo P002838 (taken in 1975)

Landforms occurring around the south-eastern border of the National Park, close to **Gartness** [NS 495 875], provide important clues about the glacial history of the Highland Border during the Late Devensian. Numerous streamlined landforms, known as drumlins, occur in this area. The drumlins are particularly clear when viewed from the ground during periods of low-angled sunlight, or by using aerial photographs. These landforms developed underneath the Main Late Devensian ice sheet, their orientation documenting a general west – east ice flow direction in the Gartness area at that time. Some of the most prominent landforms around Gartness are a series of terminal moraine ridges that formed at the glacier margin during the later, Loch Lomond Stadial. The outermost of the ridges extends from near Drumhead [NS 494 882] to Upper Gartness [NS 496 868], broadly along the boundary of the National Park. Sediments preserved in this ridge provide a record of proglacial lake formation during initial ice sheet retreat, followed by marine invasion and a subsequent glacier readvance during the Loch Lomond Stadial. The sediments on the western side of the ridge were heavily deformed by the readvancing ice, but to the east they remain undisturbed demonstrating that the renewed glaciation did not extend that far.

Further evidence documenting the readvance of ice in the southern part of the National Park can be observed at **Croftamie** [NS 473 861]. Here, sediments exposed by railway cuttings reveal an organic layer containing plant remains, lying on top of till deposited by the Main Late Devensian ice-sheet, but under till deposited during the Loch Lomond Stadial. The plant remains are typical of colder climates, but importantly, they demonstrate that the area was ice-free for a short period. The Croftamie section is the type site for the Loch Lomond Stadial in this area, and is a GCR site.

Further to the north, the **Lake of Menteith** [NN 575 006] marks where a Loch Lomond Stadial glacier thrust material up into a series of ridges that can be observed on the eastern side of the lake. A source depression was left to the west of the ridges, and this is now occupied by the lake. The Lake of Menteith and associated ridges are an excellent example of a glacial landform known as a ‘hill-hole pair’.

Peat and lake sediments recovered from an infilled kettlehole at **Mollands** [NN 628 068] have provided a valuable and detailed record of vegetational history for the south-eastern part of the National Park. Crucially, these deposits lie just up-valley from a chain of important end moraines near **Auchenlaich (**south-east of Callander; [NN 642 077 to NN 638 051]), marking the maximum extent of Loch Lomond Stadial glaciation in that area. Occurring in association with the Callander moraines, basal sediments from the Mollands kettlehole provide a constraint on the timing of final deglaciation in this area. Radiocarbon dates from these sediments demonstrate that ice began to withdraw from the Callander area about 12,600 years ago.

The interplay between recent glaciations and fluctuating sea-levels is well illustrated along the southern shore of Loch Lomond. Here, a well developed shore platform extends up to half a kilometre offshore. It can be observed at **Ross Priory** [NS 413 876], **Portnellan** [NS 404 873] and **Claddochside** [NS 427 878] and is associated, in places, with a backing cliff up to 15 metres high. The shore platform meets the backing cliff at about 12 metres above present sea-level, demonstrating that the feature was formed when sea-level stood at that height, inundating the Loch Lomond basin. It has been correlated with the Main Lateglacial shoreline in Western Scotland. Importantly, glacial deposits left by readvancing ice in Loch Lomond sit on top of the platform at southern Loch Lomond, clearly showing that the shoreline was cut before the glacier readvance reached its maximum extent. Further shoreline features relating to a mid-Holocene marine invasion of Loch Lomond can also been seen here.

Evidence of former high sea-levels also exists along the shores of **Loch Long** and **Loch Goil** to the west. Here, fragments of flat-topped raised beach deposits can be seen at altitudes of up to 12 m above sea-level. Indeed, raised shoreline deposits also occur around the southern end of **Loch Eck** [NS 142 872], demonstrating that it too was once inundated by the sea.

The repeated growth and removal of ice caps and glaciers in the Scottish Highlands made mountainous areas vulnerable to slope failures. Periods of glacial erosion and valley steepening, followed by destabilisation of mountainsides due to the removal of ice, allowed both slow and rapid rock slope failures to occur following glaciations. One of the most spectacular summits in the National Park area, **The Cobbler** [NN 260 058], was formed as a result of such processes. Elsewhere, differential rebound of previously ice-covered mountains has been considered a mechanism for triggering slope failure and deformation (for example on **Ben Vane** [NN 533 122]). However, the origin of a further, remarkable suite of rock slope failures at **Glen Ample** [NN 596 100] remains less certain.

