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Potential for renewed quarrying of West Highland Slate: a preliminary assessment of the island of Luing and the Ballachulish district

Decarbonisation & Resource Management Programme

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BRITISH GEOLOGICAL SURVEY

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Potential for renewed quarrying of West Highland Slate: a preliminary assessment of the island of Luing and the Ballachulish district

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Keywords

Report; roofing slate, quarry, quarrying, Ballachulish, Cullipool, Luing, Easdale, West Highland Slate.

Front cover

Cubic crystals of pyrite in a block of slate-rock at Cullipool No.2 Quarry, on Luing

Bibliographical reference

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Contents

FIGURES

Summary

This report describes the outcomes of a preliminary geological assessment of the potential to renew quarrying of West Highland Slate on the island of Luing and in the Ballachulish district. The assessment is based upon a brief field visit to each area, and a desktop review of published materials. The project was commissioned by Historic Environment Scotland (HES), with Highlands and Islands Enterprise (HIE) as a funding partner, and is part of ongoing efforts by both organisations to assess the feasibility of renewed quarrying of building stone resources in Scotland.

One section of this report provides some geological background to slate-rock, including an overview of the geological factors that can reduce the amount or quality of recoverable rock. Descriptions of the historical quarries and the geological setting and character of slate-rock in each area are presented in subsequent sections.

The key conclusion is that substantial resources of good-quality slate-rock almost certainly remain in both areas and, from a geological point of view, it certainly should be possible to renew quarrying in either area in disused or new quarries. However, the geology of the Ballachulish district is more challenging, and a significantly more detailed field-based assessment than has been possible here would be needed to identify the most promising localities there. Furthermore, all of the most prospective areas for slate-rock in the Ballachulish district lie within remote, topographically challenging ground with currently limited (or no) vehicle access. For these reasons, if investigations continue it would seem sensible to focus initially on existing workings in the Cullipool district of Luing, where topography and access are relatively favourable, and the geological framework is reasonably well understood and apparently relatively straightforward.

1 Introduction

West Highland Slate is one of the most important traditional building stones in Scotland. The dark grey metamorphic slate, which was used primarily for roofing and to a much lesser extent for masonry, was produced historically from numerous quarries distributed within a swathe of ground between Islay in the south and Fort William in the north (Figure 1). Slate production centred mainly on the villages of Ballachulish, Easdale, Cullipool and Tayvallich, and in the past most of the product now classed as West Highland Slate was known by the name of the local area from which it was sourced: *Ballachulish Slate, Easdale Slate, Cullipool Slate* etc. At its peak in the 19th century, many millions of roofing slates were produced annually from these areas and transported to markets throughout the UK and around the world. Following a long decline, production in the last functioning quarry finally ceased in the 1960s, and West Highland Slate has not been quarried since.

This report describes the outcomes of a preliminary geological assessment of the potential to renew quarrying of West Highland Slate in two parts of its outcrop: on the island of Luing, and in the Ballachulish district (Figure 1). The project was commissioned by Historic Environment Scotland (HES), with Highlands and Islands Enterprise (HIE) as a funding partner, and is part of ongoing efforts by both organisations to assess the feasibility of renewed quarrying of building stone resources in Scotland. The assessment was conducted by the BGS Building Stones Team and is based on a brief (half-day) field visit to each area, with a desktop review of BGS resources (including geological maps, memoirs, reports and rock collections), HES publications, other historical documents and aerial photographs.

Only a small number of published accounts contain information that is directly relevant to this assessment.

- The publication *Scottish Slates* by Richey and Anderson (1944) provides a highly informative account of the geological character and setting of the various 'slate belts' of Scotland, and a description of the associated workings and remaining reserves, as they were understood at the time. That publication is one of a series of 'wartime pamphlets' that collectively summarised the status of key natural resources in Britain at a time when national resource security was paramount. Several of the slate quarries on Luing and around Ballachulish were still active at the time *Scottish Slates* was published, though the industry was much reduced from its peak.

- More recently, Historic Scotland (now Historic Environment Scotland) commissioned two studies related to Scottish slate as part of early attempts to lay groundwork for renewed production of traditional Scottish building stones generally. These studies resulted in detailed reviews of: (i) the quarries and quarrying history in each of the main slate-producing areas of Scotland, with descriptions of the geological and performance characteristics (especially durability) of associated slates (Walsh, 2000); and (ii) the technical characteristics of the different Scottish slates, in particular their crystallinity, fabric and weathering properties (Walsh, 2002). The latter publication included an assessment of the feasibility of reviving the Scottish slate industry. Both publications are thorough and well-illustrated.

In geological terms, slate is probably the most complex type of building stone. A basic understanding of the geological setting in which slate-rock forms, and of the geological factors that can affect its character and distribution, is therefore needed to fully appreciate the assessment presented in this report. Section 2 of the report therefore provides some background to the geological concepts and terminology associated with slate-rock, before the outcomes of our geological assessments of Luing and the Ballachulish district are described in subsequent sections.

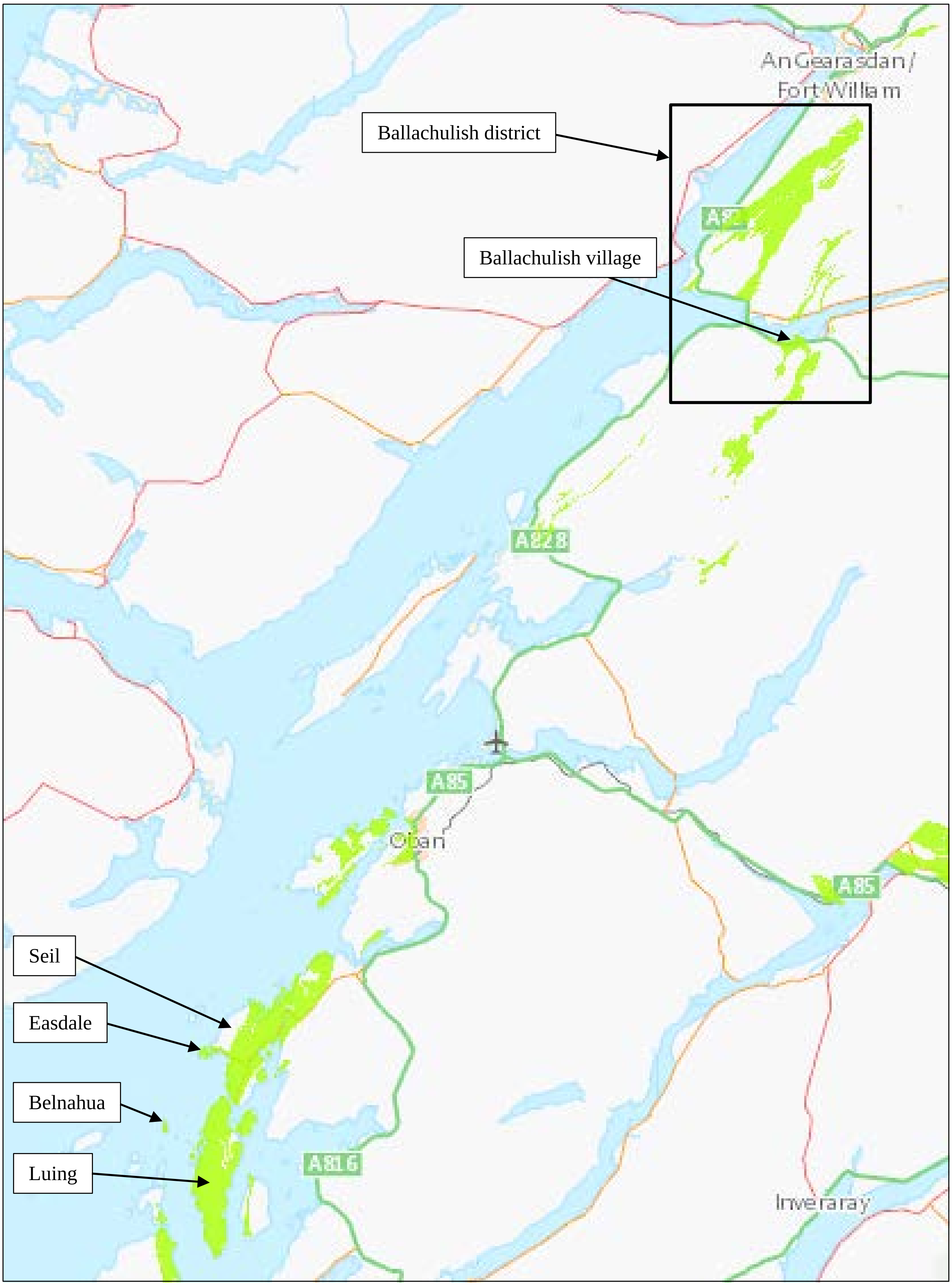

Figure 1. Map of key localities referred to in this report

The distribution of bedrock units from which West Highland Slate has been produced is shown in green. The full outcrop extends a further 80 km south-west of this map extent, to the southern tip of Islay. In the Ballachulish district, West Highland Slate was sourced from the *Ballachulish Slate Formation*, while in the ground between Luing and Oban it was sourced from the *Easdale Slate Formation*. Screen-shot from the *Building Stones Database for Scotland*.

2 Geological background

This section of the report provides some context for the geological setting of West Highland Slate and the processes that led to its formation, and introduces some of the relevant technical terminology. The term *slate* is used widely to refer to both a type of rock and a roofing material, and as such can be confusing; for clarity, therefore, the more specific terms *slate-rock* and *roofing slate* are used respectively in this report to distinguish the natural geological material from the man-made product.

The Grampian Highlands of Scotland, which includes all of the ground between the Great Glen and the Highland Border, are underlain predominantly by a single geological entity: the *Dalradian Supergroup*. This very large geological unit comprises a thick pile of mainly sedimentary strata that accumulated between 800 and 540 million years ago on the floor of a shallow sea bordering an ancient continent called Laurentia. Different types of sediment within the strata formed in different depositional settings: in very general terms, layers of mud were deposited in still water, layers of sand in agitated water, layers of gravel in flowing water, and layers of lime precipitated in still or agitated water. Layers of volcanic rock of mainly basalt composition also formed in periods when volcanoes were active; some volcanic layers formed on the surface of the sediment pile while others formed as sheets or layers of magma that were injected into it and then solidified. As the pile accumulated, buried sediment was transformed into solid rock: mud sediment became mudstone, sand became sandstone, gravel became conglomerate, and lime became limestone. Each layer is a *bed*, and that layering is referred to generally as *bedding*.

Around 470 million years ago, all of the rocks in the *Dalradian Supergroup* were affected by the *Caledonian Orogeny*, a continent-scale mountain-building event caused by collision of tectonic plates. *Metamorphism* – due to elevated temperature and pressure – transformed the sedimentary and volcanic rocks into metamorphic rocks: mudstone became *metamudstone* (or *pelite* if it was strongly metamorphosed), sandstone became *metasandstone* (or *psammite* if it was strongly metamorphosed), quartz-rich sandstone became *quartzite*, limestone became *metalimestone*, and volcanic rock became *metabasite*.

At the same time, *deformation* – resulting from compression as continental blocks first approached each other and then collided – caused the strata to become folded at a range of scales; the smallest individual folds can be less than one millimetre in size, while the largest recognised folds are more than 100 kilometres in extent. A fold that is convex upwards is an *anticline*, and one that is concave upwards is a *syncline*. These and other terms that are used to refer to the different parts of a fold are shown in Figure 2.

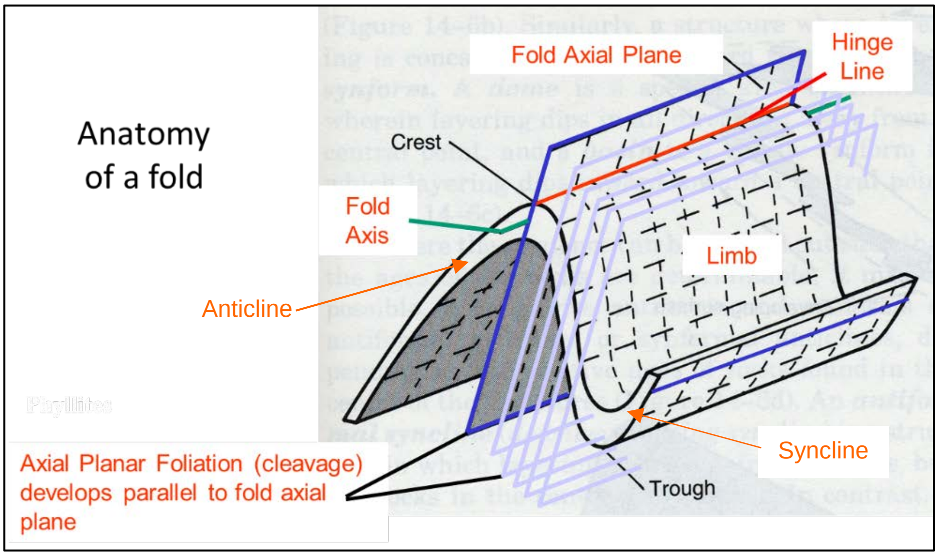

Figure 2. Three-dimensional relationship between a metamorphic cleavage and a fold structure

The compressive force that caused the strata to fold also caused individual crystals to recrystallise and re-organise, such that closely spaced, often mineralogically distinct layers developed in the rocks. New crystals grew within these layers, often aligned with each other and parallel to the direction of minimum force (i.e. at right angles to the direction of compression). The folded rocks therefore contain closely spaced thin layers and surfaces orientated parallel to the fold axis, along which the rock is often prone to part, or cleave; the parallel layers and surfaces that result from folding are therefore referred to collectively as *cleavage* (Figures 2–4).

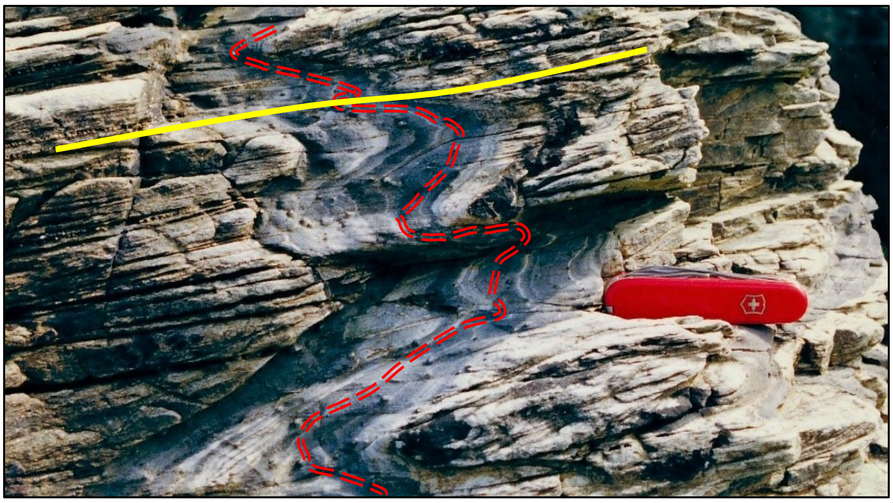

Figure 3. An example of bedding and cleavage at outcrop

Several small folds (shown by the red trace) are developed in beds of buff metasandstone and grey-blue metamudstone. A strong metamorphic cleavage is superimposed throughout (general trend shown in yellow), parallel to the fold axial planes (*cf*. Fig. 2). The angular relationship between bedding and cleavage changes in different parts of each fold. Penknife for scale.

Cleavage develops best in rocks containing crystals that grow naturally as thin 'plates', as these can most effectively re-align to form parallel layers and surfaces. One of the best minerals in this regard is *mica*, which occurs in many rock types. Mica is actually a 'family' of minerals, the commonest types being *biotite* and *muscovite*. Mudstone usually contains a large proportion of very fine-grained mica, so folded and metamorphosed layers of mudstone usually have a well-formed and closely spaced cleavage defined mainly by aligned flakes of mica. Metamudstone that parts readily along cleavage into thin, tabular blocks is known as *slate* (referred to in this report as *slate-rock*). The closely spaced and well-formed cleavage that is typical of slate-rock is commonly referred to as *slaty cleavage* (Figure 4). Cleavage is usually much less well developed in rocks that typically have little or no mica, such as sandstone.

Figure 4. A typical block of slate-rock in a Cullipool quarry

The block has split (possibly through human intervention) along the slaty cleavage into several smaller blocks with tabular form. Hammer for scale.

All three of the main building stones of Scotland that have produced roofing slate – *West Highland Slate, Highland Border Slate* and *Macduff Slate* – correspond to metamudstone layers developed in different parts of the Dalradian Supergroup.

Sedimentary rocks that have not been metamorphosed and folded tend to part most easily along *bedding surfaces* (i.e. crudely parallel surfaces that separate, and form within, the rock layers). If a cleavage forms subsequently, there are then two sets of surfaces in the rock along which it can part – bedding and cleavage; the extent to which a rock prefers to part along one or both of these sets of surfaces depends on how cohesive they are.

In folded strata, the angular relationship between bedding and cleavage changes in different parts of each fold, because bedding follows the curve of the fold while cleavage related to that folding is everywhere parallel to the fold axial plane (Figures 3 and 5). Thus, bedding and cleavage can be essentially parallel, or nearly so, on the *limbs* of a fold, and more nearly at right angles (normal) to each other in the *fold hinge* (the *crest* or *trough* part of a fold where the two opposing limbs meet). Those differences become more accentuated as the fold becomes more strongly developed and drawn out (*attenuated*).

The quality of slate-rock quarried for roofing purposes often depends on the *bedding-cleavage relationship*. Traditionally, the best and largest slates come from fold limbs, where bedding and cleavage can be near-parallel and the rock therefore will tend to split along just one set of parallel surfaces. By contrast, a fold hinge setting would generally be considered the less prospective, largely because bedding and cleavage are highly oblique to each other and the rock therefore can split along two non-parallel sets of surfaces. In many rocks this will tend to produce squat, angular fragments of rock, or narrow elongate ‘pencils’ of rock, rather than thin, tabular (slate-shaped) blocks. However, thick beds of uniform composition and character may show less tendency to split along individual bedding planes and so may also be a good prospect for quality slate-rock.

Folds can be symmetrical or asymmetrical; in the latter case, they have one shorter and one longer limb (Figure 5). On long fold limbs, the angular difference between bedding and cleavage may be only a few degrees and thus hard to spot.

