The Dalradian rocks of the south-west Grampian Highlands of Scotland

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ABSTRACT

The South-west Grampian Highlands, as defined here, include the Inner Hebridean islands of Islay and Jura, and extend north-east as far as Dalmally at the northern tip of Loch Awe. Due to a favourable combination of excellent coastal exposures and low tectonic strain, the late-Neoproterozoic rocks of the Dalradian Supergroup in this region are ideal for studying sedimentary structures. In addition, the diversity in protolith lithology from carbonate rocks to siliciclastic rocks of all grain sizes and volcanic rocks makes it possible to establish a very detailed lithostratigraphical succession and to recognize lateral facies changes. The stratigraphical range extends from the base of the Appin Group to the base of the Southern Highland Group and the area provides type localities for many regionally extensive formations of the Argyll Group. Rocks forming part of the basement to the Dalradian basins, the Rhinns Complex, are seen on Islay, where they

are overlain by the Colonsay Group, a thick metasedimentary siliciclastic sequence of uncertain stratigraphical affinity.

The structure of the Dalradian rocks in the South-west Grampian Highlands is controlled by early (D1) major folds (Islay Anticline, Loch Awe Syncline, and Ardrishaig Anticline), associated with a ubiquitous, penetrative, slaty or spaced cleavage. Most of the Dalradian rocks have been regionally metamorphosed under greenschist-facies conditions and amphibolite-facies (garnet zone) assemblages occur only in a narrow central zone, strongly affected by the D2 deformation.

The area provides GCR sites of international importance for studying Neoproterozoic glacial deposits, splendidly preserved stromatolite bioherms and calcite pseudomorphs after gypsum. Deformed and undeformed sandstone dykes and interstratal dewatering structures are well displayed at several sites. Other features include thick sills of basic meta-igneous rock with unusual minerals such as stilpnomelane, and greenschist-facies rocks containing regional metamorphic kyanite. The area is of historical interest for the first recognition in Scotland, prior to 1910, of sedimentary way-up structures and pillow lavas in regionally deformed and metamorphosed rocks.

1 INTRODUCTION

P.W.G. Tanner

The South-west Grampian Highlands region, as defined in this paper, includes the islands of Islay, Jura, and the Garvellach Isles in the north-west. It is bounded to the south-east by the base of the Southern Highland Group, which runs from Campbeltown along the Kintyre Peninsula and the south-east side of Loch Fyne, to Ben Lui (Figure 1). The north-eastern boundary follows the lower part of Loch Etive and the A85 road to Dalmally and Ben Lui. The region has an extremely long, indented coastline that faces into the prevailing south-west wind, which results in many kilometres of clean, well-scoured, coastal rock exposures being available for detailed study. Thus, 19 out of 21 of the GCR sites reported here are on coastal exposures.

The primary survey of the South-west Grampian Highlands was begun in 1880 and culminated in the publication of 'The Geology of the Seaboard of Mid-Argyll' (Peach *et al.*, 1909). The Geological Survey memoirs and accompanying geological maps produced during this period remain the sole source of reference to the distribution of rock types, and their petrography, for a considerable part of the region. This work was carried out whilst major advances were being made in structural geology and sedimentology worldwide, but much of this work came too late to help define and resolve some of the more fundamental problems in Highland geology. For example, the stratigraphical sequences established by the early workers such as Green (1924), Hill (1899, 1909) and Wilkinson (1907) were later shown to be wrong, as these geologists did not have the tools to identify way-up, and based their interpretations on Uniformitarian principles, such as the Law of Superposition, and the dip direction. This approach was successful in areas with simple upright, open folds but obviously failed in situations where the rocks had, for example, already been inverted by regional-scale folding. As a result, some parts of the stratigraphical sequence had to be revised when way-up techniques were first applied (Vogt, 1930; Bailey, 1930; Allison, 1933).

Despite the progress made by Pumpelly *et al.* (1894) in interpreting bedding/cleavage relationships in the USA, and by Clough (in Gunn *et al.*, 1897) in recognizing the effects of polyphase deformation in the Cowal peninsula, there is no indication from the work published prior to 1909 that these techniques were used in the areas described in this paper. The overall structure of this region was finally established by Bailey (1922); this framework has not been superseded but was progressively modified as modern techniques of structural geology were applied from the late 1950s onwards (i.e. Shackleton, 1958; Knill, 1960; Rast, 1963; Borradaile, 1970, 1973; Roberts, 1974).

The Dalradian rocks of this region, with their great diversity in lithology, relatively simple structure and low-grade regional metamorphism, have played a very important part in establishing the overall stratigraphical sequence in the Grampian Highlands as a whole. All subgroups of the Argyll Group are named after localities in this region, and these encompass a wide range of metamorphosed rock types from tillites to carbonate rocks and basic igneous rocks, and mudrocks to conglomerates. The Argyll Group includes two important marker horizons: the Port Askaig Tillite Formation at the base, and the Loch Tay Limestone Formation at the top (see Stephenson et al., 2013a for discussion) (Figure 2).

The environment in which the Argyll Group was deposited shows increasing tectonic instability with time (Anderton, 1985). Syndepositional basin-bounding faults became increasingly active throughout this period, as witnessed by marked lateral variations in the thickness and facies of both members and formations, together with the incoming and increasing frequency of debris flows and coarse-grained turbidite-facies rocks. Sediments of the Islay Subgroup were deposited in shallow water, some even in the intertidal zone, as indicated by storm deposits in the Jura Quartzite Formation, and pseudomorphs after gypsum in the Craignish Phyllite Formation. Deepening of the basin in Easdale Subgroup times is indicated by the deposition of a considerable thickness of black, euxinic mudrock, which was followed by a thick sequence of coarse-grained quartzofeldspathic turbidites in Crinan Subgroup times. Volcanicity reached a peak during Tayvallich Subgroup times as the now sediment-starved basin subsided further and the underlying lithosphere thinned and finally ruptured.

In view of the possibility that one or more orogenic unconformities is present in the Dalradian rocks of the South-west Grampian Highlands (Dempster *et al*., 2002; Hutton and Alsop 2004; but see Tanner, 2005), emphasis in this paper is placed upon relationships between the various stratigraphical units, and especially on the nature of the contacts between subgroups, including the critical junction between the Jura Quartzite and the Easdale Slate.

The overall structure of the South-west Grampian Highlands is controlled by two upward-facing major folds, the Islay Anticline and the Loch Awe Syncline, both of D1 age. The axial plane of the Islay Anticline dips to the south-east, and the fold faces up to the north-west, whereas the Loch Awe Syncline is an upright, symmetrical structure. The Dalradian rocks are least deformed along the western seaboard and, in areas of particularly low strain such as on Islay and Jura, many of the original sedimentary features are preserved. There it is also possible to examine the earliest tectonic structures in their pristine state. In over 70% of the GCR sites included in this paper, the rocks have been affected by only a single major ductile tectonic event (D1), followed by weak, late-stage deformations. The Dalradian rocks at two of these GCR sites (*Caol Isla* and *Craignish Point*) appear in the field to be almost undeformed, and only two of the remaining sites show the full effects of polyphase deformation (*Black Mill Bay* and *Port Cill Maluaig*). The metamorphic grade throughout the area is generally of greenschist facies, with some garnet-bearing epidote-amphibolite-facies rocks occurring along the south-east margin.

In this paper, the GCR site reports are arranged in stratigraphical sequence with the oldest first, but there are some anomalies where either subject matter or geographical location takes precedence. Of the 21 site reports, three are concerned with contemporaneous igneous activity (dykes and sills); two record the occurrence of minerals not normally found in Dalradian rocks that are unusual for their form (gypsum), or are in some way unique in their particular setting (kyanite and stilpnomelane); two deal largely with water-escape structures and clastic dykes, respectively; and the remaining 14 are focussed on stratigraphical and structural aspects. Examples of innovatory studies in the region include the first uses in the United Kingdom of sedimentary cross-bedding and graded bedding in metasedimentary rocks to determine the younging direction (see the *Kilmory Bay* GCR site report).

1.1 The pre-Dalradian basement and units of uncertain stratigraphical affinity

The Dalradian Supergroup is not seen in contact with its basement anywhere in the South-west Grampian Highlands but the Palaeoproterozoic Rhinns Complex on Islay almost certainly represents at least the local basement. Intervening structurally between the Rhinns Complex and rocks of undoubted Dalradian affinity on Islay are two groups of Dalradian-like rocks, the Colonsay Group and the Bowmore Sandstone Group. Both are rather monotonous sequences of metasandstone and lack any specific characteristics that would help to confirm their Dalradian identity. The Bowmore Sandstone Group, described in the *Bun-an-uilt, Islay* CGR site report, is separated from the Dalradian proper by the Loch Skerrols Thrust and might be equivalent to the Crinan Grit Formation, described below (Fitches and Maltman, 1984). The Colonsay Group has a tectonized, unconformable contact with the Rhinns Complex, exposed in the *Kilchiaran to Ardnave Point* GCR site, but it cannot be correlated directly with the Dalradian sequence; it has been compared to the Grampian Group and possibly the lower part of the Appin Group (Stephenson and Gould, 1995). U-Pb ages on detrital zircons from the Colonsay Group strongly support its correlation with the Grampian Group, and help to confirm that the Rhinns Complex is part of the basement to the Dalradian (McAteer, *et al.*, 2010). See Stephenson et al. (2013a) for more detailed discussions of these units and their possible affinities.

1.2 Dalradian stratigraphy

Appin Group rocks are only exposed in this region on the Isle of Islay, within the core of the Islay Anticline (Rast and Litherland, 1970; Basahel, 1971; Wright, 1988; see also BGS 1:50 000 sheets 19, South Islay, 1998 and 27, North Islay, 1994). Strata of all three subgroups are present, and show a remarkable similarity to the mainland succession, some 80 km to the north-east along strike (see Treagus et al., 2013). However, they are poorly exposed and are not represented by any GCR sites.

The Lochaber Subgroup on Islay is divided into two units. The lower, **Maol an Fhithich Quartzite Formation**, consists of massive, cross-bedded quartzites with phyllitic metamudstones and pebble beds containing extrabasinal granite clasts. The overlying **Glen Egedale Slate Formation** is composed of striped greenish, phyllitic or slaty metasiltstones that become more calcareous upwards. The Ballachulish Subgroup consists of the **Kintra Dolostone Formation**, **Mulindry Bridge Slate Formation**, **Cnoc Donn Quartzite Formation** and the **Neriby Formation**, and can be matched confidently with the type succession of the Appin–Loch Leven area, with little variation in facies. In the Blair Atholl Subgroup, the **Ballygrant Formation**, consisting of dark grey, slaty and phyllitic graphitic metamudstones, followed by a bluish grey metalimestone, can be equated confidently with the Cuil Bay Slate and Lismore Limestone. Owing to the south-westerly plunge of the major folds in the Appin–Lismore area, any higher beds of the Blair Atholl Subgroup that may have been deposited there lie beneath the Firth of Lorn, but an extended sequence is present on Islay. There, the Ballygrant Formation is overlain by dark grey phyllitic metamudstones with graded metasandstone or calcareous beds, the **Mullach Dubh Phyllite Formation**, and a distinctive banded unit containing partly ooidal and stromatolitic, thin-bedded metalimestones, the **Lossit Limestone Formation** (formerly the Islay Limestone, Spencer, 1971), which is overlain unconformably by the Port Askaig Tillite Formation.

The stratigraphical sequence covered by the GCR sites in this paper begins with the **Port Askaig Tillite Formation** at the base of the Argyll Group, which is magnificently exposed in the *Garvellach Isles* (Spencer, 1971) (Figure 2a). This GCR site is of international importance as it is the best-preserved example of a Precambrian tillite in the British Isles. The tillite is also instrumental, because of its distinctive character and association with a thick quartzite unit above, and a dolomitic unit below, in forging a stratigraphical correlation between the Dalradian rocks of Scotland and those of Connemara and Donegal (Kilburn *et al.*, 1965). Currently, it plays a major role in the search for a continuation of the Dalradian tract prior to the break-up of Rodinia. This is despite the fact that the origin of the formation is still in dispute, the precise age of deposition is not known, and a debate as to whether it represents a 'Snowball Earth' situation has ensued (Dempster *et al.*, 2002).

The important features of tillite formation include the 'Great Breccia' and the neighbouring 'Disturbed Beds', which occur in a well-documented sequence of 47 metadiamictites. Within the metadiamictites there is a change from locally derived stones to an incoming of foreign exotic stones at bed 12. The top of the sequence can be examined north of Port Askaig on Islay, where a transition to the overlying Bonahaven Dolomite Formation can be seen at the *Caol Isla* GCR site. The current interpretation for its origin is that the tillite was deposited sub-aqueously from icebergs, and was then partly reworked by tidal currents.

The **Bonahaven Dolomite Formation** (Spencer and Spencer, 1972) was interpreted by Fairchild (1993) to be the 'cap carbonate' to the Portaskaig Tillite and, apart from the lowest beds, consists almost entirely of orange-yellow, Fe-rich dolomitic rocks. It is divided into four members, the lowest of which is subdivided into five units. The lowermost unit contains isolated boulders and has an affinity with the tillite, and unit 2 consists of well-bedded metasandstones with channel deposits. The metasandstone beds are almost undeformed and contain mud cracks. Sedimentary dykes result from the injection of water-saturated, over-pressured sand and silt as dyke-like bodies into the adjoining sediments. Those at Caol Isla have recently been interpreted as being the result of interstratal dewatering, probably caused by earthquake activity associated with the synsedimentary Bolsa Fault (Tanner, 1998a). The *Caol Isla* GCR site also became famous, briefly, for the reported presence of Neoproterozoic trace fossils by Brasier and McIlroy (1998). However, this identification was withdrawn subsequently by Brasier and Shields (2000).

The upper part of the Bonahaven Dolomite Formation is best exposed along the north coast of Islay at the *Rubha a' Mhail* GCR site. There, distinctive stratigraphically controlled beds contain stromatolites, which have either spherical or elliptical shapes up to 3 m across, or occur as layer-form sheets. The rocks at this GCR site are more deformed than those at Caol Isla but fine-grained siliciclastic beds still preserve water-escape structures and small clastic dykelets. In addition, there is possible evidence for the former presence of anhydrite, a mineral that, like gypsum, is characteristic of evaporite deposits.

The **Jura Quartzite Formation** is not represented by a GCR site, as this unit crops out over a large area and is particularly well exposed. It is a clean, locally feldspathic, cross-bedded and cross-laminated quartzite deposited in a wave- and storm-dominated environment (Anderton, 1976). Anderton (1979) suggested that deposition took place in a series of fault-controlled basins as the formation shows extreme lateral thickness changes from 5 km on Jura to approximately 1000 km on Islay to the south-west, and thinning to *c*. 100 m on Lunga to the north-east.