Although major rock slope failures are now largely relict, a number of more recent, smaller landslides have also occurred in the National Park area. For example, shallow landslides have occurred in **Glen Ogle** [NN 573 266] in 2004 and at the **Rest and be Thankful** pass [NN 236 070] at the end of 2007. In both cases, the landslides were believed to have been triggered by prolonged, intense rainfall and involved mass flow of mostly glacial deposits.

As the landscape adjusts to non-glacial conditions, much of the more recent modification has been carried out by water. The spectacular **Falls of Dochart** [NN 571 324] occur where a wide, shallow area of bedrock is exposed within an otherwise, largely sediment-filled river basin. The river gradient steepens at this point and a stepped series of waterfalls occur where water flow has been deflected along lines of weakness within the metasedimentary rock. The falls may have begun to form during the most recent glacial episode, although the major erosional features probably formed following retreat of the last glaciers. In contrast to the largely erosional Falls of Dochart, the delta where the lower **River Balvag** [NN 560 153] enters Loch Lubnaig provides an excellent example of rapid sediment accumulation in a lower energy environment. Indeed, sedimentation rates here have been so rapid that a small lochan, 'Loch Buidhe', became isolated from Loch Lubnaig in 1951. Only 200 years earlier, the area occupied by the lochan was part of the main loch. Further recent landscape modification occurs where the lower **River Endrick** [NS 455 880] enters the south-eastern corner of Loch Lomond. Here, the river actively meanders through low, gently undulating ground - much of which was deposited as a delta around 6000 years ago, when the sea stood 12 metres higher than today, inundating the loch. The lower Endrick floodplain provides excellent examples of cut-off channels, ox-bow lakes and point bars which have formed as the river has laterally migrated over recent times.

Figure 5: Aerial photo of the River Endrick as it enters Loch Lomond. BGS photo P001248

5 Suggestions for geological management in the National Park

5.1 GEODIVERSITY SITES

Geodiversity can be defined as:

> *'the variety of rocks, minerals, fossils, landforms, sediments and soils, together with the natural processes which form and alter them'*

Geodiversity is a fundamental natural resource – all raw materials that cannot be grown and all energy that cannot be generated by renewables have to be won from the Earth's crust using geological science. It is the source of much of our prosperity, a key factor in our cultural identity, and will play a fundamental role in our nation's future development. Understanding of geology is vital to the design and location of buildings and infrastructure as well as to the safe disposal of waste, and the identification and management of a wide range of natural and man-made hazards. An awareness of geodiversity also helps us to understand our environment and predict environmental change in the future.

Geology is a field-based science and so geodiversity sites are of crucial importance for geological research, teaching and training. The geodiversity sites of the Loch Lomond and The Trossachs National Park represent an important educational resource, both for professionals and students in the geosciences, and for all other visitors; this resource needs to be managed so that it is available to all.

Some geological localities within the National Park have been recognised as Geological Conservation Review (GCR) sites (Figure 8), and about half of those have been notified as Sites of Special Scientific Interest (SSSI). The Geological Conservation Review process was carried out between 1977 and 1990, and involved systematic selection of geological sites that are considered either to be of *international* importance; to contain *exceptional*, rare or unique, features; or to be *representative* of the geological heritage of the UK. GCR sites within the National Park are listed at Appendix 1. Those sites that are notified as SSSI are protected under the Nature Conservation (Scotland) Act 2004 – planning authorities are required to consult SNH when determining an application for a development which might affect a SSSI – but un-notified GCR sites do not have any statutory protection. However, notification of GCR sites as SSSIs was not necessarily carried out in a structured way, and so un-notified GCR sites may be at least as important for the geological heritage as notified sites. All GCR sites are considered to be worthy of the protection afforded to SSSIs.

Sections 3 and 4 above mention a number of localities and areas that are of regional importance for their geological and geomorphological features, but that are not recognised as GCR sites. These sites could be recognised as Local Nature Conservation Sites (LNCS), although it should be noted that the list of sites given here is not exhaustive, and that a complete assessment of geological LNCS within the National Park could only be carried out as part of a full Geodiversity Audit. Management of LNCS should follow the recommendations in the document *Guidance on Establishing and Managing Local Nature Conservation Site Systems in Scotland*, published by Scottish Natural Heritage in March 2006, including the following points:

- The Local Plan should include an explanation of the purpose of the LNCS designation. It should set this in the context of other nature conservation policies, including statutory designations. The Local Plan should make available full details of the process followed in selecting sites. Ensuring that LNCS are an effective mechanism requires good communication between development control officers and officers dealing with LNCS. The presence of LNCS should be included early in discussions about the location of development, and planning authorities should consider opportunities to enhance LNCS during development (Para. 5.3).

