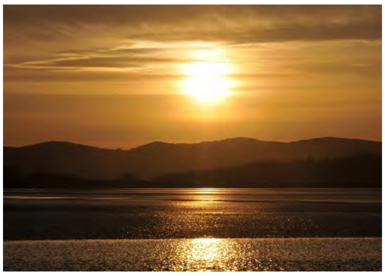
Arnside & Silverdale
Area of Outstanding Natural Beauty

The Geological Story of the Arnside & Silverdale Area of Outstanding Natural Beauty





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Introduction

The highly varied landscape of the Arnside & Silverdale Area of Outstanding Natural Beauty (AONB) owes its origin to nearly half a billion years of geological history and evolution. It is an intricate, close-knit landscape that has been shaped, primarily, by its geology and by the range of natural processes which have acted upon it over unimaginable periods of time.

Understanding how the various rocks within the area were formed, and how they have since been sculptured by ice, wind, rain and rivers, provides a fascinating insight into the nature of the area and the reasons behind its remarkable variety.

The underlying geology, topography and diversity are reflected in the wide range of special ('priority') habitats which have developed in this area over the last 10,000 years or more, and which now contribute further to its natural heritage. In more recent times, generations of farming, tourism, built development and other land uses have also left their mark on the landscape, but in many cases, even these reflect the underlying geology and landforms of the area.

Geo-Jargon - A few essential terms explained

This booklet is intended primarily for those who are interested in the origins of the landscape and features of the AONB but who do not, necessarily, have any prior geological knowledge. It aims to do so without the use of unnecessary technical terms, so that anyone can follow the geological 'story' of the area without needing to be an expert. In short, it seeks to explain things, as far as possible, in 'Plain English'. There are, however, a small number of geological terms which are difficult to avoid and very useful to understand. The main ones are explained briefly below, and a few others are explained as and when they are first used, in the text.

Geology is simply the scientific study of the Earth. It encompasses the study of all ***rocks***, ***superficial deposits***, ***minerals*** and ***fossils***, including how they were formed, how old they are, and what evidence they provide about the conditions which prevailed in a particular area at the time of their formation.

Rocks are the solid materials which make up the surface of the Earth and much of its internal structure. They include ***igneous rocks*** (formed by the solidification of molten material either deep inside the Earth or, in the case of '*volcanic*' rocks, ejected at the surface through volcanoes and fissures); ***sedimentary rocks*** (formed either by the erosion of older rocks, and the subsequent deposition of the eroded material into new layers, or by the accumulation of shells and other organic remains, usually in water); and ***metamorphic rocks*** (those which have been changed from their original form, either by high temperatures and/or pressures within the Earth's crust).

Superficial deposits are sediments which have been deposited on the surface of the Earth, generally within the last 2 million years, and which have not yet become hardened into rocks.

Minerals are the inorganic constituents of rocks and sediments, occurring as individual crystals (in the case of igneous and metamorphic rocks) or eroded grains of sand etc. (in sedimentary rocks). Individual minerals are distinct chemical compounds, such as Calcium Carbonate (or Calcite, the main constituent of limestone), or Silicon Dioxide (Silica, the main constituent of most sandstones). Rocks may comprise just one or (usually) more than one type of mineral.

Fossils are the preserved traces or remains of animals and other organisms which formerly inhabited the Earth. In most cases, it is only the shells or skeletons which are preserved, often as a result of the recrystallisation or even replacement of the original minerals that were present within the structures.

Geomorphology literally means the scientific study of the shape of the Earth's surface features (landforms), and of the natural ***geomorphological*** processes which have been responsible for their formation. These include the processes of weathering, erosion, sediment transportation and deposition. They may involve rivers, glaciers, landslides, rockfalls, mudflows, tidal currents and wind, along with mechanical effects of temperature variations and the chemical dissolution or precipitation of minerals in water.

Karst, and '***karstic***' are more specialised terms which have particular relevance to areas, such as the Arnside & Silverdale AONB, where limestone rocks are exposed at the surface. They relate to the special landforms and processes which are associated with the natural dissolution of limestone by water. Further details of these are given on pages 18 and 19 below.

Geodiversity

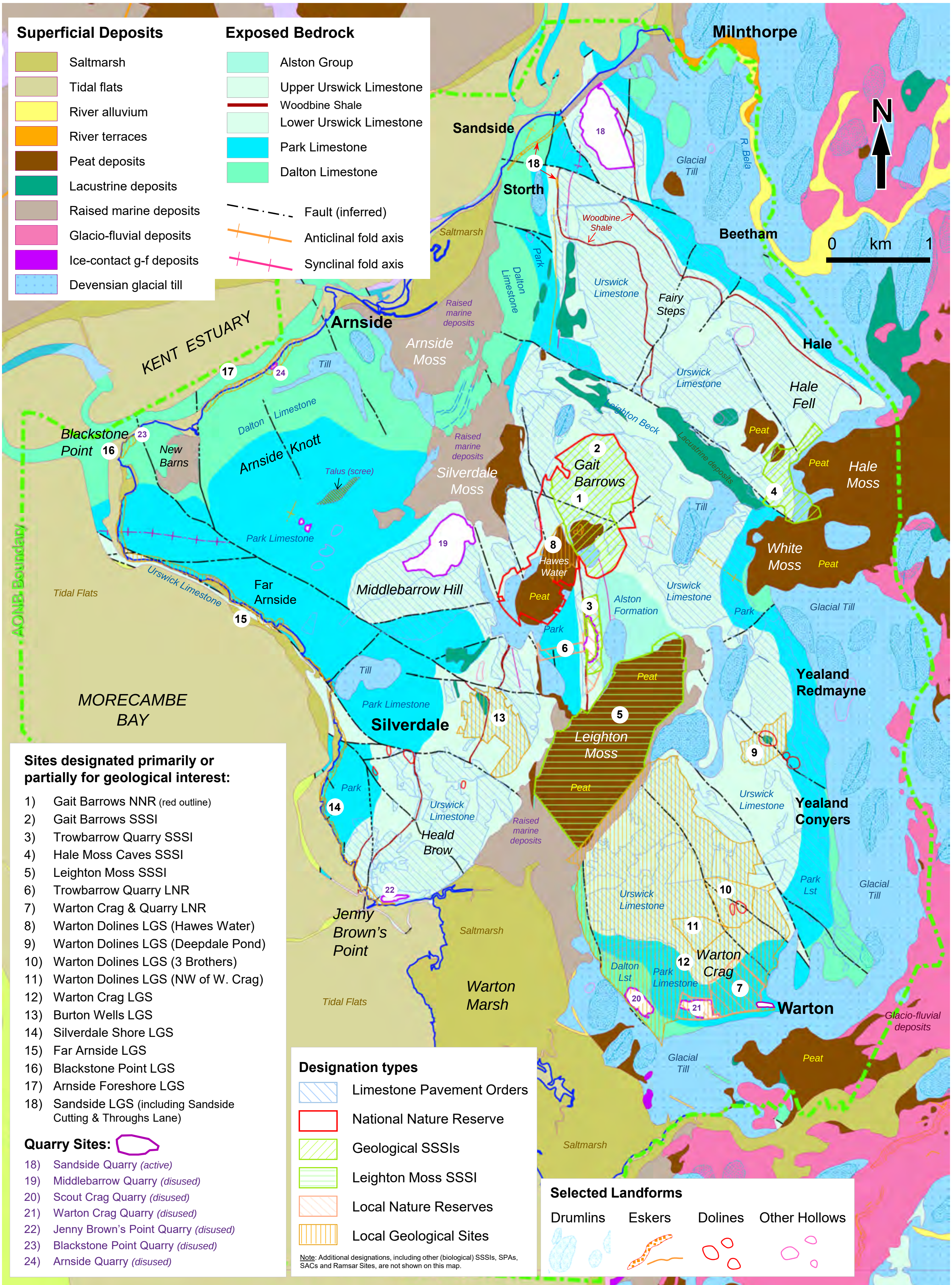
In addition to the technical terms explained above, it is worth understanding the importance of one other, and that is '***geodiversity***'. This is a term which is used to describe the sheer variety of all geological and geomorphological features (and processes) which can be seen within a given area. It is the geological equivalent of 'biodiversity', which covers the variety of living things, and is a key aspect of geological conservation.

In the case of the Arnside & Silverdale AONB, the rocks themselves (almost entirely of limestone) are quite limited in their variety – at least to the casual observer – but the detailed evidence which they provide regarding past environments, and the intricate variety of structures, features and landforms which have been created over time through the action of natural processes upon these rocks, is quite astonishing for such a small geographical area.

Some, though by no means all, of this geodiversity is reflected in a range of environmental designations (protected areas) within the AONB which relate (in part, at least) to geological or geomorphological features. These range from Local Geological Sites (**LGS**), proposed by the local geo-conservation groups (Cumbria Geo-Conservation and Geo-Lancashire) and designated by the County Councils, and Local Nature Reserves (**LNRs**) to nationally-designated Sites of Special Scientific Interest (**SSSIs**), National Nature Reserves (**NNRs**) and Limestone Pavement Orders (**LPOs**). **Map 1**, on the following page, attempts to capture this diversity and importance by combining information on the distribution of different rock formations and superficial sediments in the area with the distribution of these geologically-influenced designations. Other maps, presented later in the booklet, show the bedrock formations and superficial deposits separately, and the accompanying text explains each of the categories along with other features shown on the map.

It should be noted that other environmental designations, relating primarily to biological characteristics (vegetation, wildlife and habitats) also occur within the AONB. These include the extensive, internationally-designated Morecambe Bay Pavements Special Area of Conservation (**SAC**), much of which is also a Special Protection Area (**SPA**) and a **Ramsar** Site for the protection of wild birds. The SAC incorporates many of the area's Limestone Pavement Orders as well as the dynamic estuary of Morecambe Bay itself, thereby emphasising the underlying importance of these geological and geomorphological features to other aspects of the natural world. Whilst similar features and designations can also be found outside this area, what sets the AONB apart more than anything is the close proximity of such a diverse range of important features within this area and the way in which they combine to produce such a fascinating ***landscape mosaic*** underpinned by a distinctive ***geological 'jigsaw'***.

Map 1 – Geodiversity



Geological linework derived from 1:50,000 scale BGS Digital Data under Licence, Natural England Licence No. 2011/052 British Geological Survey. ©NERC.