Over a distance of 110 km between Port Ellen, on Islay and Benderloch to the north-east, the contact between the Jura Quartzite and the overlying **Scarba Conglomerate Formation** at the base of the Easdale Subgroup appears to be conformable, with no evidence of an orogenic unconformity at this level in the Dalradian succession (see the *Camas Nathais* CGR site report for further discussion in Treagus et al., 2013). However, marked lateral changes occur within the rock units immediately above this boundary (Figure 2a). For example, the **Jura Slate Member** is 60 m thick in the south-west at the *Kilnaughton Bay* GCR site on Islay, reaches a maximum thickness of over 200 m a the *Lussa Bay* site on Jura (Tanner 2005), and is absent from the north-east of Jura at the *Kinuachdrachd* GCR site. The overlying **Pebbly Sandstone Member** is not as well developed on Jura as in the type area on the Isle of Scarba where individual blocks are on a metre scale (Anderton, 1979). At the *Kinuachdrachd* and *Lussa Bay* GCR sites on Jura the clasts seldom exceed one to two centimetres across and are commonly accompanied by rip-up clasts of mudstone. Individual beds commonly show normal grading in units 1–2 m thick. Cross-lamination is found in the tops of many beds, and slump structures, channelling, bottom structures and erosional bases to beds are common.

The **Easdale Slate Formation** consists mainly of dark grey to black graphitic slaty metamudstone, generally pyrite-rich, with pods and bands of orange-brown-weathering dolostone, and some layers of metasiltstone and metasandstone. The formation maintains the same monotonous lithology from the island of Kerrera, near Oban, southwards across the whole outcrop. The *Black Mill Bay* GCR site displays examples of all of the main lithologies. In addition, at this site there are black gritty metasandstones and a 4 m-thick debris flow containing strongly elongated sandstone clasts. This latter deposit is of the same type as that found at the *Port Selma* GCR site (Treagus et al., 2013). A clastic dyke sourced by a sandstone bed below the debrite flow was folded and cleaved during D1.

On Islay and Jura, the **Kilbride Limestone Member** of the Port Ellen Phyllite Formation that occurs above the Easdale Slates (Figure 2a), is equated with the **Degnish Limestone Formation** and its equivalent, the **Shuna Limestone** (Figure 2b), on the mainland. These metalimestones are correlated with the Cranford Limestone in Donegal (Pitcher and Berger, 1976), which has recently been taken as marking the plane of an orogenic unconformity within the Dalradian block (Hutton and Alsop, 2004). To date, no evidence has been reported from the South-west Grampian Highlands to support this contention (Tanner, 2005).

The outcrop of the **Port Ellen Phyllite Formation** on the islands of Islay and Jura lies in strike continuity, and is correlated with the **Craignish Phyllite Formation** on the mainland (Figure 2b) (Hill, 1879). The latter formation is well exposed at the *Craignish Point* and *Fearnach Bay* GCR sites and is characterized by grey-green calcareous phyllites with 1—2 m-thick beds of fine-grained quartzite, and thinner bands of orange-brown-weathering metacarbonate rock. Minor components include foliated sheets of basic meta-igneous rock, generally sills, whose 'volcanic' association was first recognized by Peach (1903). Where they are protected from subsequent deformation by thick basic sills, the metasedimentary rocks preserve a unique twinned form of gypsum, now pseudomorphed by calcite (*Craignish Point* GCR site), whose precise palaeoenvironmental significance is not clear at present.

On Islay, the **Laphroaig Quartzite Formation** (Figure 2a) (see the (*Surnaig Farm* GCR site report) marks the top of the Easdale Subgroup. The *Surnaig Farm* GCR site is also an exceptional locality for studying deformed clastic dykes. Over 30 dykes are exposed in a small area; they were originally described by Borradaile (1976) as Neptunian dykes but are re-interpreted here as injected clastic material and could be of interstratal origin. They were both folded and cleaved during D1.

On the east limb of the Loch Awe Syncline, the **Ardrishaig Phyllite Formation** is well exposed in the *Port Cill Maluaig* and *Strone Point* GCR sites. Despite the higher degree of metamorphism and deformation, the Ardrishaig Phyllites show the same field appearance, and maintain the same range in lithologies, as the Craignish Phyllites at the *Loch Fearnach* GCR site. The **Crinan Grit Formation** is best exposed in the *Kilmory Bay* GCR site where it has a conglomeratic unit, the Ardnoe Member at the base. The **Ardmore Formation** represents the base of the Crinan Subgroup on the islands, and is correlated with the Ardnoe Member on the mainland. A local calcareous unit, the **Shira Limestone and Slate Formation** occurs at the junction between the Easdale and Crinan subgroups (Figure 2a) and is seen on the mainland as a dolomitic breccia at the base of the Ardnoe Member. The top part of the Crinan Subgroup is best exposed in the *South Bay, Barmore Island* GCR site were it is represented by the **Stonefield Schist Formation**, which has a conformable and transitional contact with the **Loch Tay Limestone Formation**. The latter is 75 m thick in Kintyre at the *South Bay, Barmore Island* GCR site but is represented in the core of the Loch Awe Syncline by the **Tayvallich Slate and Limestone Formation** and the **Tayvallich Volcanic Formation**, which have a combined thickness of 3200 m (of which the metalimestone accounts for *c*. 100 m). At the top of the Tayvallich Slate and Limestone Formation is the **Kilchrenan Conglomerate Member**, described in the *Kilchrenan Burn and Shore* GCR site report.

The **Loch Na Cille Boulder Bed** found near the top of the Tayvallich Subgroup (see the *West Tayvallich Peninsula* GCR site report) has been variously interpreted as a tectonic breccia (Peach *et al.*, 1911), a volcaniclastic debris flow (Pickett *et al.*, 2006) or a glacial deposit (Elles, 1935; Prave, 1999). In the core of the Loch Awe Syncline the Tayvallich Subgroup passes up into the **Loch Avich Grit Formation** and **Loch Avich Lavas Formation**, belonging to the Southern Highland Group (Figure 2b).

1.3 Pre-tectonic igneous dykes and sills

Basic sills that were emplaced before the regional deformation and metamorphism are common in the upper part of the Argyll Group in the South-west Grampian Highlands, and in places they make up more than 50 per cent of the succession. Contact metamorphism adjacent to the thicker sills causes local baking and hardening of the country rocks. As a result these beds are protected from much of the subsequent deformation, so preserving features such as pseudomorphs after gypsum (*Craignish Point* GCR site), and sedimentary structures (*Kilmory Bay* GCR site). Massive sills of this type are reported from the *Ardilistry Bay, Ardbeg, Craignish Point and Kilmory Bay* GCR sites. Those at Ardbeg and Ardilistry Bay are considered to be representative.

Igneous dykes and sills either of unusual composition (i.e. more mafic than normal) or containing unusual minerals, are found at three localities in South Islay, close to the Port Ellen Phyllite-Laphroaig Quartzite contact. At Ardbeg, there is a folded 70 m-thick sill that is unusual for containing large crystals (up to 1 mm long) of the brittle mica, stilpnomelane. At Ardilistry Bay, there is a unique, 12–14 m-thick basic sill containing at the base a 3 m-thick layer of metapyroxenite and a 1 m-thick meta-anorthosite. The clinopyroxene has been altered to actinolite, and the anorthosite to an assemblage containing albite and epidote. At the *Surnaig Farm* GCR site, there is a unique occurrence of a cleaved dyke of metamafic rock.

1.4 Structure

The area has a simple structural geometry controlled by a series of upward-facing F1 major folds. These are (from south-east to north-west) the Ardrishaig Anticline (equivalent to the Tay Nappe), the compound Loch Awe Syncline, and the Islay Anticline (Figures 1, 3). The slaty cleavage shared by these structures changes orientation from vertical in the south-east, to dipping south-east at a moderate angle on Islay. The folds are gently curvilinear and the stretching lineation has a regional down-dip orientation. No major tectonic breaks have been recognized.

The Tay Nappe and its relationship with the Ardrishaig Anticline are fully described and discussed by Tanner et al. (2013b). The Loch Awe Syncline, being a more-obvious, open structure, has been known about for much longer and MacCulloch reported a 'fan structure' in this region in 1819. Hill (1899) recognized that it is a major fold and he was the first person to correlate the Craignish Phyllites on the north-west limb with the Ardrishaig Phyllites on the south-east limb. Roberts (1974) identified it as a major F1 structure, correcting Bailey's (1913) interpretation of it as a secondary fold (see the *Kilmory Bay* GCR site report). The Loch Awe Syncline has a tripartite hinge comprising the Tayvallich Syncline, the Loch Sween Anticline and the Kilmory Bay Syncline. The Kilmory Bay Syncline is the more complex of these three structures and its hinge-zone consists of a bundle of at least five mesoscopic fold closures (see the *Kilmory Bay* GCR site report).

The Islay Anticline was first recognized by Peach and Wilkinson (1909) but both the stratigraphy and the structure were completely re-interpreted by Bailey (1917). Part of his map is reproduced here (Figure 4), as it is a fine example of the style of map produced during this period, and is accompanied by a dynamic cross-section, which has not been bettered. There was an early dispute over whether this fold is a syncline or an anticline, and this was not resolved conclusively until the work of Allison (1933). The Islay Anticline is poorly exposed; for such a large structure, there is surprisingly little published information on its geometry, and few structural symbols on the BGS 1:50 000 sheets for the area. The fold trace appears to consist of en-echelon segments displaced by faulting (Figure 1). The fold axis plunges gently to the north-east for most of its outcrop on Islay, except at the far north end of the island where it plunges to the south-west (see the *Rubha a' Mhail* GCR site report).

The area also lies on the north-west limb of the F4 Cowal Antiform, a major arch-like structure that folds the early fabrics and the Ardrishaig Anticline/Tay Nappe (see Tanner et al., 2013b). It has a broad hinge-zone represented by the Cowal Flat Belt, the north-west limit of which was designated the Tarbert Monoform by Roberts (1977c). However, although F4 box folds occur locally in the position of the proposed monoform, examination of the Geological Survey map sheets 29 and 37 suggests that there is a gradual change in overall curvature of the strata across this zone, and no evidence of an abrupt increase in regional dip.

In the context of these major structures, the *Rubha a' Mhail* GCR site lies in the core of the Islay Anticline; the *West Tayvallich Peninsula* GCR site contains the hinge-zone of the Tayvallich Syncline; the *Kilmory Bay* GCR site straddles the complex hinge-zone of the Kilmory Bay Syncline; the *Loch Avich* GCR site lies in the core of the Kilchrenan Syncline, a component of the Loch Awe

Syncline; and the *Strone Point* GCR site is located a short distance south-east of the hinge of the Ardrishaig Anticline where there is a analogous pair of congruous mesoscopic F1 folds.

Of the remaining sites, 14 lie on the common limb between the Islay Anticline and the Loch Awe Syncline. Bedding dips to the south-east at a moderate angle at all of these sites, except at the *Caol Isla* GCR site, which is affected by its proximity to the hinge-zone of the Islay Anticline. It is everywhere cut by the S1 penetrative to spaced cleavage, which dips more steeply in the same direction. F1 fold hinges generally plunge to the north-east or south-west but are locally strongly curvilinear. There is a weak down-dip L1 stretching lineation at most of these localities. A gently dipping to horizontal crenulation cleavage is sporadically developed throughout this fold limb, and is only associated with mesoscopic folds at the *Black Mill Bay* GCR site. This fabric represents a late deformation, which is of post-D2 age. The effects of the D2 deformation, seen as an intense planar fabric that overprints and almost completely reworks S1, is seen only at the *Port Cill Malluaig* GCR site.

1.5 Regional metamorphism

Metamorphic grade is largely of greenschist facies, except along the south-east margin of the region, where it reaches the garnet zone of the epidote-amphibolite facies at a temperature of over 500°C and a pressure estimated at 10 kbar (Graham *et al*., 1983). A number of studies have been carried out on the regional metamorphism of the concordant basic meta-igneous sheets, and models have been formulated for the regional circulation of metamorphic fluids in these rocks (i.e. Graham *et al.,* 1985; Skelton *et al.,* 1995), with the major antiformal fold closures acting as conduits for the fluids. Apparently anomalous high pressures, calculated using the phengite geobarometer (Graham *et al*., 1983; Dymoke, 1989), are partly substantiated by the local presence of regional metamorphic kyanite in greenschist-facies rocks (see the *Kilnaughton Bay* GCR site report).

1.6 Features of specialized interest

Topics of particular interest covered in the GCR reports in this paper include:

- Origin of a Neoproterozoic glacial deposit: the Port Askaig Tillite (*Garvellachs Isles* GCR site)
- Extremely well-preserved Neoproterozoic stromatolites (*Rubha a'Mhail* GCR site)
- Water-escape structures and sedimentary or clastic dykes (*Coal Isla* and *Surnaig Farm* GCR sites)
- The unique form of gypsum, and its environmental implications (*Craignish Point* GCR site)
- Pre-tectonic igneous dykes and sills, and some unusual minerals
- The geometry of cylindrical and curvilinear folds (*Strone Point*, *Fearnach Bay* and *Port Cill Maluaig* GCR sites)
- The development of kyanite in greenschist-facies regional metamorphic rocks (*Kilnaughton Bay* GCR site)

• A putative orogenic unconformity in the Dalradian (*Kilnaughton Bay*, *Lussa Bay* and *Kinuachdrachd* GCR sites

• Nature of the Dalradian basement (*Kilchiaran to Ardnave Point* GCR site).

2 GARVELLACH ISLES (NM 633 088–NM 683 128)

P.W.G. Tanner

2.1 Introduction

The Garvellachs ('Isles of the Sea') are an isolated group of uninhabited islands in the Firth of Lorn, which preserve the best-exposed section through a Precambrian glacial deposit to be found in the United Kingdom. This unit, the Port Askaig Tillite Formation, consists of a succession of 'boulder beds' (metadiamictites) and interbedded metasedimentary rocks that, although gently tilted, is largely unaffected by tectonic distortion or faulting. Its relationship with the underlying Lossit (formerly Islay) Limestone Formation may be examined in the Garvellachs, and the top of the tillite sequence can be seen on Islay, 50 km to the south-west, where it passes conformably upwards into rocks of the Bonahaven Dolomite Formation (see the *Caol Isla* GCR site report) (Figure 1). The Port Askaig Tillite marks the base of the Argyll Group (Figure 2) and has been used as a key lithostratigraphical marker for correlating the Scottish and Irish Dalradian successions (Kilburn *et al.*, 1965).

The architecture and internal morphology of the tillite formation are magnificently exposed on the 7.6 m (25 ft) raised rock platform around the islands, and individual beds can be reliably traced across each island due to the excellent exposures. Here the beds preserve a wealth of sedimentological features, which have been largely destroyed in rocks of similar age elsewhere in Scotland and Ireland due to the effects of later intense deformation and metamorphism. The tillite sequence on the Garvellachs consists of numerous boulder beds, which together with the interstratified sedimentary rocks, has an exposed thickness of 578 m (Spencer, 1971, 1981). Together with a further 172 m of beds at the top of the sequence, seen on Islay but not exposed on the Garvellachs, it represents the thickest known development of the Port Askaig Tillite.