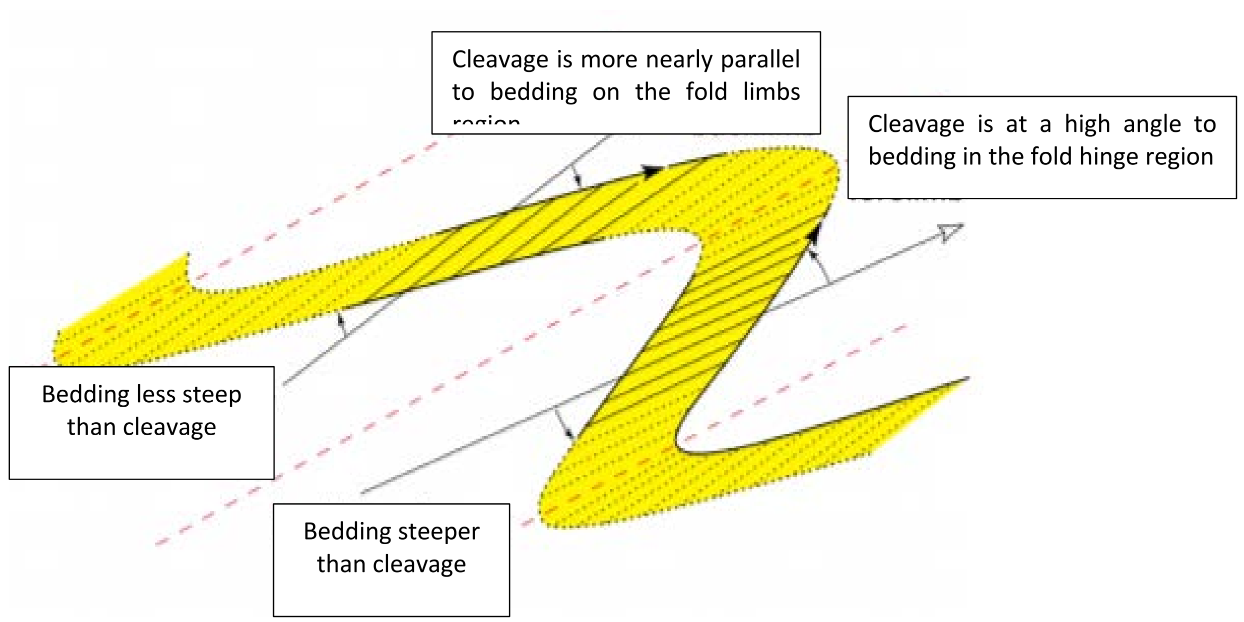

Figure 5. Changing bedding-cleavage relationship across an asymmetrical fold

Bedding follows the curve of the fold. Note how the angle that cleavage makes with bedding changes systematically from one fold limb, across the fold hinge region, to the opposing fold limb.

Coloured banding that characterises some roofing slates, and is often referred to as *ribboning*, occurs when bedding and cleavage are oblique and the rock parts along cleavage rather than bedding; the coloured bands are the original sediment layers (i.e. bedding) now cut through by the cleavage and exposed on the cleaved surface.

Orogenies (such as the Caledonian Orogeny) are often complex, multi-stage events involving multiple phases of collision between tectonic plates. Rocks will likely be folded more than once, in different orientations, to differing degrees in different places, and under different geological conditions. New fold structures can form during each stage of deformation, and with each phase of folding a new cleavage usually forms; cleavage formed during younger events tends to overprint and modify (or even obliterate) older ones. Geologists will often refer to each phase of collision, and its deformation products, using the letter 'D'; thus, D1 would signify the earliest discrete deformation event. Geologists then attribute other features related to that event in a similar manner, for example, F1 folds and S1 cleavage (S=surface) would both be related to D1.

The Caledonian Orogeny involved at least four more-or-less discrete phases of deformation. Of these, the first two – D1 and D2 – can be thought of as working together to produce very large-scale (km- to many 10s of km-scale) fold structures that created the essential architecture of the 'Scottish Caledonides' *c.* 470 million years ago. The main Dalradian rock units are, broadly speaking, aligned parallel to the trends of those major folds. As a general guide, major fold structures can be traced from northeast to southwest across the Grampian Highlands; however, in Argyll and Bute they trend rather more NNE–SSW. Where the second (D2) deformation is more strongly developed, folds and cleavage already formed in D1 may become strongly aligned with the superimposed D2 structures and are said to have become *transposed*. Where D2 deformation was most intense, D2 structures will tend to dominate and it can be difficult to distinguish the earlier-formed D1 structures.

The two later stages of deformation (D3 and D4) tend to be rather more localised in development but can be the dominant structural features in some places. More often, D3 and D4 produced small-scale folds and structures that wrinkle (or *crenulate*), buckle or 'kink' the rocks; such structures can be seen in many exposures of West Highland Slate. The orientation of these structures is quite variable and often strongly oblique to the trend of the earlier D1 and D2 fold structures. As a very general rule, it would be reasonable to expect that folds developed during the later stages of deformation would be more angular in form and style (i.e. kinked rather than curved), especially those related to D4. This is a consequence of the more brittle (tending to break) rather than ductile (tending to bend or flow) nature of the deformation at this time, as the structures formed under conditions of rather lower temperature and confining pressure. Given the more brittle deformation conditions, these later folds may also be spatially associated with discrete breaks (*fractures*) in the rock mass.

Several geological factors can reduce the amount or quality of slate-rock in any given area. The following are among the most important.

- *Interbedded layers of other rock types* – this problem occurs most commonly near the top and bottom of thick beds of slate-rock, where layers of rock that are more characteristic of the preceding and succeeding layers (which could be, for example, metalimestone or quartzite) can be interbedded with the slate-rock, as a result of a transitional change from one depositional setting and/or sediment source to another.
- *Mineral impurities in the slate-rock* – some mineral impurities can adversely affect the quality and appearance of slate-rock; for example, the mineral *graphite* (which is quite common in metamudstone) tends to greatly reduce its cohesiveness, and crystals of *pyrite* can occur in such abundance or size that they can render roofing slates visually unattractive or undesirable in terms of performance.

- *Quartz veins* – these tend to occur in closely spaced sets and irregular masses, and where they do the quality and amount of slate-rock that can be extracted can be greatly reduced. Quartz veins form in slate-rock because the metamorphism and deformation that converts mudstone into slate-rock releases silica from minerals in the rock at the same time; the silica moves through the rock by migrating along cleavage surfaces, and tends to accumulate – and crystallise into quartz – in zones of relatively low pressure, such as fold hinges.

- *Fractures* – all types of fractures, including unmineralised joints, mineralised joints (veins) and faults, disrupt the continuity of the rock in which they form; in beds of slate-rock, they can greatly reduce the quality and amount of rock that can be extracted. Whereas folds tend to form when rocks are hot and deforming in a ductile manner, fractures tend to form later when they are cool and deforming in a brittle manner.

- *Thermal metamorphism* – intense heat can cause the minerals in slate-rock to recrystallise, and in so doing any pre-existing planar structures such as cleavage and bedding can be destroyed. The main sources of intense heat in strata are bodies of injected magma, which cool to form intrusions of igneous rock. These come in two main forms: *major intrusions*, which range from 1–30 km in diameter and are usually crudely circular or oval at outcrop; and *minor intrusions*, which are less than 1 km in diameter and have circular to linear forms at outcrop. Most minor intrusions are sheet-like structures (steeply inclined *dykes* and gently inclined *sills*) usually around 1 m and rarely exceeding 5 m wide. Thermal metamorphism around major intrusions can destroy cleavage up to 0.5 km (and occasionally more) from them, while minor intrusions usually do not destroy the cleavage in adjacent rocks beyond a few metres (rarely a few tens of metres) from them. Where the edge of an intrusion dips beneath the ground surface at a shallow angle, the zone of heat-affected rock may appear to be significantly wider than if the edge were vertical.

  The Dalradian Supergroup is cut by numerous major and minor intrusions. In the area within which the West Highland Slate occurs, these intrusions were emplaced at two different times in geological history. Major intrusions of *granite* (a coarse-grained, silica-rich igneous rock) – including the Etive and Ben Nevis plutons – and minor intrusions mainly of *felsite* (a general term for rock types like *rhyolite* and *microgranite*, which are finer-grained equivalents of granite) were emplaced into the Dalradian Supergroup around 420 million years ago, during the latter stages of the Caledonian Orogeny when most of the deformation and metamorphism had ceased. Much later, around 60 million years ago, major intrusions of granite and *gabbro* (a coarse-grained, silica-poor igneous rock) – including those underlying Skye, Ardnamurchan, Rum and Arran – and minor intrusions mainly of *mafite* (a general term for rock types like *basalt* and *dolerite*, which are finer-grained equivalents of gabbro) were emplaced when the North Atlantic Ocean experienced a phase of rapid opening.

- *Overburden and ice damage* – superficial deposits, such as glacial till, sand, gravel, soil and peat, overlie much of the bedrock in Scotland, and can restrict access to it; in places, the thickness and instability (in engineering terms) of overburden impose a significant constraint on quarrying. Large ice sheets have moved across Scotland on several occasions during the ‘Ice Age’ (i.e. in the last 2.6 million years), and the abrasive effect of the ice as it moved has in some places damaged the bedrock immediately beneath. The *fissility* (propensity to split) of slate-rock makes it particularly susceptible to this process, and such rock can be physically damaged (and consequently more strongly weathered than usual) to a depth of several metres where this has happened.

3 Luing

3.1 INTRODUCTION

Luing is one of the 'Slate Islands' – a cluster of islands off the west coast of Argyllshire that were quarried extensively until the 20th century, producing vast quantities of 'Easdale Slate' that was used throughout Scotland and around the world for roofing. The other main islands in the group are Seil, Easdale and Belnahua (Figure 1). The district is currently administered by Argyll and Bute Council.

Most of the coastline of Luing is bordered by a raised beach – a flat bench a few metres above current sea level that is backed by a 'fossil' cliff line (Figure 6). The raised beach has formed during the last 10–20,000 years, as land that had been topographically depressed beneath an ice sheet rebounded upwards – a process that continues today. Inland, the island is characterised by mainly rough, knobbly ground, with a high point of just 94 m at Cnoc Dhomhnuill in the north. A hill-shade overlay, which emphasises topographical features by creating an artificial shadow effect, reveals a strong NNE–SSW-trending topographical 'grain' in the northern part of Luing, which has been produced by differential erosion of the folded rock strata (Figure 6).

3.2 BEDROCK GEOLOGY

More than 90% of Luing is underlain by the *Easdale Slate Formation*, which formed around 700 million years ago as a component of the *Dalradian Supergroup* (Figure 7; see also section 2). This unit, which underlies the productive parts of all the Slate Islands, was deposited originally as thick layers of mud interbedded in places with much smaller proportions of lime, sand and volcanic material. After a long geological history that includes a period of significant metamorphism and deformation, the outcrop on Luing today comprises folded strata of predominantly black, pyrite-bearing and locally graphite-bearing slate-rock, with interbedded layers of metasandstone and metalimestone developed locally (Baldwin and Johnson, 1977). In places, metalimestone occurs as ovoid or lens-shaped masses up to metre-scale in size that are 'wrapped' by the main slaty cleavage.

The only other bedrock units of any significance on Luing are a few thick layers of *metabasite* that are interbedded with the Easdale Slate Formation and crop out in the north-eastern part of the island, and two sets of dykes – an older set of felsite dykes trending NNE–SSW, and a younger set of mafite dykes trending NW–SE (Figure 7). The dykes are mainly between 0.5 and 2 m thick.

3.3 QUARRIES

Most of the historical quarrying on Luing was focussed on the north-west coast of the island, within and to the north of the village of Cullipool (Figure 6). A few slate quarries were also developed further south on the west coast, at Tir-na-Oig and Black Mill Bay; only one slate quarry was developed on the east coast, at Toberonochy (Figure 6). All of the quarries were sited on the raised beach; some were developed by excavating downwards into the flat raised-beach platform, while others exploited the bedrock immediately behind the 'fossil' cliff (by excavating sideways, or downwards, or both). The 'fossil' cliff line would have been relatively easy to explore and identify sites suitable for quarrying, and the flat raised-beach platform would have provided good access to quarry sites (via land or sea) and a convenient place to process slate-rock.

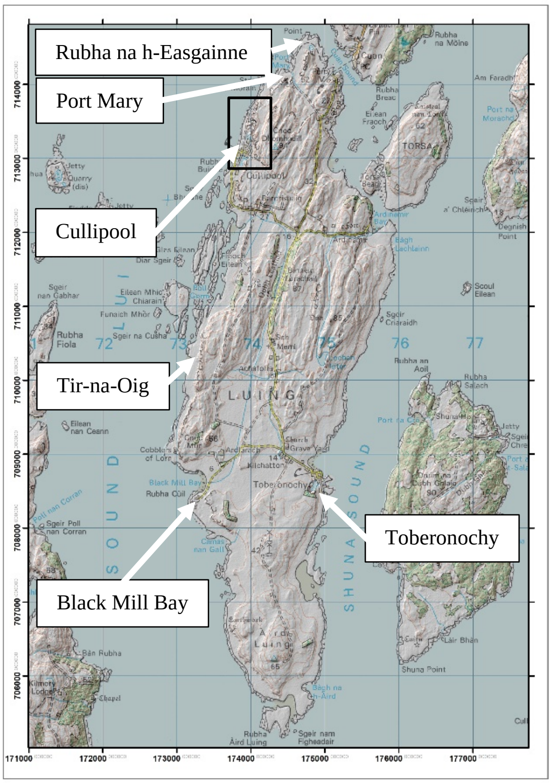

Figure 6. Topographical map of Luing with ‘hill-shade’ data superimposed

The strong NNE–SSW topographic ‘grain’ is clearly visible in the northern half of the island. A narrow strip of flat land (lacking contours) adjacent to the coast is a raised beach. The positions of the main historical slate-producing quarries and quarry clusters are shown. Black box shows the area encompassed by Figure 8.

Grid squares are 1 km on each side. ‘Hill-shade’ overlay derived from NEXTMap Britain elevation data, from Intermap Technologies. Contains Ordnance Survey data © Crown Copyright and database rights 2020.

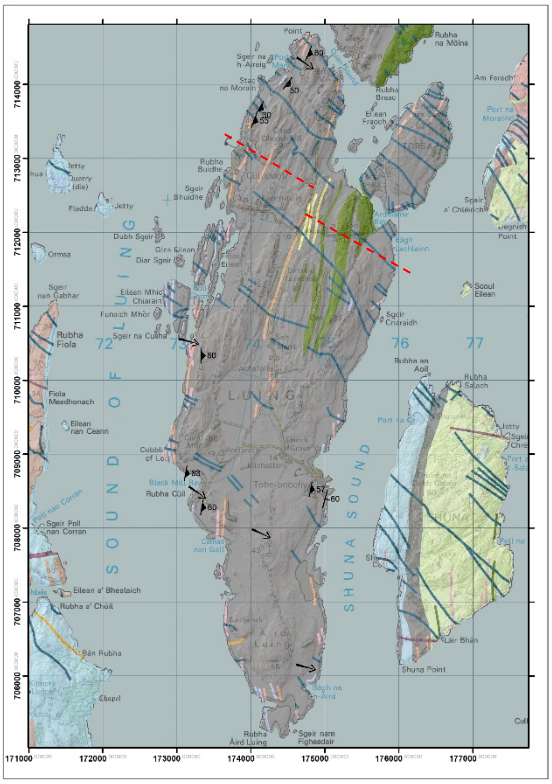

Figure 7. Bedrock geology of Luing on a topographical map with ‘hill-shade’ data

Colour scheme (key units only): grey = Easdale Slate Formation; green = Dalradian metabasite; pink lines = felsite dykes; blue lines = mafite dykes (Mull Dyke Swarm). Black symbols = orientation of the main slaty cleavage, including dip direction and amount[1]. Only the larger dykes are shown; numerous smaller ones are omitted. Red dashed line is the position of the cross-section on Figure 22.

Grid squares are 1 km on each side. Geology information from BGS DiGMapGB50 (the BGS 1:50,000 scale digital geological map of Great Britain). ‘Hill-shade’ overlay derived from NEXTMap Britain elevation data, from Intermap Technologies. Contains Ordnance Survey data © Crown Copyright and database rights 2020.

[1] Black symbols show the locations of orientation measurements for the main slaty cleavage, as recorded on historical maps and in other records: the ‘line’ part of each symbol represents the strike of the cleavage; the ‘triangle’ part represents the dip direction of cleavage (two triangles in opposing directions indicate cleavage is vertical); and the number indicates the size of the dip, in degrees from horizontal. Arrows denote generalised dip direction only.

The *BGS Database of Mines and Quarries* (also known as *BritPits*) has records for eleven slate quarries in the ground between Cullipool and Cuan Point at the northernmost tip of Luing (Figure 6); these are assigned to three quarry 'clusters' in the *Building Stone Database for Scotland* (BSDS).

- The *Rubha na h-Easgainne Cluster* at the northern tip of the island has three quarries.
- The *Port Mary Cluster* beside Port Mary (a few hundred metres SW of Rubha na h-Easgainne) has two quarries.
- The *Cullipool Cluster* has six quarries situated within an 800 m-long strip of ground extending from Cullipool northwards.

The locations of all quarries in the Cullipool Cluster are shown on Figure 8. Richey and Anderson (1944) used (and may have introduced) a numerical system for referring to five of the quarries (No.1, No.2 etc). In BritPits and the BSDS, the word 'Cullipool' precedes the same numbers in the names assigned to these quarries (Cullipool No.1, Cullipool No.2 etc.). We have found no record of older names for these quarries, and it is possible that only informal colloquial terms were used at the time they were being worked (e.g. 'the quarry', 'the old quarry'). The sixth quarry in the cluster, which is a few metres east of Cullipool No.1, was not mentioned by Richey and Anderson, and was referred to as 'Unnamed Quarry' by Walsh (2000). This quarry has been assigned the name 'Cullipool' in BritPits and the BSDS (Figure 8). Another quarry, roughly 100 m north of 'Cullipool' quarry, does not appear on OS maps and currently is not recorded in BritPits and the BSDS (Figure 8). Yet another quarry, labelled 'Quarry (dis)' on the current OS 1:25,000 scale topographic map, lies near the summit of Cnoc Dhomhnuill, some 300 m east of Cullipool (Figure 8); this quarry was not visited during this study, and it is not clear if the quarrying target was slate-rock.