- Planning policies for the protection of LNCS should be distinct from policies relating to statutory designations, and should be set out in the context of these policies. Where a planning application concerns land selected as a LNCS, the developer should carry out an assessment of the impact of the proposal on the nature conservation interest of the site. Where it is decided, for significant reasons of social and economic importance, that development should go ahead, there should be provision as far as possible for retention of nature conservation interest through planning conditions. Where this is not possible, the loss should be compensated for by site enhancement elsewhere through planning agreements or conditions (Para. 5.4).
- The location of LNCS should be clearly identified on the Local Plan proposals map, and boundaries shown where scale allows. A formal record of the evaluation of the site should also be readily available within the planning process. To this end, Site Statements should be made available as supplementary planning guidance within the Local Plan, and included in the consultation process for the Local Plan (Para. 5.5).

5.2 GEODIVERSITY AND PLANNING

Currently, the best guide to geodiversity and the planning system is Planning Policy Statement 9 (PPS9): Biodiversity and Geological Conservation. This introduces the concept of geodiversity into the planning process in England and Wales and states clearly that both Regional Spatial Strategies and Local Development Documents must have regard to the national guidance on geodiversity set out in PPS 9. Complementary to PPS 9, *Planning for Biodiversity and Geological Conservation - A Guide to Practice* (2006) provides good practice guidance, via case studies and examples, on the ways in which regional planning bodies and local planning authorities can help deliver the national policies in PPS9 and comply with legal requirements. They key principles of PPS 9 are:

(i) Development plan policies and planning decisions should be based upon up-to-date information about the environmental characteristics of their areas. These characteristics should include the relevant biodiversity and geological resources of the area. In reviewing environmental characteristics local authorities should assess the potential to sustain and enhance those resources.

(ii) Plan policies and planning decisions should aim to maintain, and enhance, restore or add to biodiversity and geological conservation interests. In taking decisions, local planning authorities should ensure that appropriate weight is attached to designated sites of international, national and local importance; protected species; and to biodiversity and geological interests within the wider environment.

(iii) Plan policies on the form and location of development should take a strategic approach to the conservation, enhancement and restoration of biodiversity and geology, and recognise the contributions that sites, areas and features, both individually and in combination, make to conserving these resources.

(iv) Plan policies should promote opportunities for the incorporation of beneficial biodiversity and geological features within the design of development.

(v) Development proposals where the principal objective is to conserve or enhance biodiversity and geological conservation interests should be permitted.

(vi) The aim of planning decisions should be to prevent harm to biodiversity and geological conservation interests. Where granting planning permission would result in significant harm to those interests, local planning authorities will need to be satisfied that the development cannot reasonably be located on any alternative sites that would result in less or no harm. In the absence of any such alternatives, local planning authorities should ensure that, before planning permission is granted, adequate mitigation measures are put in place. Where a planning decision would result in significant harm to biodiversity and geological interests which cannot be prevented or adequately mitigated against, appropriate compensation measures should be sought. If that significant harm cannot be prevented, adequately mitigated against, or compensated for, then planning permission should be refused.

These key principles require that planning policies and decisions not only avoid, mitigate or compensate for harm, but seek ways to enhance and restore biodiversity and geodiversity. The guidance suggests ways in which these principles might be achieved. These include identifying the geodiversity value of previously developed sites and the opportunities for incorporating this in developments, as well as recognizing areas of Earth heritage value, which would benefit from enhancement and management. Geodiversity must now be considered at every stage of the planning and development process, and at all scales (local, regional and national), following clear policy guidelines on the best ways to conserve and enhance it.

The Scottish Government has no current plans to produce an SPP on geodiversity in Scotland, but in discussions with BGS and SNH have suggested that a PAN (Planning Advice Note) on geodiversity will be considered.

5.3 MANAGEMENT ISSUES

Geological features develop and change over relatively long timescales, and thus may appear not to require specific management. However, many human activities can have both positive and negative effects on geodiversity; for example, quarrying and mining can open up valuable new geological exposures, but can also destroy spatially restricted geological features such as mineral veins, fossil beds or glacial landforms. This section discusses specific threats and management issues relating to the geodiversity of the National Park.