The Geological Timescale

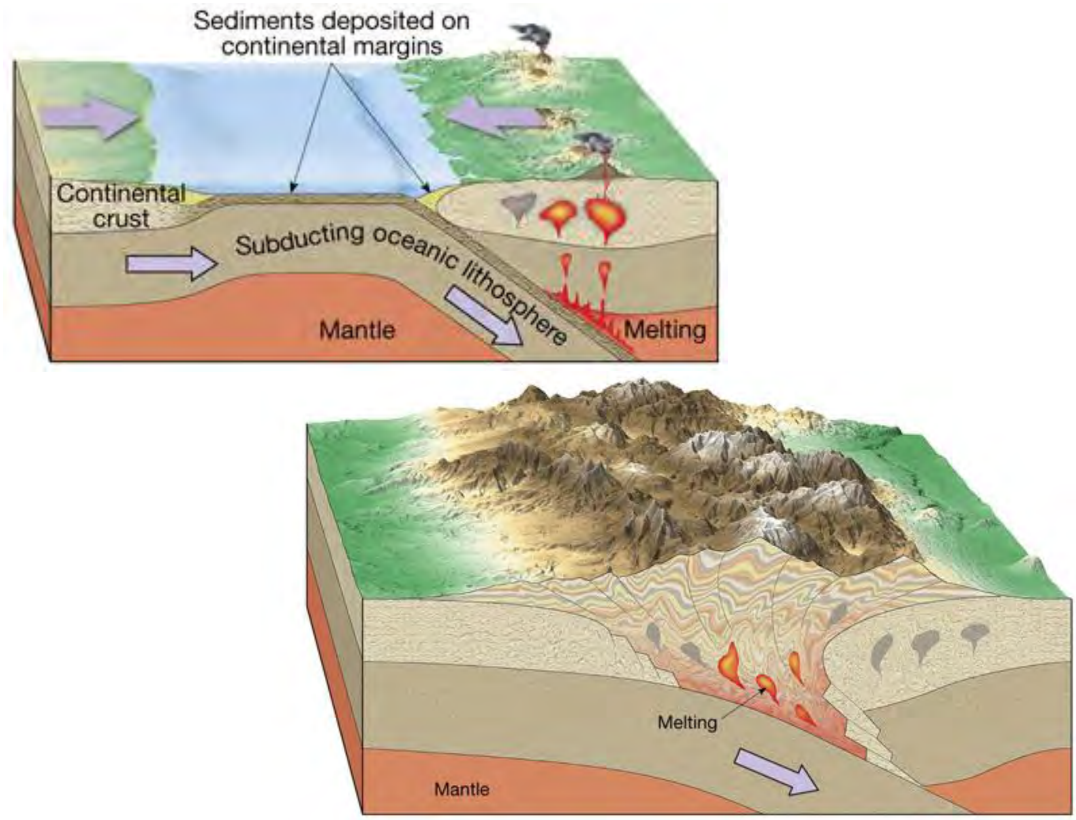
In order to understand the geological 'story' of the area, it is important to know something about the timescales involved, and the names which geologists have given to each successive part of the sequence. The names are not all that important but are often used to describe the age of particular rocks or features, so it is useful to know how these names tie-in with the overall timescale, expressed in years before the present day. It should be noted that the various divisions shown do not represent equal time intervals and that not all sub-Periods and Ages are shown – only those which have relevance to this area. Further details of selected geological 'events' and of the various 'strata' (layers of rock, or sediment) mentioned in the right-hand column will be explained as the story unfolds.

Start (Years Before Present)	End (Years Before Present)	Period	Sub-Period	Age (& selected events)	Strata within the AONB
2,750	ongoing	**Quaternary**	Holocene	Sub-Atlantic	**Tidal flats, alluvium, saltmarsh, soils, +** increasing human influence
5,950	2,750			Sub-Boreal	
8,200	5,950			Atlantic; Flandrian marine transgression	**Raised marine clays, marl, lacustrine clays, peat, raised bog, soils**
10,500	8,200			Boreal	
11,700	10,500			Pre-Boreal	**Marl, lacustrine clays**
12,600	11,700		Pleistocene	Late Devensian	**Screes, loess**
14,700	12,600			Late Devensian, Windermere interstadial	**Marl, lacustrine clays, peat, soils**
29,000	14,700			Late Devensian, Dimlington Stadial (Last Glaciation)	**Glacial till, glacio-fluvial sediments, screes, loess**
2.58 million	29,000			Earlier glaciations and interglacials	No undisturbed deposits remain
65.5 million	2.58 million	**Tertiary** (= Neogene & Palaeogene)		Alpine Orogeny	No deposits remain
145.5 million	65.5 million	**Cretaceous**			
200 million	145.5 million	**Jurassic**			
251 million	200 million	**Triassic**		Mineralisation	**Haematite ore**
299 million	251 million	**Permian**			No deposits remain
326 million	299 million	**Carboniferous**	Silesian	Variscan Orogeny	**Millstone Grit Pendle Grit**
331 million	326 million		Dinantian	Brigantian	**Alston Formation**
335 million	331 million			Asbian	**Urswick Limestone Fm.** Incl. the Woodbine Shale
339 million	335 million			Holkerian	**Park Limestone Fm.**
343 million	339 million			Arundian	**Dalton Formation & Red Hill Lst. Fm.**
347 million	343 million			Chadian	**Martin Limestone**
359 million	347 million			Courceyan	No deposition?
416 million	359 million	**Devonian**			**Shap Granite**
444 million	416 million	**Silurian**		Caledonian Orogeny	**Kirkby Moor Formation Bannisdale Formation**
488 million	444 million	**Ordovician**			**Borrowdale Volcanics**
4.56 billion	488 million	**Cambrian & Pre-Cambrian**			No surviving evidence

Before the Rocks were Made

Long before the present-day landscape began to take shape, and before even the rocks from which it is sculptured had been formed, the Arnside – Silverdale area would have been largely a barren semi-arid upland landscape. This was during the "**Devonian**" Period of Earth history, some 359 to 416 million years ago. Much of what is now northern England and southern Scotland were above sea level at this time and it was on this Devonian landscape that the more recent rocks that we see today were laid down. However, to fully understand the origins of this area, we need to go back much further in time. In geology, the spans of time involved are enormous – almost beyond comprehension – and are measured in hundreds of millions of years, as shown in the table on the previous page. The origins of this area can be traced back more than 400 million years.

Prior to, and during the early part of the Devonian Period, the upland landscape had been created towards the end of a complex episode of mountain-building known as the "**Caledonian Orogeny**". At the beginning of this sequence, during the "**Ordovician**" Period, gradual movements within the Earth's crust had resulted in two former continents moving towards each other. What is now Scotland formed part of one continent, and what is now the north of England formed part of the other. In between lay the former 'Iapetus' ocean. As the continents moved towards each other, over an interval of more than 160 million years, the rocks beneath the ocean were pushed down ('subducted') below what is now the Lake District. This caused partial melting of the rocks at depth and large bodies of molten rock (known as '*magma*') gradually rose up into the overlying crust. This, combined with the intense compression and buckling of rocks on the southern continent created a vast mountain range - much higher than the present-day hills.



Stages in the collision of continents, leading to the creation of volcanoes and fold mountains[1]

[1] Diagrams obtained freely from internet source here, accessed 17 July 2018.

Volcanic eruptions above the rising magma chamber resulted in the formation of a wide range of volcanic rocks at the surface within the central part of the Lake District. These are known collectively as the ***Borrowdale Volcanics***. None of the eruptions extended as far south as the Arnside area but some of the resulting rocks can be seen in the form of '**erratics**' – boulders and smaller rock fragments eroded from the Lake District and carried south by glaciers during more recent ice ages.

As the Lake District volcanism began to subside, during the "**Silurian**" Period, the whole area fell below sea level and marine sediments began to accumulate on the continental shelf. The resulting rocks probably remain at depth within the AONB, but lie buried beneath more recent strata. Some of them, including the ***Bannisdale Formation*** slates and ***Kirkby Moor Formation*** sandstones are known to occur in the far north of the area, but only beneath the present-day Kent Estuary. As with the Borrowdale Volcanics, however, they also occur as glacial erratics, deposited by glaciers on top of more recent strata. The same is true of the ***Shap Granite*** – a very distinctive, coarse-grained igneous rock which was intruded into the eastern side of the Lake District during the Devonian Period, at the end of the Caledonian Orogeny.

Erratic boulder of Silurian sandstone on the Arnside foreshore, with distinctive lichens, quite unlike those found on the Carboniferous rocks

Detail of Shap Granite showing large, interlocking crystal structure

Shallow Seas and Advancing Deltas – the Carboniferous Period

*As the old Caledonian land mass was eroded down during the Devonian Period, and as global sea levels began to rise, the scene was set for the onset of the "**Carboniferous**" Period (so-called because of the extensive coal deposits which formed in much of northern England – and elsewhere – during the latter part of this Period). Previously emergent land within the AONB area became submerged beneath warm, tropical seas, allowing the deposition of shallow marine sediments across the area. This 'marine transgression' began about 347 million years ago during the Early Carboniferous.*

The sediments laid down beneath the seas were '*carbonates*' – made up almost entirely of calcium carbonate shell fragments, corals and other marine organisms which lived within the shallow seas. As they became compressed by the weight of other sediments laid down above them, these deposits were gradually transformed into the limestone rock that we see today. Sedimentation beneath the sea continued for approximately 21 million years, interrupted at times by episodes of emergence at times when sea levels fell. At such times, the depositional surfaces would have been exposed to atmospheric weathering, including the formation of '*karstic*' surfaces, as the limestone began to be dissolved by rainwater. Old surfaces and features of this type, which were subsequently buried by younger sediments, are generally referred to as '*palaeokarst*'. Whilst emergent, the limestone surfaces were also subject to the formation of soils and vegetation, now preserved as thin '*palaeosols*' (fossil soil horizons) between some of the beds.

The Carboniferous Limestone Sequence

The sequence of strata laid down during the Carboniferous Period in this area are shown in the right-hand column of the table on page 6, above. The oldest strata - those at the bottom of the list - are the Martin Limestone Formation and the succeeding Red Hill Limestone Formation. Neither of these is seen at outcrop within the area; they are found only beneath much younger, superficial sediments. The Martin Limestone is made up of fairly pure carbonate deposits, laid down within tropical beach, tidal flat and lagoon environments. The Red Hill Limestone is also a shallow water sediment deposited within a high energy reef environment.

By contrast, the ***Dalton Formation*** *which follows represents a rapid change of environment to deeper water conditions within a subsiding basin. Most of the sediments were laid down within relatively still water below the reach of storm waves, probably at depths of more than 100m. This enabled fine-grained mud to settle out of suspension as well as the deposition of carbonate sediment. The formation therefore comprises relatively dark-coloured, well-bedded muddy limestones, often with thin beds of shale, representing periods of mud deposition. The formation crops out along much of the AONB's northern coast and is particularly well-displayed along the foreshore and low cliffs between Arnside promenade and Blackstone Point.*

Typical outcrop of the Dalton Beds within the Arnside Foreshore Local Geological Site, showing alternation of limestones and shales.

The succeeding ***Park Limestone Formation*** *marks a return to relatively shallow water carbonate sedimentation, with deposition taking place around the 'wave base' in something like 10 to 30m of water. It thus comprises mostly cream or pale grey limestones, typically composed of carbonate sands, often in a muddy matrix. In contrast to the Dalton Formation, bedding within the Park Limestone is often indistinct. Irregular, blocky jointing is common within some of the beds, as seen in the photograph below, giving outcrops a more rubbly appearance than either the Dalton or Urswick limestones. These characteristics lend themselves to the formation of 'scree' slopes, made up of angular, broken rock fragments, below outcrops such as those on Arnside Knott.*

Typical outcrop of the Park Limestone within the Far Arnside Local Geological Site, showing characteristic blocky jointing and lack of clear bedding.