Following regional mapping by the Geological Survey (Peach *et al.*, 1907), the first detailed account was by Kilburn *et al.* (1965) who prepared a measured section across the boulder beds as part of a survey of glacial deposits in the Dalradian successions of Scotland and Ireland. Spencer (1971) then published the definitive monograph on the Port Askaig Tillite, which has proved a *vade-mechum* for all future work and interpretation. However, despite the benefit of its excellent state of preservation, the age, origin, and source of the tillite have been hotly disputed. Hypotheses for its formation have ranged from non-glacial causes, such as subaqueous mud or debris flows (Schermerhorn, 1974, 1975), to a glacial origin, either by deposition from grounded glacier ice (Kilburn *et al.*, 1965; Spencer, 1971, 1985), or from floating icebergs supplying exotic materials to a tidally-influenced marine basin (Eyles and Eyles, 1983; Eyles and Clark, 1985; Eyles, 1988). Source terrains for the exotic stones have been sought in Sweden and Finland (Spencer, 1981); Labrador and Greenland (Evans *et al.*, 1998); and even South America (Dalziel, 1994). An additional problem is its age of deposition. For many years the tillite was assumed to be equivalent to the Varanger Tillites of Scandinavia, Greenland and Svalbard (Hambrey, 1983; Hambrey and Harland, 1985). However, the long-accepted, though imprecise, *c*. 653 Ma age of these tillites has now been revised to 620–590 Ma, which is more comparable with the top of the Argyll Group than the bottom. Hence various alternative suggestions have been made, which correlate the Port Askaig Tillite with either the Marinoan (*c*. 635 Ma) or Sturtian (*c*. 723 Ma) global glacial events (see Stephenson et al., 2013a).

There has been a recent resurgence of interest in the number, age, and causes of the late-Precambrian glaciations and their temporal relationship to the evolution of metazoan life forms in the Cambrian, and the Garvellach Isles GCR site has a key role to play in this work.

2.2 Description

The sequence on the Garvellachs begins with the dolomitized, 70 m-thick, upper part of the Lossit Limestone Formation, which is exposed on the most westerly and accessible of the islands, Garbh Eileach (Figure 5). An interesting feature of the metalimestone is that locally it contains arrays of radiating, stellate pseudomorphs a few centimetres long (Spencer, 1971, plate 6), which consist of a quartz-dolomite intergrowth. These pseudomorphs can be examined at (NM 676 127) and are of disputed parentage.

The Lossit Limestone is overlain conformably by the Port Askaig Tillite Formation ('Boulder Bed' or 'Conglomerate' of the early authors). Although the type area of the tillite is at Port Askaig on Islay, it is best seen on the Garvellachs where it consists of 38 individual metadiamictites, from less than 1 m to over 20 m thick, with boulders to 2 m across. The upper dolomitized part of the Lossit Limestone together with the first 12 metadiamictite units are seen only on the Garvellachs, being absent on Islay where Unit 13 lies unconformably upon the metalimestone.

The boulder beds were called 'mixtites' by Spencer (1971), but modern workers prefer the non-genetic term 'diamictite', to describe a rock consisting of a poorly sorted aggregate of mud-, sand-, and gravel-sized detritus. The tillite sequence, which includes considerable thicknesses of tabular bedded sedimentary rocks and breccias, was divided into 5 units by Spencer (1971), and includes two distinctive members, the Great Breccia and the Disrupted Beds. The uppermost part of the tillite is not preserved in the Garvallachs, but is seen in the Port Askaig area of Islay.

The tillite is excellently exposed on the rock platform around the north-east end of Garbh Eilach and is accessible from 200 m north-west of Belach Buidhe (NM 676 127) to Sloc a' Cheatharnaich (NM 675

119). The field relationships have been described in detail by Fairchild (1991). The sequence begins with metadiamictites 1–12, containing mainly dolostone clasts, passes upwards into the Great Breccia and the Disrupted Beds, and ends with the upper metadiamictites (18–32) which are characterized by their high content of 'exotic', usually granitic, boulders (Figure 5). Most features of the succession are well displayed in this section, with the upper metadiamictites being best seen between NM 675 119 and NM 670 118, close to the landing stage. These include dropstones, erosion surfaces, sandstone wedges, load structures, slumped horizons, wave-ripples, and varve-like sequences (Kilburn *et al.*, 1965; Spencer, 1971; Eyles and Eyles, 1983; Eyles and Clark, 1985).

The metadiamictites decrease in thickness and frequency upwards, and the whole formation is an upwards-fining sequence that shows a transitional passage into the overlying Bonahaven Dolomite Formation (see the *Caol Isla* GCR site report). The associated interbeds, which occur in units up to 11 m thick, include rippled and cross-bedded white and brown metasandstones, orange-brown metadolostones, and metaconglomerates, are rich in dolomite at the base of the sequence and become less dolomitic and more feldspathic upwards. Most of the metadolostones have been shown to be detrital in origin and derived from the underlying Lossit (formerly Islay) Limestone (Fairchild, 1983, 1985), and therefore have no palaeoclimatical significance.

The clasts in the metadiamictite horizons can be divided into *intrabasinal* stones derived from the local substrate, and *extrabasinal*, or 'exotic,' stones of unknown provenance. The intrabasinal stones consist of abundant, angular, metadolostone fragments, with dolomitic metasiltstone, metaconglomerate and very rare metalimestones; the exotic ones are mainly of pink granite (commonly referred to as being of Rapakivi-type or nordmakite e.g. Spencer, 1971), with some gneiss, schist and quartz clasts. The extrabasinal stones are subrounded and reach 1.5–2.0 m in diameter. The lowest metadiamictites contain locally-derived stones but exotic stones appear above Unit 12 and become common in the upper beds in which a feldspar-rich matrix is also developed. This upward change in provenance is reflected in the whole-rock geochemistry (Panahi and Young, 1997), which distinguishes lower metadiamictites derived by the erosion of sediments, which had already undergone a previous cycle of post-Archaean weathering, from upper metadiamictites derived from a mixed granitic and post-Achaean sedimentary source.

Two distinctive members are thicker and coarser grained than on Islay, and are not seen elsewhere in the tillite outcrop. The Great Breccia is 40 m thick and contains enormous intrabasinal clasts of metadolostone, the largest, occurring at NM 639 099 on Eileach an Naoimh, being over 70 m long and folded into an antiform. The overlying Disrupted Beds is a unit 29–40 m thick, well exposed at NM 666 122 on Garbh Eilach, which consists of semicontinuous beds of metadolostone and cross-bedded metasandstone that have been partially boudinaged and pulled-apart.

Special features of the metadiamictites that have provided clues as to their glacial origin, or are of particular interest, include: numerous dropstones in finely bedded or laminated sequences; large polygonal structures on bedding surfaces, illustrated and described in detail by Kilburn *et al*. (1965), Spencer (1971) and Eyles and Clark (1985) and seen at NM 646 101; millimetre-thick, varve-like, laminations in metasiltstone beds, some with over 2500 laminae (Spencer, 1981) (NM 675 119); sedimentary dykes up to 30 cm thick and traceable for several hundred metres (NM 667 124); and sandstone downfold structures above metadiamictites (Spencer, 1971; Eyles and Clark, 1985), which can be seen at a number of places.

The Port Askaig Tillite on the Garvellachs has a simple structural setting: the entire sequence of beds dips to the south or south-east at around 35°, and forms part of the north-western limb of the Loch Awe Syncline (F1). A single main penetrative cleavage is developed locally, which dips to the south-east more steeply than bedding and appears to belong to the same generation as the major syncline; it can be seen as a spaced cleavage in some of the metasandstones. The early cleavage is crenulated locally, and late kink bands are also seen (Spencer, 1971). The beds are affected by some internal strain, as shown by the deformation of pebbles and by the slight distortion of the polygonal patterns seen on bedding surfaces.

2.3 Interpretation

The mode of origin and source of the tillite have been the subject of lively geological interest since MacCulloch, one of the earliest geological travellers in the region, reported the presence of a conglomerate on the Garvellachs in 1819, and suggested that it might be correlated with similar deposits at Schihallion, and on Islay. However it was Thomson (1877, p. 211) who first suggested a glacial origin for this boulder bed and anticipated the modern, most widely accepted, interpretation for the deposit, writing that 'the entire absence of stratification in one part of the section, which in another shows signs of regular deposition, and the occurrence of far transported rocks of the character already stated, indicate that the mass had been transported and dropped from melting ice in a shallow, tranquil sea, the bottom consisting of mud and sand'.

Spencer (1971) concluded that the tillite was deposited from a grounded ice sheet, an interpretation challenged by Schermerhorn (1974) who interpreted it as a mass-flow deposit, and by Eyles and Eyles (1983) who argued for glacimarine deposition beneath floating icebergs, with much reworking of the sediments by currents. These interpretations are dependent upon understanding not only the overall architecture of the deposit, but the depositional environment of the sedimentary interbeds, and the degree to which the diamictites have been reworked by currents. The interpretation of minor features diagnostic of particular environments, such as polygonal sets of sediment-filled cracks, varves, pseudomorphs etc. also plays a vital role in this work and these features have been much discussed in recent years. For example, large polygonal networks seen on bedding surfaces at NM 646 101 on Eileach an Naoimh were interpreted as ice-wedge polygons (indicating subareal exposure in a cold climate) by Spencer (1971, plate 8), but as subaqueous soft-sediment dykes whose formation is not dependent upon the presence of ice, by Eyles and Clark (1985). Likewise, the pseudomorphs seen in the Lossit Limestone, which Spencer (1971) speculated may be of glendonite (and hence derived from ikaite, a mineral stable only below 4°C (Shearman and Smith, 1985), and diagnostic of a cold climate), could equally well be secondary after gypsum, and indicative of warm, arid conditions.

On a continental scale, glacial deposits have been used to reconstruct past plate configurations, by determining the direction of transport of the tillite and tracing the origin of the boulders to their source region. U-Pb dating of zircon from two granitic clasts from the Port Askaig Tillite on the Garvellachs and Islay has yielded ages of *c*. 1800 Ma (Evans *et al.*, 1998). These dates, together with Nd model ages (Fitches *et al.*, 1996), show that the material was derived from a Palaeoproterozoic source, with no involvement of Archaean crust. The exotic clasts might have been derived from Palaeoproterozoic (*c*. 1800 Ma) terranes in Labrador, South Greenland or Scandinavia. A Laurentian, rather than Gondwanian, source is favoured. It is unfortunate in this respect that a palaeomagnetic study of the Port Askaig Tillite on Garbh Eileach has shown that the rocks were remagnetized during the Early Ordovician (Stuparsky *et al*., 1982), and hence this technique cannot be used to determine the palaeolatitude at which the tillite was deposited, as had been suggested previously by Tarling (1974).

Physical evidence for the direction of movement of the glacial material is also ambiguous. The Great Breccia has been interpreted as either a debris flow (Eyles and Eyles, 1983) or as a grounded-ice till (Fairchild, 1985, 1991). The large fold in the Great Breccia (first figured by Peach *et al.*, 1909) has been much discussed in the literature as it is considered by some workers to be a glacial-push fold (Spencer, 1971), with movement from the south-east, or a soft-sediment slump fold (Eyles and Eyles, 1983), with movement in the opposite direction.

2.4 Conclusions

The Garvellach Isles GCR site preserves internationally important exposures of a Precambrian glacial deposit, the Port Askaig Tillite, which is unique in the UK for its excellent state of preservation and wealth of small-scale sedimentary features. This stratigraphical unit has been used as a marker horizon for correlating Dalradian sequences in Scotland and Ireland, and has been proposed as a link for use in global-scale tectonic plate reconstructions. Although its precise environment of deposition is still being debated, it is generally agreed to be of glacial origin, as evidenced by the presence of numerous, large, ‘exotic’, far-travelled dropstones in finely laminated metasedimentary rock. It was probably formed largely of material dropped from floating icebergs and reworked by tidal currents, and is the thickest deposit of this type in the Dalradian Supergroup. The Port Askaig Tillite is evidence for a major glacial episode having occurred in late-Precambrian times.

This GCR site continues to provide a classical testing ground in which to distinguish between different models for Precambrian tillite formation, and for examining the morphology of a wealth of controversial features such as fossil ice-wedge polygons, soft-sediment deformation structures, varves, exotic boulders of problematical origin, and unusual pseudomorphs. The interpretation of these features is important in understanding the climatic conditions, and hence the latitude, at which these rocks were deposited on the Earth’s surface prior to the subsequent break-up and dispersal of the continental blocks in the North Atlantic region. The value of this site is considerably enhanced by the current interest worldwide in the timing, correlation, and causes of Neoproterozoic glaciations.

3 CAOL ISLA, ISLAY (NR 429 701–NR 429 710)

P.W.G. Tanner

3.1 Introduction

The coastal rock platform and low cliffs north of the Caol Isla Distillery, on the east coast of the Isle of Islay (Figure 1), provide excellent exposures of rocks belonging to the uppermost part of the Port Askaig Tillite Formation and the lower part of the overlying Bonahaven Dolomite Formation, interpreted by some as a cap carbonate. The gently dipping metasedimentary rocks are on the east limb of the F1 Islay Anticline. The Dalradian rocks in this part of Islay show little evidence of deformation, and have been affected by only low-grade (greenschist-facies) metamorphism.

The main Dalradian lithological units on Islay such as the ‘Dolomitic Group’ at Caol Isla were recognized by the Geological Survey (Wilkinson, 1907), but were not placed into their correct stratigraphical sequence until the work of Bailey (1917). In one of the first studies to use sedimentary ‘way-up’ structures in metamorphic rocks in the British Isles, Allison (1933) confirmed Bailey’s interpretation that the ‘Dolomitic Group’ lies stratigraphically between the older, Port Askaig Tillite, and the Jura Quartzite above. Spencer and Spencer (1972) later combined groups 3–5 of Wilkinson (1907) to erect the Bonahaven Dolomite Formation, which is made up of four members and has a maximum total thickness of some 350 m (Fairchild, 1991, fig. 14). Wilkinson (1907) included a cross-section, and the rocks were mapped in detail by Spencer (1971). An excellent field guide is provided by Fairchild (1991).

The GCR site encompasses the best-exposed section through members 1 and 2 of the Bonahaven Dolomite Formation, the main focus being on the five units that make up Member 1. Members 3 and 4 of this formation are much better exposed on the north coast of Islay and are the subject of the *Rubha a’Mhail* GCR site report. The rocks at Caol Isla preserve a great variety of sedimentary structures characteristic of a tidal-dominated shelf environment (Klein, 1970; Kessler and Gollop, 1988). Of particular note are sand-filled cracks in alternating sandstone–mudstone sequences that give rise to well-organized polygonal patterns on bedding surfaces. These patterns reach over 10 cm in diameter, and have been variously interpreted as 'sun-cracks' indicative of subaerial exposure and drying out of mud layers; synaeresis structures formed at the water–sediment interface; or sections through dykelets resulting from dewatering of the sediment pile during burial. Considerable interest in these rocks was aroused briefly by the report by Brasier and McIlroy (1998) of fossil faecal pellets, of a type produced by the earliest organisms to have developed a gut capable of expelling such material. This identification has been subsequently retracted (Brasier and Shields, 2000).

3.2 Description

The rocks in the section at Caol Isla dip at 22–28° to the north, are right-way-up, and are unaffected by any major faults. The succession starts at the top of the Con Tom Member of the Port Askaig Tillite Formation (Member 5 of Spencer, 1971), and includes members 1–3 of the Bonahaven Dolomite Formation (Figure 7). There is a transitional contact between the Port Askaig Tillite and the Bonahaven Dolomite. In the vicinity of Caol Isla, Member 1 is seen only on the coastal section due to a local erosion surface having developed at this level farther inland, towards the inferred edge of the original sedimentary basin (Fairchild, 1991). This member is divided into 5 units, for which sedimentary logs were presented by Fairchild (1991, fig. 17).