The Loch Lomond and The Trossachs National Park contains a number of quarries, both working and disused. In general, small-scale bedrock quarrying benefits the geological resource by opening up new exposures; this is nowhere clearer than at Leny and Lime Craig quarries, which are key localities for researchers working on the rocks of the Highland Border. Preservation of open faces at these quarries is important both for research and education purposes. Building stone from these quarries made an important contribution to the built heritage of the National Park, and further research into this aspect would be part of a full Geodiversity Audit. Continued small-scale quarrying in these areas might well be beneficial to geodiversity, although any large-scale quarrying would almost certainly be detrimental, in that it could destroy rock units with limited outcrop. Similarly, the disused mines around Tyndrum currently provide excellent three-dimensional exposures of mineral veins, and further small-scale exploitation (e.g. at Cononish) would not significantly damage the geodiversity of the area, although it is recognised that this could result in other damaging impacts on the special qualities of the National Park.

In contrast, exploitation of sand and gravel from areally restricted glacial landforms can have serious consequences for the geodiversity. An example of this is the recent (withdrawn) planning application to extend ongoing sand and gravel quarrying into glacial landforms near Callander. Glacial landforms of this type provide key evidence about the history of glaciation in Britain, and are a vital resource both for education and for research into past climate changes. These features should be protected as far as possible. At the present time, these features have not been comprehensively mapped and identified across the National Park area; such work would be part of a full Geodiversity Audit. In the meantime, it is recommended that BGS should be contacted for advice about any planned removal of sand and gravel from glacial landforms within the park.

As an example, BGS geologists recently provided advice to golf course developers on the west side of Loch Lomond, and a compromise was reached that allowed the development to continue, whilst preserving a suite of glacial features.

Other developments, such as new roads, housing, telecommunications masts, and renewable energy schemes such as wind farms, most commonly do not have a major effect on the geodiversity. As discussed above, the effect on areally restricted landforms should always be considered. New road cuttings may actually be beneficial to geodiversity, since they open up new exposures; the large cutting at Rubha Mòr on Loch Lomond is a good example.

Forestry plantations are abundant within the National Park. Tree planting does not materially damage the geological resource, but it may obscure key rock outcrops or landforms, rendering them inaccessible for research or education purposes. Access to key geodiversity localities should be taken into account in any new planting. More open, native woodland does not create the same access problems as tightly packed conifer plantations.

Natural coastal and shoreline erosion may slowly remove geological features, but in most cases new features will also be revealed. Of greater concern are coastal defence or shoreline stabilisation works, which can obscure and potentially damage geological features. Geodiversity features should be taken into consideration when any works of this type are being planned.

The most significant geological hazards within the National Park are landslides, such as the recent examples in Glen Ogle (2004) and at the Rest and be Thankful (2007). BGS maintains a landslide database for the whole country, and has specialists in geohazards who can provide advice as required. Areas of significant landslide hazard can be identified, although of course landslides cannot be predicted in detail. This work would be part of a full Geodiversity Audit.