*The **Urswick Limestone Formation** rests on a palaeo-karstic surface which had developed on top of the Park Limestone at a time when the area was above sea level. This, and several other similar surfaces within the formation have been interpreted as being a consequence of global sea level changes linked to periods of glaciation – mostly within the southern hemisphere. During periods of emergence, the whole of the AONB area would have been flat, low-lying land with soil cover (now preserved as palaeosols on some of the palaeo-karstic surfaces) and extensive vegetation – including (at times at least) quite substantial trees.*

As illustrated in the photographs below, sections though the Urswick Limestone are exposed at the top of high faces at both Middlebarrow and Sandside Quarries, and also at the more accessible disused Trowbarrow Quarry where the beds are tilted into a vertical position. Far more accessible are the numerous horizontal or gently-dipping limestone 'pavements' which are found extensively within the AONB and which are almost entirely developed on Urswick Formation outcrops. These are described in more detail on pages 18 and 19.

The lower part of the Urswick limestone overlying darker-coloured Park Limestone beds in Middlebarrow Quarry

Vertical beds of Urswick Limestone exposed in the Trowbarrow Quarry SSSI.

*The **Woodbine Shale**, a 4- to 8- metre-thick dark grey bed representing either a period of deeper water conditions and/or a temporary influx of muddier sediment, occurs within the Urswick Limestone sequence – approximately 30m above the base of the Formation. This is most clearly seen in the section exposed at Holme Park Quarry, just outside the AONB (pictured below left). Within the AONB, the shale is not easily seen, but differential weathering of the relatively soft shale generally produces a distinctive notch in the surface topography, marking its position between harder beds of limestone. This is best seen in the Throughs Lane LGS at Storth and in 'The Trough' at Silverdale (pictured below right), where the strata (and therefore the notch) are vertical.*

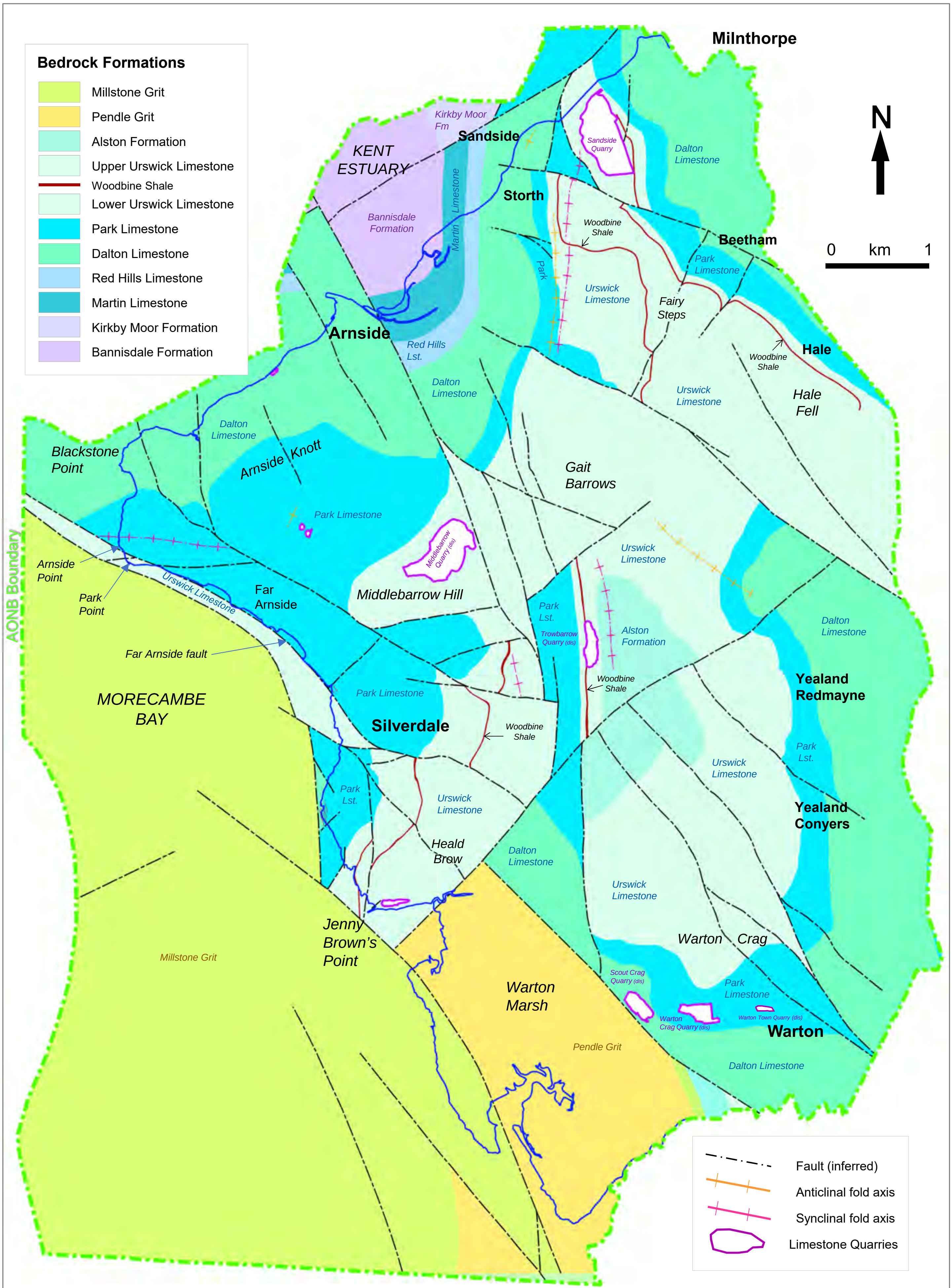
*The **Alston Formation** – previously known as the 'Gleaston Group', and often referred to as such in local literature – forms the highest part of the Carboniferous Limestone sequence within the AONB and marks a change to quite different depositional conditions. It comprises a highly variable unit of shales, mudstones, sandstones and limestones, deposited in varying depths of water, and it marks a transition towards the deltaic sequences of the Millstone Grit which followed (see below).*

The Woodbine Shale exposed between beds of Urswick Limestone at Holme Park Quarry

'The Trough' at Trowbarrow – the eroded outcrop of vertically-bedded Woodbine Shale

As the carbonate sediments increased in thickness and became compressed and consolidated over millions of years, they were transformed into Carboniferous Limestone rock. Fossils preserved within the limestone, including many different types of corals, brachiopods, and gastropods have been used by geologists (notably Garwood, 1912) to subdivide the sequence into distinctive zones. These are now recognised as separate geological formations which can be traced throughout the AONB and beyond, as illustrated in **Map 2**.

Map 2 – Bedrock Geology



Fossils of a colonial rugose coral (*Siphonodendron (formerly Lithostrotion) martini*) within the Park Limestone Formation exposed in the Far Arnside LGS shoreline.

Fossils of gastropods and small, solitary corals within the Dalton Formation exposed at Blackstone Point in the Far Arnside LGS.

Following the deposition of the youngest (Alston Formation) limestones, deltas of fluvial sediment, brought down by large river systems from ancient uplands to the north and east, built out over the infilled limestone basins, laying down coarsening-upward sequences of sandstones and shales known collectively as the ***Millstone Grit***. These sediments would have been thinner in this area than in the subsiding basin of the Bowland Trough, just to the south, and virtually all traces of them have been removed by subsequent erosion. ***Pendle Grit*** sandstones, from the lowest part of the sequence, are preserved beneath Warton Marsh, but are not exposed at the surface.

Cracking the Crust – the Variscan Orogeny

*Carboniferous sedimentation was followed by another period of tectonic upheaval and mountain-building, known as the "**Variscan**" Orogeny. This involved the collision of various small tectonic plates, including land that is now southern England, SW Ireland and Brittany, with 'Laurentia' (comprising what is now North America, Greenland, Northern Ireland and Scotland).*

Within the AONB, the effects of this orogeny are seen in a variety of '*normal*' faults, indicative of lateral pulling-apart of the Earth's crust, together with localised folding of the rocks, indicative of compression, at different times. The various structures are orientated predominantly NW-SE and occasionally NE-SW or N-S, as shown on **Map 2**. They are well-displayed on the coast between Far Arnside and Blackstone Point and examples of both folds and faults are shown in the photographs below.

One of the main features, known as the Far Arnside Fault, is responsible for the entire shape of the coastline facing Morecambe Bay, and has resulted in the Urswick Limestone dropping down by around 1000m to the same level as the Park Limestone.

Broad synclinal (‘u’-shaped) fold in the Park Limestone Formation at Arnside Point. Notice how the strata are tilted upwards at either end of the cliffs, with the centre-line or ‘axis’ of the syncline being close to the centre of the image

Normal fault within the Park Limestone Formation at Arnside Point showing abrupt downward displacement to the left.

Further east, between Sandside and Leighton Moss, there is a more complex zone of deformation known as the ***Silverdale Disturbance***. This zone provides evidence of east-west compression (tight folding and reverse faulting) which may have developed from older, Caledonian features in the underlying rocks. Over much of its length, the feature is seen to be an east-facing ‘*monocline*’ – an asymmetric ‘s-shaped’ fold in which some of the strata have been pushed up into a vertical or slightly overturned (westerly-dipping) position, as seen most spectacularly at Trowbarrow Quarry.

The Variscan Earth movements thus divided the Carboniferous strata up into a series of irregular blocks, raised up to different levels, tilted in places and affected to varying degrees by deep-seated fracturing. These blocks form the basic geological structure of the AONB and provide the starting point for the subsequent evolution of the modern landscape.

Areas capped by the Urswick Limestone (such as Warton Crag, Middlebarrow Hill, Hale Fell, Summerhouse Hill, Heald Brow and the area around Sandside Quarry), together with those which form the crests of gently-dipping escarpments, such as Arnside Knott (capped by Park Limestone), have tended to become areas of higher ground, whilst the intervening areas have been exploited to a greater extent by subsequent erosion.

Arnside Knott – a wooded limestone hill capped by Park Limestone and flanked by scree slopes.

Movement along the faults also changed the orientation of the geological beds from their original horizontal placement. The gentle dip of some of the limestone beds has greatly influenced the way in which they are weathered and the subsequent landforms and landscapes which have developed.

This evolution of the landscape - sculpturing of the bedrock into its present form and further modification by the deposition of more recent sediments - has taken place under a wide range of climatic regimes over a period of at least 300 million years, since the end of the Carboniferous. The processes involved, at different times, have included:

- mechanical erosion by glaciers, waves and flowing water;
- intense mechanical weathering by freeze-thaw action;
- down-slope 'mass movement' of weathered soils and rock under the influence of gravity;
- intricate dissolution of the limestone by both rainwater and percolating groundwater; and
- deposition of sediments by ice-sheets, glacial meltwater, wind, rivers and tides.