Before describing the rocks from this site it is necessary first to clear up confusion over the previous stratigraphical nomenclature. Bailey (1917) introduced the term 'Lower Fine-grained Quartzite' to describe a thick quartzite, which occurs between the Port Askaig Tillite and the 'Dolomitic Group', to distinguish it from the Jura Quartzite (his 'Upper Fine-grained Quartzite'), which lies above the 'Dolomitic Group'. Klein (1970) misused this term (Spencer, 1971; Klein, 1971) to include part of the 'Dolomitic Group', and both Kessler and Gollop (1988) and Tanner (1998a) perpetuated this misuse for historical reasons. The correct reading of the stratigraphy of this section (as followed here) is that the Con Tom Member of the Port Askaig Tillite (Bailey's 'Lower Fine-grained Quartzite') is succeeded by Member 1 of the Bonahaven Dolomite Formation. Most of the rocks described by Klein (1970), and all of those studied by Kessler and Gollop (1988), and Tanner (1998a), occur within the Bonahaven Dolomite Formation.

3.2.1 Member 1. (Carraig Artair Member, BGS, 1997)

Unit 1 (Figure 7) consists of metamudstones and appears to be conformable with the underlying Port Askaig Tillite. Exceptionally, a slaty cleavage cut by a crenulation cleavage affects the metamudstone by the shelter at Carraig Artair (NR 4292 7020) and even more unexpectedly, for a sequence of rocks which appear to be so little deformed and of very low metamorphic grade, metamorphic biotite is developed (Fairchild, 1985, fig. 3e).

Unit 2 consists of up to 18 m of flaser-bedded and rippled metasandstones.

Unit 3 is highly significant in that the cross-bedded metasandstones that make up this unit include a metaconglomerate at the base (at NR 4294 7029), which contains 'exotic' granitic clasts similar to those found throughout the upper part of the Port Askaig Tillite. This metaconglomerate is the youngest bed in the Bonahaven Dolomitic Formation to preserve glacially transported material, albeit reworked by current action, and this occurrence provides a link between this formation and the underlying Port Askaig Tillite.

Unit 4, comprising interbedded metasandstones, metasiltstones, and metamudstones, is well exposed in a small cliff and rocky promontory at Leac Thiolastaraidh (NR 4297 7037), 370 m north of the pier at Caol Isla Distillery, and its sedimentary structures and lithofacies have been closely studied by a number of workers. Klein (1970, figs 2–4) illustrated cross-lamination, flaser bedding, and two intersecting sets of ripple marks from this locality. Kessler and Gollop (1988) visited the cliff face at Leac Thiolastaraidh and published a measured 14 m section, from which they recorded the possible presence of desiccated algal mats at a number of levels; channels (including 'gutter casts') containing cross-bedded strata; possible hummocky and swaley cross-stratification; ripples; and cross-sets with irregularly-spaced foreset laminae of tidal origin (the 'tidal bundles' of Boersma, 1969).

'Sun-cracks' were first reported from these rocks (together with ripple marks) by Thomson (1877). They occur as sand-filled cracks in alternating sandstone–mudstone sequences and form polygonal patterns on bedding surfaces (Figure 8a). The polygons commonly form orthogonal patterns (in which the majority of the cracks meet at right angles) and vary from centimetre-scale to larger structures over 20 cm across. Within the larger structures, a basic framework of cracks over 1 cm wide divide the surface into crude polygonal shapes, within which sets of thinner cracks define a second-order pattern. Tanner (1998a) analysed their 3-D morphology in detail, based on slabbed and sectioned material, and found that many of the cracks could be traced through a number of different beds.

These rocks also contain possible fossil remains; Fairchild (1977) recorded the presence of numerous phengite spherules, 50–150 mm across, which he considered to be possible glauconitized microfossils, from a metamudstone at the top of Member 1 in an equivalent section farther north at Bonahaven (not exposed in the Caol Islay section).

Unit 5 consists of a poorly exposed, honeycomb-weathered, dolomitic metasandstone.

3.2.2 Member 2. (Giur Bheinn Member, BGS, 1997)

This member is a cross-bedded meta-quartz-arenite, some 30 m thick, exposed in a small cliff section at NR 4293 7044 (Figure 7). It is of historical interest, for this horizon was named the 'Pipe Rock' by Peach (in Wilkinson, 1907) and, together with the other weakly deformed and metamorphosed mudstones, quartzites, and carbonate rocks on Islay, was inferred to be of Cambro-Ordovician age, and incorrectly correlated with the foreland sequence in the North-west Highlands.

3.2.3 Member 3. (Margadale Member, BGS, 1997)

In-situ dolomitic metasandstones belonging to this member are uncommon but there are many large tumbled blocks along the tide line. It was correlated with the 'Fucoid Beds' by Peach (in Wilkinson, 1907) and Peach and Horne (1930), but neither Bailey (1917) nor any subsequent workers (e.g. Fairchild, 1977) have been able to confirm the presence of 'small pipes', 'ordinary pipes' and 'trumpet pipes' in the 'Pipe Rock' (Peach and Horne, 1930), or 'worm-casts' in this member. These structures are artifacts associated with the patterns of filled cracks seen on bedding surfaces and in cross-section, in both metasandstones and metacarbonate rocks of the Bonahaven Formation. Some of these filled cracks have been strongly affected by bedding-normal compaction and the small buckle folds appear vermiform in cross-section.

3.3 Interpretation

In one of the first sedimentological studies of Dalradian rocks, Klein (1970) identified a wide range of sedimentary structures including cross-bedding, ripple marks, 'tidal bedding', and flaser bedding, in the section north of Caol Isla Distillery. He concluded that the sequence had been deposited in a tide-dominated, shallow water environment. Unfortunately, as pointed out by Spencer (1972), this study suffered from a lack of stratigraphical control and appears to encompass both the metasandstones immediately north of the distillery, which belong to the top of the Port Askaig Tillite, and members 1 and 2 of the Bonahaven Formation.

From their detailed study of part of Unit 4 in Member 1, Kessler and Gollop (1988) concluded that the depositional environment was transitional between that of a shallow shelf or shoreface and an intertidal setting. However recognition of the 'intertidal' setting relies in part upon their interpretation of the polygonal sets of sand and silt-filled cracks having formed by the subaerial desiccation of 'algal mats'. Thin sections of these rocks show micro-cross-laminated silty layers alternating with homogeneous, non-laminated muddy layers (Tanner, 1998a, fig. 9), with no suggestion of the mediation of desiccated microbial mats in the formation of the filled cracks. From a study of the complete section, Fairchild (1991) concluded that units 1 and 2 were deposited in a nearshore, wave-dominated situation, which became landward of a barrier island during the time that units 4 and 5 were laid down, followed by an eventual drowning of the barrier system (Member 2). Fairchild (1980a) also studied the origin of the dolomite in these rocks and concluded that it formed in two stages; penecontemporaneous with sedimentation, and during burial diagenesis.

Following Thomson (1877), most workers have interpreted the polygonal patterns seen on the bedding surfaces as 'sun cracks' (Knill, 1963) or mud cracks (Klein, 1970; Fairchild, 1991) which had formed as a result of desiccation during subaerial exposure, and had been infilled subsequently with sand. From a detailed study of the filled cracks, Tanner (1998a) concluded that they are sections through 3-D patterns of dykelets resulting from interstratal dewatering of the sediments, possibly soon after their deposition, with no evidence of subaerial exposure (Figure 8b). However, it is not clear what caused the homogeneous, layer-parallel contraction in the mudstone layers. There are two possibilities: it could have been triggered by earth tremors associated with movements on the synsedimentary Bolsa Fault (Figure 1) (see the *Rubha a'Mhail* GCR site report) or a related structure (Tanner, 1998a), or simply be the result of uniform contraction of material held together by microbial slime, as the latter decayed. The second explanation is the less likely, for, apart from the lack of evidence for its presence, such algal growths usually develop in calcareous not muddy rocks.

The rocks show little evidence of having been deformed, apart from the sporadic development of a slaty cleavage (generally only visible in thin section), and the slight distortion of some of the polygonal patterns seen on the bedding surfaces. The local presence of metamorphic biotite is consistent with greenschist-facies regional metamorphism. It is of historical interest to note that, in an attempt to date this metamorphic event in these low-grade Dalradian rocks, Leggo *et al.* (1966) obtained a Rb-Sr isochron apparent age of 572 ± 20 Ma from samples of metasandstone collected from the small cliff at Leac Thiolastaraidh. The result remains enigmatic.

Late-Precambrian tillites are characterized by having a 'cap' of carbonate rocks, whose significance is the subject of current worldwide research interest, and Fairchild (1993) has suggested that the Bonahaven Dolomite is the 'cap carbonate' to the Port Askaig Tillite, though this has been disputed by others. The paradox presented by these carbonate rocks is that they are usually considered to have formed in a warm or temperate climate, so their presence could require a rapid, unexplained, change in climate immediately following the glacial event. Alternatively, deposition of carbonate rocks both before and after the glacial event could have taken place in cold water conditions. It is therefore important to determine the precise climatic conditions under which the cap carbonate was laid down.

3.4 Conclusions

The *Caol Isla* GCR site is of international importance for determining the environment of deposition of the rocks immediately overlying a late-Precambrian glacial deposit, the Port Askaig Tillite. The sequence is crucial in this respect for it forms a transition between the tillite and its possible 'cap carbonate', the Bonahaven Dolomite Formation (the upper part of which is described in the *Rubha a'Mhail* GCR site report).

In addition, the well-exposed coastal section provides a representative section for the lower part of the Bonahaven Dolomite Formation of the Argyll Group, and enables a bed-by-bed study to be made of the sedimentary structures in this tide-dominated, shallow water sequence. Features of particular interest include sand-filled cracks, which form polygonal patterns on the bedding surfaces. Their 3-dimensional morphology suggests that they originated by loss of water from the sediments after burial, possibly triggered by movements on a fault that was active during development of the sedimentary basin (see the *Rubha a'Mhail* GCR site report). The site is made more valuable by the fact that the rocks are almost unaffected by tectonic strain, an unusual situation in the Dalradian.

4 RUBHA A' MHAIL, ISLAY (NR 377 781–NR 426 793)

P.W.G. Tanner

4.1 Introduction

This rocky, isolated stretch of coastline at the northern tip of Islay (Figure 1), with its raised beaches, sea cliffs and caves, presents a number of magnificent sections through members 3 and 4 of the Bonahaven Dolomite Formation. The stratigraphical succession is a continuation of that seen at the *Caol Isla* GCR site, in which the lower two members of the Bonahaven Dolomite are best preserved. Although the outcrop of Member 3 is displaced a number of times by faulting, marker horizons in the sequence can be correlated for up to 3 km along strike. An abrupt change in thickness of this member in the west of the section is interpreted as being the result of movement on an important syndepositional listric discontinuity, the Bolsa Fault. At the top of the sequence there is a transitional contact between Member 4 and the younger Jura Quartzite Formation.

This GCR site is renowned for its outstanding 3-dimensional exposures and natural sections through both isolated, rounded stromatolite bodies (bioherms), and stratiform, continuous stromatolite beds (biostromes). Stromatolites are algal bodies that originated as thin, slimy surface films, called microbial mats, which trapped fine-grained carbonate sediment as they grew and progressively accreted into symmetrical masses or layers up to several metres across. The algal filaments are no longer preserved, but evidence of microbial growth is preserved by numerous, parallel, millimetre-scale laminations, now largely of dolomite. This laminar texture can be seen clearly where erosion has exposed the interior of these ball-like and sheet-like structures.

The locality lies astride the complex hinge-zone of the F1 Islay Anticline (Bailey, 1917), and the rocks are more highly strained than at the *Caol Isla* GCR site, with the development of large open folds, a penetrative cleavage oblique to bedding, and an evident distortion of angular relationships between sediment-filled cracks and the bedding planes (Borradaile and Johnson, 1973). The rocks belong to the greenschist facies, with the local development of phlogopite in metacarbonate rocks suggesting that temperatures of around 400°C were reached during the regional metamorphism (Fairchild, 1980c).

This part of Islay appears not to have been visited by the early geological travellers in the Western Isles such as MacCulloch and Thomson, and the earliest work was carried out by the Geological Survey (Wilkinson, 1907; Bailey, 1917) and Green (1924). Allison (1933) confirmed Bailey's (1917) stratigraphical sequence by the use of way-up structures, and published the first detailed sketch map of part of the site. Spencer (1972) established the current informal subdivision of the Bonahaven Dolomite into 4 units and prepared a detailed map of the whole section. However, it is Fairchild to whom we largely owe our current understanding of these rocks. With rare perseverance he has investigated in minute detail the stratigraphy, structure, petrography, chemistry, and other aspects of the formation (Fairchild, 1977, 1980a, 1980b, 1980c, 1985, 1989), and the description of the rocks given here relies heavily on his field guide to the section (Fairchild, 1991).

4.2 Description

The eastern end of the GCR site around Rhuvaal Lighthouse (1 km east of the east end of the section shown in Figure 9) is in the Jura Quartzite, but the main interest lies in the folded and faulted outcrops of members 3 and 4 of the Bonahaven Dolomite Formation. The Dalradian rocks are cut by numerous NW-trending dolerite dykes of Palaeogene age, which act as convenient waymarks in the section.

Member 3 is up to 200 m thick and forms two main outcrops west of Bagh an Da Dhoruis (Figure 9). The base is seen at only one locality, immediately west of the Bolsa Fault at NR 385 780. The member consists almost entirely of fine-grained dolomitic rocks, with abundant sedimentary structures, which may be divided into three facies (Fairchild, 1980b):

(1) rocks consisting of one-centimetre-scale alternations of dolomitic metasandstone and metamudstone;

(2) cross-stratified dolomitic metasandstones (to 3 m thick) and lesser pure metadolostone interbeds; and

(3) stromatolitic beds, of which ten continuous stromatolitic units (biostromes) are recognized.

Stromatolites showing columnar and domal forms are seen at NR 410 788; outstanding exposures showing clusters of ellipsoidal and bun-shaped stromatolites of different sizes are found at NR 407 789 (Figure 10a); and a number of large bioherms, several metres across, are seen at NR 387 782 (Figure 10b), where they lie in beds folded by F1 folds with axial planes dipping eastwards.

Special features of these rocks, which give a clue as to their environment of deposition, include shrinkage cracks, stromatolite flake breccias, and quartz-calcite nodules. They are accompanied by abundant cross-lamination, ripple marks on a variety of scales (up to 0.22 m in wavelength), graded bedding, and some striking examples of load structures (Fairchild, 1991). The shrinkage cracks are filled with fine-grained dolomitic material, and are seen as pale-coloured dykelets, up to 0.5 cm wide and 3 cm (exceptionally 40 cm) long, which in cross-section are seen to descend from the bases of beds (Spencer and Spencer, 1972; Borradaile and Johnson, 1973; Fairchild, 1980b). They are commonly ptygmatically folded, and form an irregular or incomplete polygonal pattern in plan view on the bedding surface. The shrinkage cracks can be seen at NR 408 709 and are particularly well exposed at NR 390 783, where they can be examined in three dimensions on small sea stacks scoured clean by the sea.