Figure 6: Landslip in Glen Ogle, 2004. BGS photo P577 302

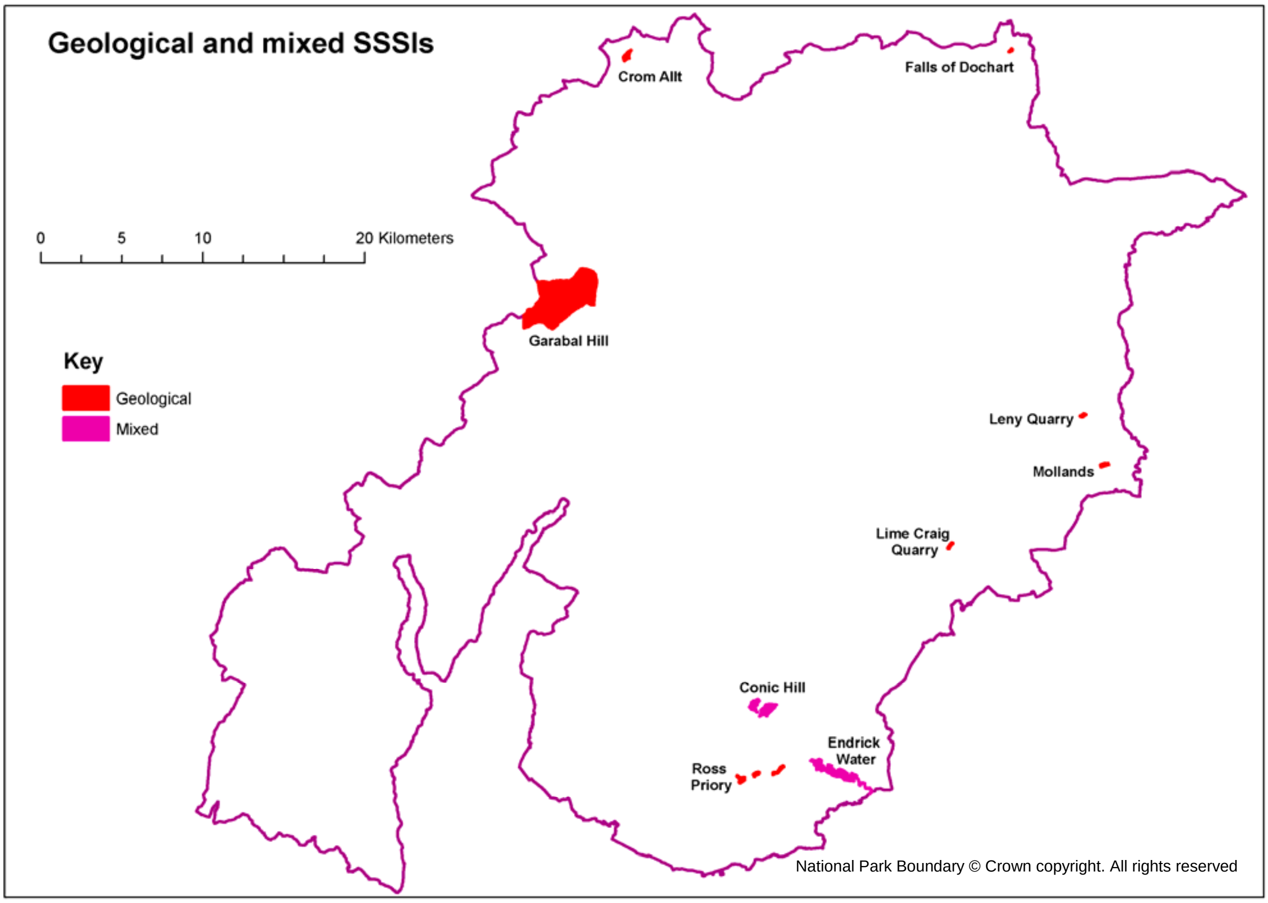

Figure 7: Geological and mixed SSSIs in the Loch Lomond and The Trossachs National Park