Collectively, these are known as '*geomorphological*' processes and the development of the present-day landscape owes as least as much to them as it does to the underlying rocks and geological structures. Many of the processes have been continuous, though varying in intensity at different times, whilst others (notably the effects of glaciation) have been restricted to certain periods of time, dictated by climatic change.

The Deserts Return – the Permian and Triassic Periods

*Immediately following the Variscan Earth movements, during the late "**Permian**" and "**Triassic**" Periods, terrestrial and shallow marine sediments were laid down within an arid, desert environment over much of North West England. Such deposits may once have existed within the Arnside – Silverdale area, but have since been removed by erosion. Further north, in the Eden Valley of Cumbria, sandstones from these Periods still remain. As with almost all desert sandstones, the rocks are characteristically red in colour, due to the presence of iron oxide (haematite) within the sediments.*

Red desert sandstones of Permian age exposed at a quarry in the Vale of Eden, Cumbria (© Cuesta) (left) and red haematite staining of Park Limestone adjacent to a vertical post-Carboniferous fault at Middlebarrow Quarry (right)

During and after the mid-Triassic Period, sometime between 200 and 250 million years ago, more concentrated deposits of haematite were emplaced within the limestone strata to form localised bodies of iron ore. Examples can be seen at Red Rake on the Silverdale coast and in Middlebarrow Quarry. The ore bodies, which included copper as well as iron, formed the basis of localised mining activity prior to the 20th Century (e.g. at the now inaccessible Crag Foot Mine at the edge of Warton Crag and, more extensively in the Furness District, on the western side of the Kent Estuary, which became the most productive iron orefield in the world for a time during the second half of the 19th century).

Sunk without Trace – the Jurassic and Cretaceous Periods

*At the end of the Triassic Period, some 200 million years ago, there was a further widespread incursion of the sea across the region, which probably remained submerged throughout the "**Jurassic**" and "**Cretaceous**" Periods.*

Jurassic limestones, sandstones and mudstones were widely deposited across much of England, as were the Cretaceous Chalk, Greensand and Gault Clay deposits. Any such strata which may once have been laid down within the Arnside-Silverdale area, however, has since been removed by the continuing action of relentless geomorphological processes.

Dissolving Limestone and Further Collisions – the Tertiary Period[2]

*The Carboniferous Limestone surfaces probably remained buried beneath Permo-Triassic sediments until at least the middle of the succeeding "**Tertiary**" Period, before being gradually exhumed by erosion. Once exposed to the elements, they would have been subjected to the onset of 'karstification' – the dissolution (dissolving) of the limestone by a combination of rainwater, surface runoff and groundwater flow to produce a range of distinctive landforms and features at a variety of different scales.*

The following page explains the formation of ***limestone pavements*** – one of the most distinctive features of the AONB - and their associated small-scale karstic features, including *'clints', 'grikes', 'runnels'* and *'kamenitzas'.* Whilst such features may originally have begun to form during the Tertiary Period, they are likely to have been refreshed after each episode of glacial erosion during the succeeding "**Quaternary**" Period, which would have stripped away the surface layers of rock, exposing new surfaces to karstic weathering. Most of the detailed karstic features seen today are therefore likely to post-date the last glaciation. Further details of the Quaternary Period are described from page 20 onwards.

By contrast, the larger-scale karstic features, as described on page 19, must have taken much longer to develop. These features include extensive cave systems, '*dolines'* (deep, circular depressions) and *'poljes'* (larger, flat-bottomed depressions with steep sides). Based on consideration of their size and on measured rates of limestone dissolution, it has been calculated that the dolines are likely to have been initiated at least 1 million years ago, in the early part of the Quaternary Period, and perhaps even earlier, as reactivated Permo-Triassic karst features.

The Deepdale Dolines are thought to have been at least partly controlled by the alignment of one of the many NW-SE – trending faults within the limestones, which either originated or were at least reactivated during the Late Tertiary '**Alpine**' episode of Earth movements (see below). The dolines located on Warton Crag contain Quaternary wind-blown sediments known as 'loess', which date from approximately 19,000 years ago, confirming that they had already been formed by that time.

The **Alpine Orogeny**, resulting from the gradual northward collision of the African and Arabian 'tectonic plates' into continental Europe during the Late Tertiary Period, was primarily responsible for the formation of the Alps and other fold mountain ranges in Europe and for more limited folding of Jurassic and Cretaceous strata in southern England. It was, however, also felt to some extent in north-west England. Here, relatively low levels of compression produced a series of low-angled thrust faults, buckles and monoclinal folds, generally reactivating or reversing the original direction of movement on some of the structures created during earlier episodes of tectonic activity, perhaps including those within the Silverdale Disturbance.

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[2]The 'Tertiary' Period of Earth history is a relatively dated term which encompasses what are now more commonly referred to as the 'Palaeogene' and 'Neogene' Periods. 'Tertiary' is however retained in this account as a more familiar term and for ease of comparison with many preceding texts.

Karstic Features of the Limestone Pavements: Clints, Grikes, Runnels & Kamenitzas

*‘**Karstic**’ features are those created by the natural dissolution of soluble rocks, such as limestone, by slightly acidic rainwater, or by groundwater percolating through the rock, beneath the surface. The smaller features, which are characteristically developed on exposed limestone bedding planes, can take on myriads of different forms, collectively referred to as ‘karren’. The terms all derive from the German name (‘Karst’) for the Kras limestone plateau near Trieste in Slovenia, where the first research on karst topography was carried out. The most common forms of karren seen within the AONB are:*

‘Clints’ *(left) - flat-topped rocky platforms representing the dissected remnant surfaces of once continuous limestone beds.*

‘Grikes’ *(left and below) - solution-widened joints within the limestone, forming deep, linear clefts which separate the clints.*

‘Runnels’ *(below) - shallower channels running down-slope across tilted clint surfaces, draining into grikes or small potholes.*

‘Kamenitzas’ *(right) - shallow, pan-shaped depressions formed by the dissolution of limestone in standing water, usually on horizontal limestone surfaces. Often with effluent runnels.*

Also present, as finer details in some areas, are:

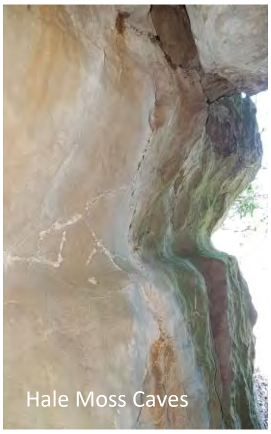
‘Rillenkarren’ *(below, left) - small flutes, 10 to 30 mm across and separated by sharp ridges and points, formed purely by the direct action of rainfall on exposed edges.*

‘Rundkarren’ *(below) - karren forms with rounded edges; formed beneath a cover of soil or superficial deposits which may since have been removed.*

Larger-scale Karst: Limestone Pavements, Cave Systems, Dolines and Poljes

*The **Limestone Pavements**, on which the various small-scale features are developed, are perhaps the most distinctive feature of the limestone outcrops seen within the AONB. Those at Gait Barrows are recognised as one of the finest examples of lowland limestone pavements in the world. The pavements are made up of individual 'bedding planes' (former surfaces of sediment deposition when the limestone was being laid down in shallow tropical seas), which have been exposed by the removal of overlying strata, either through dissolution and/or mechanical erosion (particularly by glaciers and ice-sheets). When first exposed, following the retreat of the ice sheets after each glaciation, these surfaces would have been more continuous than they are now, but dissolution would quickly begin to etch the familiar patterns of grikes, runnels and kamenitzas into the limestone.*

Gait Barrows



Hale Moss Caves

***Cave systems** provide evidence of limestone dissolution by flowing groundwater. This includes both 'phreatic' action (full-bore groundwater flow, creating characteristic circular cross sections) and 'vadose' action (evidenced by keyhole cross sections, formed by underground streams flowing at or above the level of the local water table). In both cases the caves indicate groundwater levels much higher than those of today. Examples are seen at the Hale Moss Caves SSSI (pictured left) and in places along the Silverdale coast.*

Deepdale Pond

***'Dolines'** – large, conical depressions on the surface of limestone outcrops, ranging from tens to hundreds of metres in diameter, and up to 100m in depth. Solutional dolines, such as those seen within the AONB (as distinct from collapse dolines and other forms) provide evidence of long-term, concentrated dissolution at particular locations, often controlled by major faults or other discontinuities within the limestone. Good examples are seen at Deepdale Pond (pictured right) and the Three Brothers on Warton Crag (below right).*

Three Brothers

***'Poljes'** – very large, flat bottomed depressions, usually with one or more steep sides, are commonly formed at the junction between limestone and interbedded impermeable strata, such as shale. Multiple springs, formed along the top of the shale beds, may contribute to the lateral expansion of Poljes, in contrast to the more focused vertical dissolution associated with solutional dolines. Examples within the AONB may include the depressions in which Hawes Water and Little Hawes Water (pictured left) have formed (but these may equally be composite dolines).*

Little Hawes Water

Climate Change and Landscape Response – the Quaternary Period.

*The "**Quaternary**" Period of Earth history began around 2.6 million years ago and continues to the present day. Throughout the Quaternary there have been considerable variations in climate, sea level and environmental conditions, all of which have left their mark on the landscape. Over a similar timescale, the evolution of human species ('hominins') has taken place, with an ever-increasing influence on landscape character.*