The stromatolite flake breccias are seen at NR 387 782. They are intriguing structures, which occur as randomly arranged aggregates of broken stromatolite laminae that occupy either shallow hollows on the surface of a bed or, less likely, partially eroded and then filled, desiccation cracks. The quartz-calcite nodules are clearly seen in cross-section on wave-scoured surfaces on an old sea stack near NR 390 783 and are deformed within a near-vertical cleavage.

Member 4 is 40–62 m thick and consists of slaty metasiltstones and fine-grained metasandstones. The base is well exposed in Bagh an Da Dhoruis near NR 410 788 (Figure 9), and the member includes a 10 m-thick massive metadolostone, exposed at NR 400 784.

The Jura Quartzite forms a large outcrop at the east end of the GCR site on Rubha a'Mhail, and a transitional contact with the underlying Bonahaven Dolomite is seen in the cliffs at NR 412 787. The quartzite is repeated by folding in the middle of the section, between NR 391 781 and NR 399 783, and crops out within and west of the Bolsa Fault (Figure 9b). It is a well-bedded, white-weathering, meta-quartz-arenite with some cross-bedding.

Stromatolites were first recognized by Wilkinson (in Peach and Horne, 1930), and were figured from the Rubha a'Mhail section at Bagh an Da Dhoruis by Anderson (1951, fig. 7), followed by Spencer and Spencer (1972). The biostromes form stratiform layers 0.1–4 m thick (generally 1–2 m), which consist of laminated yellow-brown dolomite with a characteristic 'elephant-skin' texture on the weathered surface. The laminae are 0.5–2 mm thick, and consist of alternating dark (finer grained) and lighter (coarser grained) dolomitic layers whose microstructure has been studied in detail by Fairchild (1980b). They generally form regular layers and rarely develop the columnar forms seen in some stromatolites. These horizons are accompanied by bioherms consisting of families of extraordinary-looking and beautifully exposed spheroidal to ellipsoidal stromatolite bodies, which can be examined in their position of growth on the bedding planes. These bodies are from 10 cm to several metres in diameter.

The major anticlinal closure seen in the eastern outcrop of Member 3 in this section plunges southwards and is accompanied by a number of minor folds (Figure 9c). The latter are up to tens of metres in wavelength and, together with a steeply dipping slaty cleavage, are generally congruous to the major structure (Fairchild, 1977). The western limb of this fold has been affected by two major faults, which throw down to the east and cause a double repetition of members 3 and 4 (Figure 9b). The complex fault-zone of one of these dislocations, the Bolsa Fault, can be examined at NR 386 780.

Borradaile and Johnson (1973) estimated the strain that has affected Member 3, by measuring the angular relationships between the penetrative cleavage, the filled dykelets and the bedding planes in these rocks. They assumed that, regardless of their origin, the dykelets would have formed initially at right angles to the bedding surfaces, and used the present angles made with bedding and cleavage to calculate the amount of strain at 5 localities within this GCR site. The measured strains indicate that the measured stratigraphical thickness is only 50–70 % of the original thickness.

4.3 Interpretation

Minor features having a direct bearing on the environmental setting of these rocks are discussed first. The precise origin of the sediment-filled cracks in the dolomitic metasandstone–metamudstone sequence is uncertain, but they must have formed by some form of contraction in the plane of the bedding, either by subaerial desiccation, interstratal dewatering, or synaeresis (Spencer and Spencer, 1972; Borradaile and Johnson, 1973; Fairchild, 1980b). The latter origin was favoured by all of these authors, but the actual mechanism by which this process takes place is not clear, and no unambiguous natural examples of synaeresis cracks have been reported (see Tanner, 1998a for discussion). The cracks closely resemble those from the Devonian rocks of Caithness, which were interpreted as synaeresis cracks by Donovan and Foster (1972), but as desiccation cracks by Astin and Rogers (1991).

The stromatolite flake breccias are very distinctive and are derived from the local breakdown or erosion of stromatolite bodies. This process does not involve subaerial exposure of the sediment surface, and the fragments could have been swept by currents into depressions or even into synaeresis cracks at the sediment–water interface. Fairchild (1985) considered the quartz-calcite nodules to be secondary after anhydrite, despite earlier doubts (Fairchild, 1980b).

Sedimentological analysis has shown that Member 3 was deposited in a shallow-water environment (Fairchild, 1980b, 1989). The layered facies represents a broad lagoonal environment, with local emergence that was affected by infrequent storms; the sandstone facies was deposited in lower intertidal sandflats; and the stromatolitic facies was mainly subtidal, with some intertidal development. Overall, the finely crystalline carbonate rocks, ooids, and pseudomorphs after (?)anhydrite, indicate semi-arid conditions and a warm climate. The petrography and carbonate chemistry of the dolomitic rocks were described by Fairchild (1980b, 1985). The dolomites are rich in Fe and Mn, and dolomitization occurred before burial and penecontemporaneous with sedimentation. Unfortunately the stromatolites are not suitable for taxonomic study, do not yield any useful chronostratigraphical information and could have grown in either warm or cold water conditions.

Five independent lines of evidence, including wave-ripple geometries and lateral facies relationships, indicate that Member 3 was derived from a landmass to the north-west (Fairchild, 1989). Current directions from cross-strata are weakly bimodal or show no preferred direction (Fairchild, 1980b).

Member 4 is also of shallow-water origin, with the thick metadolostone having been deposited in a supratidal-flat environment (Fairchild, 1991). It is succeeded, by the tidal-shelf Jura Quartzite.

The Islay Anticline was first recognized by Bailey (1917), who considered it to be a 'secondary' structure. Later workers (Roberts, 1974; Fairchild, 1977) concluded that it is a major primary (D1) structure but it has a number of anomalous features. For example, the structure of its closure at this GCR site, where it is best exposed, is not fully understood. Over most of Islay, the anticline plunges and closes to the north, but at this GCR site the closure plunges south, suggesting that the Bonahaven Dolomite Formation has been brought back to ground level by a plunge culmination in the major structure. However, there is an area (between NR 398 787 and NR 410 788) which has an 'anomalous' cleavage orientation (Fairchild, 1977), suggesting that there may be a cleavage that pre-dates the main cleavage associated with the Islay Anticline. These structural problems clearly warrant further investigation. Another interesting structural aspect of the area is that the Bolsa Fault is inferred, from an abrupt change in thickness of Member 3 across the fault-zone, to have been active during sedimentation (Fairchild, 1980c; Anderton, 1985).

4.4 Conclusions

The Rubha a'Mhail GCR site is of international importance for the excellent state of preservation, in three dimensions, and in their position of growth, of fossil algal bodies (stromatolites). These are amongst the most primitive fossil forms to be preserved in the geological record, and pre-date the evolution of more advanced organisms, the metazoans, which used them as a food source. Stromatolites originated as a microbial slime, which coated the sea floor and, by trapping grains of sediment, enabled a variety of different forms to develop. At this locality, these range from continuous layers to a variety of intriguing spheroidal and elliptical bodies up to 3 m across. The range in morphological types, and excellent state of preservation of these stromatolites is unique in the Precambrian rocks of the British Isles, and they are of value for future study.

Sedimentary structures at this GCR site show that the stromatolites grew within a sequence of rocks that was deposited in a shallow-water, subtidal to intertidal environment. Due to the low degree of metamorphism and deformation, the mode of formation of these organisms, and their relationship to bedding and other sedimentary structures can be examined in detail. Some problematical small-scale structures found only at this site could shed more light on the environment in which the stromatolites thrived. These include possible desiccation cracks and pseudomorphs after anhydrite (calcium sulphate, normally formed by the evaporation of seawater and hence indicating a warm climate).

The dolomitic rocks described from here and the *Caol Isla* GCR site overlie the Port Askaig Tillite, and this site has provided a type section for a detailed comparison with dolostones associated with other late-Precambrian tillites, in particular those in East Greenland (Fairchild, 1989).

5 KILNAUGHTON BAY, ISLAY
(NR 346441–NR 345450)

C.A. Bendall

5.1 Introduction

The transition from the Islay Subgroup to the Easdale Subgroup is important in terms of the sedimentary evolution of the Dalradian Supergroup in the South-west Grampian Highlands. It marks the change from shallow-water marine sands to deeper water muds and gravity-flow deposits. An almost complete succession through this transition is exposed on the south-west side of Kilnaughton Bay near Port Ellen in south Islay (Figure 11). Approximately 550 m of the succession is exposed along the foreshore and in the low cliffs 20–50 m inland. The succession here comprises the Jura Quartzite Formation (Islay Subgroup) and the overlying Scarba Conglomerate Formation (Easdale Subgroup). The latter formation includes the Jura Slate Member at the base and the upper part is referred to here as the Pebble Beds for ease of description. These correlate well with the succession found on Jura (see the *Lussa Bay* and *Kinuachdrachd* GCR site reports). The Pebble Beds are of particular interest here. The beds are generally about a metre thick and consist of rounded pebbles of quartzite between 1 and 2 cm in size. These beds have a well-developed pressure-solution cleavage and the pebbles, although rounded, are distinctively either flattened or ellipsoidal and therefore are potentially good strain indicators. Hence they would enable quantification of the strain associated with the Islay Anticline.

Some white bladed porphyroblasts of highly altered kyanite occur in white-mica-rich rocks belonging to the Jura Quartzite Formation (Figure 13). Much of the original kyanite has been replaced by fine-grained pyrophyllite and kaolinite (Burgess *et al.*, 1981). The rocks at this locality, which also include chloritoid-bearing assemblages, have undergone greenschist-facies metamorphism and lie within the biotite zone. In the Dalradian it is most unusual to find kyanite in rocks of biotite grade, as kyanite is usually associated with much higher grade (amphibolite-facies) rocks, according to the ideal Barrovian mineral-zone sequence.

5.2 Description

Some 300 m thickness of the Jura Quartzite Formation is exposed along the foreshore (Figure 11). At its maximum thickness on Jura, the quartzite is of the order of 5000 m thick, whereas on Islay the thickness varies from *c.* 3000 m in the north to 1000 m around Kilnaughton Bay (Anderton, 1985). At Kilnaughton Bay the rocks are predominantly coarse-grained metasandstones, with scattered pebbles ranging up to about 5 mm in size. The thickness of the metasandstone beds ranges from a few centimetres to massive beds some 2.5 m thick. Thin partings of metamudstone are common and there are interbedded metasiltstone–metamudstone units several metres thick. Beds of fine- to medium-grained metasandstone are also quite common. Cross-bedding is ubiquitous throughout the succession and is generally planar. The rocks do not appear to be well sorted and thin-section analysis reveals a bimodal grain-size distribution with the coarser grains supported in a matrix of finer sand grade. Most grains appear to be subangular to subrounded, although the grain shape may have been modified by quartz overgrowth. Although white feldspar can be found, the sandstones are not generally feldspathic.

Conformably overlying this formation are approximately 60 m of the Jura Slate Member, which is not fully exposed on the foreshore but can be seen in a disused quarry just inland (NR 3470 4435). These are fine-grained rocks with a prominent slaty cleavage. Bedding is defined by thin partings of coarser material, and shows that these rocks are folded by minor folds with wavelengths generally less than 1 m.

Conformable above this are the Pebble Beds. This unit consists of a series of pebbly beds that occur within a succession of finer metasandstones and metamudstones whose top is not exposed (see Figure 12). Individual pebbly beds are usually no more than about a metre thick and fine upwards into metasandstone units; they have sharp erosional bases. The pebbles are of rounded quartzite and range from 1–5 cm in size. The pebbly beds are generally matrix supported, with the matrix being of coarse sand grade. Up to 13 pebbly beds occur between the top of the Jura Slate Member and the lighthouse (NR 3479 4440–NR 3495 4464). The top of the Scarba Conglomerate Formation is not exposed but it grades up into the pelitic Port Ellen Phyllite Formation.

These rocks lie on the south-eastern limb of the Islay Anticline (Figures 1 and 3) (Bailey, 1917). The quartzites have an anastamosing spaced cleavage defined by cleavage domains of white micas, which appears to be a primary cleavage as no earlier fabric can be seen in the quartz microlithons. The vergence of cleavage on bedding is to the north-west, which is consistent with the cleavage having formed at the same time as the Islay Anticline. The Islay Anticline is believed to have formed during the first phase (D1) of Dalradian regional deformation (Roberts and Treagus, 1977c). The cleavage in the Jura Slate is a primary slaty cleavage. At least one crenulation cleavage is also found in the slaty rocks. It dips between 25 and 50° to the south and gives a sense of vergence (on bedding and the primary cleavage) to the south-east. This cleavage, in places, consists of very closely spaced (less than 0.5 mm) planar micaceous surfaces and looks superficially like a slaty cleavage.

There is also a spaced cleavage in the pebbly beds that appears to be primary, and contemporaneous with the formation of the Islay Anticline. The pebbles are generally elliptical with aspect ratios (long axis: short axis) of between 1.5:1 and 3:1, and appear to show a consistent alignment, clearly demonstrating that the rocks have been strained.

At the top of the Jura Quartzite Formation there is a fine-grained quartzite that contains planar cleavage planes. These cleavage planes are formed by thin partings of white-mica-rich rock, and hence these rocks are likely to be aluminium rich. Lying on the cleavage planes are white bladed grains up to about 1 cm long

(Figure 13). These blades have been interpreted as porphyroblasts of kyanite that have subsequently been retrogressed to a mixture of kaolinite and, more rarely, pyrophyllite (Burgess *et al.*, 1981). The blades lie within the cleavage plane but are randomly orientated within that plane.

Other rocks cropping out on the site reveal little about the grade of metamorphism. However, elsewhere in south-east Islay, intrusions of mafic meta-igneous rocks indicate that the grade of metamorphism reached greenschist facies, and pelitic rock assemblages usually contain biotite as the highest grade index mineral. The rocks therefore lie within the Barrovian biotite zone and the presence of kyanite is anomalous.

5.3 Interpretation

The rocks at this site, together with the GCR sites on Jura, preserve an important episode in Dalradian sedimentation; namely the change from the shallow-marine sandstones of the Jura Quartzite Formation, to the deeper water slump deposits of the Scarba Conglomerate Formation. According to Anderton (1979) this represents a change from a stable tectonic environment to an unstable environment, with rapid subsidence of a basin taking place along syndepositional faults.

At this GCR site the cross-bedded metasandstones, along with the interbedded metasandstones and metamudstones, are typical of shallow tidal-shelf deposits (Anderton, 1976). The Jura Slate Member was originally laid down as mud with thin sand beds, indicating a rapid change in depositional environment to deeper water conditions. The pebbly beds are slump deposits or debris-flow deposits, which were laid down on a deep-water marine slope in a similar fashion to those described from the Scarba Conglomerate on Jura (e.g. Anderton, 1979). This apparent rapid change in depositional environment indicates tectonic instability and rapid subsidence along basin-bounding faults.