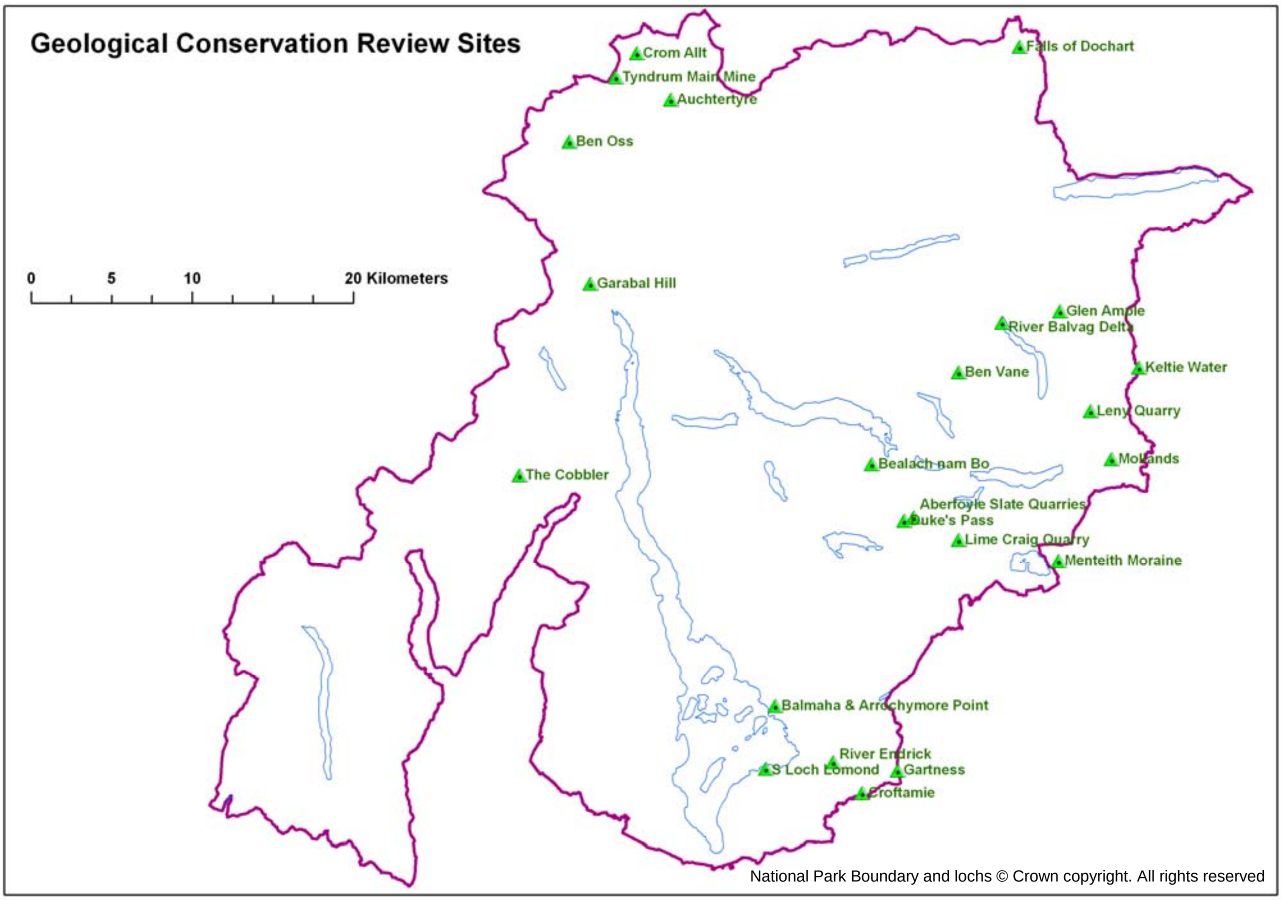

Figure 8: Geological Conservation Review Sites in the Loch Lomond and The Trossachs National Park

5.4 GEODIVERSITY AUDIT

This report only provides a summary of the issues that may affect the National Park. A full geodiversity audit, including fieldwork, could be carried out by BGS. This would involve detailed field visits to identify and map out boundaries for all the key geodiversity sites within the National Park, and to suggest a list of Local Nature Conservation Sites that could be included in the Local Plan. This work would provide much more detail about the geological and geomorphological interest at these localities, together with greater details on the management pressures. Such an audit would also map out geological hazards, sources and use of building stones in the park, and soils (in partnership with the Macaulay Land Use Research Institute). A Geodiversity Audit would also look in more detail at opportunities for geological interpretation within the National Park. As part of the process, BGS geologists would engage with National Park staff through a process of geodiversity knowledge exchange, training and development.

6 Opportunities for interpretation of geodiversity in the National Park

Positive management of the National Park's geodiversity is perhaps best achieved through interpretation of the geological heritage for all those who use the park. The geodiversity of the Loch Lomond and The Trossachs National Park provides a superb resource through which local residents and visitors can learn more about geological history and about the environment as a whole. This section of the report makes some suggestions for interpretation of the geodiversity.

Many visitors to the National Park will pay at least one visit to a visitor centre, such as the National Park Gateway Centre or the David Marshall Lodge in Aberfoyle. These centres provide ideal locations for introductory displays about the general geological history of the park, and indeed some (relatively limited) information is already available in these visitor centres. BGS would be able to advise on any further geological interpretation that may be planned for the centres.

However, interpretation of the geodiversity is inevitably more easily carried out in the field. Unlike some aspects of biodiversity, geological features do not change with the seasons or with the approach of visitors, and so geological features can be very successfully interpreted through fixed interpretation boards or through guides to walks and cycle rides. The 2003 Loch Lomond Visitor Survey (State of the Park report 2005) showed that 25% of visitors would do some low-level walking, and 19% would go hillwalking. Leaflets, books or even audio guides to walking routes are an ideal way of enhancing the visitor experience and allowing them to learn about the local environment. Perhaps an even better way to provide interpretation is through guided walks with enthusiastic, knowledgeable leaders.

The list below makes some suggestions for geodiversity localities and features that could be interpreted either through fixed interpretation boards, or as walking or cycling routes interpreted through books and leaflets. Some interpretation may already exist for some of these locations; however, it is worth noting that continuing research has changed the way we view many of these features, particularly around the Highland Border. It is thus always worthwhile reviewing interpretive material regularly.

6.1 SINGLE LOCALITIES FOR FIXED INTERPRETATION

Fixed interpretive boards, often in roadside locations, have been used successfully in many areas to interpret geodiversity features. A good example is the 'Rock Route' in the North-west Highlands Geopark (http://www.knockan-crag.co.uk/RockRoute/index.asp). Some localities in the Loch Lomond and The Trossachs National Park that could benefit from fixed interpretation of geodiversity features are listed below (Figure 9).