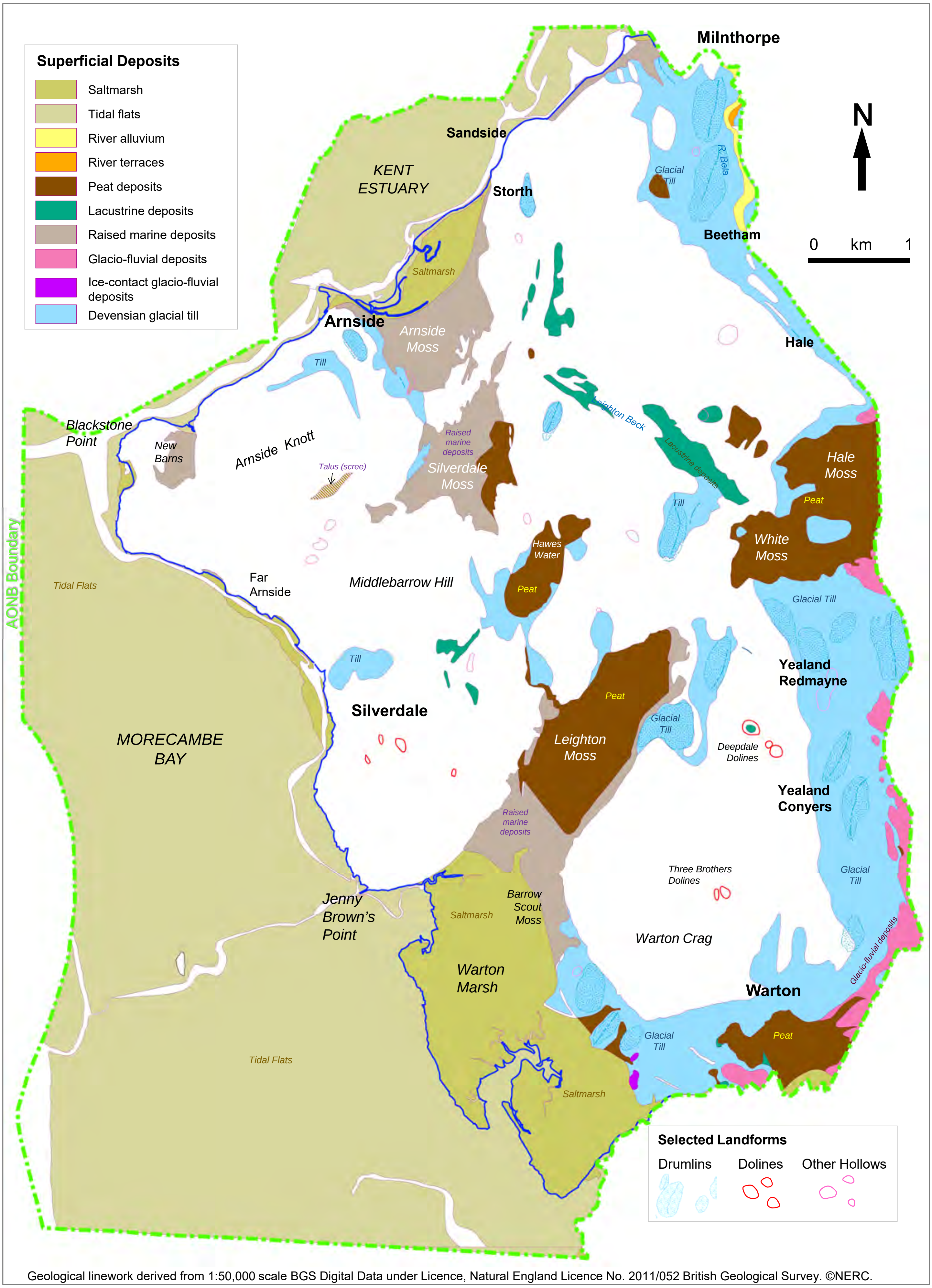
Geologically, the Period is divided into the "**Pleistocene**" (prior to about 11,700 years ago), during which Britain and Europe were subject to a series of alternating cold (glacial) and warm (interglacial) conditions; and the succeeding "**Holocene**" (the present interglacial) during which most of the present-day flora of the British Isles has developed, in parallel with the steadily increasing influence of human activity. The most recent part of the Holocene is often referred to as the "**Anthropocene**", in recognition of the growing influence of human civilisations, although the starting point for this has yet to be agreed.

As in previous episodes of geological history, the geomorphological processes operating during the Quaternary Period were responsible for the deposition of a wide range of sediments, as well as for the creation of both erosional and depositional landforms – the most recent of which are preserved in the modern landscape. In contrast to the deposits from earlier times, which became transformed into rock by the weight of overlying strata, the Quaternary sediments are relatively unconsolidated and are mapped separately as '*Superficial*' deposits, superimposed onto the surface of pre-existing 'bedrock' formations. The distribution of these deposits, as mapped by the BGS, is shown on **Map 3** on the next page.

Also included on this map are various landforms, including the solutional dolines noted above, other enclosed hollows (which may or may not be dolines) and a series of '*drumlins*' – large, oval-shaped, rounded hills (as pictured below) which were formed by the streamlined moulding of glacial sediments beneath advancing glaciers and ice sheets.

Classic drumlin landforms on the skyline at Crooklands, just outside the AONB (© Cuesta)

Map 3 – Superficial Geology & Landforms



Geological linework derived from 1:50,000 scale BGS Digital Data under Licence, Natural England Licence No. 2011/052 British Geological Survey. ©NERC.

These characteristic glacial features are captured beautifully in the low-angled sunlit scene from an early false-colour Landsat satellite image (below) and are also clearly discernible from the contour patterns on Ordnance Survey maps. In the satellite image, areas of lush vegetation are shown in shades of orange and red, thin soils and bare rock outcrops in shades of blue and green, and areas of forest, open water and deep shadow in black. Areas of saltmarsh, which have changed substantially since this image was captured, appear blueish-grey in colour.

False colour Landsat image of the AONB and surrounding areas, with the drumlin 'swarms' picked out by low-angled sunlight (© British Geological Survey)

As the image clearly shows, the drumlins within the AONB form part of a much larger 'swarm' of similar landforms extending southwards from the eastern flanks of the Lake District and the western side of the Yorkshire Dales, providing dramatic visual evidence of the directions of ice flow during the last (Late Devensian) glaciation.

Pleistocene – the Quaternary Ice Ages

The Pleistocene saw not just one but several '*Ice Ages*' in Britain, separated by warmer *'interglacial'* stages. The alternation of warmer and colder climates during the Pleistocene has been revealed through the analysis of oxygen isotope variations over time in marine sediment cores. During each of the colder stages, glaciers developed in mountainous areas of northern Britain and coalesced into ice sheets which, in combination with others from Scandinavia, gradually extended southwards across much of England.

Each glaciation would have had a significant effect on the landscape of northern Britain, including the Arnside-Silverdale area. On each occasion, glacial erosion would have removed previously-weathered rocks and soils on the AONB's limestone hills, exposing fresh limestone surfaces to karstic dissolution. Each glaciation would also have contributed, incrementally, to the formation of over-deepened rock basins forming the areas of lower ground in between the hills – subsequently to become occupied by tidal inlets, inland lakes and eventually lowland mosses during the "**Holocene**" (see below). The precise effects of each glaciation can only be speculated upon, however, since evidence of both erosion and deposition during these stages will have been obliterated or heavily modified by succeeding glaciations. Overall, the glacial sculpturing of the physical landscape was a cumulative process, taking place over many hundreds of thousands of years, adding detail to the changes which had been taking place more gradually over a much longer period of time, since the Carboniferous limestones were first exposed to weathering, erosion and dissolution, up to 300 million years ago.

The Last Glaciation

Around 109,000 years ago, the climate began to deteriorate at the start of the "**Devensian**" glaciation – the most recent extensive glaciation in Britain, and the last one to have affected the AONB area. Local ice sheets and glaciers expanded from centres in the Lake District and North Pennines but did not reach their maximum extent until about 23,000 years ago.

As well as contributing further to the scouring of limestone surfaces, the Devensian glaciation also saw the renewed deposition of glacial '*till*' at the base of the advancing ice sheets, and created the spectacular drumlins noted earlier. '*Till*' is a general term for the deposits produced by glaciers and ice sheets and is synonymous with the out-dated term '*boulder clay*'. The deposits comprise a very wide range of unsorted sediment sizes, from fine-grained clays to very large boulders. This is in contrast to the deposits laid down by water, which are generally much better sorted into different sized sediments and also far more stratified (laid down in distinct layers).

Within the AONB, the long-axes of the drumlins are predominantly oriented NNE to SSW – broadly similar to the orientation of the major ice-scoured depressions beneath Arnside, Silverdale, Hawes Water and Leighton Mosses (see **Map 3**, above). Glacial till was also deposited more generally in between and beyond the drumlin features along the eastern side of the AONB and, to a far more limited extent, within other parts of the area, usually in areas of lower ground (including the ice-scoured depressions noted above) and at the base of steeper limestone slopes. Natural exposures of till within the area are limited but can be seen (from a view point on the A6) where the River Bela cuts into the large drumlin within the Dallam Estate deer park, to the south of Milnthorpe (see below).

Drumlins near Milnthorpe

Glacial till exposed by the River Bela at the base of a drumlin in Dallam Tower Park

In parallel with the formation of drumlins, and during the retreat of the Devensian ice, meltwater deposited '***glacio-fluvial***' sediments and created landforms such as ***'kames'*** (irregular, rounded mounds of sand & gravel formed by deposition within or on the surface of glaciers, which have since melted); ***'kettle holes'*** (circular, often peat-filled subsidence hollows within sand & gravel deposits, formed by the melting of underlying ice) and '***eskers***' (similar to kames but forming sinuous ridges, representing the former courses of meltwater streams within or at the base of glaciers).

None of these landforms, and only limited areas of glacio-fluvial sediments are found within the AONB itself, but both landforms and deposits are well-developed just beyond the AONB boundary to the east of Carnforth. Within that area, close to the M6 motorway, the sand & gravel deposits have been extensively worked as a source of construction aggregate, leaving behind large, flooded excavations.

Glaciofluvial landforms – kettle hole and kames near Carnforth

Cave systems, which may also be of Devensian age, occur in the outcrop of Urswick Limestone adjacent to Hale Moss. They provide evidence of both '*phreatic*' action (full-bore groundwater flow, beneath the water table, dissolving the limestone on all sides to create characteristic circular cross sections) and '*vadose*' action (evidenced by keyhole cross sections, where the limestone was dissolved only on the sides and base of underground streams flowing at or above the level of the local water table). In both cases, the caves indicate groundwater levels much higher than those of today, with vadose systems being linked to the levels of former lakes at Hale Moss, and the phreatic caves perhaps being formed under higher hydrostatic pressures beneath ice sheets. Caves of phreatic origin are also exposed in places at the coast.

Hale Moss Caves SSSI, developed within the Urswick Limestone outcrop to the south of Hale Fell

On Warton Crag, there is evidence of active stalagmite formation dating from 59,000 to 29,000 years ago (during the Middle Devensian), revealing that the caves here had already been formed and had ceased to be active phreatic systems, prior to that date. Other cave systems at lower elevations may, however, have continued to experience phreatic flow conditions in more recent times, and will have continued as vadose systems until the water table fell below the current base.

As noted earlier, relatively small-scale surface features on newly-exposed limestone pavements, such as *clints* (remnant surfaces), *grikes* (deep, solution-widened joints), *runnels* (shallower channels running down-slope across clint surfaces) and *kamenitzas* (shallow, pan-shaped depressions) will have developed following each phase of glaciation, and most of those seen today are likely to have been initiated during and after the last glaciation.

During the immediate **Postglacial** period, as the ice sheets retreated between 23,000 and 14,700 years ago, extensive areas of land would have been uncovered and exposed to intense '*periglacial*' weathering, in conditions similar to those found in Arctic tundra regions today. The slow process of soil formation would have recommenced as pioneer plant species began to colonise the exposed terrain. Evidence for the gradual spread of different plant species as the ice retreated is found in the record of contemporary pollen grains preserved in lake sediments and peat deposits at sites such as Hawes Water and Silverdale Moss (see next page for further details).

Hawes Water: a natural carbonate lake within a large karstic depression ('polje')

The pollen records from these sites show that vegetation would initially have been minimal, such that loose glacial sediments and frost-shattered limestone screes would have easily been washed downslope by surface runoff and mass-movement processes, including '*solifluction*' (the gradual movement of water-saturated soils and rocks affected by freeze-thaw processes). Stratified screes are particularly well-developed on the southern face of Arnside Knott and on all sides of Middlebarrow Hill (though here, they are now largely concealed by dense woodland). In both cases, the screes developed where the underlying rock (Park Limestone) is intensively jointed, making it particularly susceptible to frost action.