A review of old topographical maps reveals that:

- the Cullipool, Cullipool No.4 and Cullipool No.5 quarries were being excavated by 1880;
- the Cullipool and Cullipool No.4 quarries had ceased working, and the latter quarry had flooded, by 1900; by the same date, Cullipool No.5 had more-or-less reached its full extent but was not flooded;
- the Cullipool No.1, 2 and 3 quarries were largely or entirely unexcavated until after 1900.

This sequence indicates that, in general, early quarrying centred on Cullipool and the focus moved up the coast only when the quarries there became exhausted or flooded.

The present appearance of all quarries in the Cullipool Cluster is shown in Figures 9–15. Summary details for all the slate quarries on Luing are presented in Appendix 1.

As part of this study, the authors made brief visits to all of the quarries in the Cullipool Cluster, on 5th February 2020. Descriptions in the remainder of this section of the report focus on the Cullipool district and take into account field observations made at that time, interpretations made from modern aerial photographs, and information gleaned from a range of historical records.

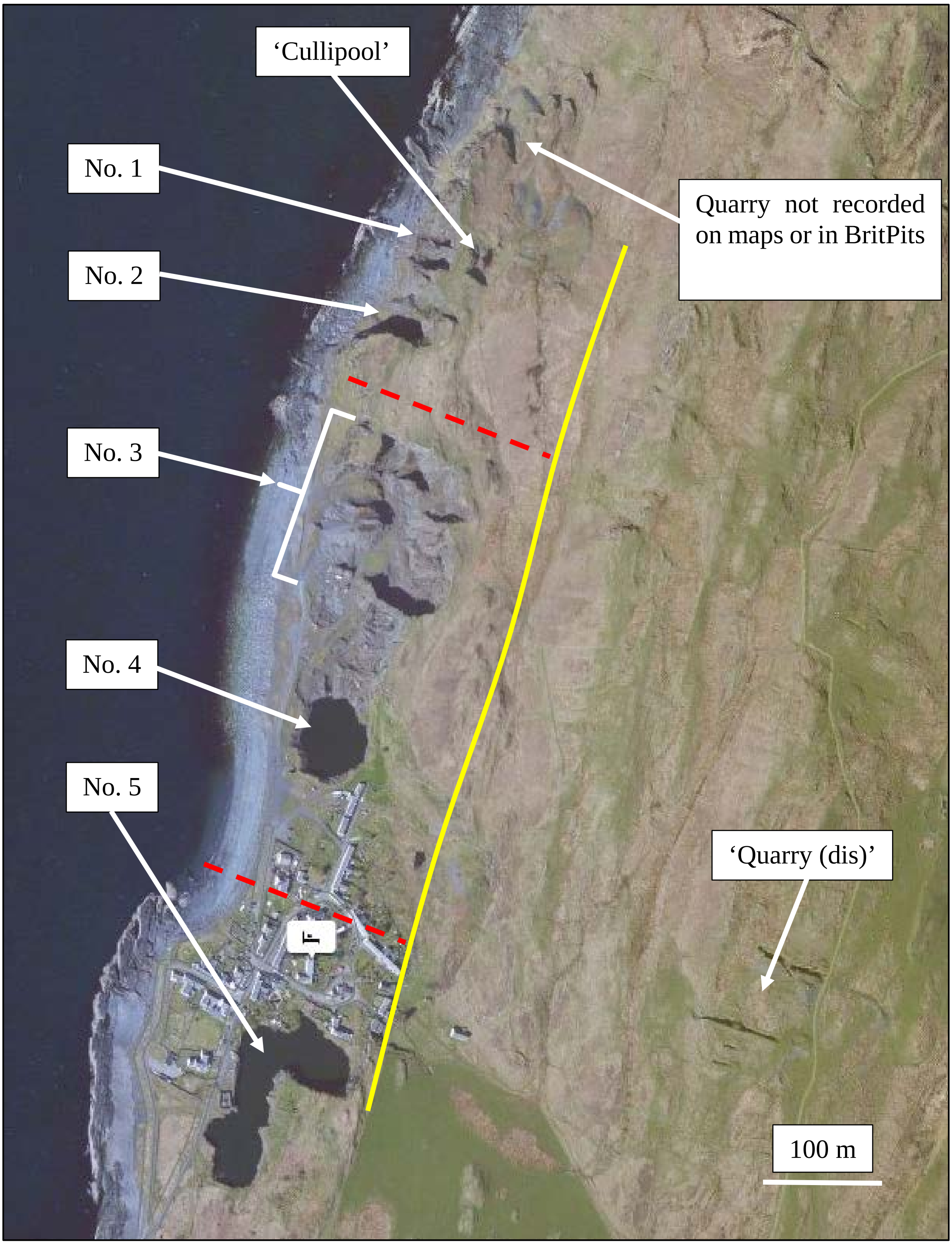

Figure 8. Locations of quarries near Cullipool

See text for details and Figure 6 for general location. The trend of the main slaty cleavage (yellow) and the approximate positions of NW–SE-trending faults along which more northerly quarries are inferred to step to the west with respect to the trend of the main slaty cleavage (red) are shown (see section 3.5 for details). Aerial screen shot from the Microsoft Bing Maps Platform. Microsoft product screen shot(s) reprinted with permission from Microsoft Corporation.

Figure 9. ‘Unnamed quarry’ (north end of the Cullipool Cluster), looking south

Note the very thin nature of slate-rock fragments in the spoil heaps, implying considerable fissility. Figure for scale.

Figure 10. ‘Cullipool’ quarry, looking NNE

The face at the far end of the quarry is roughly 8 m high.

Figure 11. Cullipool No.1 quarry, looking ESE

The quarry has two pits separated by a vertical panel of rock that has been left unquarried around a mafite dyke. Horizontal banding faintly visible in the upper part of the back wall is bedding. The back wall is *c.* 25 m high.

Figure 12. Cullipool No.2 quarry, looking ESE

The back wall of the quarry is roughly 25 m high.

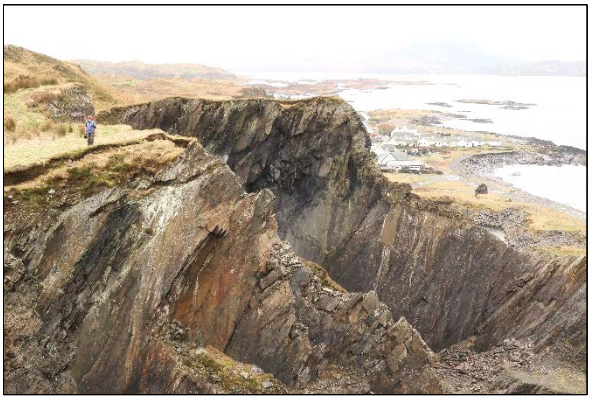

Figure 13. Cullipool No.3 quarry

Left image is looking down and east from the top of the west face of the north section of the quarry, over its lower, middle and upper levels. The total vertical elevation of all three levels is roughly 50 metres. Right image is looking south from the top of the north face of the north section, over the voids of the north (near) and south (far) sections of the quarry. Figure for scale.

Figure 14. Cullipool No.4 quarry and Cullipool village, looking SSW

Figure 15. Cullipool No.5 quarry (NE 'arm'), looking SE

Figure 16. Looking SE across the southern part of Cullipool No.3 quarry

Bedding (red) is clearly visible in the cliff right of centre as a form of ribboning. A panel of unquarried rock descending from the highest point of the main face towards the photographer’s feet contains a mafite dyke that takes an obvious ‘step’ to the right in the middle distance. Another dyke in the same set cuts the main face at right.

Figure 17. Bedding and cleavage in an unquarried part of the former sea-cliff

Looking north from a point near the NW limit of Cullipool No.3 quarry, with the general trends of folded bedding (red) and fold axial planar cleavage (yellow) indicated. The top half of the exposure, where bedding is most obvious, is probably sandstone-dominated, whereas the bottom half is probably slate-rock.

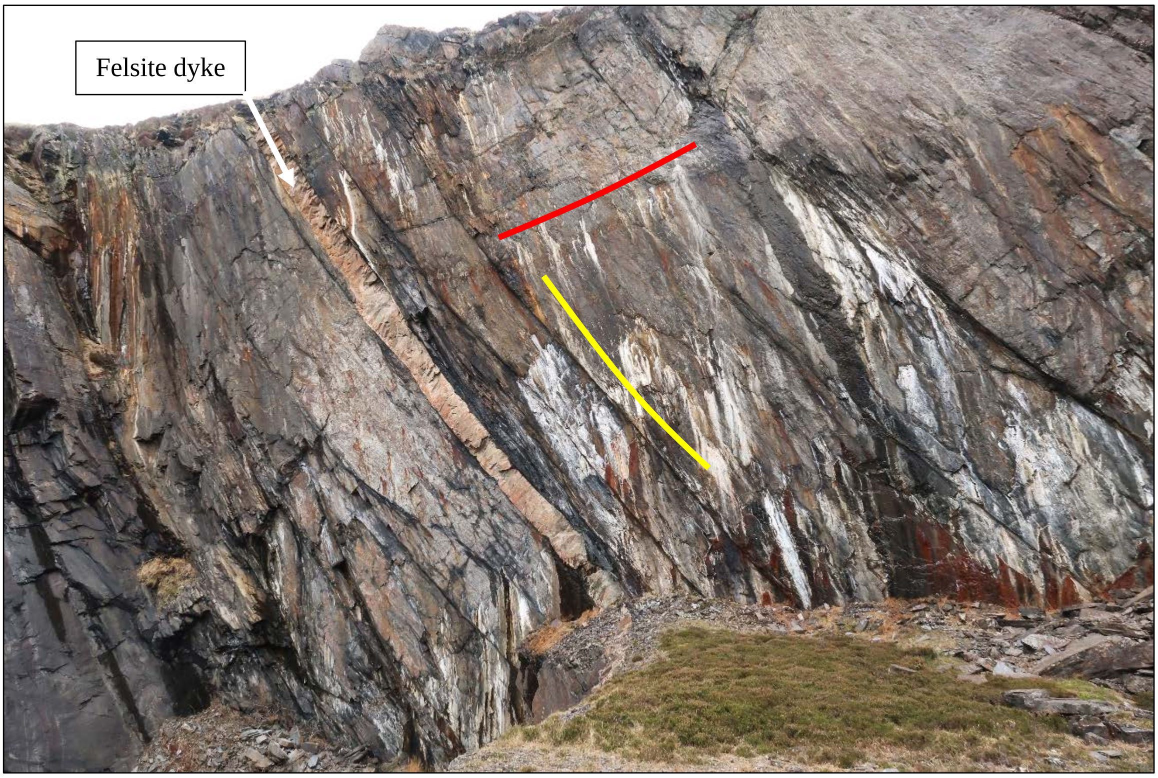

Figure 18. Bedding and cleavage in Cullipool No.3 quarry

Looking NNE from the middle level towards the north face of the quarry, which is around 20 metres high here. The general trends of west-dipping bedding (red) and east-dipping cleavage (yellow) are indicated. The top part of the cliff, where bedding is most obvious, may consist of interbedded sandstone and mudstone, whereas the lower part may be mainly slate-rock. A felsite dyke has been emplaced along the main slaty cleavage.

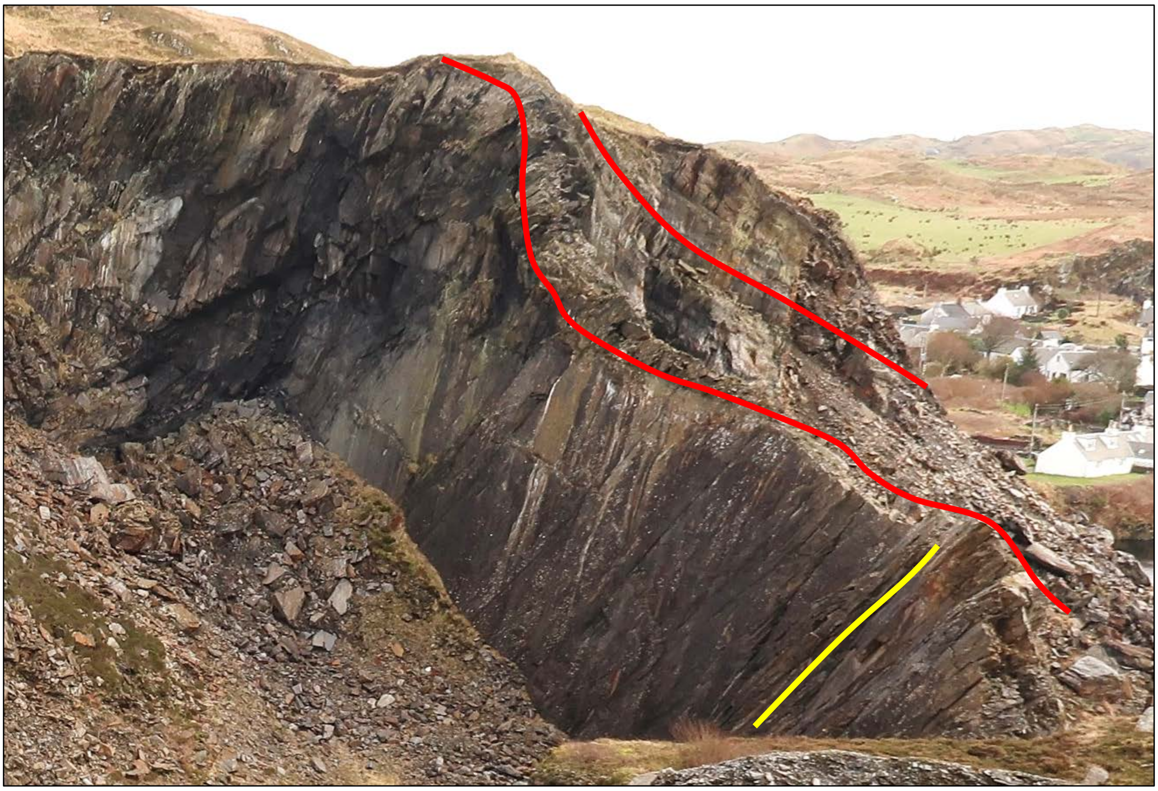

Figure 19. West-dipping strata in the south part of Cullipool No.3 quarry

Looking SSE from a point near the NW limit of Cullipool No.3 quarry, with the general trends of bedding (red) and cleavage (yellow) indicated. The top half of the exposure, where bedding is most obvious, is probably sandstone-dominated, whereas the bottom half is probably slate-rock.

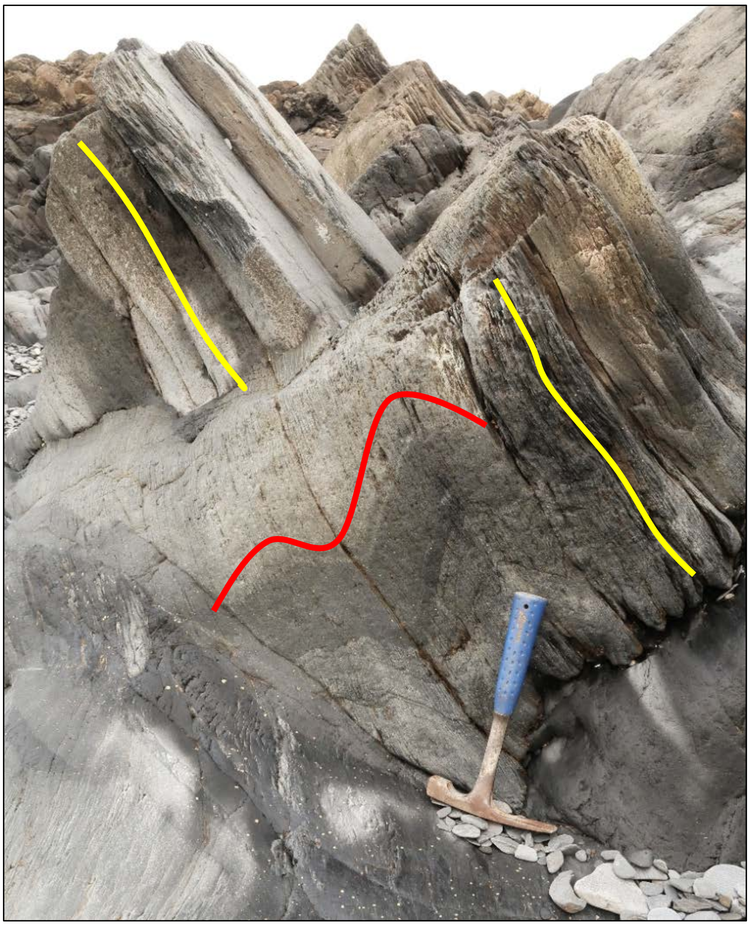

Figure 20. Bedding and cleavage on the shore opposite Cullipool No.1 quarry

Bedding with decimetre-scale folding (red) is visible just above the hammer. A well-developed, closely spaced S1/S2 cleavage (yellow) is parallel to the fold hinges and is the dominant surface on which the rock has parted.

Figure 21. Top surface of a decametre-scale fold on the shore near Cullipool No.1 quarry

Looking NNE along the fold hinge. Cracks on the fold surface have formed along the axial planar (S1/S2) cleavage.

3.4 GEOLOGICAL FEATURES IN THE CULLIPOOL QUARRIES

3.4.1 Early structures

Bedding is often difficult to discern in bedrock hosting the Cullipool quarries, but is usually most obvious where layers of sandstone are interbedded with the slate-rock. Bedrock exposed in the upper parts of No.3, No.2 and No.1 quarries consists of sandstone-dominated strata up to several metres thick, beneath which is a thick unit of slate-rock (Figures 16–19). The strata undulate but in the main are broadly horizontal to gently west-dipping, and become more conspicuously west-dipping towards the present coast and cliffs (Figure 19). Conspicuous folds on a decimetre to decametre scale are also developed in coastal outcrops, most notably between No.1 and No.3 quarries (Figure 20 and Figure 21), and there are excellent examples there of slaty cleavage cutting steeply and sharply across folded primary bedding (Figure 20).