The main phase of deformation in the eastern part of Islay was the first, D1 and this resulted in the formation of the Islay Anticline (Roberts and Treagus, 1977c). The predominant cleavage in the Dalradian rocks is associated with this phase, while later stages of deformation have been responsible for the development of crenulation cleavages and minor folding. There are no major fold structures associated with these later events, and it is likely that the bulk of the strain that the rocks have experienced occurred during the formation of the Islay Anticline. Pebble beds are useful strain indicators; in this case the pebbles have been flattened rather than stretched, with X:Z ratios (length:height) varying between about 1.5:1 to 3:1. It is possible to discern a stretching direction in these rocks, which appears to plunge approximately east at *c*. 20°. However, more detailed studies are necessary to quantify the strain.

Establishing the temperatures and pressures of metamorphism using geothermometers and geobarometers based on mineral compositions is not straightforward in greenschist-facies rocks, as the rocks do not always attain thermodynamic equilibrium between the constituent mineral phases. Hence it is important to consider other lines of evidence.

Kyanite is very rarely found in low-grade Dalradian rocks, as it can only form in highly aluminous pelitic rocks at this grade. The majority of Dalradian pelites are relatively aluminium poor and are correspondingly richer in iron and magnesium; hence the consistency of the Barrovian Zones across the central Grampian Highlands. This GCR site has the only reported occurrence of kyanite in the greenschist-facies rocks of the Dalradian of the South-west Grampian Highlands. Using the occurrence of kyanite, and its growth at the expense of pyrophyllite, Skelton *et al.* (1995) have proposed that the peak metamorphic temperature for this area of Islay was in excess of 430 °C. Indeed, this is one of the critical localities for establishing the grade of metamorphism in the South-west Grampian Highlands.

5.4 Conclusions

The Dalradian of the South-west Grampian Highlands has undergone a long convoluted history in terms of sedimentation, deformation, and metamorphism, and the Kilnaughton Bay GCR site provides information on all three of these aspects. The metasedimentary rocks here and in the *Lussa Bay* and *Kinuachdrachd* GCR sites record an episode of rapid sea-level change, which was probably caused by movements along major basin-bounding faults. All three sites lie on the south-east limb of the Islay Anticline but the rocks at Kilnaughton Bay have undergone greater deformation, which can be quantified by measurements of pebbles within the Scarba Conglomerate Formation.

An unusual occurrence of kyanite within the Jura Quartzite indicates that these rocks were heated up to over 430°C during the metamorphism that accompanied the deformation. Kyanite is normally found in medium- to high-pressure, upper amphibolite-facies assemblages its occurrence here in rocks of lower metamorphic grade is thought to be due to an unusually high aluminium content in the sediments that the rocks were derived from. This might be the only known example of kyanite-bearing low-grade metamorphic rocks in Britain.

6 LUSSA BAY, JURA (NR 637 865–NR 648 870)

C.A. Bendall

6.1 Introduction

Much of the island of Jura consists of rugged hills, which are composed almost entirely of monotonous Jura Quartzite, but along the south-east coast there are excellent exposures of spectacular rocks that reflect the change in the depositional environment from the shallow-water Jura Quartzite Formation to the deeper water Scarba Conglomerate Formation. The transition between these formations is well exposed at Lussa Bay, which is located about half way along the south-east coast of the island. Sedimentary structures are particularly well preserved in the coarser-grained metasedimentary rocks of Jura, and this is superbly demonstrated around Lussa Bay.

The Dalradian rocks of Jura were first described by Peach *et al*. (1911) and later by Allison (1933). More recent work includes that of Anderton (1976, 1977, 1979, 1980), which is mainly concerned with the sedimentology of the Islay and Easdale subgroups of the Argyll Group. A revised edition of the BGS 1:50 000 Sheet 28W (South Jura) was published in 1996.

6.2 Description

The coastal section at Lussa Bay is described below from west to east (Figure 14).

Cross-bedding may be observed in the metasandstones of the Jura Quartzite Formation (e.g. at NR 6383 8662), where the overall bedding dips moderately steeply to the south-east. The Jura Quartzite is overlain conformably by a thin unit of slaty metamudstone with subordinate metasandstones that almost certainly correlates with the Jura Slate Member that forms the base of the Scarba Conglomerate Formation elsewhere on Jura. This slaty unit is around 20 metres thick and is overlain conformably by fine-grained, grey metasandstone. Beds in this metasandstone unit are around half a metre thick and they exhibit small-scale cross-bedding, load structures and abundant graded bedding (Allison, 1933).

At least one conglomeratic bed occurs in this succession. This consists of a pebbly bed with subangular quartzite clasts up to 1.5 cm across. It varies in thickness, with a maximum of about 1 m.

The succession of metasandstones and rare metaconglomerates is approximately 150 m thick and is overlain by another metamudstone unit. This metamudstone crops out along both the north-west and south-east shores of Lussa Bay itself (Figure 14), and erosion of this unit is probably responsible for the development of the bay. On both shores the metamudstone has a well-developed slaty cleavage. Along the south-east shore there is an abrupt facies change from the metamudstone to a superb section of metaconglomerates. Approximately 200 m of this succession are exposed along the coastline from Lussa Bay around Lussa Point and then north-east along the coast. The massive beds vary from a few tens of centimetres to a metre or more in thickness. Most fine upwards from coarse pebbly bases (clast sizes up to 10 cm and generally matrix-supported) to coarse metasandstone. Individual beds have sharp bases, and erosional features such as rip-up clasts of mudstone and sandstone are quite common (Figure 15). The phyllitic mudstone rip-up clasts are irregularly shaped lenses varying in size from a few centimetres to a few tens of centimetres. They are generally elongate and are aligned approximately parallel to bedding. Sandstone clasts also form lenses but generally tend to be flatter and more elongate. They vary from a few tens of centimetres to around 1 m in length, and are also aligned approximately parallel to bedding. There are rare beds of fine-grained material (metamudstone and metasiltsone) interbedded with the metaconglomerates. Mass-flow deposits of incompletely mixed mud, sand, and gravel with large partially disintegrated boulders of sand and mudrock also occur (Anderton, 1977). Towards the top of the succession the beds take on a more-recognizable turbiditic nature; they are coarse grained but the grading is more pronounced.

Structurally this site lies on the south-east limb of the Islay Anticline (Bailey, 1917; Roberts and Treagus, 1977c). Bedding strikes approximately north-east and dips between 35 and 50° to the south-east. The slaty cleavage has approximately the same strike and dip direction but is steeper, giving a sense of vergence towards the Islay Anticline to the north-west. Tectonic structures appear to be restricted to the finer grained lithologies, and are expressed as minor folds and a slaty cleavage. The coarser grained lithologies are only weakly deformed and show little evidence of tectonic strain. The majority of the clasts in the metaconglomerate appear to be undeformed. Hence, because of the low strain in the coarse-grained rocks, they retain their original sedimentary characteristics.

The rocks here have been subjected to greenschist-facies metamorphism although, apart from the slaty cleavage in the finer grained horizons, there is little direct evidence of metamorphism. The deformation and the metamorphism occurred during the Grampian Event.

6.3 Interpretation

The transition from the Islay Subgroup into the Easdale Subgroup at Lussa Bay and elsewhere on Islay and Jura (see the *Kilnaughton Bay* and *Kinuachdrachd* GCR site reports) demonstrates a distinct change in sedimentary environment from shallow-marine shelf to a deeper marine slope. This is clearly shown by the metasedimentary rocks that crop out at Lussa Bay. The metasandstones of the Jura Quartzite were interpreted by Anderton (1976) as shallow-marine tidal deposits, as is indicated by sedimentary structures such as cross-bedding. The metamudstones indicate basin deepening, and the metaconglomerates were interpreted by Anderton (1979) as marine-slope slump deposits. These are deposits that formed when clastic material building up on the upper parts of a marine slope became unstable and started to flow down slope. This process tends to disrupt the material, and results in the deposition of coarse-grained, poorly sorted massive beds. The slumping commonly ceases before the material can mix with water and develop into turbidity flows. However, some mixing probably took place and this resulted in the observed grading. Towards the top of the succession, where the grading is better developed, it is likely that this water-sediment mixing proceeded further, producing the coarse-grained turbidites. Most of the fine-grained material would have been winnowed out and removed as suspended load, which was then deposited farther out into the basin.

The rapid deepening event, from the shallow-water Jura Quartzite to the deeper water Scarba Conglomerate, indicates tectonic instability and is good evidence for fault-controlled rifting, which probably had a strong control on sedimentation during the deposition of much of the Easdale, Crinan and Tayvallich subgroups of the Argyll Group.

6.4 Conclusions

Along with exposures at other GCR sites along strike at *Kilnaughton Bay* on Islay and *Kinuachdrachd* on Jura, the Lussa Bay GCR site provides vital clues for tracing the evolution of the Dalradian basin in early Argyll Group time. This GCR site exposes in particular an almost complete representative section through the Scarba Conglomerate Formation, which occurs here in a region of relatively low tectonic strain and hence has spectacular exposures of some of the best-preserved sedimentary features seen in Dalradian metaconglomerates. On the islands of Scarba and Jura, these rocks are particularly coarse grained and formed by material 'slumping' down a deep marine slope. Such was the energy of this slumping that material was ripped up from the sea floor and incorporated into the slump deposit as large 'rip up clasts'.

7 KINUACHDRACHD, JURA (NR 694 953–NR 708 974, NR 705 985–NM 700 012)

C.A. Bendall

7.1 Introduction

The Kinuachdrachd GCR site occupies a coastal strip in the remote north-east of the Island of Jura (Figure 16). The strata at this site are from the same stratigraphical interval as those described at the *Kilnaughton Bay* GCR site on Islay and the *Lussa Bay* GCR site on Jura. To the west of the site is the Jura Quartzite, which forms the spine of the island, but along the eastern coast are rocks of the overlying Scarba Conglomerate Formation. The rocks of Jura have been described by Peach *et al.* (1909, 1911) and more recently by Anderton (1976, 1977, 1979, and 1980). Anderton interpreted the succession as representing a change from shallow-water shelf sandstones (Jura Quartzite) to deeper water muds, slump deposits and turbidites (Jura Slate and Scarba Conglomerate). Exposed intermittently inland, and unique in the Scottish Dalradian, is a possible fossil slump scar (a result of erosion caused by material slumping down a marine slope) that forms the boundary between the Jura Quartzite and the Scarba Conglomerate (Anderton 1977, 1979).

Also cropping out at this site are dykes of metamafic rock. Whereas mafic sills are common throughout the Dalradian of the South-west Grampian Highlands, recognizable dykes are relatively rare.

7.2 Description

The Jura Quartzite Formation, which crops out inland from this coastal GCR site, has been described in detail by Anderton (1976).

Sedimentary structures, such as cross-bedding, scours, possible synaeresis cracks, and sandstone dykes, are well preserved. At this north-eastern end of Jura, unlike at Lussa Bay or at Kilnaughton Bay on Islay, the Jura Slate Member is absent, and the Jura Quartzite is overlain directly by the conglomeratic facies of the Scarba Conglomerate Formation. The nature of the Scarba Conglomerate here was described by Anderton (1977). South of Barnhill (NR 7050 9705), the lowest part of the Scarba Conglomerate consists of pebbly beds, which pass upwards into fining-up sequences (metasandstone–metamudstone). These then pass upwards into a black metamudstone with a well-developed slaty cleavage, which is probably equivalent to the Easdale Slate Formation elsewhere in the South-west Grampian Highlands. Evidence of slumping may be found in the lower part of the Scarba Conglomerate Formation at (NR 702 966) where the succession is a chaotic mass of boulders, with slump folds and mass flows (Anderton, 1977).

North of Barnhill, the boundary between the Jura Quartzite and the Scarba Conglomerate has been interpreted by Anderton (1977, 1979) as a possible fossilized slump scar. This slump scar truncates both the Jura Quartzite and the lowermost Scarba Conglomerate (Figure 16). The debris flows found above the slump scar range from 1 m to 15 m in thickness and contain intraformational boulders up to 6 m in size. The matrix is a poorly sorted mixture of sand and mud. Soft-sediment deformation structures are common as are other sedimentary structures such as sole marks, rip-up clasts and small channel deposits, all indicative of high-energy dynamic sedimentary environments.

Structurally this site lies on the south-east limb of the Islay Anticline (Bailey, 1917; Roberts and Treagus, 1977c). Sedimentary structures tend to dominate over tectonic structures, the most obvious tectonic structures being the slaty cleavage found in the finer-grained lithologies. A spaced cleavage developed in the metasandstones shows marked cleavage refraction across beds that preserve compositional grading (Figure 17). The tectonic strain here is low, hence the retention of some rather subtle sedimentary structures.

Also exposed here are dykes of metamafic rock. These dykes are the predominant type of meta-igneous intrusion in north-east Jura, unlike in much of the younger Dalradian succession in the South-west Grampian Highlands where sills are ubiquitous. In northern Jura the dykes have been examined in detail by Graham and Borradaile (1984). They described the dykes as having a typical greenschist-facies assemblage of albite, epidote, actinolite and chlorite. Thinner dykes tend to be schistose, but thicker ones retain a relict ophitic texture in their centres. The dykes have a less-evolved chemical composition than the sills and metavolcanic rocks of the South-west Grampian Highlands, and Graham and Borradaile (1984) concluded that the dykes are likely to have been feeders to the more-evolved rocks. These authors also estimated that the pre-tectonic orientation of the dykes was north-west, and that they were intruded perpendicular to bedding.

7.3 Interpretation

The transition from the Islay Subgroup into the Easdale Subgroup on Jura demonstrates a distinct change in sedimentary environment from shallow-marine shelf to a deeper marine slope. This is clearly shown by the metasedimentary rocks that crop out at Kinuachdrachd. The rocks described above are probably contemporaneous with those described at the *Lussa Bay* and *Kilnaughton Bay* GCR sites and therefore demonstrate that there are lateral facies changes along strike. All of these three GCR sites provide evidence for rapid deepening of the basin from a shallow-marine tidal environment, where sedimentation was in approximate equilibrium with subsidence, to a deep-water marine slope (Anderton, 1977, 1979). Therefore, fault-controlled rifting probably had strong control on sedimentation during the deposition of much of the Easdale, Crinan and Tayvallich subgroups of the Argyll Group.

This rifting may have resulted in partial melting of mantle rocks, giving rise to the ubiquitous basic igneous intrusive and extrusive rocks evident in the Dalradian rocks of the South-west Grampian Highlands. For this igneous activity to have occurred, the extension of the Dalradian basin must have been in the order of a factor of 2; that is the basin was twice as wide as it was before rifting commenced (e.g. McKenzie and Bickle, 1988). The meta-igneous dykes on Jura probably represent the conduits through which the magma travelled upwards to higher crustal levels. From the pre-tectonic trend of these dykes (north-west), Graham and Borradaile (1984) proposed that the extension direction of the Dalradian basin was north-east–south-west at the time of intrusion.

7.4 Conclusions

Like the GCR sites at *Kilnaughton Bay* on Islay and *Lussa Bay* in central Jura, strata at the Kinuachdrachd GCR site in the north-east of Jura demonstrate the abrupt change in sedimentary depositional environment from shallow-marine shelf to deep-marine slope on the Laurentian margin in early Argyll Group time. Here, a putative fossil slump scar, which is an erosional feature formed by rapid erosion of sea-floor sediments by material slumping down a marine slope, forms the boundary between the Jura Quartzite and the Scarba Conglomerate. Evidence of sediment sliding down the marine slope has been preserved in the form of spectacular slump beds, which contain boulders up to 6 m in size. Other dramatic evidence of such high-energy sedimentation is provided by scours, and by material that has been ripped up from the sea floor and incorporated into the slump deposits.