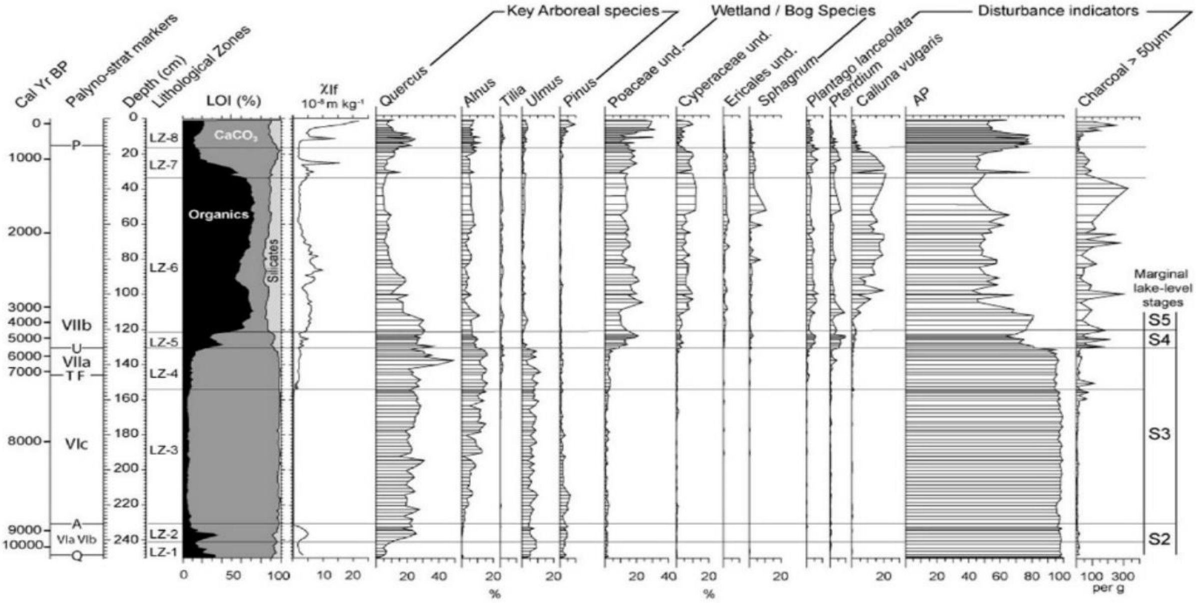
Scree slopes on the south side of Arnside Knott

Detail of cemented scree on Arnside Knott

Hawes Water: A Natural Archive of Quaternary Climate Change

*Hawes Water – one of only two natural lakes remaining in Lancashire – has a special place in understanding the chronology of post-glacial environmental and climate change. Unusually, it is a carbonate lake, meaning that it is fed by surface water streams and groundwater which are rich in calcium carbonate, dissolved from the surrounding limestone hills. As the water flows into the lake, the calcium carbonate is precipitated out of solution to form deposits of carbonate mud, or '**marl**'. In the past, such deposits have accumulated around the margins of the lake, forming a 'bench' several metres thick. Whilst precipitation still occurs during the summer months, the mineral is re-dissolved back into the water during the winter, so that the marl no longer accumulates. Instead, peat is developing across the water-saturated surface of the marginal bench. Sediment cores, taken from various locations within the 'north field' adjacent to the lake, reveal the sequence of deposits which have accumulated here over all but the most recent part of the post-glacial period. They show a thick accumulation of marl above late glacial sediments, passing upwards into terrestrial fen peat deposits. Whilst the sediments themselves tell something of the changing conditions, the pollen grains within the layers of sediment reveal far more detail about the vegetation of the surrounding area during each stage of development.*

Pioneering research by Professor Frank Oldfield of Liverpool University, published in 1960, provided a detailed analysis of this natural 'archive', enabling the sequence of change to be established. More recently, researchers from the Universities of Liverpool, Exeter, Edge Hill and Lancaster have carried out further investigations of both the marginal bench and the lake floor to build up a 'multi-proxy' analysis of almost 14,000 years of the site's history.



The diagram shown here (reproduced with thanks to the authors from the paper by Jones et al 2011), relates to the last 10,000 years, and combines the results of palynology (pollen analysis) with sediment stratigraphy. The paper itself combines these with stable isotope records and changes in local chirominid (midge) populations, to produce a high-resolution record of climate and environmental change.

Returning to the story itself, sediment input from hillslopes into streams and rivers – particularly the River Kent – would have been much greater during immediate postglacial period than it is from the completely vegetated landscape seen today, adding to the substantial sediment load supplied from the retreating glaciers themselves. Together, these sediments would have caused the rivers to build-up broad floodplains occupied by highly dynamic braided channels with only limited stabilising vegetation.

Contemporary braided river within a broad valley 'sandur' with minimal valley-floor vegetation, in Iceland. (©Cuesta)

The braided floodplain surfaces would have been well below the present level of estuarine sediments, which have built-up in response to rising sea levels since the end of the Devensian Age. Buried valleys cut into solid rock beneath Morecambe Bay, at elevations of -60 to -80m below present-day sea levels, testify to the much lower levels of the rivers during the Devensian (and earlier) glaciations.

Vast expanses of sand and gravel, grading downstream to finer-grained sand, silt and mud would thus have extended from the Kent floodplain and estuary far out beyond the present shoreline, into Morecambe Bay. Wind erosion of unvegetated silts and clays from these surfaces would have created frequent clouds of fine-grained dust, blown back onshore by prevailing south-westerly winds, to be deposited as '*loess*' on the surrounding hills. The limestone screes on Arnside Knott are in places mixed with loess sediments and with re-precipitated calcium carbonate (calcite crystals) giving rise to locally cemented scree deposits (see photo on page 26 above).

Along with much of northern Britain, the Arnside - Silverdale area would have been uninhabitable during the Devensian glaciation. Human (*Upper Palaeolithic*) occupation at that time would have been limited to areas beyond the glacial limits. Around 14,700 years ago, however, there was an abrupt amelioration in climate as temperate waters of the Gulf Stream returned to the western coasts of the British Isles, following the retreat of the North American ('*Laurentide*') ice sheet which had previously been blocking the circulation. It is likely that Palaeolithic hunter-gatherers would have begun to migrate northwards at this time, as the climate improved, and caves on the rocky outcrop of Warton Crag, in the southern part of the

AONB may well have provided shelter for such people. The earliest known evidence for human occupation in the area, from Kent's Bank Cavern on the northern side of the Kent estuary, dates from around 10,000 years ago.

The warming climate is recognised as a marked change in the pollen record at Hawes Water and elsewhere and is known as the '**Windermere Interstadial**'. Whilst still cooler than the present day, the interstadial allowed previously exposed sediment to become stabilised by vegetation and allowed soil formation to recommence. Soils would have developed readily on areas of loess and glacial sediments, but much more slowly on exposed limestone surfaces.

At Hawes Water, distinctive shelly marl deposits of this Age are preserved beneath younger (Late Glacial and Holocene) sediments, including peat deposits. The marl is a particular type of *lacustrine* (lake) sediment associated with the natural precipitation of calcium carbonate from surface water draining in to the lake. The deposits indicate that, at this time, the lake was smaller than it is today and at least 2 metres lower than its present level. The hollow containing the lake is thought to have formed initially by karstic dissolution – perhaps as a large, pre-Devensian *polje* (see page 19) or as a composite *doline* feature – but was subsequently modified by glacial erosion and by the deposition of glacial till during the Devensian. The till would initially have sealed the permeable limestone surface, allowing surface water to collect.

Wetland developed over peat and marl deposits at the NW margin of Hawes Water

Detail of the shelly marl deposits at Hawes Water

The Windermere interstadial was followed, between 12,600 and 11,700 years ago by a final resurgence of glacial conditions, during the Late Devensian - a period also known as the '**Younger Dryas**' stadial or '**Loch Lomond Readvance**'. Whilst the re-advance of glaciers was significant in parts of Scotland, in northern England it was limited to small corrie glaciers in the Lake District mountains. There was no glacial activity within the AONB itself. However, intensely cold periglacial conditions would have been more widespread, bringing a return to tundra vegetation and causing the disruption or even destruction of the immature soils that had begun to develop during the preceding interstadial. Lake sediments (lacustrine silts and clays) from this Age are preserved at Hawes Water, overlying the interstadial marl. Such deposits are also mapped elsewhere by the BGS (as shown on **Map 3**), in locations which are no longer lakes, and lake sediments are also likely to be present beneath more recent peat deposits at Hale Moss and White Moss.

Holocene – Global Warming, Rising Seas and the Growing Influence of Man

The succeeding "**Holocene**" sub-period (also referred to in some literature as the '**Flandrian**') began abruptly some 11,700 years Before Present (BP[3]), when the warm Gulf Stream current once more became re-established, providing a rapid ameliorating influence on the climate of the British Isles. The first stage of the Holocene, known as the '**Pre-Boreal**' Age, from 11,700 to 10,500 BP, was initially very cold, with low shrubs and only sparse stands of birch and pine trees, but the period was then characterised by very rapid warming after 11,500 BP. Trees colonised the area from the south, mainly via the coastal lowlands, which were much more extensive than they are now, owing to lower sea level at that time (approximately 3m below that seen today).

It was during this interval when modern soil profiles would have finally begun to develop. These would have built on the remains of earlier, immature soils which had developed during the Windermere interstadial, before being disrupted by periglacial action, and also on freshly-exposed bedrock surfaces. The process of soil formation – especially on bedrock – has inevitably been extremely slow, continuing throughout the Holocene sub-period. It has also gone hand-in-hand with changes in climate, sea level, natural vegetation and human intervention, as described below.

The '**Boreal**' Age of the Holocene began some 10,500 years ago and coincided with the beginnings of a rapid, progressive rise in sea levels known as the "*Flandrian Transgression*". The rising sea levels were responsible for the deposition of marine clays and silts in each of the low-lying coastal areas within the AONB. These are shown on **Map 3** as '*raised marine deposits*' because they are well above present-day sea levels. At Silverdale Moss, core sampling, pollen analysis and dating of the Holocene sediments has revealed that, by the end of the Boreal Age, the sea had deposited marine clays over early Holocene peats before the area became re-colonised by sedges and finally raised mire (within the area shown as peat deposits on **Map 3**). A similar history took place at Leighton Moss, which had originally been a deep coastal inlet but subsequently developed into an extensive raised bog with peat developing on top of the marine clays[4].

Raised marine sediments are also mapped by the BGS more extensively in the Silverdale Moss area (beyond the peat deposits) and in the coastal lowlands at Arnside Moss and New Barns, although in those areas, no overlying peat deposits are shown on the BGS maps – presumably having been removed by cutting or ploughed for agriculture.