Throughout the Cullipool district, cleavage generally dips at around 55–65° to the ESE, while bedding is typically more directly E- or W-dipping at angles less (often much less) than 50° (Figures 16–19). In general terms, therefore, bedding is more gently-dipping than the main slaty cleavage, and in most of the district is actually at a high angle or even broadly perpendicular to it. This observation suggests that the rock mass within which the Cullipool quarries sit lies within the hinge region of a large (km-scale), open fold (Figure 22; see also Figure 2). The geometry of this fold suggests it is located on the upper limb of a much larger fold, and general geological considerations indicate this is the Islay Anticline – a major fold that has been mapped in this part of Scotland (Figure 23).

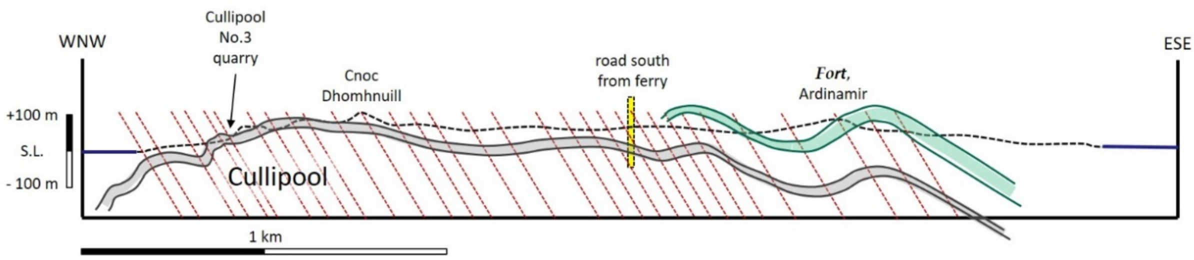

Figure 22. Schematic geological cross-section through the northern part of Luing

This cross-section is based on a preliminary assessment of limited geological data; more detailed field data and further analysis are needed to test its accuracy. See Figure 7 for the geographical position of the cross-section. Key: blue lines = sea; dashed grey line = land surface; dashed red lines = main slaty cleavage; grey polygon = '70 foot' slate-rock; blue-green polygon = metabasite. Horizontal scale = vertical scale. For clarity, only selected units in the Dalradian strata are shown and dykes are omitted. The layer of slate-rock defines a gentle, km-scale fold, with the Cullipool district (and ground to the east) sitting in the broad hinge zone. Bedding is everywhere highly oblique to cleavage.

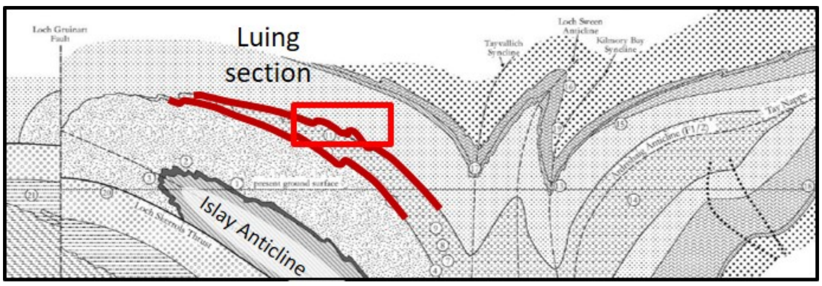

Figure 23. Schematic geological cross-section through the west part of Argyllshire

The section extends from west (left side) to east (right side), and spans approximately 40 kilometres. The red box shows where the open, km-scale fold shown in Figure 22 is inferred to sit within the regional geology of this part of Scotland: on the upper limb of a much larger fold, the Islay Anticline. Modified after Tanner *et al*. (2013).

The Islay Anticline is a composite ‘D1/D2’ structure (see section 2 for additional context). The relative effects of D1 and D2 on Luing cannot be determined in detail with the currently available data, but close inspection of individual fold hinges in the Cullipool district shows that the main slaty cleavage is likely to be a composite of S1 and S2 cleavages; in other words, S1 (the cleavage related to D1) was transposed by D2 and is now largely coincident with S2.

A preliminary examination of ‘Easdale Slate’ samples held in the BGS Collection of UK Building Stones supports this field observation. Evidence of very thin bedding (essentially a lamination) aligned at a very high angle to the main slaty cleavage can be seen with a hand lens on the long edges of most samples from the Toberonochy, Cullipool, north Luing, Easdale and Balvicar quarries (note that this feature can only be seen on the long edges of prepared slates which are assumed to be looking along the alignment of the fold axis in those cases). The lamination is expressed as thin layers with differing relative proportions of quartz and mica, representing sandier and muddier layers (beds) respectively in the original sediment. It can also be seen that the cleavage is actually a composite of two separate elements. The cleavage along which the rock has been split to make the roofing slates is the second one to have formed (i.e. S2). S2 cuts across (transects) an earlier mica-defined cleavage (S1), which has been rotated (transposed) to be nearly parallel to S2 but still makes a small (5–10°) angle with it; some of the SEM images in Walsh (2000; e.g. figure 3.5 [i]) show this relationship clearly. Millimetre-scale folds with axial planes that appear to be parallel to the S1 cleavage can be seen in samples from Toberonochy quarry. The S2 fabric cuts across these very small structural features, and is apparently unaffected by them.

The rocks of the Cullipool district are notable for the lack of any significant development of vein quartz. In the best example seen during the site visit, the quartz vein is very clearly affected by the folding that produced the main slaty cleavage, confirming it formed at an early stage in the history of metamorphism and deformation (Figure 24).

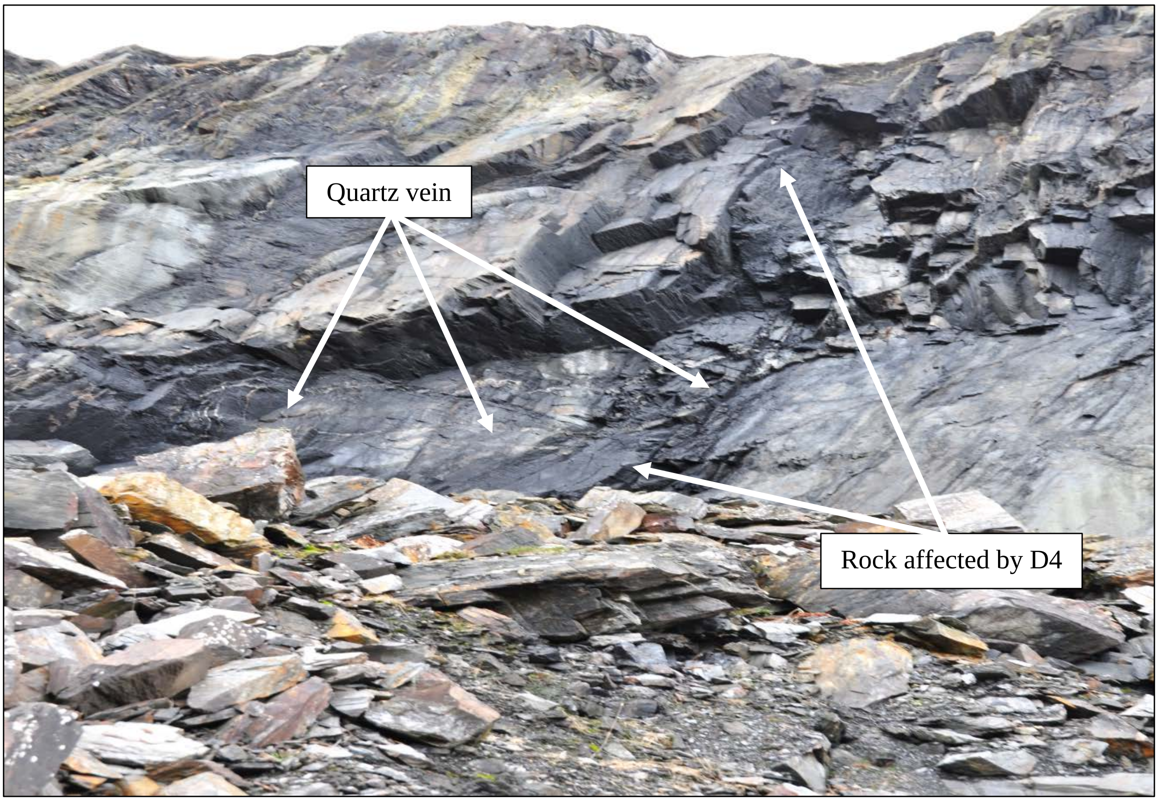

Figure 24. Quartz vein in slate-rock

A rare vein of white quartz exposed in the south face of the south section of Cullipool No.3 quarry has been folded into a highly irregular, contorted shape by the deformation that produced the main slaty cleavage. Part of the vein on the right side of this view lies within a volume of rock affected by superimposed D4 folding.

3.4.2 Later structures

At least two late-stage deformation fabrics have affected the slate-rocks in the Cullipool district, and these can almost certainly be correlated with the D3 and D4 regional deformation events that were described in section 2. The D3 fabric is (to the unaided eye, at least) a relatively widely spaced cleavage that is highly oblique to the main slaty cleavage (S1/S2) and typically manifests as a delicate wrinkling – or *crenulation* – of the S1/S2 surfaces (Figures 25 and 26). This crenulation is almost ubiquitous in the slate-rocks of the Cullipool district, but ranges from being extremely faint to the naked eye to a very obvious pattern of anastomosing ridge features 1–2 mm apart and up to *c.* 1 mm in amplitude. The crenulation gives roofing slates from Cullipool and elsewhere in the Easdale Slate Belt a distinctive character, and in most cases has little effect on the quality and productivity of slate-rock; however, the fissility (propensity to split) of the main slaty cleavage will be rather less pronounced and workable where the crenulation is most strongly developed. In addition to the relatively widely spaced crenulation that is visible to the naked eye, a closely spaced cleavage related to D3 may also be developed at the microscopic scale, which in places could further diminish fissility along the main slaty cleavage.

A later episode of folding and cleavage development (D4) is expressed in the slate-rock as isolated rock volumes characterised by angular folds – so-called *kink bands* – that produce quite marked chevron-like (knee-bend) folds of the main slaty cleavage (Figures 27 and 28). Affected volumes of rock are often lenticular in general outline but appear to be almost randomly distributed. Some generalised alignment is likely though, and such structures will tend to 'cluster' in certain parts of the rock mass; for example, features of this type seem to be common in the east part of No. 3 quarry. D4 probably affects around 10% of the thick slate-rock layer. Slate-rock within the kink bands is likely to be of poorer quality than rock which is not.

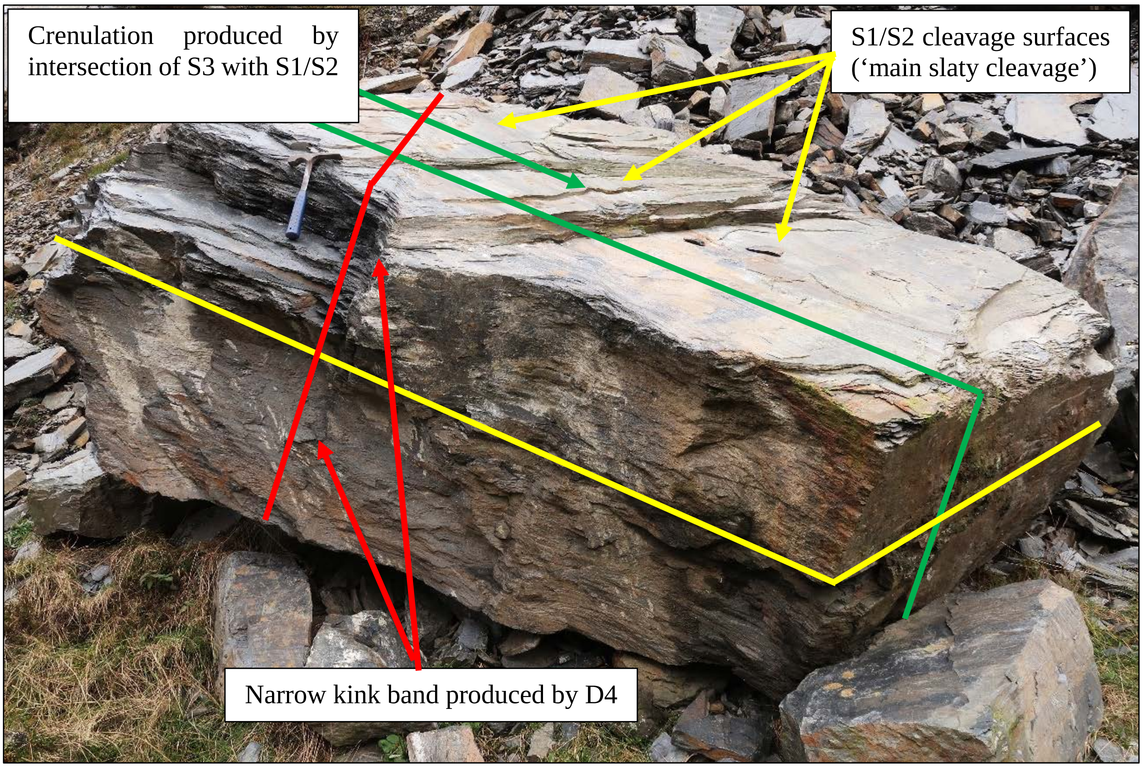

Figure 25. Small-scale geological structures in a block of slate-rock in Cullipool No.3 quarry

Bedding is not readily discernible, but small-scale superimposed structures created by all the main deformation events are represented. The orientations of planes parallel to the S1/S2 (yellow) and S3 (green) cleavages are shown, as is the orientation of a narrow band containing rock affected by D4 (red). Arrows of the same colour highlight examples of each generation of feature.

Figure 26. A specimen of roofing slate similar to that produced in the Cullipool quarries

The specimen is from Balvicar quarry on Seil, but displays features typical of roofing slates produced from the Cullipool quarries. The main surfaces of the roofing slate have been created by splitting the rock along the S1/S2 main slaty cleavage. Faint, slightly sinuous, closely spaced (mm-scale) colour bands trending steeply from top left to bottom right probably represent the trace of an oblique intersection of bedding lamination on the roofing slate surface. Faint wrinkles or ridges trending obliquely from top right to bottom left are D3 crenulation created by the intersection of S3 and S1/S2. Small gold spots scattered on the surface are crystals of fresh pyrite. Sample EMC 5738 in the BGS Collection of UK Building Stones. The specimen measures 30 cm from top to bottom.

Figure 27. Slate-rock affected by D4

Nearly all of the rock seen in this view is affected by D4. The yellow line traces the orientation of the main slaty cleavage in one part of the exposure, revealing the typical abrupt changes in orientation ('kinks') that characterise slate-rock affected by D4. The main slaty cleavage has been made more obvious than usual by the combined effects of D4 and incipient separation along the cleavage during and after quarrying. The field of view is around 8 m wide and the exposure is on the south wall of the middle level in the north section of Cullipool No.3 quarry.

Figure 28. Slate-rock affected by D4

A vertical band of rock around 2 m wide affected by D4 (displaying rough surfaces) cuts through rock unaffected by this deformation (smooth surfaces) on the east wall of the upper level in the north section of Cullipool No.3 quarry. Figure for scale.

3.4.3 Fractures and intrusions

Fractures

Examination of the 'hill-shade' data for Luing (shown at a low resolution in Figures 6 and 7) reveals that the bedrock is cut by several sets of fractures with a characteristic geometrical relationship that suggests they formed at the same time, in response to the same regional-scale tectonic event and stress regime. Discrete sets of fractures that are orientated NW–SE, WNW–ESE, NE–SW, and NNE–SSW are all clearly expressed in the topographic surface and observed at outcrop. These features are probably related to displacements that occurred around 400 million years ago on the Great Glen Fault Zone (GGFZ). The central part, or core, of this very large NE–SW-trending fault passes beneath the Firth of Lorn roughly 8 km west of Cullipool. A zone of rock known as a *damage zone*, which contains many smaller faults and fractures that formed as a consequence of displacements on the main structure, usually forms in the rock mass around many geological faults. The damage zone associated with the GGFZ extends for many kilometres on either side of the fault core.

The set of NW–SE trending fractures in this system can be observed throughout the volume of rock that was worked for roofing slate at Cullipool (Figure 29), and clearly exerted a strong control on the shape of the excavated voids. Pulverised rock formed by crushing is preserved locally within these fractures, for example in No. 3 quarry (Figure 30), indicating that such fractures accommodated lateral displacement (i.e. they were small geological faults); the pulverised rock is known as *fault-rock*. Two of the fracture sets – those trending NNE–SSW and NW–SE – appear to have been exploited by later sets of dykes (see below).

Intrusions

The Dalradian strata on Luing are cut by two sets of dykes (steeply inclined minor intrusions of tabular shape), which in general are between 0.5 and 2 m thick. An older set, which was likely emplaced around 420 million years ago during the later stages of the Caledonian Orogeny, trends NNE–SSW and is formed of felsite. The felsite dykes generally are in the same orientation as the main slaty cleavage, and appear to have exploited this relative weakness in the rock when they were emplaced (Figure 18). A younger set, which was emplaced around 60 million years ago as part of the Mull Dyke Swarm, trends NW–SE and is formed of mafite. The mafite dykes are much more numerous than the felsite dykes, in some areas being just a few metres apart. They cut across most of the earlier features in the bedrock, including the main slaty cleavage and the felsite dykes, at a high angle; however, they have a similar orientation to the set of NW–SE-trending small faults described above, and some mafite dykes were probably emplaced along these planes of relative weakness in the rock (Figure 29 and 31). Many of the mafite dykes are composite; in other words, formed of two or more parallel dykes that exploited the same fracture (Figure 32). Though generally steep and broadly of tabular shape, the mafite dykes have a tendency to become somewhat reclined (i.e. more gently inclined), and occasionally they 'step' to the left or right for several metres (Figures 16 and 32); this makes it difficult to predict where they will be encountered in unquarried rock.

The two sets of intrusions are at roughly right angles, and together they act to compartmentalise the workable slate-rock into discrete volumes; this is reflected today to some extent in the layout of the Cullipool quarries, in particular the No. 1, 2 and 3 quarries.