- **The Falls of Dochart, Killin.** Waterfalls and Dalradian outcrops.
- **Tyndrum.** Views of the mine, formation of mineralisation and lead mining history.
- **Loch Lubnaig and the River Balvag Delta.** Excellent example of rapid landscape change through infill of the loch with sediment.
- **Balmaha.** The Highland Border ophiolite and views along Loch Lomond
- **Rowardennan.** Glacially smoothed whalebacks with glacial striae at Rowardennan Pier.
- **The Lake of Menteith.** Glacial features.
- **Glen Finglas.** Geological information could be meshed with existing interpretation relating to the woodlands.
- **Duke's Pass.** Dalradian outcrops and the old slate quarries.
- **Loch Katrine.** The area around Loch Katrine receives many visitors and would be a good locality for general geological and landscape interpretation.

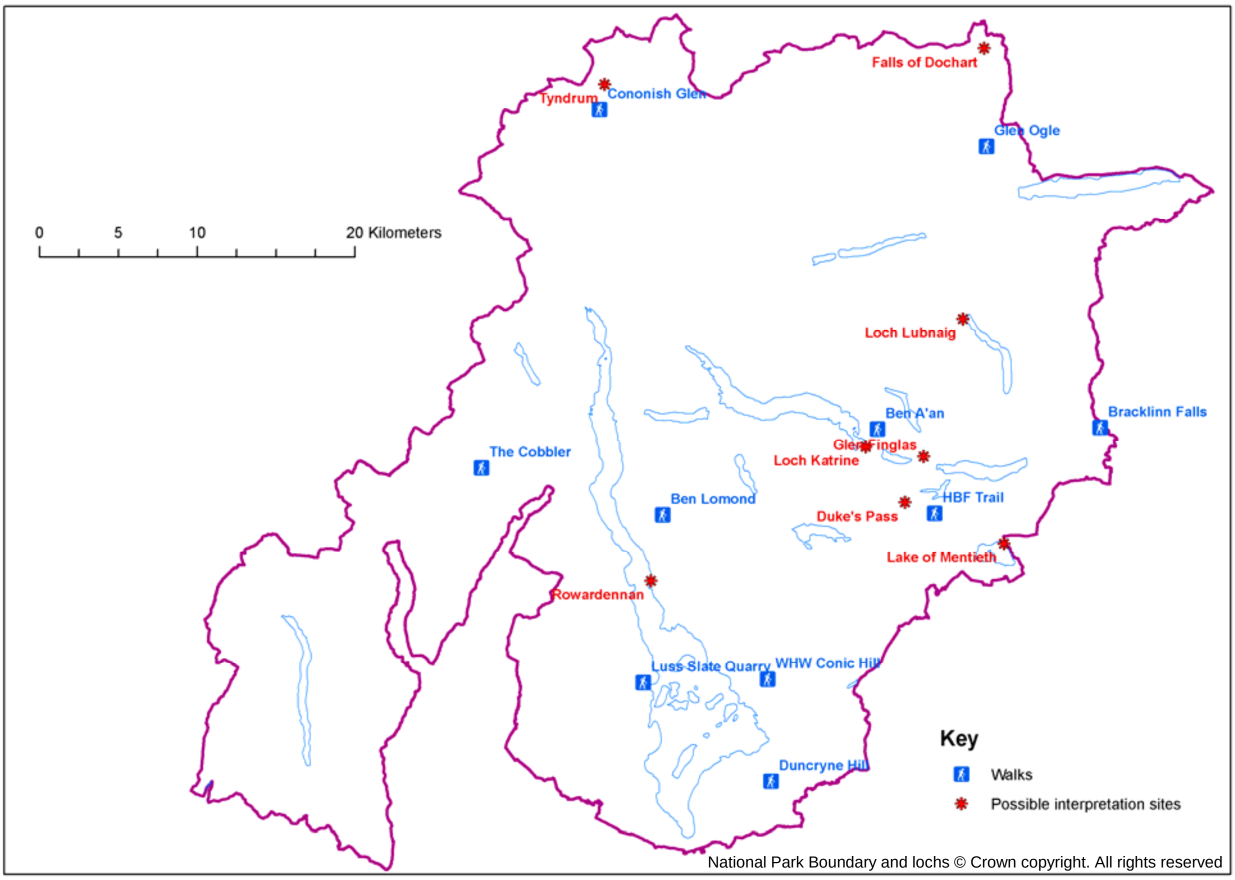

Figure 9: Potential interpretation sites and geological walks in the Loch Lomond and The Trossachs National Park