Both the Flandrian Transgression and the development of Holocene peat deposits continued into the succeeding 'Atlantic' Age, which extended from 8,000 to 5,950 BP. This time interval was warmer and moister than today's climate, reaching a 'climatic optimum' - the maximum extent of forest ecosystems across Europe - around 6,000 BP.

[3] Holocene dates are usually given in the form of years 'Before Present', where 'present' means the calendar year of 1950. In most cases the dates are obtained from radio-Carbon analysis of organic materials found within particular layers of sediment and those reported here are all calibrated dates (cal.BP) which have been corrected for systematic errors in some of the original analyses.

[4] It is important to note that, although raised bogs had initially developed in these areas, with the bogs being sustained purely by rainfall (rather than groundwater), they have since been damaged by human activity, and the areas now contain only lowland fen peats and/or reedbeds (where the peat has been removed altogether, as at Leighton Moss).

Silverdale Moss, seen from the slopes of Arnside Knott

Leighton Moss: an area of reedbed and open water habitat developed over peat deposits

At Hawes Water, relatively low lake levels persisted until around this time, after which there was an abrupt and substantial rise of water level to about 1m above its present-day level. This sharp rise in lake level is out of sync with patterns of climate change at this time (when lake levels elsewhere often fell), but is coincident with the rise in sea levels, and suggests that the lake was, by this time, connected to the local groundwater regime, which would have responded to the progressive rise in sea level.

Detailed research on the sediment cores from Hawes Water has revealed that the abrupt rise in lake level was also coincident with a rise in human activity within the area. This is evidenced by characteristic changes in the pollen record – a rapid decline in tree pollen and a rise in that of species associated with open ground – which are indicative of forest clearance by Late Mesolithic farmers. This may have reflected the migration of coastal Mesolithic communities inland, in response to the rising sea levels. Andy Denwood's (2014) account of the post-glacial history of nearby Leighton Moss notes that buried wooden artefacts dating from 4,200 BC (i.e. 6,150 BP) mark the first evidence for human occupation in that area.

The time interval following 5,950 BP is known as the '**Sub-Boreal**' Age. It corresponds in time to the introduction of Neolithic cultures to northern Britain, bringing increased rates of forest clearance for agriculture. A stone axe originating from Langdale in the Lake District, and used by Neolithic farmers to clear land, was found on Warton Crag. Rates of forest clearance (in northern England generally) increased further as the Neolithic gave way to the Bronze Age, especially between 4,300 and 2,900 BP. Bronze Age weapons have been found near Leighton Moss and a large kerbed cairn on the south eastern edge of Summerhouse Hill also dates from around that time, testifying to the presence of Bronze Age culture within the area.

Limestone Woodland on Arnside Knott

At Hawes Water, the lake level is thought likely to have remained high until at least 5,000 BP. Thereafter, the sediment cores suggest that there was a significant drop in water level, resulting in a shrinkage of the lake and exposure of the calcareous marl around the edges of the lake to colonisation by terrestrial plants, leading to the development of organic-rich fen peat within a marginal wetland/swamp environment.

The warm temperatures of the Holocene thermal optimum persisted until the start of the Bronze Age, but the climate then began to cool, marking the start of a generally downward trend – linked primarily to declining levels of incoming solar energy (insolation) over this period. This continued into the succeeding '**Sub-Atlantic**' Age, and through to the start of the 'industrial' era in post-Medieval times, punctuated by relatively short-lived warming episodes during the early Bronze Age, during the Roman era and in the early Medieval period.

The early part of the Sub-Atlantic was characterised not only by climate change but also by the steadily increasing influence of humans on the landscape. Forest clearance (across much of northern England) gathered momentum during the Iron Age, particularly between about 2,400 and 1,800 BP, and again during the Early Medieval period. It is not specifically known whether these trends were mirrored in the Arnside-Silverdale area, but Iron-age communities are likely to have been present in the area.

Buildings and settlements constructed from local limestone, dating back to Medieval times around 800 years ago, are scattered throughout the AONB and contribute to the character and quality of the modern landscape. Warton village is listed in the Domesday Book of 1086 and its church is thought to have Anglo-Saxon origins, as may the oldest part of St Michael's Church in Beetham.

Warton Village, clustered around its Medieval church, with Warton Crag behind

Other notable Medieval buildings include Arnside Tower – a defensive 'tower house', built originally around 1340 AD, similar but smaller Pele towers at Hazelslack and Dallam, the older parts of Leighton Hall, Beetham Hall, and a number of farmsteads.

Arnside Tower

From the 16th Century onwards the agricultural landscape would gradually have been transformed by the process of 'enclosure' – division of the land into smaller fields by the construction of drystone walls (particularly on outcrops of the Dalton and Urswick Limestones) or hedgerows (more characteristic of the Park Limestone, which weathers into smaller fragments and is therefore less suitable, in some areas, for building walls).

Limestone walls on Dalton Limestone outcrop at Scar Close, below Warton Crag

Limestone wall in Urswick Limestone, on Warton Crag

Hedgerow boundaries on Park Limestone near Yealand Redmayne

The Sub-Atlantic trend of falling temperatures which had been seen from the Iron-Age through to the Medieval period, culminated in the '*Little Ice Age*' – the most recent thermal minimum, between the 17th and 19th centuries. Whilst that period of time saw glaciers advancing in some parts of the northern Hemisphere, including Europe and Iceland, there was no such impact in the UK, and therefore no obvious effects on landscape evolution.

A much greater impact on the AONB landscape over this period has been the further influence of human settlement and land use. Peat cutting for fuel in all of the former areas of lowland raised bog, primarily during the 18th Century, destroyed these habitats which are now extremely rare in the UK. Much of the peat cutting was linked to the operation of a former iron-smelting furnace at Leighton Beck or to the salt industry and domestic fuel, in the case of Warton Moss.

This was followed, during the 19th Century, by various attempts to 'improve' such areas for agricultural use. At Hawes Water, for example, an artificial inflow and outflow were created in the 1800s, which lowered lake water levels enabling the surrounding land to be 'improved' from fen to arable land. Similar 'improvements', achieved by means of pumping rather than simple drainage, were seen at Leighton, Storrs and Arnside Mosses, beginning in 1830. In the case of Leighton Moss, a substantial embankment (1km in length) was constructed across the valley from the foot of Heald Brow to the base of Warton Crag and a steam engine with a paddle wheel pump was installed near Crag Foot. This pump drained water from behind the embankment to provide land for growing crops. Whilst the pump was in operation, the soil proved to be exceptionally fertile and the valley became known as the 'Golden Vale'. The pump became redundant in 1917 because of difficulties in maintaining fuel supplies, and the tall chimney at Crag Foot (see photo below) is the only surviving landmark.

Crag Foot Chimney

Leighton Hall Park - originally laid out in 1763

Other industrial heritage features, scattered throughout the AONB, include the remains of 36 lime kilns, where locally quarried limestone was 'burnt' to produce lime for agricultural and other uses. One of the most recently active kilns was constructed adjacent to Trowbarrow Quarry, which opened in 1868. Most of the buildings there were cleared in the 1970s, but remains of the kiln can still be seen.

The 18th Century saw the beginnings of quite different landscape transformations through the creation of historic designed landscapes such as those at Leighton Hall and the Dallam Tower estate. The registered parkland at Dallam Tower is of national importance. Here, the presence of glacial landforms (drumlins) and the floodplain of the River Bela provide a natural setting into which the parkland has been introduced to dramatic effect.

Dallam Tower Deer Park and listed deer shelter

Stone-built houses in Yealand Redmayne conservation area

The 18th and 19th Centuries also saw the progressive development of Arnside, Silverdale, Warton and other villages, particularly following the introduction of the Lancaster - Furness Railway, including the Arnside Viaduct across the Kent Estuary in 1857 and the construction of the Sandside - Kendal branch line in 1867. The railways also facilitated the development of relatively large limestone quarries at Trowbarrow, Middlebarrow and Sandside. All of these now provide opportunities, in varying degrees, to observe the geology of the limestones, although Sandside is still an active quarry and Middlebarrow, though closed since 2000, has no public access other than a viewpoint from the quarry entrance. Trowbarrow, which closed as an active quarry in 1959, is now a geological Site of Special Scientific Interest and a Local Nature Reserve as well as a popular visitor attraction and climbing venue. It also has industrial historical interest relating to its former kiln, tramway and details of its pioneering role in the development of tarmacadam, which continued for a few years after the quarry itself was closed, using stone imported from nearby Sandside and Middlebarrow quarries. The works buildings were eventually demolished in the 1970s. Photographs of Middlebarrow and Trowbarrow Quarries are shown on page 11, above.

In parallel with these direct human interventions in the landscape, since the Little Ice Age, there has been a progressive warming trend and an associated 'eustatic' rise in global sea levels. This has been despite a stable or further declining trend in solar activity and is considered to be linked (in part, at least) to the accelerating post-industrial increase in atmospheric 'greenhouse' gases. Global temperatures began to rise noticeably during the 'Industrial Era', from about 1860 onwards, and global sea level is believed to have risen by between 10 and 20 cm during the past century. The latest 'best estimates', as noted in the area's Shoreline Management Plan (SMP2)[5], are that it will rise by approximately 50 cm in the next 100 years (i.e. an acceleration of a factor of 3 in the rate of change).

Relative sea levels in north west England[6] are currently rising at a rate of approximately 2.5 mm per year, and are likely to increase to around 7 mm/year after 2025 and to 10 mm/year after 2055.

[5] Halcrow (2011): North West England and North Wales Shoreline Management Plan SMP2. Appendix C – Baseline Process Understanding.

[6] *'Relative'* sea level changes are those which take account of localised *'isostatic'* changes in the elevation of the land as well as global *'eustatic'* changes in the level of the oceans. In north-west England, the land surface has been rising since the end of the Pleistocene epoch, due to the isostatic 'rebound' of the landscape after the weight of former ice sheets was removed. The rebound has now almost ceased, however, so that continuing global sea level rise is now having a more immediate and direct impact on the coastline. The rates of relative change quoted here are the allowances recommended in Defra's latest (2006) guidance.

Morecambe Bay: tidal flats and migrating channels

The inner Kent Estuary, seen from Arnside Knott

Unlike the preceding cooling trend, the recent and continuing climate changes are beginning to have effects on the landscape. Rising sea levels inevitably change the morphology and sediment dynamics of estuaries and coastal systems, such as Morecambe Bay, giving rise to increasing flood risk in low-lying coastal areas (including former coastal inlets such as Leighton Moss) and to changes in saltmarsh and beach levels. Such changes are gradual and have been barely noticeable so far within the Arnside-Silverdale area but the SMP2 document notes that the estuary is progressively infilling with sediment sourced from offshore, as sea levels rise, and will continue to do so.