The felsite magma would have been at a temperature of around 600 °C when it was emplaced, and the strata on either side of each dyke would have been heated accordingly; however, there is little evidence that the heating around felsite dykes destroyed the slaty cleavage to any significant degree. By contrast, the mafite magma would have been in excess of 1,000 °C when it was emplaced, and the presence of envelopes of unquarried slate-rock on either side of mafite dykes indicates the cleavage here has been damaged to an extent that renders the rock unusable as roofing slate. The zone of heat-affected slate-rock around the mafite dykes appears to be *c.* 7 m wide for every 1 m thickness of dyke rock.

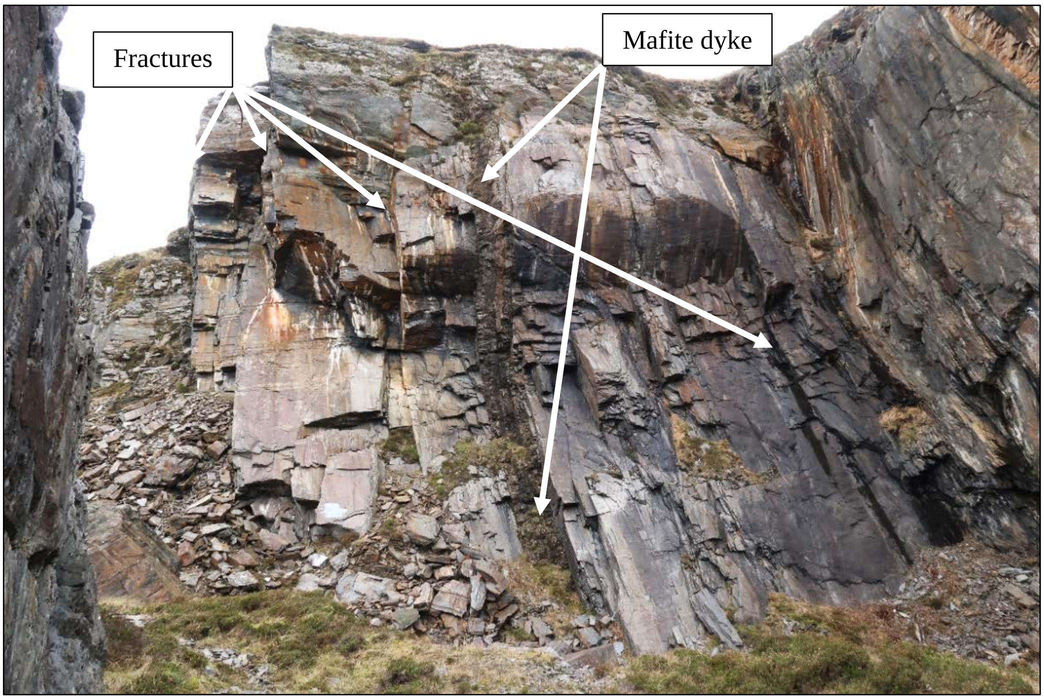

Figure 29. Fractures and intrusions in Cullipool No.3 quarry

Looking WNW towards the west face of the north section of Cullipool No.3 quarry, from the middle level. The face is cut by subvertical NW–SE-trending fractures, some of which are small faults. A mafite dyke also cuts the face, and has probably exploited one of the fractures. Most of the face has formed along the main slaty cleavage, which dips ESE (towards the photographer) at around 55°. The face is around 30 m high. The pale band of rock seen in the very top right of the image is a felsite dyke cutting the north wall of the quarry (see also Figure 18).

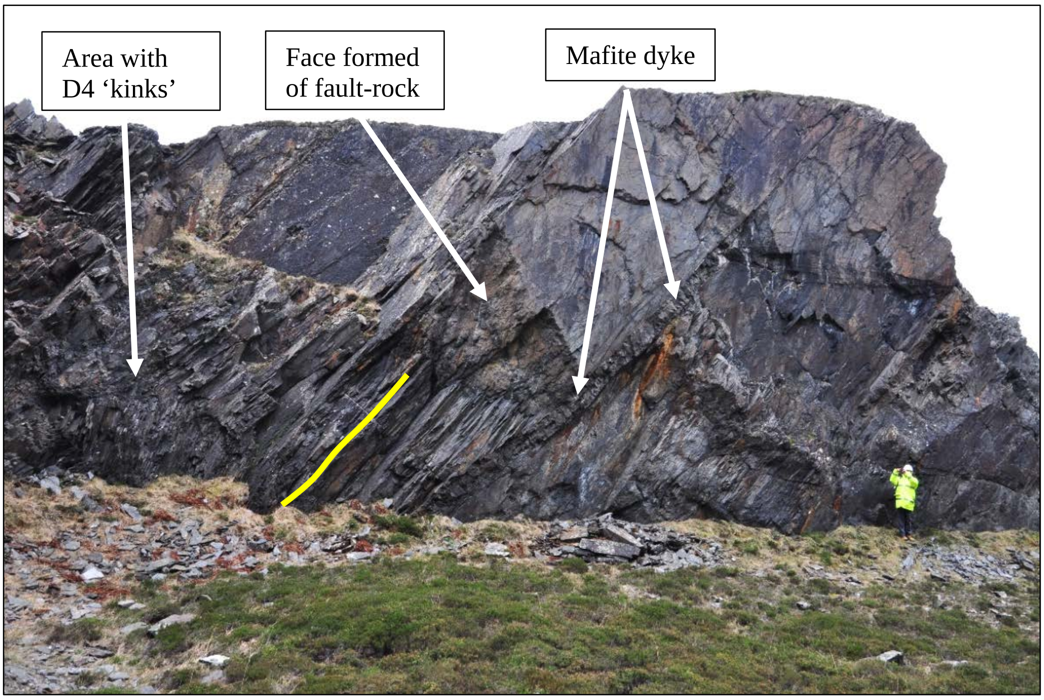

Figure 30. Fractures and intrusions in Cullipool No.3 quarry

Looking SSW towards the south face of the middle level, in the north section of Cullipool No.3 quarry. The main slaty cleavage (yellow) dips ESE at around 55°. The large flat surfaces in the top part of the face have formed where the rock has parted along one of the NW–SE-trending fractures seen in Figure 29. Pulverised rock (fault-rock) formed within one of the NW–SE-trending fractures is preserved on one (rough-looking) section of the face. A thin mafite dyke has exploited the main slaty cleavage (a rare orientation for this dyke set). The part of the face forming the left side of the image consists of slate-rock in which the main slaty cleavage has been 'kinked' by D4 (*cf.* Figures 27 and 28).

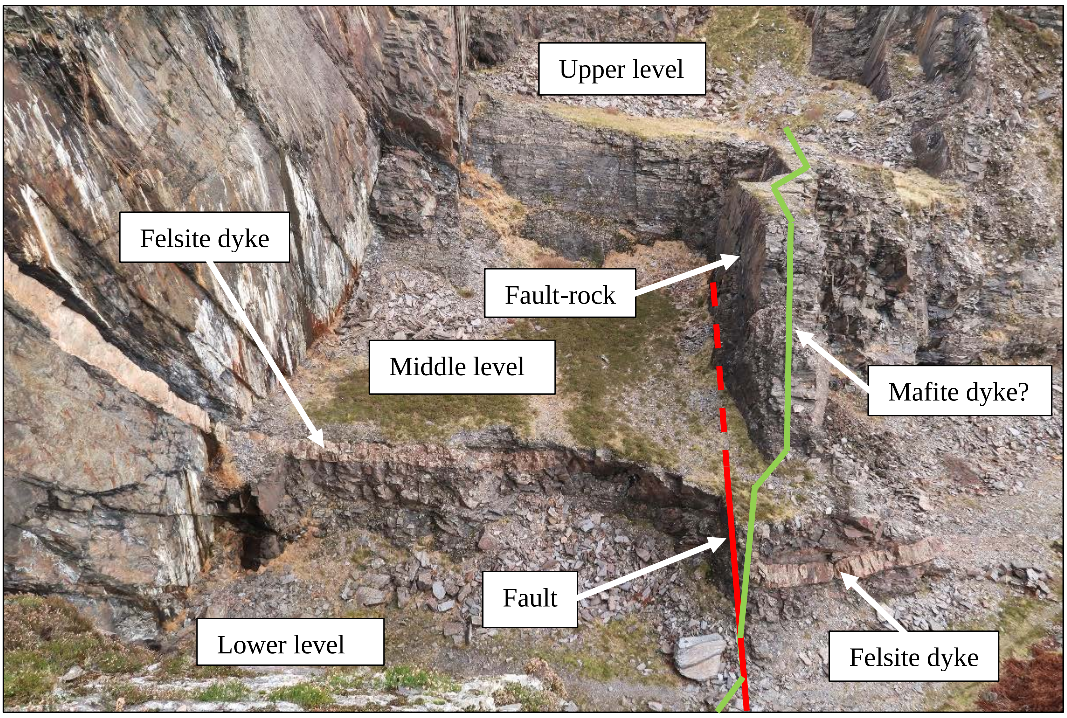

Figure 31. Felsite dyke offset by a small fault

Looking down and east from the top of the west face of the north section of Cullipool No.3 quarry, over its lower, middle and upper levels. The felsite dyke (the same one that appears on Figures 18 and 29) is displaced by several metres along one of the NW–SE-trending faults (red) shown on Figure 29. The fault-rock that is preserved on the south face of the middle level (see Figure 30) may have been produced by movement on the same small fault. The mafite dyke seen in Figure 29 must also cut the felsite dyke, but it is not obvious where; it may exploit the fault where it has offset the felsite dyke, and beyond that point it probably occupies the central part of the vertical slab of unquarried rock that forms the south wall of the middle level (green line).

Figure 32. Mafite dyke on the shore beside Cullipool No.1 quarry

Looking down and west from the cliff top above Cullipool No.1 quarry, to a coastal exposure in which a relatively large, composite mafite dyke (green) cuts west-dipping interbedded metasandstone and slate-rock. The dyke makes a lateral step of several metres in the middle part of the exposure, before resuming its generally NW–SE trend. In the lower part of the image, a dense set of fractures is developed in the strata a few metres on either side of the dyke; these probably represent the zone of damaged rock around a NW–SE-trending fault, which the dyke has exploited.

3.5 GEOLOGICAL CONTROLS ON QUARRYING IN THE CULLIPOOL CLUSTER

Richey and Anderson (1944) commented that a "belt of slate-rock, 60–70 feet in depth (measured vertically) has been most sought after" in the Cullipool quarries. This 'belt', which was worked in all five of the main Cullipool quarries, corresponds to the '70 foot' slate-rock shown on Figure 22. The relative positions of the worked volumes within these quarries provide some indication of how the layer is distributed in three-dimensional space.

- *Vertical distribution*
  The two southernmost quarries (No.5 and No.4) exploited rock below the level of the raised beach; a large part of the quarried rock was actually below sea-level (Richey and Anderson reported that the floor of No.5 quarry is *c.* 25 m below sea-level). By contrast, the lowest point in each of the three northern quarries (No.3, No.2 and No.1) is more-or-less coincident with the level of the raised beach, so the worked volumes in those quarries are entirely above the raised beach. Richey and Anderson reported that the base of the 'belt' could be seen in the floor of No.1 quarry, overlying poor-quality slate-rock in that excavation. The reason for the change in quality was not discussed, but it seems likely to be due to a change in lithology (perhaps a return to sandstone-bearing strata) rather than a change in structural character. The development downwards of all the main Cullipool quarries may have been constrained by this change to poorer quality material. A simple calculation suggests that such a 'floor' on average dips very gently (plunges) SSW at 3–5° in the Cullipool district. This could be accounted for by a small amount of dip in the folded strata hereabouts, but it is likely that some of the change in elevation of the slate-rock belt is due to a component of vertical displacement on the NW–SE-trending faults described above.

- *Horizontal distribution*
  Viewed in plan, it is clear that the Cullipool quarries are not arranged linearly, but instead are offset such that the more northerly quarries step progressively to the west with respect to the trend of the main slaty cleavage; the most obvious steps occur between No.5 and No.4 quarries, and between No.3 and No.2 quarries (Figure 8). Thus, the set of NW–SE-trending small faults described above may have accommodated a horizontal as well as a vertical component of displacement. The contacts of the mafite dykes that have been emplaced along some of these faults show no evidence for renewed faulting since they were emplaced. Thus, lateral offsetting of the 'belt of slate rock' by the NW–SE-trending faults must have occurred prior to emplacement of the mafite dykes.

Two important conclusions follow from the foregoing interpretations.

1. The position of unquarried parts of the 'belt' of good-quality slate-rock that was exploited historically in the Cullipool quarries can probably be predicted with some confidence. For example, it is likely to underlie ground to the south of No.5 quarry, and is likely to form the rock mass adjacent to (i) the lower sections of the south and north walls of No.3 quarry, and (ii) the lowermost parts of No.1 and No.2 quarries.
2. The worked volume of 'Cullipool' quarry (the sixth quarry in the Cullipool Cluster, which was not described by Richey and Anderson [1944]) probably sits structurally and topographically above the belt of good-quality slate-rock, in a different bed of slate-rock that overlies an intervening layer of interbedded metasandstone and slate-rock. Spoil heaps left in this quarry (Figure 10) suggest the slate-rock here had a somewhat different character to that in the main band, being apparently more fissile and with smoother 'S2' surfaces that typically do not show any conspicuous development of the D3 crenulation; however, it is unclear how this slate-rock compares in terms of quality.

3.6 SLATE PROSPECTIVITY

The best quality slates from the Cullipool district on Luing appear to have been produced from a (perhaps unusually) thick and lithologically homogeneous layer of slate-rock. This layer is interpreted to sit in the hinge zone of a large open fold, and the original mudstone bed in this structural setting may have been thickened somewhat during folding. The lithological character of this layer (specifically its homogeneous nature, largely lacking impurities and beds of other rock types) appears to be the primary control on roofing slate quality; bedding-cleavage relationships, often the primary control on quality in other slate belts, appear to be relatively unimportant here.

The geological model for Luing that has been proposed tentatively above suggests that good-quality slate-rock may underlie most of the island. The 'prospectivity polygon' is therefore drawn around the Luing 'mainland' coastline, excluding the area of heterolithic ground in the north-east (Figure 33).

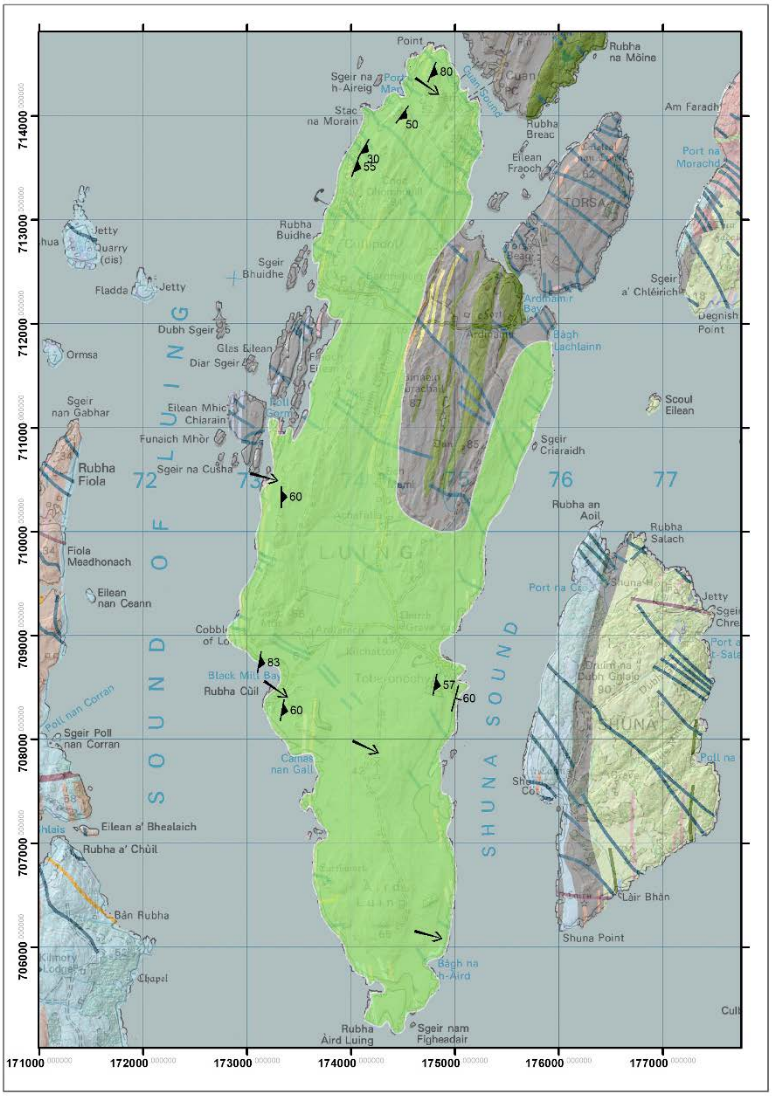

Figure 33. Most prospective areas for slate-rock on Luing

The green polygon indicates the area within which good-quality slate-rock (suitable for the production of roofing slates) may crop out on Luing, according to this preliminary geological assessment. Black symbols are structural data relating to the main slaty cleavage (see Figure 7 footnote for details). Grid squares are 1 km on each side. 'Hill-shade' overlay derived from NEXTMap Britain elevation data, from Intermap Technologies. Contains Ordnance Survey data © Crown Copyright and database rights 2020.

4 Ballachulish district

4.1 INTRODUCTION

The term *Ballachulish district* is used here to refer to the traditional slate-producing part of Scotland that is broadly centred on the village of Ballachulish (see Figure 1). The district, which lies near the southern border of the area currently administered by The Highland Council, includes two geographically distinct areas of ground on either side of Loch Leven: a smaller area on the south side of the loch in the immediate vicinity of Ballachulish village, and a larger area on the north side of the loch that stretches for around 7 km northwards from the village of Onich. These areas are referred to hereafter as *Ballachulish South* and *Ballachulish North*, respectively (Figure 34). Ballachulish South was the main focus of roofing-slate production, and historically is by far the more important of the two.

Production of roofing slate in the Ballachulish district started only after a major industry had been established for some time in the Slate Islands, but ultimately the Ballachulish district displaced the Slate Islands as the pre-eminent source of roofing slate in Scotland due in part to better connectivity to markets arising from easier access to the railway network. *Ballachulish Slate* is probably the best known of all the traditional Scottish roofing slates, with arguably the best reputation for quality.