In addition, this GCR site includes metamorphosed basaltic dykes, which were probably emplaced as a result of stretching of the crust and the upper mantle. They are thought to have been feeders to the sills that are ubiquitous in upper Argyll Group rocks of the South-west Grampian Highlands (e.g. at the *Ardbeg* and *Ardilistry Bay* GCR sites), and in the overlying Tayvallich Volcanic Formation (see the *West Tayvallich Peninsula* GCR site). The orientation of the dykes gives an indication of the direction in which the stretching took place (north-east–south-west) and suggests that by late Argyll Group time the Dalradian crust had stretched by a factor of two.

8 SURNAIG FARM, ISLAY (NR 396 451–NR 403 453)

C.A. Bendall

8.1 Introduction

Much of the detailed sedimentological history of the Dalradian Supergroup has been deciphered from rocks in the South-west Grampian Highlands (e.g. Anderton, 1985). This is because the tectonic strain and metamorphic grade are relatively low, and hence the original sedimentary structures are preserved. This is superbly illustrated near Surnaig Farm, to the south-east of Lagavulin Bay on the south-east coast of Islay (Figure 18), where spectacular sandstone dykes are exposed on the rocky foreshore. The dykes occur in rocks that are assigned to the Laphroaig Quartzite Formation (Easdale Subgroup), which at this locality is at least 260 m thick. Its boundary with the underlying Port Ellen Phyllite Formation is gradational, representing a change from a succession dominated by metamudstones to one dominated by metasandstones. Poor exposure makes the positioning of this boundary somewhat arbitrary. Elsewhere on Islay, the Laphroaig Quartzite is overlain by the conglomeratic basal member of the Ardmore Formation (Crinan Subgroup).

Other rocks that crop out at this locality include sills of metamafic rock. The basal contact of one of these sills is exposed at the west end of Lagavulin Bay (NR 4025 4536). Here the country rocks are contact metamorphosed (Wilkinson, 1907) but have been little affected by the subsequent regional metamorphism associated with the Grampian Event. There is also a good exposure of a dyke of metamafic rock on the foreshore at NR 3927 4523.

The Laphroaig Quartzite Formation was first described by Wilkinson (1907). However, the sequence he proposed was upside-down as was later demonstrated by Bailey (1917) and Allison (1933), using sedimentary way-up indicators. The sandstone dykes were first described by Borradaile (1974) who used the angular relationships between the dykes, the cleavage and the bedding to estimate the amount of strain associated with the formation of the Islay Anticline.

8.2 Description

Sandstone dykes are not uncommon in Dalradian metasedimentary rocks (e.g. Smith and Rast, 1958) and have been described from several localities on Islay (Borradaile and Johnson, 1973; Borradaile, 1974). Most are small, being only a few centimetres or so wide and a few tens of centimetres long. However, much larger sedimentary dykes occur within the Laphroaig Quartzite Formation along the south-east coast of Islay. The best exposed and most impressive of these occur at this GCR site in a rocky bay 400 m west-south-west of Lagavulin Bay (Figure 18). Here, the largest sedimentary dyke is 0.5 m wide and penetrates 16 m beneath the source bed (outcrop 3 of Borradaile, 1974).

The dykes occur in the middle of the formation and are intruded into beds of metamudstone, which are 2–3 m thick (Figure 19). These metamudstone beds are interbedded with metasandstone beds, which vary in thickness from 1 m to a few centimetres and form the source rocks for the sedimentary dykes. However, it is not always clear which metasandstone bodies represent true bedding and which are cross-cutting sedimentary dykes. Some of the metasandstones are original orthoquartzites, whilst others are calcareous. There are also rare metalimestones, but none are more than 2–3 cm thick. This part of the succession is *c.* 30 m thick. Above this, metamudstone beds are much thinner (generally less than 10 cm thick), and the succession is dominated by massive metasandstone beds, which vary between 0.5 and 2 m in thickness. The strike of bedding here is *c.* 280° and the dip is about 30° to the south.

Upwards of thirty sedimentary dykes may be observed here, the majority of which are only a few centimetres thick and 1–5 m long. All lie at an acute angle to the bedding and are both folded and planar. The planar dykes make angles with bedding of around 20° and the long limbs of the folded dykes make higher angles, around 44°, with the bedding (Borradaile, 1974). The largest dyke (mentioned above) is spectacularly folded (Figure 19). The folds are close to tight and the cleavage in the host rock metamudstone is axial planar to them. Some of the smaller dykes also show a similar style of folding. There is one clearly exposed example of two planar dykes cross-cutting each other and other examples of dykes forming offshoots from other dykes. All the examples of sedimentary dykes described above occur in a relatively small exposure at NR 3978 4523.

Locally the sills of metamafic rock, which dip at 20 to 30° to the east-south-east, dominate the landscape as they form prominent ridges. One forms the headland on the western side of Lagavulin Bay. This sill is *c.* 15–20 m thick and retains a relict ophitic igneous texture. Also preserved at the base of the sill, at NR 4020 4535, are metasedimentary rocks that have been subjected to contact metamorphism and, because of this, have been little affected by the later regional metamorphism. Whereas sills are common, dykes of metamafic rock are rare. There is an unequivocal example of a highly schistose dyke on the foreshore 50 m to the east of the sedimentary dyke locality. It is intruded into rocks that are predominantly quartzitic metasandstones, is 2 m wide, vertical and trends north–south, clearly cross-cutting the metasedimentary rocks.

The rocks here were deformed and metamorphosed up to the greenschist facies during the Grampian Event and the metamudstones have been recrystallized into phyllites. The dominant cleavage is an S1 penetrative cleavage, and it is this cleavage that is axial planar to the folds of the sedimentary dyke described above. The cleavage observed in the meta-igneous dyke is also S1.

8.3 Interpretation

Borradaile (1974) interpreted the metasedimentary dykes as neptunian, that is the infilling with sand of fractures in already consolidated sediment. He used the angular relationships between bedding, cleavage and the dykes to estimate the amount of strain that these rocks were subjected to during the D1 phase of deformation that produced the major Islay Anticline (Roberts and Treagus, 1977c). He concluded that there was 70% shortening normal to the slaty cleavage and extensions of 63 % and 109 % within the plane of the cleavage in the phyllitic rocks. More recently, many sedimentary dykes elsewhere have been interpreted as due to the forceful injection of sand from an unconsolidated source bed into adjacent consolidated beds (Collinson, 1994); and, furthermore, the formation of large sedimentary dykes due to passive infilling of cracks requires the presence nearby of an unconformity or at least the formation of an erosion surface in cohesive sediments. Hence it may be that none of the dykes described here is neptunian in origin.

Neptunian dykes indicate a break in sedimentation and dessication of surface sediments. However, if the dykes resulted from forceful injection, then they might have formed in buried sediments in which liquefied sand was injected into a cohesive host, in this case clay-rich sediment. This process usually requires overpressured pore fluid, which commonly arises from rapid burial of the host sediments, with the formation of sand-filled dykes possibly being triggered by earthquakes (Collinson, 1994).

Dykes of metamafic rock up to 30 m wide have been described from Jura (Graham and Borradaile, 1984) but they are rare on Islay and on the mainland, where sills predominate. Graham and Borradaile made the significant point that on Jura the host rocks are stratigraphically older than those on Islay and the mainland. This suggests that the igneous ‘plumbing system’ here may have followed the model of Francis (1982), where the level of intrusion of sills is constrained by the lithostatic pressure in the country rock and the hydrostatic pressure in the feeder dyke. Intrusion of sills will only occur where the hydrostatic pressure of the magma in the feeder dyke is greater than the lithostatic pressure of the country rocks; the lithostatic pressure directly relates to depth of burial. At the time of intrusion of the sills and dykes, the stratigraphically older rocks on Jura will have been at a greater depth than the Port Ellen Phyllite and Laphroaig Quartzite formations on Islay and, critically, too deep for the intrusion of sills. It is probable that the dyke described above was a feeder dyke for the nearby or higher sills.

The igneous dykes are important indicators of the extensional stress regime associated with the Dalradian sedimentary basin. The orientation of this dyke is similar to the majority found on Jura and indicates an extension direction approximately east–west.

8.4 Conclusions

Although sedimentary dykes are not uncommon in the Scottish Dalradian, none of the other reported examples are as spectacular as those found at the Surnaig Farm GCR site. In fact these are some of the best examples of sedimentary dykes in Britain and are certainly the best found in deformed rocks. They are most likely to have resulted from interstratal dewatering, as has been proposed here for sandstone dykes at the *Caol Isla* GCR site, but some of the diagnostic features have been obscured or destroyed at Surnaig Farm by subsequent deformation.

The shoreline here also reveals several other intriguing aspects of Dalradian geology, including a fine example of a sill of metamafic rock and, rare for Islay, an unequivocal example of a metamafic-rock dyke. The GCR site, therefore, provides evocative snapshots of the evolution of the Argyll Group, from the sedimentation and igneous activity associated with its early depositional history, to the deformation and metamorphism of these rocks in the subsequent mountain building episode now referred to as the Grampian Event.

9 ARDBEG, ISLAY (NR 413 459–NR 422 464)

C.A. Bendall

9.1 Introduction

The rocks on the foreshore near the Ardbeg Distillery on the south-east coast of Islay (Figure 20) include a tightly folded and metamorphosed doleritic sill, first described by Wilkinson (1907). Towards the top of this sill, there are lenses containing the mineral stilpnomelane. This rather unusual mineral (a sheet silicate) is found scattered sporadically through low-grade metamorphic rocks in the British Isles, but it is comparatively rare. It is unusual to find it in such high concentrations and as coarsely grained as it is at this locality.

The sill is one of a suite of pre-tectonic basic intrusions that are ubiquitous throughout the Dalradian of the South-west Grampian Highlands. However, this sheet has clearly been folded which is rarely seen on Islay, although folded sills are commonly observed on the mainland, for example at Tayvallich (Wilson and Leake, 1972) and at the Point of Knap (Roberts, 1969). The mineral paragenesis of the sill gives an indication of the grade of regional metamorphism that the rocks have experienced.

The host rocks are metasandstones, metasiltstones and metamudstones belonging to the Port Ellen Phyllite and Laphroaig Quartzite formations of the Easdale Subgroup, and are at approximately the same stratigraphical level as the rocks at the *Surnaig Farm* and *Ardilistry Bay* GCR sites. These rocks demonstrate a variety of sedimentary features, but are also quite important in unravelling the geological history of the area, as they preserve evidence, in the form of tectonic cleavages, for at least three deformational events. Hence at this locality the growth of the stilpnomelane may be considered in both a structural and metamorphic context.

9.2 Description

The metasedimentary rocks at this GCR site comprise the upper part of the Port Ellen Phyllite Formation and the lower part of the Laphroaig Quartzite Formation. North of the site, the Port Ellen Phyllite consists mostly of metamudstone but towards the top of the formation (within the GCR site), metasandstone beds become more prevalent. The boundary with the overlying Laphroaig Quartzite is gradational, passing up into interbedded metasandstones and metamudstones with rare metacarbonate rocks. The metasandstone beds are dominant and vary in thickness between *c.* 0.5 and 2 m. A wide range of sedimentary structures may be observed in this formation, such as cross-bedding, dewatering structures and scours, and sandstone dykes may be seen cross-cutting the bedding in the metamudstones (Borradaile, 1974).

Subsequent basic magmatism resulted in the intrusion of a series of doleritic sills. The sills are conspicuous in this part of the island, as the intervening metasedimentary rocks have been preferentially eroded leaving prominent ridges of metadolerite. It is highly likely that they are genetically and spatially related to the Tayvallich lavas found on the mainland, which have been dated at *c.* 600 Ma using U-Pb dating techniques on zircons (Halliday *et al.*, 1989; Dempster *et al.*, 2002).

The major structure in the Dalradian of Islay is the upward- and north-west-facing Islay Anticline that formed during the first phase of deformation of the Grampian Event (Bailey, 1917; Roberts and Treagus, 1977c). This GCR site lies on the south-east limb of the anticline, so the beds generally have moderate (40–60°) dips and young to the south-east. The syncline–anticline fold pair that folds the stilpnomelane-bearing metadolerite sill is parasitic to the major Islay Anticline (as indicated by their north-west sense of vergence). Associated with this folding is a penetrative cleavage, which is best developed in the finer grained rocks such as those found in the Port Ellen Phyllite Formation, where it is continuous and slaty in some beds. This cleavage dips steeply to the south-east and is axial planar to minor F1 folds (*e.g.* at NR 4170 4619).

At least two later stages of deformation can be recognized on the foreshore beneath the distillery; these take the form of crenulation cleavages and some minor open folding. One of the crenulation cleavages dips steeply (*c.* 80°) to the north and in places is the dominant fabric in the rock. The other crenulation cleavage is only developed sporadically, and dips at a shallow angle to the east. It is not clear which of these later cleavages pre-dates the other, and there is no record of any major folds on Islay associated with either cleavage.

Stilpnomelane is found in irregular lenses towards the top of the 70 m-thick folded metadolerite sill that crops out on the foreshore just to the west of the distillery at NR 4185 4625 (Figure 20). It is a bronze-coloured mineral with a metallic lustre and forms radiating clusters, with individual grains up to 1 mm in length. In thin section it resembles biotite but has a more reddish brown colour and lacks the perfect mica cleavage (Figure 21). The colour indicates that it is probably ferri-stilpnomelane. The metadolerite host rock has a relict ophitic texture that is obvious in hand specimen but less well defined in thin section. The stilpnomelane-bearing lenses also contain actinolite, epidote, albite, quartz, chlorite, calcite (rare) and leucoxene. The actinolite is distinctly green and pleochroic; microprobe analysis shows it to be iron-rich (Bendall, 1995) and recalculation of microprobe data, based on the procedure outlined in Droop (1987), implies a high ferric iron component. There does not appear to be a tectonic fabric in the rock and the stilpnomelane clearly cross-cuts all the other mineral phases; it is randomly orientated, commonly forming radiating clusters (Figure 21).

9.3 Interpretation

Stilpnomelanes have the general formula:
$(K,Na,Ca)_{0.6}(Mg,Fe^{2+},Fe^{3+})_6Si_8Al(O,OH)_{27}.2–4H_2O$ (Deer *et al.*, 1992). They tend to be iron-rich but the composition can vary between the ferric end-member ferri-stilpnomelane and the ferrous end-member, ferro-stilpnomelane. Consequently stilpnomelanes are most likely to occur in iron-rich rocks, such as metamorphosed ironstones and iron-rich meta-igneous rocks, but they are generally restricted to lower- to middle-greenschist-facies metamorphic rocks. At Ardbeg, the ferri-stilpnomelane is associated with actinolite that has high ferrous and ferric iron concentrations with respect to its Mg concentrations, supporting the association of stilpnomelane with Fe-rich rocks.