6.2 SUGGESTED WALKING ROUTES THAT WOULD BENEFIT FROM GEOLOGICAL INTERPRETATION

- **The 'Highland Boundary Fault Trail' at Aberfoyle**. This walk crosses the Highland Boundary fault zone, visits the quarry at Lime Craig, and has excellent views from the top of Lime Craig. It already has some limited, and perhaps out of date, geological interpretation, but would be very suitable for better interpretative material. It is of high geological interest, and the geological features are distinctive and thus accessible to many walkers.
- **The West Highland Way section over Conic Hill**. The panorama from Conic Hill is an iconic view of the Highland Boundary fault zone and Loch Lomond, and the path also crosses outcrops of the Highland Border ophiolite.
- **Bracklinn Falls and Callander Craigs**. This popular short route takes in good outcrops of Devonian sedimentary rocks as well as excellent views of the Highland Border. It could be extended to take in the glacial landforms at Auchenlaich.
- **The Luss Slate Quarry Path**. This short path passes the abandoned slate quarries at Luss.
- **Glen Ogle**. The old railway track in Glen Ogle gives excellent views of recent rockfalls and landslides.
- **Cononish Glen**. A walk along this glen takes in many glacial features as well as the mining interest. An extension to Ben Lui could also be described.
- **Duncryne Hill**. This popular short walk near Gartocharn ascends a volcanic plug to obtain classic views of Loch Lomond.
- **Ben A'an**. This short hillwalk is very popular. It passes outcrops of Dalradian rocks, as well as having superb views from the top.
- **The Cobbler**. A classic hill-walking route, with many glacial features and interesting rock outcrops (and boulders!).
- **Ben Lomond**. One of the country's most popular hillwalks, with Dalradian outcrops and glacial features.

Figure 10: Hillwalker on Ben Lomond. Photo: K. Goodenough.

7 Further Reading

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TREWIN, N H. 2002. *The Geology of Scotland (*4th edition). (The Geological Society, London.)

Figure 11: Stuc a' Chroin from Ben Vorlich, above Glen Ample. Photo: H F Barron.

Appendix 1 Geological Conservation Review sites in the National Park

GCR site name	GCR interest	SSSI name	Easting	Northing
Croftamie	Quaternary of Scotland	Not notified	247300	686100
Gartness	Quaternary of Scotland	Partly within Endrick Water	249500	687500
South Loch Lomond: Portnellan, Ross Priory and Claddochside	Quaternary of Scotland	Portnellan – Ross Priory - Claddochside	241300	687600
Western Forth Valley (Menteith Moraine)	Quaternary of Scotland	Partly within Flanders Moss SSSI	259500	700500
River Endrick	Fluvial Geomorphology of Scotland	Endrick Water	245500	688000
Balmaha & Arrochymore Point	Ordovician - Silurian Igneous	Conic Hill	241900	691500
Lime Craig Quarry	Arenig - Llanvirn	Lime Craig Quarry	253300	701800
Aberfoyle Slate Quarries (included now within Duke's Pass site)	Dalradian	Not notified	250500	703200
Mollands	Quaternary of Scotland	Mollands	262800	706800
Leny Quarry	Cambrian	Leny Quarry	261500	709800
Keltie Water, Callander	Dalradian/Highland Border	Not notified	264500	712500
River Balvag Delta	Fluvial Geomorphology of Scotland	Loch Lubnaig Marshes	256000	715300
Garabal Hill to Lochan Strath Dubh-uisge	Caledonian Igneous	Garabal Hill	230400	717700
Tyndrum Main Mine	Mineralogy of Scotland	Not notified	232000	730500
Crom Allt	Mineralogy of Scotland	Crom Allt	233300	732000
Falls of Dochart	Fluvial Geomorphology of Scotland	Falls of Dochart	257100	732400
Bealach nam Bo	Dalradian/Highland Border	Not notified	247900	706500
Duke's Pass	Dalradian/Highland Border	Not notified	249900	703000
Auchtertyre	Dalradian/Central Grampian Highlands	Not notified	235400	729100
Ben Oss	Dalradian/Central Grampian Highlands	Not notified	229100	726500
Ben Vane	Mass Movement	Not notified	253300	712200
Glen Ample, Stirling	Mass Movement	Not notified	259600	716000
The Cobbler (Beinn Arthur)	Mass Movement	Not notified	226000	705800