The district is almost entirely hilly, characterised by smooth-sided hills that rise to 616 m above sea level at Beinn na Gucaig on the north side of Loch Leven (Figure 34). Most of the slate quarries are sited on moderately to steeply sloping ground. Substantial areas of ground lie under conifer plantation, much of which is managed by Forestry and Land Scotland (FLS); land managed by FLS is indicated on Figures 34 and 35.

4.2 BEDROCK GEOLOGY

All of the slate-rock in the Ballachulish district comes from a single bedrock unit, the *Ballachulish Slate Formation* (Figure 35). Like the *Easdale Slate Formation* on Luing, this unit formed around 700 million years ago as a component of the *Dalradian Supergroup* (see section 2 for further details). The main part of the formation comprises up to 400 m thickness of black slate-rock and interbedded graphite-bearing pelite. The formation has transitional boundaries with the units that lie above and below it in the Dalradian succession: layers of metalimestone are interbedded with the slate-rock near its boundary with the underlying *Ballachulish Limestone Formation*, and layers of psammite and quartzite ranging from a few millimetres to about a metre thick are interbedded with the slate-rock in the top 100 m or so of the formation, near the boundary with the overlying *Appin Quartzite Formation* (Figure 35).

Several major intrusions, and numerous minor intrusions, cut the Dalradian strata in the Ballachulish district: the largest major intrusion is the *Ballachulish Granite–diorite Pluton*, which crops out immediately west of the area shown on Figure 35 [top], underlies the mountain massif of Beinn a' Bheithir to the west of Ballachulish village; the *Mullach Nan Coirean Granite Pluton*, which crops out a few km east of the area shown on Figure 35 [bottom], underlies peaks forming the west end of the Mamores mountain range, just NE of the Ballachulish North area; and two much smaller unnamed intrusions crop out within the Ballachulish North area (Figure 35 [bottom]). Two sets of dykes – a set of felsite dykes and a set of mafite dykes – trend NE–SW (Figure 35 [top and bottom]); both formed during the later stages of the Caledonian Orogeny. Most of the dykes in these sets are less than 2 m thick.

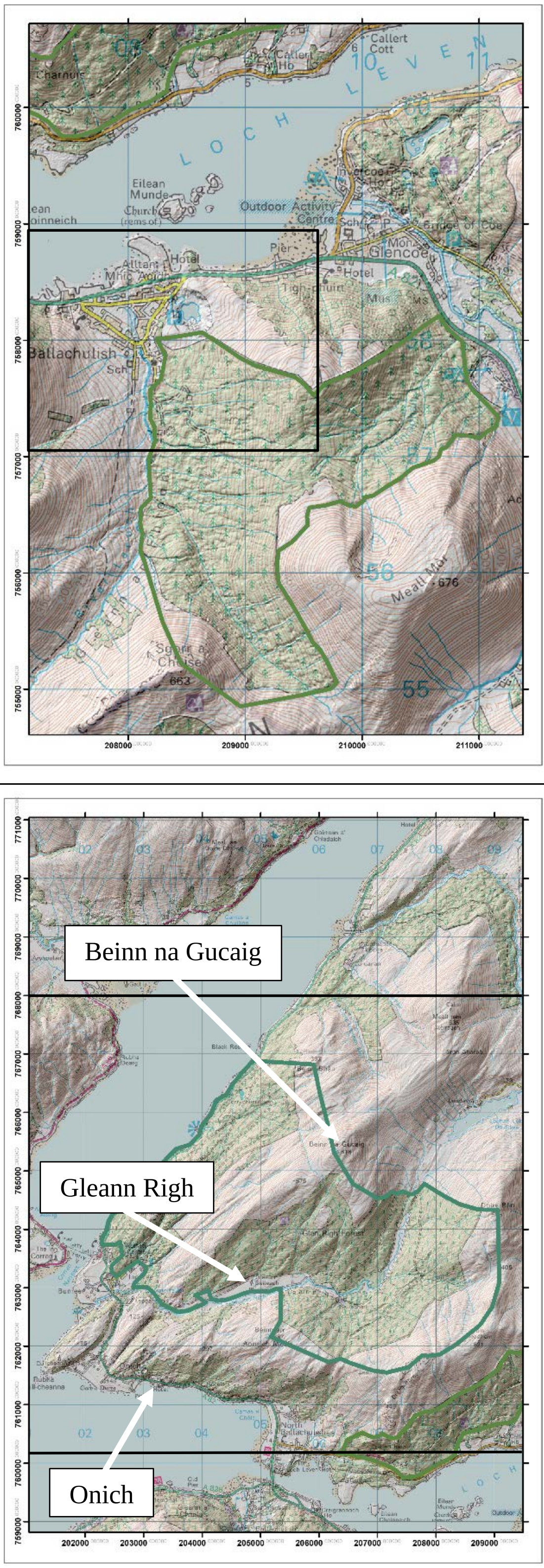

Figure 34. Topographical maps of the Ballachulish South (top) and Ballachulish North (bottom) areas, with 'hill-shade' data superimposed

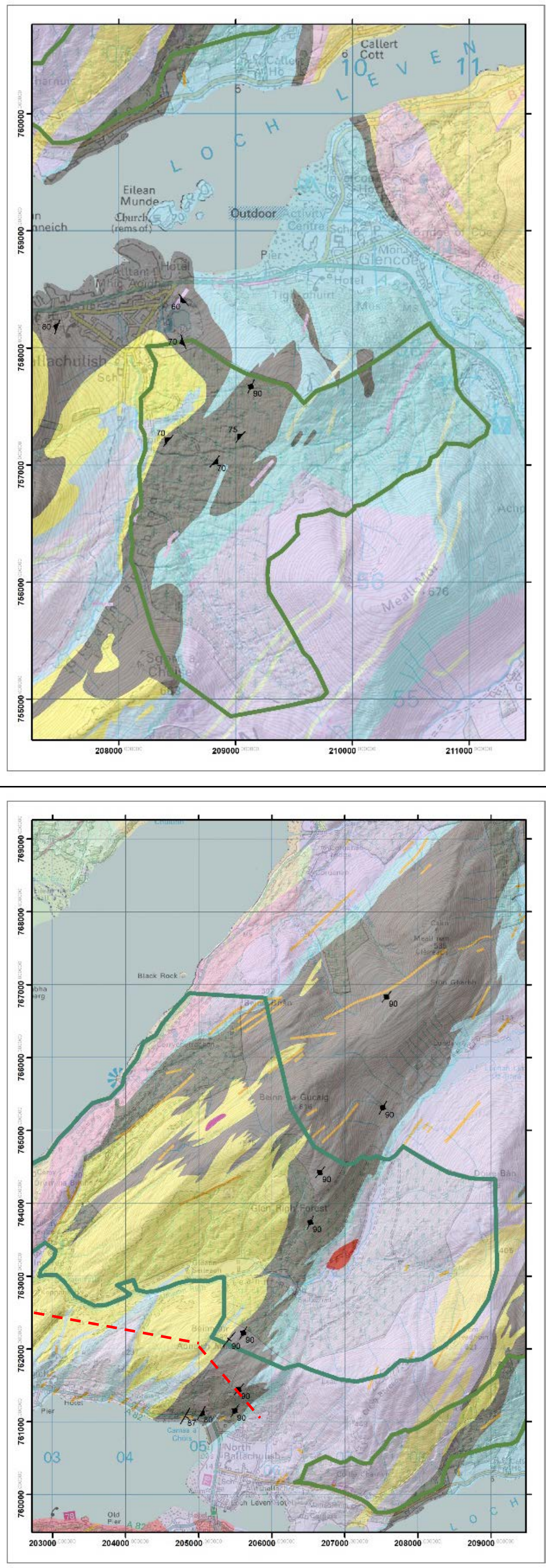

Figure 35. Bedrock geology of the Ballachulish South (top) and Ballachulish North (bottom) areas, on a topographical map with 'hill-shade' data

Figure 34: Black boxes = areas on Figure 36. Figure 35: Geology information from the BGS 1:50,000 scale digital geological map of Great Britain. Black symbols = orientation of main slaty cleavage (see Figure 7 footnote for details). Colours (key units only): grey = Ballachulish Slate Formation; yellow = Appin Quartzite Formation; blue = Ballachulish Limestone Formation; red = granite intrusion; cream and orange lines = felsite dykes; lilac lines = mafite dykes; only larger dykes are shown. Red dashed line is the position of the cross-section on Figure 45. Both figures: Green polygons = land managed by Forestry and Land Scotland. Grid squares are 1 km on each side. 'Hill-shade' overlay derived from NEXTMap Britain elevation data, from Intermap Technologies. Contains Ordnance Survey data © Crown Copyright and database rights 2020.

4.3 QUARRIES

The *BGS Database of Mines and Quarries* (also known as *BritPits*) has records for eighteen slate quarries in the Ballachulish district, eleven lying south of Loch Leven and seven to the north (Figure 36). In the *Building Stone Database for Scotland* (BSDS), all of the slate quarries south of Loch Leven are grouped within the *Ballachulish Slate Supercluster* and many quarries on both sides of the loch are assigned to quarry 'clusters', as follows.

Ballachulish South:

- The *Ballachulish Main Quarry Cluster* includes *East Laroch Slate Quarry*, the largest and most important slate quarry in the district, and two smaller pits that are adjacent to it – *Ballachulish Slate Quarries* and *Brecklet Slate Quarry*.
- The *West Laroch Cluster* includes two moderately large quarries that are just separated by just a few metres – *West Laroch West Quarry* and *West Laroch East Quarry*.
- The *Am Meall Cluster* encompasses five small pits, each one named *Am Meall Quarries*.
- *Khartoum Slate Quarry* is not part of a cluster.

Ballachulish North:

- The *North Ballachulish Cluster* encompasses four quarries on wooded slopes above Onich – *North Ballachulish West Quarry*, *North Ballachulish Middle Quarry*, *North Ballachulish East Quarry* and *North Ballachulish High Quarry*.
- The *Coire Uainean Mor Cluster* includes two small pits named *Coire Uainean Mor Slate Quarry* and an underground working called *Coire Uainean Mor Slate Mine*.
- *Creag Nam Meall Workings* are not part of a cluster. The 'workings' here are mainly above ground, but an 'adit' marked on an old geological field slip suggests there may have been some underground working too.

Geological and historical details for many of these quarries are provided in Richey and Anderson (1944) and Walsh (2000, 2002). Useful details about the *Am Meall Cluster* and *Creag Nam Meall Workings* can be found at http://www.ballachulish.org.uk/the-quarry/brecklet-quarries/ and https://her.highland.gov.uk/Monument/MHG50310, respectively.

As part of this study, the authors made brief visits to several accessible quarries near the shores of Loch Leven on 4th February 2020; these included the East Laroch, Khartoum and West Laroch quarries near the south shore of the loch, and three quarries of the North Ballachulish Cluster on the north shore. Descriptions in the remainder of this section of the report incorporate the field observations made at that time, interpretations made from modern aerial photographs, and information gleaned from a range of historical records.

The present appearance of visited quarries is shown in Figures 37–43. Summary details for all the slate quarries in the Ballachulish district are presented in Appendix 2.

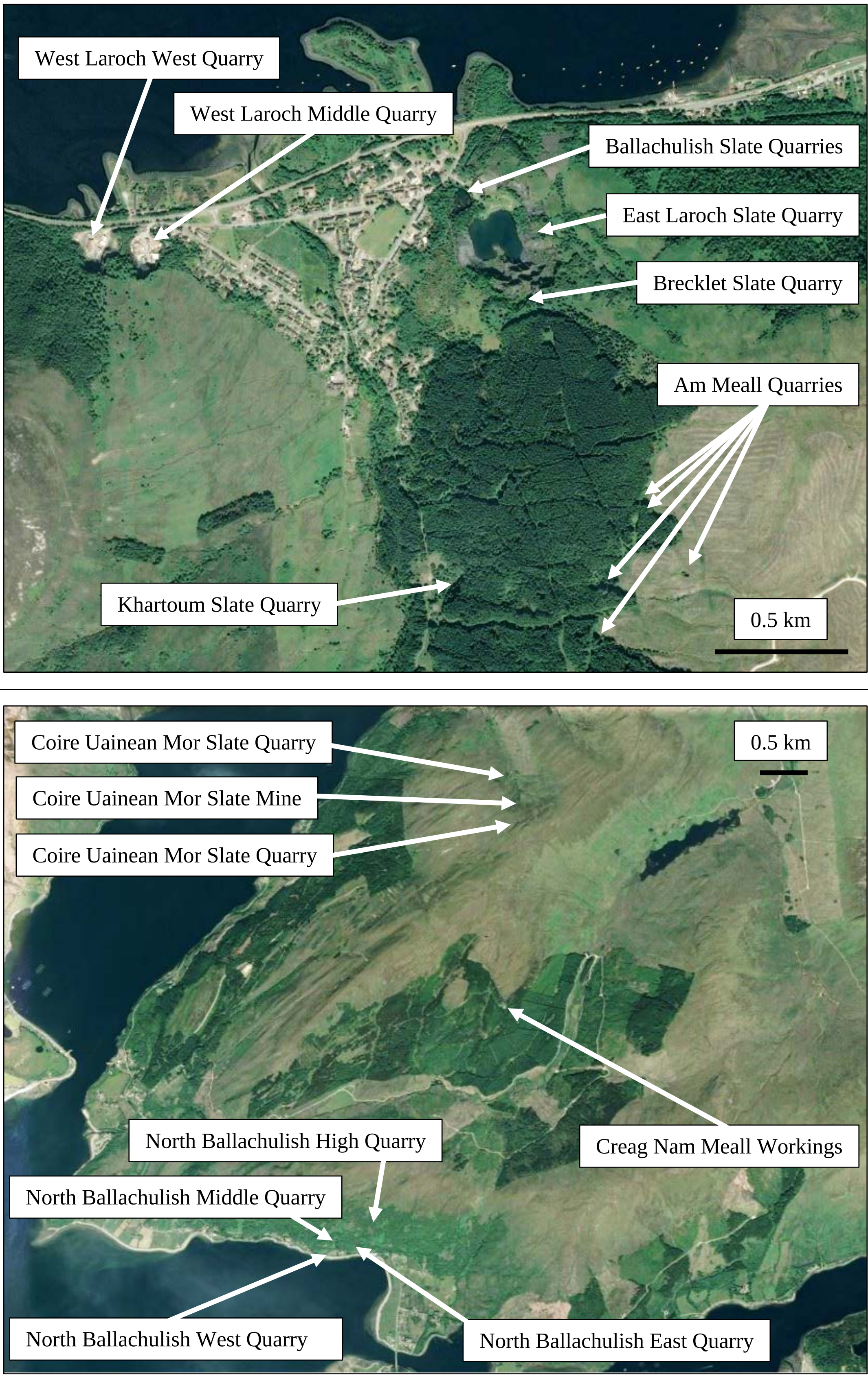

Figure 36. Locations of quarries in the Ballachulish district

Top (a) is south of Loch Leven, Bottom (b) is north of Loch Leven. See text for details. Quarry names are as they are assigned in the BGS BritPits database and in the BSDS. Aerial screen shots from the Microsoft Bing Maps Platform. Microsoft product screen shot(s) reprinted with permission from Microsoft Corporation.

Figure 37. East Laroch Slate Quarry, viewed from the north

Five worked levels that sit above the flooded surface are obvious; the pond conceals a further two levels. The left side of this view includes ground affected by a large landslip. Brecklet Slate Quarry is in the trees on the skyline.

Figure 38. Worked face in good quality slate-rock, East Laroch Slate Quarry

The face encloses an embayment on the north side of the main quarry void, which was obviously a source of good slate-rock. The prominent faces dipping steeply to the left in this view are formed along the main slaty cleavage. Narrow, sub-parallel dark grey bands dipping gently to the right probably consist of rock affected by D4. Small benches have formed along these bands, indicating the rock within them is relatively weak.

Figure 39. Khartoum Slate Quarry, looking NE

The photograph was taken near the quarry entrance, looking along its 'long' dimension (which is essentially parallel to the main slaty cleavage). The lower, flooded, level is to the left and the figure is walking on the upper level.

Figure 40. Worked face in Khartoum Slate Quarry

The face in this view forms the prominent rib in the centre of Figure 39. The large flat surfaces at the right side of the image have formed where the rock has parted along the main slaty cleavage. Note the rock 'pillars' that have been left at the base of the rib to support the face above. Figure for scale.

Figure 41. Former worked faces in North Ballachulish West Quarry

Figure 42. Former worked faces in the top level of North Ballachulish East Quarry

Figure 43. Looking down into the nearly cubic void of North Ballachulish Middle Quarry

4.4 GEOLOGICAL FEATURES IN THE BALLACHULISH DISTRICT

Away from the generally well-exposed coastal sections, detailed geological mapping on the ground has not been carried out in the Ballachulish district in modern times; the published geological map therefore relies heavily on the primary geological mapping from the early part of the 20th century. However, more recent academic research in the district means that the stratigraphical and structural relationships are well understood.

The structural geology of the Ballachulish district is challenging and the area is rightly used as a training ground for University students. The large-scale fold structures that can be recognised here through careful observation and detailed analysis provide an important insight into the effects of the Caledonian Orogeny and the geological processes associated with that ancient mountain-building event.

4.4.1 Early structures

The basic bedrock structure of the Ballachulish district comprises three large (each 15–20 km in size) inclined F1 folds – the *Appin Syncline, Kinlochleven Anticline* and *Ballachulish Syncline* – each of which was refolded during D2 to form composite D1/D2 structures (Figure 44). The Ballachulish Slate Formation crops out in settings associated with the two F1 syncline folds (areas shown in red on Figure 44): the large outcrop in Ballachulish North is on the eastern limb of the Appin Syncline, and the smaller outcrops in Ballachulish South are in the core of the Ballachulish Syncline where it has been refolded on the eastern limb of another large F2 fold structure (the *Stob Bhan Syncline*). The combined effects of the original distribution of mudstone in the strata and the subsequent phases of deformation are such that the slate-rock outcrops today are all essentially found in the limb regions of these very large folds. The fold limbs have been substantially stretched and thinned, and any slate-rock within them has been very strongly deformed. Original bedding and the superimposed slaty cleavage are often sub-parallel (having been completely transposed), and close examination of roofing slates from the Ballachulish district shows that the main slaty cleavage typically has a strongly platy, very finely sub-parallel laminated character (unlike those from Easdale and Cullipool, where the main slaty cleavage is less laminar and bedding, S1, and S2 are discernibly non-parallel).