Saltmarsh elevations generally keep pace with rising sea levels, but the pattern of saltmarsh accretion (growth) in some areas and erosion in other parts of the estuary is highly variable over time, being dependent on the unpredictable shifting of the main deep-water channels, driven by strong tidal currents. Similarly, beach elevations are constantly changing in response to the wider circulation of sediment within coastal cells. Whilst the limestone cliffs which occur around much of the AONB coastline have been more resilient to change – being generally subject to only very slow rates of coastal erosion, the degree of exposure of geodiversity features within the coastal rock outcrops is highly dependent upon the continually changing elevations of saltmarsh and beach deposits.

Recently developed active saltmarsh at Hazelslack Marsh

Eroding Saltmarsh on the Silverdale Shore

In recent decades, an important new aspect of direct human intervention has featured in the development of the area's landscape: **conservation**. The AONB itself was designated in 1972, to conserve and enhance the natural beauty of the area. In addition, there are numerous scientific, environmental and historical designations which, between them, cover a high proportion of the terrestrial landscape and all of the marine environment of Morecambe Bay and the Kent estuary.

As an important part of this trend, some of the wetland areas are gradually being restored for the benefits of both wildlife conservation and tourism. Hawes Water, for example, is now managed as part of the Gait Barrows National Nature Reserve and re-naturalisation of the lake and its margins are being encouraged. As part of this, a sluice will be added to the artificial ditch that flows into Hawes Water from Little Hawes Water in order to manage water levels in Little Hawes Water to increase the amount of alkaline fen surrounding it. At Leighton Moss, which has previously been more extensively damaged by peat cutting and artificial drainage, recent dredging work has been carried out to further deepen the lagoons and channels to benefit wildlife, in particular the bittern. In addition, a large area at Warton Mires is currently being restored to wet grassland as part of the Warton Mires Project.

The Present-Day Landscape and Seascape

The long history of geological and geomorphological evolution described in the foregoing sections, including the progressively increasing influence of human activity in recent centuries, has culminated in the landscapes and seascapes that we see today. These form an intricate mosaic of different landscape types, as illustrated in **Map 4**, on the following page.

The categories shown on this map are from a detailed landscape and seascape character assessment undertaken by the Arnside & Silverdale AONB Partnership and LUC in 2015.

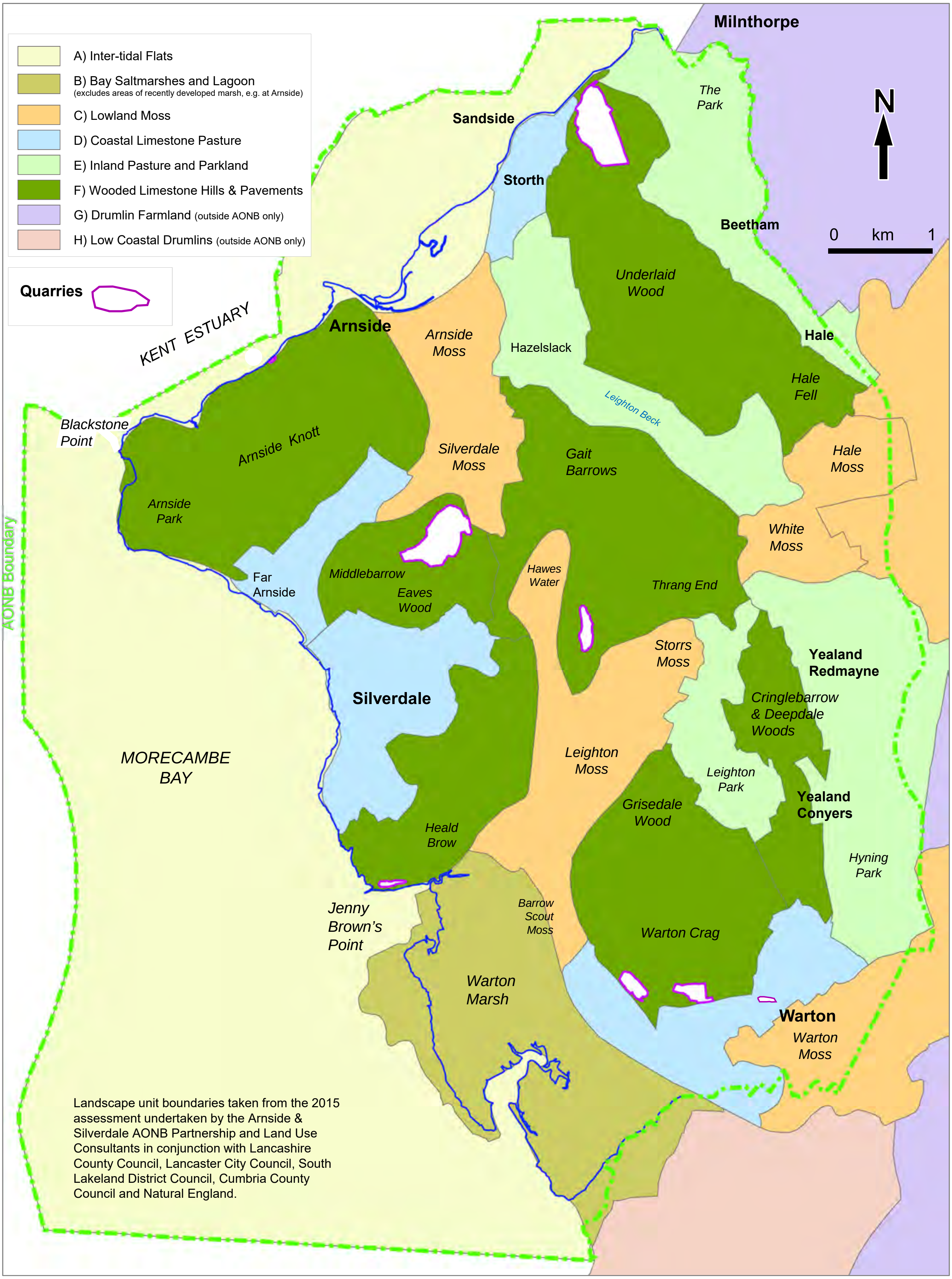
Six main character types are identified within the AONB, together with three others in directly adjoining areas, which form part of the AONB's setting. The six categories within the AONB are:

A. **Intertidal Flats**
B. **Bay Saltmarshes and Lagoons**
C. **Lowland Moss**
D. **Coastal Limestone Pasture**
E. **Inland Pasture and Parkland**
F. **Wooded Limestone Hills and Pavements**

The three additional character types adjoining the AONB are:

G. **Drumlin Farmland**
H. **Low Coastal Drumlins**
I. **Lowland Valley & Coastal Margins** *(identified primarily on the northern shore of the Kent estuary and therefore not shown on Map 4)*

Map 4 – Landscape & Seascape Character Types



Landscape unit boundaries taken from the 2015 assessment undertaken by the Arnside & Silverdale AONB Partnership and Land Use Consultants in conjunction with Lancashire County Council, Lancaster City Council, South Lakeland District Council, Cumbria County Council and Natural England.

Further Reading

General Publications & Leaflets:

What is Special about Arnside and Silverdale Area of Outstanding Natural Beauty? Arnside and Silverdale AONB, 2016, 51pp (https://www.arnsidesilverdaleaonb.org.uk/wp-content/uploads/2018/10/ASAONB-Special-Qualities-Report-2016-FINAL.pdf)

A Guide to Warton Crag Nature Reserves. Arnside and Silverdale AONB. (https://www.arnsidesilverdaleaonb.org.uk/wp-content/uploads/2018/09/warton_crag_reserves_guide_2018.pdf)

A Guide to Trowbarrow Local Nature Reserve. Arnside and Silverdale AONB. (https://www.arnsidesilverdaleaonb.org.uk/uploads/2016/04/guide_to_trowbarrow.pdf)

Clints and Grykes: The Limestone Heritage of the Arnside & Silverdale AONB. Arnside and Silverdale AONB.

The Limestone Link: A Walk through the Limestone Country of South Cumbria. South Lakeland District Council.

Denwood, A. (2014): *Leighton Moss: Ice Age to Present Day*. Carnegie Publishing Limited, 128pp;

Dewey, M. (2008) Limestones of the Arnside Area: Walk 9 in *Exploring Lakeland Rocks & Landscape*, Cumberland Geological Society 79-86;

Evans, B. (2010) *Walking in Silverdale and Arnside: 21 Easy Walks exploring the AONB*, 2nd edition, 156pp;

Jones, M. *A Walk through the Tropical Seas of Arnside*, Arnside and Silverdale AONB, 4pp;

Petley-Jones, R. (2013) *Gait Barrows National Nature Reserve*, Natural England, 21pp;

Standing, P (2015) *An Atlas and Guide to the Rocks and Soils of the Arnside and Silverdale AONB*, Bittern Countryside Community Interest Company, 19pp;

Geotrail Guides by Peter Standing:

(2015) *Storth Geotrail Guide*, 16pp; (https://www.arnsidesilverdaleaonb.org.uk/uploads/2016/04/storth_geotrail.pdf);

(2016) *Beetham and Hale Geotrail*, Exploring the Landscapes around Beetham: A Guide to Geology, History and Ecology, 24pp;

(2017) *Arnside Geotrail*, Exploring the Landscapes of Arnside Parish: A Guide to Geology, History, Ecology and the Estuary; 32pp

(2018) *Gait Barrows to Trowbarrow Geotrail includes Hawes Water and Leighton Moss*, Geology, Ecology, History, Conservation, 28pp

Photo North Discovery Walks by Joan Martin (2016) 2pp each: https://www.photonorth.uk/-/image-library/walks/arnside-and-silverdale-walks: *including walks from Arnside*, *Beetham*, *Silverdale*, *Warton* and *Waterslack*;

Key academic papers and technical reports:

Arnside and Silverdale AONB Partnership and LUC (2015) *Landscape and Seascape Character Assessment*. Produced in conjunction with Lancashire County Council, Lancaster City Council, South Lakeland District Council, Cumbria County Council and Natural England, 172pp.

Balderstone, M. and Dewey, M. (2003) The Dinantian Limestones of the Far Arnside and Silverdale Shoreline, *Proceedings of the Westmorland Geological Society* **31**, 6-22;

Gale, S. J. (2000) *Classic Landforms of Morecambe Bay*, Geographical Association in conjunction with the British Geomorphological Research Group, 47pp;

Garwood, E. J. (1912) The Lower Carboniferous succession in the north-west of England, *Quarterly Journal of the Geological Society of London,* **68**, 499-586;

Jones, R.T., Marshall, J.D., Fisher, E., Hatton, J., Patrick, C., Anderson, K., Lang, B., Bedford, A. and Oldfield, F. (2011): Controls on lake level in the early to mid-Holocene, Hawes Water, Lancashire, UK. *The Holocene* 21 (7), 1061–1072

Oldfield, F. (1960): Studies in the post-glacial history of British vegetation: Lowland Lonsdale. *New Phytologist* 59, 192-217

Thompson, A and Poole, J.S. 2019a: *Arnside & Silverdale AONB Landscape Monitoring Project - Geology Audit and Assessment: Final Report***.** Cuesta Consulting Limited, East Lambrook, 152pp + Appendices.