Measurements of the main slaty cleavage in Ballachulish North have a markedly consistent orientation – trending NNE–SSW and essentially vertical (Figure 35 [bottom]) – reflecting the fact that this large outcrop of slate-rock is on the sub-vertical limb of a large fold (Figure 44 and Figure 45). Most measurements of the main slaty cleavage in Ballachulish South also trend broadly NNE–SSW, but the dip of the cleavage here is more variable and the trend varies markedly in some parts of the outcrop (Figure 35 [top]); these observations reflect the fact that in this area the early folds have been refolded.

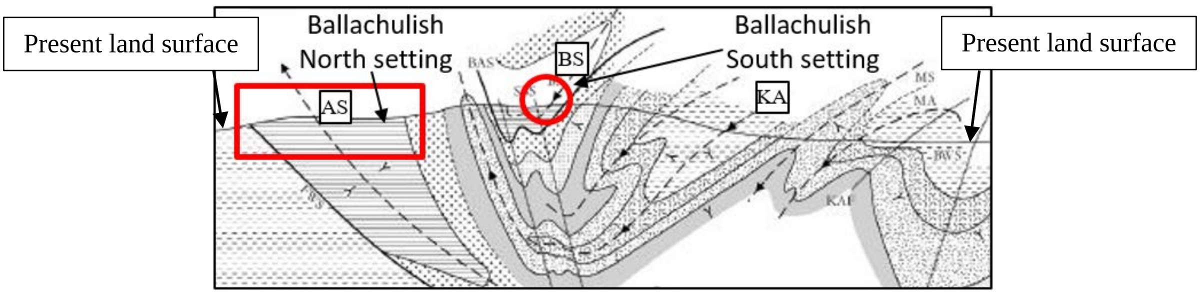

Figure 44. Schematic geological cross-section through the west Highlands near Ballachulish

The section extends from west (left side) to east (right side), and spans approximately 40 kilometres. Key: horizontal hachure = slate-rock of the Ballachulish Slate Formation; stippled and dashed ornaments = other rock types and bedrock units; dashed lines = F1 fold hinge lines (note that these early F1 folds were refolded during D2; solid lines mark F2 fold hinge lines. AS = Appin Syncline; BS = Ballachulish Syncline; KA = Kinlochleven Anticline. The red box shows where the outcrop of the Ballachulish Slate Formation in the Ballachulish North area is inferred to sit within the regional geology of this part of Scotland. The red circle does the same for the Ballachulish Slate Formation in the Ballachulish South area. Modified after Stephenson *et al*. (2013).

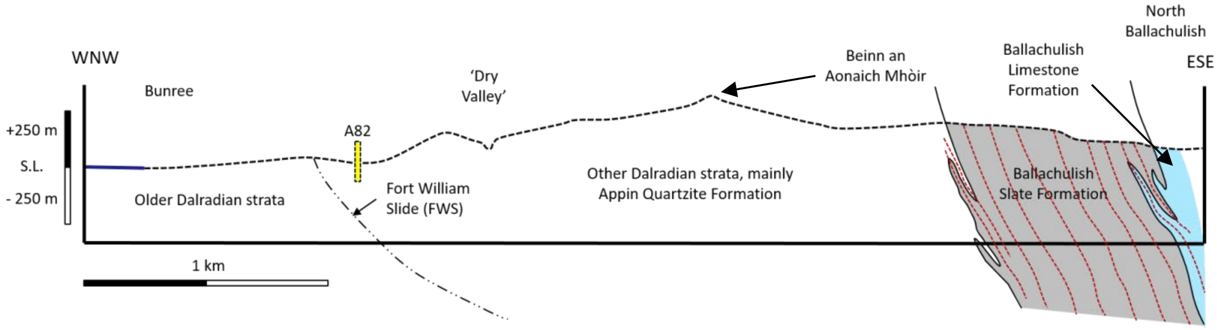

Figure 45. Schematic geological cross-section through the Ballachulish North area

See Figure 35 [bottom] for the geographical position of the cross-section. Key: blue line = sea; dashed grey line = current land surface; dashed red lines = main slaty cleavage; grey = Ballachulish Slate Formation; blue = Ballachulish Limestone Formation. For clarity, only selected units in the Dalradian strata are shown and dykes are omitted.

Evidence for bedding is essentially never seen in slate-rock exposures of the Ballachulish district, and an examination (using the unaided eye and a hand lens) of roofing slate samples from the East Laroch and Khartoum quarries held in the BGS Collection of UK Building Stones revealed no clear evidence of bedding or bedding lamination in the rock at that smaller scale. This evidence, and the characteristic development of a very strong slaty cleavage in all Ballachulish slate-rock, indicates that bedding has been thoroughly transposed with the S2 fabric (along with any S1 cleavage), such that bedding and cleavage are now everywhere essentially parallel. Samples of Ballachulish roofing slates appear more dense and compact to the naked eye than samples from the Easdale region and may be somewhat *annealed* (hardened) in response to the relatively intense deformation and metamorphism experienced in the Loch Leven district.

The slate-rock of the Ballachulish district is notable for locally significant developments of white vein quartz. Some quartz forms thin 'streaks' entrained along the main slaty cleavage, and this seems to have formed relatively early in the history of metamorphism and deformation. Elsewhere, quartz forms irregular, crosscutting veins and masses, and these examples will have formed at a later stage in the deformation history. The irregular masses in particular will reduce the amount and quality of slate-rock that can be recovered.

4.4.2 Later structures

At least two late-stage deformation fabrics have affected the slate-rock in the Ballachulish district, and (as on Luing) these can almost certainly be correlated with the D3 and D4 regional deformation events that were described in section 2. Both fabrics are similar in many respects to those observed on Luing. The D3 fabric is (to the unaided eye, at least) a relatively widely spaced cleavage that is oblique to the main slaty cleavage (S1/S2) and typically manifests as a delicate wrinkling (or *crenulation*) of the S1/S2 surfaces (Figure 46). This crenulation is almost ubiquitous in the slate-rocks of the Ballachulish district, but ranges from being barely visible to the naked eye to a very obvious pattern of 'wrinkles' 1–2 mm apart and up to *c.* 1 mm in amplitude. The crenulation gives roofing slates from the Ballachulish district (and the West Highland Slate generally) a distinctive character, and in most cases has little effect on the quality and productivity of slate-rock; however, the fissility (propensity to split) of the main slaty cleavage will be less pronounced and workable where the crenulation is most strongly developed. In addition to the relatively widely spaced crenulation that is visible to the naked eye, a closely spaced cleavage related to D3 may also be developed at the microscopic scale, which in places could further diminish fissility along the main slaty cleavage.

A later episode of folding and cleavage development (D4) is expressed as isolated rock volumes characterised by angular folds – so-called *kink bands* that produce quite marked chevron-like (knee-bend) folds of the primary slaty cleavage. Affected volumes of rock are often lenticular in general outline, but can appear to be almost randomly distributed. Some generalised alignment is likely though, and such structures will tend to 'cluster' in certain parts of the rock mass; for example, features of this type are readily observed in the north-eastern parts of East Laroch Slate Quarry (Figure 38) and in Khartoum Slate Quarry. Slate-rock within the 'kink bands' is likely to be of poorer quality than rock which is not.

Figure 46. A specimen of roofing slate from East Laroch Slate Quarry

The main surfaces of the roofing slate have been created by splitting the rock along the S1/S2 main slaty cleavage. Faint wrinkles or ridges trending vertically from top to bottom are D3 crenulation created by the intersection of S3 and S1/S2. Sample E 8544 in the BGS Collection of UK Building Stones. The specimen measures 38 cm from top to bottom.

4.4.3 Fractures and intrusions

4.4.3.1 FRACTURES

Examination of 'hill-shade' data for Ballachulish North (shown at a low resolution on Figure 34 [bottom]) reveals an array of unmapped fractures between Onich and Gleann Righ with a geometrical relationship that suggests they formed at the same time, in response to the same regional-scale tectonic event. The best developed sets trend NNE–SSW and NE–SW. Both transect the trend of the main slaty cleavage and make striking linear features across the hillslope between Onich and Gleann Righ. They are probably related to displacements that occurred around 400 million years ago on the Great Glen Fault Zone (GGFZ), a very large NE–SW-trending fault that passes beneath Loch Linnhe just a few km west of the Ballachulish district; the fracture array is consistent with one that would be expected to form in association with the principal motions on this substantial geological fault. Overburden and plantations obscure bedrock fracture patterns elsewhere in the Ballachulish North area; however, it is likely that the same fracture sets occur throughout the area, though the size and density of fractures will vary from place to place. Locally, the fractures will reduce the amount and quality of slate-rock that can be extracted, but it is unlikely that large volumes of slate-rock would be compromised in this way in any given area.

The ground within Ballachulish South is strongly affected by anthropogenic activity, including forestry, such that structural geological features are very strongly masked and do not stand out in the hill-shade data (shown at a low resolution on Figure 34 [top]). The distribution and character of bedrock fractures has therefore not been determined in this area, but available evidence suggests the overall effect of fractures on slate-rock quality here is unlikely to differ significantly from the situation in Ballachulish North.

4.4.3.2 INTRUSIONS

Several major intrusions – the *Ballachulish Granite–diorite Pluton*, *Ben Nevis Granite Pluton* and *Mullach nan Coirean Granite Pluton* – are emplaced into the Dalradian strata within a few kilometres of the outcrops of slate-rock in the Ballachulish district, but none of them are close enough to affect large volumes of the slate-rock under consideration (see section 2 for further details).

Dalradian strata throughout the Ballachulish district are also cut by numerous minor intrusions, specifically dykes of felsite and mafite that have a broadly consistent NE–SW trend (Figure 35) and formed contemporaneously with the major intrusions during the later stages of the Caledonian Orogeny. The dykes are of similar orientation to the dominant trend of the main slaty cleavage in the district and the superimposed NE–SW-trending fracture set (Figure 35), and probably exploited these planes of relative weakness in the rock when they were emplaced. The dykes do not obviously appear to have been a focus of later tectonic stress (as has been the case in some dykes in the Cullipool district). Two minor intrusions that have broadly oval form at outcrop have been mapped in the Ballachulish North area (Figure 35 [bottom]). Neither occurs within the outcrop of slate-rock, but they are substantially larger than the dykes and each may be surrounded by a significant zone of heat-affected rock, particularly if their edges dip at a gentle angle into the subsurface.

No examples of the much younger (60 million year old) set of mafite dykes that are abundant on Luing (see section 3.4.3) have been mapped in the Ballachulish district, though it is unlikely they are entirely absent from the area.

Dykes were not encountered during the brief visit to slate quarries in the Ballachulish district that was made for this study, so currently we have no more detailed information about their character and effect on adjacent rock. However, while they will undoubtedly be an inconvenience if encountered in quarrying for slate-rock, available evidence indicates they are unlikely to be of sufficient density and size to cause a significant problem in any part of the Ballachulish district.

4.5 GEOLOGICAL CONTROLS ON QUARRYING IN THE BALLACHULISH DISTRICT

Available evidence indicates that the principal geological control on slate-rock quarrying in the Ballachulish district has been the structural complexity of the bedrock; though there is presently insufficient evidence to prove the point unambiguously, it is likely that all the main slate-rock quarries in the district are located on the limbs of major fold structures, where mudstone strata have been thoroughly stretched and compressed, and bedding has become transposed with a well-developed main slaty cleavage.

Historical descriptions often refer to several ‘seams’ of good-quality slate-rock being worked in a single quarry, and multiple regularly spaced embayments in quarry walls (where the best slate-rock has evidently been ‘chased’ into a slope) are good evidence that this was the case. In places, the distribution of these seams may be controlled by primary lithological variation (i.e. where slate-rock and other lithologies are interbedded). However, in general, a structural control is more likely, whereby the same layer of slate-rock is intersected multiple times in the same quarry because it is tightly folded (and thereby repeated) on a relatively small (*c*. 10 m) scale.

Dykes and faults are relatively sparse in the Ballachulish district, and appear to have been much less significant in controlling quarry development here than is the case on Luing.

Though not a geological control, restricted access due to steep slopes and/or high, remote ground has been a significant factor in controlling how quarries are distributed in the Ballachulish district. The largest and most successful quarries are all located on relatively flat ground beside Loch Leven. Many of the smaller quarries – including the Creag Nam Meall Workings and all those in the Am Meall Cluster and the Coire Uainean Mor Cluster – are in relatively inaccessible, elevated locations inland, and were probably abandoned due to the logistical and economic difficulties of quarrying slate-rock in such settings.

4.6 SLATE PROSPECTIVITY

Taking all the geological factors into account, it seems reasonable to predict that the best quality slate-rock in the Ballachulish district occurs on the eastern limbs of the regional-scale synclinal folds, in the ‘interior’ parts of the known outcrops of the Ballachulish Slate Formation. In this setting, any lithological variation (bedding) in the slate-rock will probably be transposed and sub-parallel with the main slaty cleavage, which should have the effect of creating significant volumes of slate-rock that is both durable and fissile. The degree of transposition, and thus parallelism, will be somewhat less on the more gently dipping, less-strongly deformed western limbs of these folds. The present outcrop pattern is such that large-scale fold hinge regions – where original sedimentary layering might be expected to have been thickened by folding deformation, thus increasing the volume of available slate-rock (as appears to be the case on Luing) – are not a feature of the geology in the Ballachulish district.

Destruction of cleavage by thermal metamorphism around intrusions is unlikely to be a significant problem in the Ballachulish district, though significant zones of heat-affected rock – that in places overlap with outcrops of slate-rock – may exist around two mapped minor intrusions that have broadly oval form at outcrop.

Based on this assessment, polygons highlighting the most prospective areas for slate-rock in the Ballachulish district are shown on Figure 47 below. Sheet-like minor intrusions (dykes) are too small to consider at this scale.

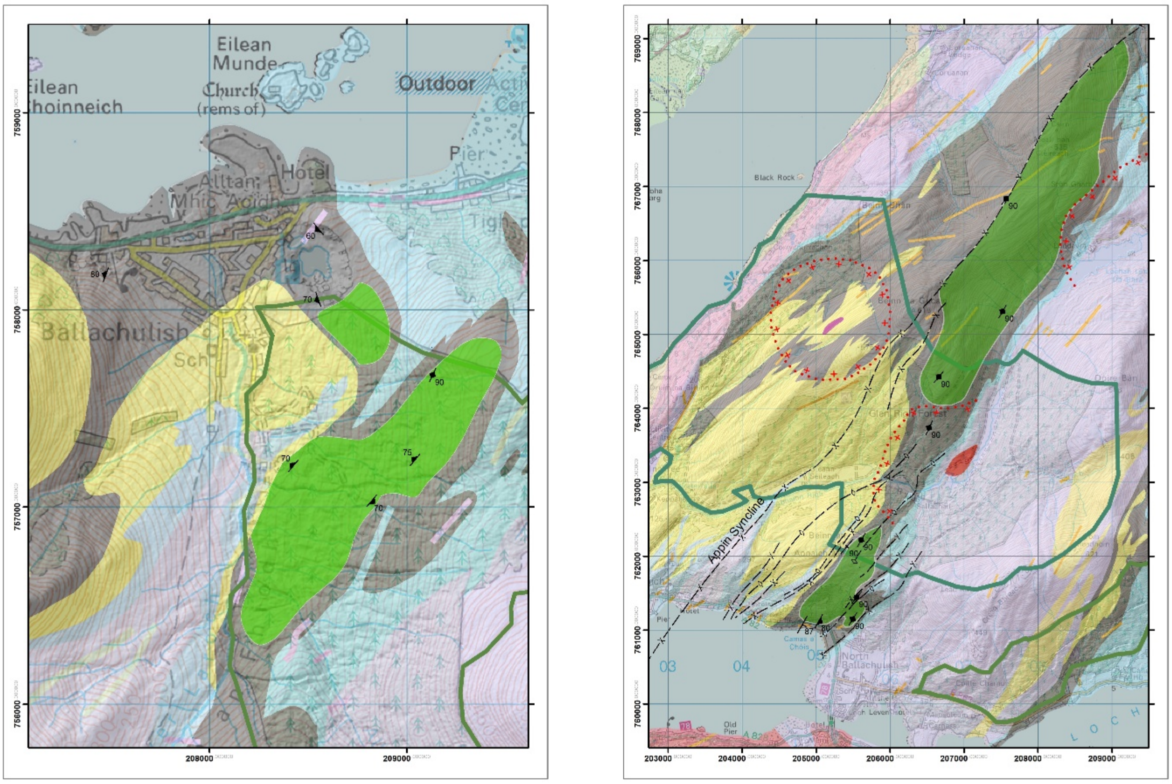

Figure 47. Most prospective areas for slate-rock in the Ballachulish district

Left (a) is Ballachulish South and right (b) is Ballachulish North. Green polygons indicate the areas considered on geological grounds only to be the most prospective for future large-scale quarrying of slate-rock. Black symbols show the locations of orientation measurements for the main slaty cleavage, as recorded on historical maps and in other records (see the footnote to Figure 7 for details). Dashed black lines represent the positions on the ground surface of fold axes; those incorporating an ‘X’ symbol are synclines whereas those incorporating a diamond symbol are anticlines. Dashed red lines indicate the approximate inferred limit of thermal metamorphism around intrusions larger than dykes; the quality of any slate-rock within these areas may have been reduced.

Geology information from the BGS 1:50,000 scale digital geological map of Great Britain. Colours: see Figure 35 for details. Green polygons = land managed by Forestry and Land Scotland. Grid squares are 1 km on each side. ‘Hill-shade’ overlay derived from NEXTMap Britain elevation data, from Intermap Technologies. Contains Ordnance Survey data © Crown Copyright and database rights 2020.

5 Summary of key points

5.1 THE CULLIPOOL DISTRICT ON LUING

- The slate-rock occurs within a single bedrock unit, the Easdale Slate Formation, which forms a continuous outcrop that underlies nearly all of Luing.
- All of the bedrock in the district sits within the hinge zone of a broad, 10 km-scale fold structure, which is inferred to sit on the upper limb of a much larger fold structure (the Islay Anticline). In this structural setting, the mudstone layer that was the progenitor of the slate-rock may have become somewhat compressed and thickened as folding progressed.
- The best slate-rock is contained within a single, relatively thick (*c.* 20 m) layer of homogeneous and lithologically 'pure' rock. Most of the 'Cullipool' quarries have exploited this slate-rock layer. A layer of sandstone-dominated bedrock at least several metres thick overlies the slate-rock across much of the outcrop.
- The strata (and therefore bedding) are broadly flat-lying across much of the outcrop, but the rock mass has been 'partitioned' into rectilinear blocks several hundred metres in size by horizontal and vertical offsets on small faults. As a result, the slate-rock layer shifts vertically and horizontally in different parts of the outcrop (for example, it is below the raised beach at Cullipool village but entirely above the raised beach north of there), but it likely remains at, or near-to, the ground surface throughout the district.
- The main slaty cleavage is a composite of two cleavages (S1 and S2) formed during two early deformation events (D1 and D2) associated with the Caledonian Orogeny; though they are nearly parallel, a small angular difference between the two cleavages is visible. Throughout the district, the main slaty cleavage dips at a moderate angle towards ESE.
- Bedding is everywhere highly discordant to the main slaty cleavage, an arrangement that normally would be considered unattractive for roofing slate production. However, the lithological purity of the slate-rock layer means the rock has little propensity to split along bedding, so in this case the angular discordance of bedding and cleavage is not considered to be a disadvantage.
- A later deformation event (D3) produced a more widely spaced cleavage (S3), which cuts the main slaty cleavage at a high angle; this cleavage manifests as a distinctive 'wrinkling' pattern (or crenulation) on surfaces created by splitting the rock on the main slaty cleavage, and in general has little or no adverse impact on slate-rock quality.
- The last significant phase of deformation (D4) to affect the bedrock produced discrete and seemingly irregularly distributed bands of rock up to several metres wide within which the slate-rock is deformed in a relatively brittle manner, resulting in quite marked chevron-like (knee-bend) folds of the main slaty cleavage. Slate-rock within these so-called 'kink bands' is likely to be of poorer quality than rock which is not.
- The slate-rock is cut by two sets of dykes: an early set of felsite dykes that was emplaced along the main slaty cleavage; and a later, much more numerous, set of mafite dykes that was emplaced at a high angle to the main slaty cleavage. The former appears to have had little effect on the quality of adjacent slate-rock, whereas envelopes of unquarried slate-rock on either side of mafite dykes in the Cullipool quarries indicates the cleavage here has been damaged to an extent that makes the rock unusable as roofing slate. The zone of heat-affected slate-rock around the mafite dykes appears to be *c.* 7 m wide for every 1 m thickness of dyke rock. Most of the dykes are less than 2 metres thick.

- The distribution of the various sets of features that intersect the body of slate-rock and disrupt its continuity (kink bands, small faults and two sets of dykes) is such that discrete bodies of slate-rock entirely unaffected by them may only rarely exceed 1,000 m^3.
- Substantial resources of good-quality slate-rock remain in the Cullipool district, and probably on Luing generally. From a geological point of view, it should be possible, and relatively straightforward, to renew quarrying (or establish new quarries) in many parts of the island, but it would seem sensible to focus initially on existing workings in the Cullipool district, where the geological framework is most clearly displayed and best understood.

Further field work in the Cullipool district (supported by laboratory analysis where appropriate) would help to test and refine some of the preliminary interpretations presented here. Specific objectives could include the following.

- Conduct a detailed structural study of the bedrock to confirm and refine our understanding of the distribution and disposition of bedrock units and fold structures, and the orientations of bedding and cleavage.
- Examine the lithological character of slate-rock throughout the main slate-rock layer to establish how homogeneous (or otherwise) it is, and the extent to which bedding may control the size of recoverable roofing slates in volumes where the main slaty cleavage is consistent in its development.
- Trace the lateral extents of the main slate-rock layer across the northern part of Luing.
- Confirm the preliminary observations regarding the relative effects of D1 and D2, and the extent to which S1 (the cleavage related to D1) was transposed by D2 and is now largely coincident with S2.
- Combining all of the above, determine the size and distribution of the slate-rock resource in the Cullipool district, and the locations of accessible volumes of good-quality rock.

5.2 THE BALLACHULISH DISTRICT

- The slate-rock occurs within a single bedrock unit, the Ballachulish Slate Formation, but a complex history of folding (more complex than on Luing) means the unit now forms multiple discrete outcrops within the district.
- All outcrops of the Ballachulish Slate Formation occur in settings associated with two very large fold structures: an extensive outcrop on the north side of Loch Leven is on the eastern limb of the Appin Syncline, and smaller outcrops on the south side of Loch Leven are in the core of the Ballachulish Syncline where it has been refolded on the eastern limb of another large fold structure.
- The combined effect of the original distribution of mudstone in the strata and the subsequent phases of deformation is such that the slate-rock outcrops today are all essentially found in the limb regions of these very large folds. In this structural setting, the mudstone layers that were the progenitors of the slate-rock layers would have become substantially stretched and thinned as folding progressed.
- The best slate-rock often occurs in multiple discrete 'seams' within the larger quarries of the Ballachulish district; the largest individual seams are around 10 metres thick. It seems likely that all (or most) of the seams in any one quarry represent the same slate-rock layer appearing repeatedly in the bedrock on the limbs of multiple relatively small-scale, tight folds that developed on the limbs of the very large fold structures as those larger folds were forming.

- The main slaty cleavage is a composite of two cleavages (S1 and S2) formed during two early deformation events (D1 and D2); these are the same events that produced the main slaty cleavage on Luing. Throughout the district, the main slaty cleavage dips at a moderate angle, generally towards ESE. North of Loch Leven, the main slaty cleavage trends NNE–SSW and is essentially vertical, reflecting the fact that this large outcrop of slate-rock is on the sub-vertical limb of a large fold (the Appin Syncline). South of Loch Leven, most measurements of the main slaty cleavage also trend broadly NNE–SSW; however, the dip here is more variable and the trend varies markedly in some parts of the outcrop, reflecting the fact that in this area the early folds have been refolded.
- Original bedding and the superimposed slaty cleavage are very often sub-parallel (having been completely transposed), and close examination of roofing slates from the Ballachulish district shows that the main slaty cleavage has a strongly platy, very finely sub-parallel, laminated character (unlike examples from Cullipool, where the main slaty cleavage is less laminar and S1 and S2 are discernibly non-parallel).
- As on Luing, a later deformation event (D3) produced a more widely spaced cleavage (S3), which cuts the main slaty cleavage at a high angle; this cleavage manifests as a distinctive 'wrinkling' pattern (or crenulation) on surfaces created by splitting the rock on the main slaty cleavage, and in general has little or no adverse impact on slate-rock quality.
- As on Luing, the last significant phase of deformation (D4) produced discrete and seemingly irregularly distributed bands of rock up to several metres wide within which the slate-rock is deformed in a relatively brittle manner, resulting in quite marked chevron-like (knee-bend) folds of the primary slaty cleavage. Slate-rock within these 'kink bands' is likely to be of poorer quality than rock which is not.
- Dalradian strata throughout the Ballachulish district are cut by numerous dykes of felsite and mafite that have a broadly consistent NE–SW trend. The dykes are of similar orientation to the dominant trends of both the main slaty cleavage in the district and a superimposed NE–SW-trending fracture set, and probably exploited these sources of relative weakness in the rock when they were emplaced. These minor intrusions are likely to have had little effect on the quality of adjacent slate-rock. However, two particular minor intrusions that have broadly oval form where they crop out in the Ballachulish North area may be surrounded by significant zones of heat-affected rock that in places overlap with outcrops of slate-rock; the quality of slate-rock may be reduced in these areas. Several major intrusions (granite plutons) are emplaced into the Dalradian strata within a few kilometres of the outcrops of slate-rock in the Ballachulish district, but it is unlikely that any of them has adversely affected a significant volume of slate-rock.
- Substantial resources of good-quality slate-rock almost certainly remain in the Ballachulish district, and from a geological point of view it should be possible to renew quarrying (or establish new quarries) in many parts of the district. However, the geology is challenging (more so than on Luing), and a significantly more detailed field-based assessment than has been possible here would be needed to identify the most promising localities. Site-specific ground investigation (e.g. detailed field mapping, trenching, coring) may then need to follow. Furthermore, all of the most prospective areas for slate-rock identified in this study consist mainly of remote, topographically challenging ground with currently limited (or no) vehicle access.

Appendix 1 Summary details for slate quarries on Luing (red text denotes information sourced from Walsh, 2000)

Name	Grid ref.	Size (m; l/w/h)	Status	Vehicle access	Resources	Notes
Toberonochy	NM 74855 08555	130 x 50 x ≥50	Flooded	Partial? (overgrown track)	Immediate surrounds very overgrown; resources probably *limited*. North face bounded by a dyke. Overburden estimated as 2 m on south side.	Bedding 003/45; cleavage 020/40-57; cleavage surface less affected by crenulation than in west Luing. Vertical walls. Pyrite present but not abundant. Three bands of slate were worked, the thickest being 20 m wide, but most were only 0.6-1.5 m wide.
Rubha na h-Easgainne No.1	NM 74870 14520	50 x 10 x ?	Flooded	No; previously serviced by a tramway from Cuan Ferry.	*Limited* to *medium*, due to considerable distortion of cleavage.	Bedding?; cleavage 022/80. The crenulation cleavage lineation pitches horizontally on the main cleavage surface, which is undulating. Pyrite crystals up to 10 mm are abundant; graphite bands are associated with crumbling slate.
Rubha na h-Easgainne No.2	NM 74805 14480	50 x 30 x ?	Flooded			
Rubha na h-Easgainne No.3	NM 74765 14400	50 x 25 (into cliff face)	Not flooded			
Port Mary	NM 74500 14025	100 x 30 x 15-20	Not flooded	Yes, by a fairly well maintained farm track.	*Limited* to *medium*, due to considerable distortion of cleavage.	Cleavage 036/40-50. The crenulation lineation pitches at 10-15 S on the main cleavage surface. Pyrite crystals are 4 x 8 mm and there are occasional graphitic bands. The axes of two anticlines can be traced from N to S in this quarry. Ribboning due to bedding is prominent. The S end of the face is cut by two dykes. Another 'Port Mary' quarry recorded in BritPits at [NM 74585 14120] appears to be the waste 'tips' from the main Port Mary quarry.
Cullipool	NM 74150 13705	50 x 30 x 30	Not flooded	No	*Medium* resources are available in the Cullipool quarries. Likely to be less productive further north, due to more intense folding. The best seam is at the southern end (of the northern part of Luing) at Cullipool and has been quarried to great depth. This seam was reported to be 20 m wide but is staggered westwards to the N and probably continues into the Sound of Luing. To the S the ground is low-lying and covered with alluvium. Further exploitation of this seam is possible within the confines of the Cullipool quarries, but the quarries have been left in an unstable state with a high cliff overhanging in places.	Walsh refers to this as 'Unnamed Quarry'. Cleavage 020-030/30. The crenulation lineation pitches at 10-15 S on the cleavage surface. At the SW face is a cluster of quartz veins and dykes, and the cleavage of the surrounding rock is flaky ('pencil cleavage').
Cullipool No.1	NM 74105 13680	20 x 40 x 40	Not flooded	No		Delimited by two dykes on NE side, and divided in two by an area that is unworked due to another dyke. Worked 20 m into the cliff face down-dip of the cleavage, leaving an overhanging face nearly 40 m high. Slate at N end is impregnated with quartz running along cleavage. A dyke meanders through the slate near top of face.
Cullipool No.2	NM 74050 13620	50 x 20 x ?	Not flooded	No		Delimited by dykes. 20 m wide and worked down-dip 50 m into the cliff. Part of the seaward side has been left unworked due to a graphitic layer and quartz veins. Pronounced folding on the seaward side of the S wall continues into No. 3.
Cullipool No.3	NM 74050 13450	200 x 100 x ≤40	Not flooded	Yes		Largest working on Luing, being nearly 200 m along strike and worked for 100 m into the cliff. N end worked at 3 levels. A dyke separates the two lower levels; slate not worked around the dyke. Two WNW-ESE dykes divide the quarry into three sections. The two southern ones were worked to a depth of 40 m. The seaward side left intact for part of its length due to folding.
Cullipool No.4	NM 73950 13250	50 x 50 x ?	Flooded	Yes		For all the Cullipool quarries: cleavage 020/50-55, the crenulation lineation pitches at 10 S on the main cleavage surface. Pyrite is ubiquitous and there are numerous quartz veins.
Cullipool No.5	NM 73900 13000	150 x 30-80 x ≥30	Flooded	Yes		
Tir-na-Oig North	NM 73330 10310	50 x 20 x ?	Not flooded	No; a farm track gets to within 300 m but is above the cliff into which the quarries are cut.	*Very large*, covering several square kilometres along the cliff to N and S of the quarries and E into the hillside. No slate has been extracted from below the level of the raised beach platform.	Cleavage 360/62 with crenulation lineation pitching 10 S on the main cleavage surface. The exposed face in the north quarry is cut by a dyke (340/60). Folding is extensive with associated veins of quartz. Also present are pyrite and several graphitic layers. Similar folding is found in both quarries.
Tir-na-Oig South	NM 73334 10276	50 x 20 x ?	Not flooded			
Black Mill Bay (east)	NM 73305 08315	Workings 1–2 m deep in raised beach platform	Flooded	Yes	Deposits in the area are *very large* but resources of usable slate are probably *limited* to *medium*.	Cleavage 010/40-60, undulating. The slate is very graphitic, with pyrite ~5 mm square. The workings are now filled in and in some places have been used as a dump.
Black Mill Bay (west)	NM 73285 08305		Not flooded	Yes		

Appendix 2 Summary details for slate quarries in the Ballachulish district (red text denotes information sourced from Walsh, 2000)

Name	Grid ref.	Size (m; l/w/h)	Status	Vehicle access	Resources	Notes
East Laroch Slate Quarry	NN 08525 58240	400 x 250 x 100	Partly flooded	Yes	'Plentiful' in the present confines of the quarry; *limited* to the NE and at the S end; *large* to the S and E.	Worked on seven levels, the lowest two now flooded; east side affected by a large rock fall that began early in the 20th century. There were five seams of "especially good quality slate" (Richey and Anderson, 1944), remnants of which are visible on the southern levels. Cleavage 140/60 in the NE to 160/70 in the S; pyrite is ubiquitous, quartz veins are common locally.
Ballachulish Slate Quarries	NN 08437 58353	50 x 50 x ?	Flooded	Yes	Not known	Essentially a flooded pit near the entrance to the much larger East Laroch quarry; geological character likely to be similar.
Brecklet Slate Quarry	NN 08570 58035	Possibly 100 x 30	Filled in & overgrown	No	Not known	According to Richey and Anderson: last worked *c.* 1905, on two levels. Geological character probably similar to East Laroch.
West Laroch West Quarry	NN 07330 58220	100 x 100 x >40	Partly filled, now used by the council and businesses	Yes	Large to the south; however, according to Richey and Anderson, there were considerable problems working the steep slope and keeping the face free of water in winter.	According to Richey and Anderson: "about 4 seams, each containing some 10 to 15ft of good slate".
West Laroch Middle Quarry	NN 07475 58215	100 x 100 x >40				According to Richey and Anderson: "two major seams around 30ft (10m) are said to have been worked. Near the centre of the face is a 3ft (1m) dyke of dark whinstone".
Khartoum Slate Quarry	NN 08380 57205	60 x 15 x 10	Partly flooded	Forest track 100 m away	*Medium* within the quarry; *large* in the immediate surroundings.	Worked on two levels, the lower one now flooded to a depth of *c.* 6 m. Cleavage 220/68; pyrite is ubiquitous. Quartz veins destroy cleavage on the east side.
Am Meall Quarries	NN 08924 57324	Relatively small, mainly <10 m in any direction, though some are 30-40 m long	Very overgrown, at least one is partly flooded	No	Probably substantial	Not marked on 1872 map but recorded as 'disused' on the 1898 map; the lack of an obvious access track and any signs of mechanisation suggest they may date back to the 1700s.
Am Meall Quarries	NN 08911 57294					
Am Meall Quarries	NN 08863 57158					
Am Meall Quarries	NN 09071 57191					
Am Meall Quarries	NN 08791 57029					
North Ballachulish West Quarry	NN 04980 61095	40 x 20 x 40	Accessible	Yes	*Very large* resources stretch many kilometres to the north of the quarries	A seam of slate about 5-10 m wide was worked for a distance of 40 m and height of 20 m in the 'West' quarry, but narrowed to the north. The 'High' quarry was worked along a band *c.* 5 m wide rising steeply up the hillside, on two or more galleries. Cleavage 038/75 (lower quarries) and 040/58 (high quarry). Pyrite is common, in places forming unusually large crystals that have been replaced by pyrrhotite.
North Ballachulish Middle Quarry	NN 05015 61125	*c.* 10 x 10 x 10	Overgrown	No		
North Ballachulish East Quarry	NN 05085 61110	*c.* 12 x 12 x 15	Very overgrown	No (though it is close to a main road)		
North Ballachulish High Quarry	NN 05150 61250	*c.* 40 x 5 x 5	Very overgrown	No		
Creag Nam Meall Workings	NN 06607 64073	40 x 30 x ?	Partly overgrown	No	"Almost inexhaustible" according to https://her.highland.gov.uk/Monument/MHG50310)	Probably abandoned by 1876. "Geological and topographical conditions" made quarrying difficult. No geological data.
Coire Uainean Mor Slate Quarry (north)	NN 06692 66812	Not known but probably small workings	Probably overgrown	No	Probably *limited* at lower levels, due to common occurrence of interbedded limestone. Probably becomes *very large* to the SE, above *c.* 450 m elevation, where pure slate was found.	Overburden very thick at lower levels but essentially absent on hill tops. No geological data (cleavage etc.).
Coire Uainean Mor Slate Quarry (south)	NN 06761 66163					
Coire Uainean Mor Slate Mine	NN 06773 66442		Opening still exists			

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

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