Metamorphic mineral assemblages in the finer grained metasedimentary rocks at this GCR site are indicative of the biotite zone, and metadolerite assemblages are typical of greenschist-facies metamorphism. The peak of metamorphism here was probably associated with the D1 phase of deformation that was responsible for the development of the Islay Anticline (Skelton *et al.*, 1995). The stilpnomelane appears to have grown later than the other minerals that occur with it. However, it does not appear to be retrogressive and therefore probably formed around the peak of metamorphism, which was somewhere around 470 °C, according to Skelton *et al.* (1995). The pressure estimates of 10 kbar assumed in that study were all derived from sources that utilise phengite equilibria (Powell and Evans, 1983). The authors conceded that they are rather on the high side and expressed reservations as to the reliability of such geothermometers. Pressures of around 5 kbar, which imply burial depths of between 15 and 20 km, are more typical of greenschist-facies metamorphism.

9.4 Conclusions

The Ardbeg GCR site is notable and of some international importance for the occurrence of the metamorphic mineral stilpnomelane within a metadolerite sill. Although stilpnomelane occurs sporadically elsewhere in the Scottish Dalradian, here it is relatively abundant and the fresh crystals are up to 1 mm in size, which is quite large for stilpnomelane. This poorly understood mineral is preserved here in a host rock that has not been significantly retrogressed. Its growth is reasonably well constrained with respect to the regional deformation and metamorphism, and the overall mineral assemblage can be used to quantify the temperature and pressure of metamorphism under which this particular stilpnomelane formed. An important constraint on the formation of stilpnomelane is the iron-rich chemical composition of the host rock, which can be reliably established at this site as the rock is relatively fresh.

This small site also exhibits good examples of sedimentary structures such as cross-bedding, dewatering structures and scours, which are found within the Laphroaig Quartzite. Three different small-scale tectonic fabrics are easily distinguished here and these could prove important in establishing tectonic relationships in south-east Islay.

10 ARDILISTRY BAY, ISLAY (NR 443 485–NR 447 483)

C.A. Bendall

10.1 Introduction

Along the coastal sections at Ardilistry Bay, 8 km east of Port Ellen in south-east Islay, metamorphosed basic sills account for over half the succession. One of the sills, exposed along the south-east shoreline of the bay (NR 4415 4816–NR 4441 4837), is almost certainly unique in the British Isles. This sill is around 12–14 m thick and, towards the base, there is a 3 m-thick layer that consists almost entirely of the amphibole, actinolite. The protolith of this rock was almost certainly a pyroxene-cumulate and the pyroxene has been replaced by actinolite during greenschist-facies metamorphism. Although the mineralogy has changed, the original cumulate texture is retained. The metapyroxenite is overlain by a metamorphosed plagioclase layer approximately 1 m thick, in which albite and epidote have replaced the original plagioclase.

The country rocks around the bay are Dalradian metasedimentary rocks belonging to the Easdale Subgroup of the Argyll Group. These rocks were first described by Wilkinson (1907), and have received relatively little attention since. Wilkinson also provided the most comprehensive description of the Islay sills, although this was rather general and he made no mention of this particular sill. The area was resurveyed by Basahel (1971) and much of the revised 1998 edition of the BGS 1: 50,000 Sheet 19 (South Islay) is based upon his work.

10.2 Description

Two formations crop out at Ardilistry Bay; the Port Ellen Phyllite is poorly exposed, especially inland, but the younger Laphroaig Quartzite is exposed intermittently around the coastline (Figure 22). The Port Ellen Phyllite Formation consists mainly of metamudstones with subordinate metasandstones and impure metasandstones. The metasandstones become more common towards the top of the formation, where there is a gradation into the thickly bedded metasandstones with subordinate metamudstones of the Laphroaig Quartzite Formation. This low-lying coastal region is dominated by a series of ridges, parallel to strike, that are formed by sills of resistant metamafic rock (Figure 23). Thinner sills are generally schistose but, while their margins may be schistose, many of the thicker sills retain relict igneous textures that are commonly ophitic. The mineral assemblage of the sills is typical of the greenschist facies and consists of chlorite, actinolite, albite, epidote, calcite, quartz and leucoxene.

Among several curious features to be found in these sills, are pods rich in the yellow-green mineral epidote. They are quite conspicuous in some of the thicker sills along the north-east shore of the bay.

The metapyroxenite-bearing sill is found at NR 4431 4831. There is good exposure in low cliffs along the shoreline, but it is poorly exposed when traced inland. A schematic section of this sill is presented in Figure 24. The basal part is schistose; little remains of the original igneous texture except for relict phenocrysts, which were probably once calcium-rich plagioclase. These have been pseudomorphed by albite, epidote and calcite during greenschist-facies metamorphism and have been flattened during the deformation that produced the schistosity. Although the base of this schistose unit cannot be observed directly, the unit appears to be no more than about a metre thick, and could represent the original fine-grained basal margin to the sill. Immediately above this is the actinolite-rich layer, which is approximately 3 m thick and consists almost entirely of actinolite pseudomorphs after clinopyroxene. These are mostly euhedral to subhedral, dark olive green crystals some 2–3 mm in size, and they are randomly orientated. In thin section the actinolite is almost colourless, indicating a high Mg/Fe ratio, which has been substantiated by electron-microprobe analyses (Bendall, 1995). Interstitial to the large actinolites is a fine-grained groundmass of epidote, albite, calcite, leucoxene, rare quartz and acicular actinolite. This layer appears to be fairly homogenous in texture and composition.

Above this layer there is a transition zone that is about a metre thick. Pseudomorphs of albite-epidote after plagioclase occur, and increase in abundance upwards at the expense of the actinolite, until they account for more than 90% of the rock, resulting in what is in essence a meta-anorthosite. The pseudomorphs after plagioclase are larger than the actinolites and are generally between 1 and 2 cm in size. Most appear to be subhedral and are quite rounded. The meta-anorthosite layer is approximately 1 metre thick and grades upwards into a layer of metamafic rock with relict ophitic texture, which is *c.* 2 m thick. About 3.8 m of finer grained schistose metamafic rock makes up the uppermost layer of the sill, and the schistosity increases in intensity upwards; the top 1.5 m is highly schistose. Whereas albite-epidote pseudomorphs still occur above the meta-anorthosite layer, they are less abundant (5–10% of the rock) and smaller (generally less than 1 cm) than at lower levels.

Structurally, these rocks lie on the south-eastern limb of the Islay Anticline and the beds dip and young to the south-east. The metapyroxenite-bearing sill is concordant with bedding, and its top dips at 45° to the south-east. The schistosity also dips to the south-east, but is somewhat steeper, giving a sense of vergence towards the north-west.

10.3 Interpretation

The relict texture defined by the actinolites in the metapyroxenite layer suggests that the igneous protolith to this rock was a clinopyroxene-cumulate. The presence of albite, epidote and calcite, interstitial to the actinolites, suggest that plagioclase was an intercumulus phase. Whole-rock analyses are low in silica (47%) and rich in MgO (19%) (Bendall, 1995). Hence, it is possible that there was some intercumulus olivine, as well as plagioclase. This layer was most likely formed by the early crystallizing phase, clinopyroxene, settling out under the influence of gravity.

Once the clinopyroxene had settled out, it appears that plagioclase was then the main crystallizing phase. The plagioclase too may have settled out to form a cumulate anorthosite layer. However, as plagioclase has a relatively low density, and may not settle out as easily as pyroxene, this layer could have formed through crystallization of plagioclase, without any subsequent movement through the magma, making the protolith to the meta-anorthosite a plagioclase-adcumulate.

The sill is probably associated with the Tayvallich volcanic rocks, which were extruded at around 600 Ma ago (Halliday *et al.*, 1989; Dempster *et al.*, 2000). During the mid Ordovician Grampian Event, the sill underwent deformation and greenschist-facies metamorphism along with the country rocks. The sense of vergence to the north-west, shown by the schistosity on bedding, is consistent with it forming during the same (D1) deformation phase that formed the Islay Anticline (Roberts and Treagus, 1977c).

Only the margins of the sill are schistose and the inner part retains the original igneous textures. Work by Skelton *et al.* (1995, 1997) has described the effect of carbonation of greenschist-facies metamafic-rock sills by infiltration of a CO_2-bearing hydrous fluid. This has produced a distinctive zoning pattern in the sills, in which the primary amphibole-epidote assemblage is preserved in the cores, whereas the schistose margins have been altered to calcite, chlorite and quartz. These authors also observed that there is an asymmetry in the width of the zones across the sill, such that one altered margin is much wider than the other. They concluded that this asymmetry was controlled by the orientation of the sill with respect to the direction of fluid flow and the partitioning of flow along and across the sill. The contrast between a narrow altered margin at the base of the sill at Ardilistry Bay (Figure 24), and a thicker one at the top, might have been controlled in this manner, and it could be significant that the metapyroxenite layer occurs immediately above the narrower, least altered margin.

10.4 Conclusions

Metapyroxenite rocks are relatively rare in the British Isles. They are found in the Lewisian Gneiss Complex of north-west

Scotland, which are generally at a high metamorphic grade (amphibolite- to granulite-facies), and occur as very low-grade rocks, such as in the Shetland and the Ballantrae Ophiolite-complexes. However, it is possible that the metapyroxenite at Ardilistry Bay might be the only greenschist-facies metapyroxenite preserved and exposed in the British Isles.

The metapyroxenite layer is up to 3 m thick and consists almost entirely of coarse-grained actinolite, a Mg-rich calcic amphibole that has replaced original clinopyroxene during metamorphism. It occurs in a sill that also has a 1 m-thick layer of meta-anorthosite, representing an original plagioclase-rich layer. The sill, therefore, is an excellent example of a layered basic igneous intrusion that has been metamorphosed to the greenschist facies. Whereas deformation and fluids associated with the metamorphism have altered the margins of the sill, which now has a schistose fabric, the inner part has retained the original igneous textures, particularly in the metapyroxenite and meta-anorthosite layers. The good exposure, and the very distinctive appearance of this rock, enhances the geological attractiveness of an already geologically fascinating small corner of Islay.

11 BLACK MILL BAY, LUING (NM 733 087–NM 729 092)

P.W.G. Tanner

11.1 Introduction

Black Mill Bay is situated on the exposed west-facing coastline of the island of Luing in the Firth of Lorn, 4 km north of the southern tip of the island. The GCR site lies on the north shore of the bay and exposes the Easdale Slate Formation, which forms the upper part of the Easdale Subgroup (Figure 25). Here, the formation shows greater lithological diversity and structural complexity than is generally seen elsewhere in its outcrop, and includes a strongly deformed debris flow deposit (or debrite). The eastern margin of the site is marked by the Cobblers of Lorn, a prominent group of rounded, pale-coloured knolls of felsic igneous rock that provide a readily identifiable mark for mariners.

The geology of Black Mill Bay has previously attracted little attention, being mentioned only briefly by Peach *et al.* (1909) and summarized in a single paragraph of a field guide by Baldwin and Johnson (1977). The Easdale Slate Formation consists of black, pyrite-rich, slaty metamudstone with subordinate metasiltstone and metasandstone, in which there are a few beds of calcareous metasandstone, centimetre-thick black pebbly metasandstone, and dark grey, brown-weathering, pods and lenses of ferroan metadolostone. Sedimentary features include the debris flow, a (now cleaved) clastic sedimentary dyke and a few graded beds of metasandstone.

The original mudstone–sandstone sequence has been deformed twice, the second event all but obliterating local evidence of the steep to vertical first cleavage (S1). The second event (D2) resulted in the formation of mesoscopic folds of bedding and slaty cleavage, accompanied by a widespread, gently dipping, crenulation cleavage.

11.2 Description

At Black Mill Bay, the metasedimentary sequence consists of black slaty metamudstone, with pyrite cubes to 0.5 cm across, and includes several horizons of dark grey, brown-weathering metacarbonate rock of the type that has been reported elsewhere to be of ferruginous 'metadolomite' (Anderton, 1979). Large bodies of metadolostone give rise to characteristic whale-back forms. Many of these are arranged in sets, or linear arrays, of doubly-plunging early folds with a consistent sense of vergence; others appear to be strings of boudins, or even primary sedimentary concretions. Also present are calcareous metasandstones, metasiltstones, and beds of black metasandstone that show graded bedding. Although it is folded locally by pairs of tight to isoclinal folds, the succession youngs overall to the east, with most beds being right-way-up.

Of greatest interest in this section is the presence of a 4 m-thick debris flow deposit (debrite) at locality A (Figure 26, a and b) (NM 7311 0875). The rocks below the debrite consist of thin, commonly gritty, metasandstones (less than 50 cm thick), that contain clasts of carbonate material and young east on graded bedding (with grains up to 2 mm across at their base). These rocks are followed by brown laminated metasandstones and a black slaty metamudstone that contains thin beds of metacarbonate rock.

The base of the debrite is marked by three or four beds of black, gritty metasandstone containing carbonate clasts. They vary in thickness laterally from 5–25 cm, and form a 40–57 cm-thick unit that has a channel-fill geometry and an irregular, erosive contact with the underlying metacarbonate rock. Both rock types are cut by numerous quartz-carbonate veins. The metasandstone unit appears to have provided the sediment for a clastic dyke that penetrates into the overlying debrite for a distance of approximately 1.5 m. The overlying 130 cm of the debrite consists of finely banded, silty metamudstone, which carries the S1 spaced cleavage and contains a matrix-supported population of spindle-shaped sandstone clasts ranging in length from 1–20 cm. This mudstone-supported metaconglomerate is overlain by a 90 cm-thick unit of black slaty metamudstone containing a population of smaller, more widely dispersed clasts. The metamudstone occupies a gully and, in contrast to the units on either side, has a structure dominated by an intense flat-lying crenulation cleavage (Figure 26c). It is succeeded by 186 cm of near-vertical, brown-weathering metasiltstone, which grades into metacarbonate rock in the top few tens of centimetres and is affected by a strongly developed pressure-solution cleavage dipping at over 80°. This unit contains matrix-supported sandstone clasts, which are generally larger and more abundant than in the metamudstone below. The top of the debrite is not seen clearly and is arbitrarily taken at the point where the last clast is seen, before the transition from metamudstone to metacarbonate rock takes place.

The F1 folds seen at the GCR site have steep to vertical axial planes and curvilinear hinges, are upward facing, and approach sheath-fold geometry in metamudstone. At the south end of the section, the S1 cleavage is near vertical and is the dominant planar fabric in metacarbonate rock and metasiltstone, where it is seen as a millimetre- to centimetre-spaced cleavage. The corresponding S1 slaty cleavage in metamudstone is associated with a steeply plunging stretching lineation and curvilinear bedding-cleavage intersection lineations. A good example of the magnitude of the D1 strain is seen in the debris flow deposit, where the clasts are elongated parallel to the L1 extension lineation and flattened in the plane of the spaced cleavage (Figure 26, a and b). The clasts have a maximum dimension (Y) in cross-section of 2–7 cm, and exceptionally up to 9 cm. They are up to 20 cm in length and plunge, on average, at 80° towards 197°.

In many places, the early structures are strongly modified by a near-horizontal to gently dipping crenulation cleavage (S2), which masks their geometry, and also locally by mesoscopic, recumbent F2 folds (Figure 26d). For example, at location B, an isoclinal F1 fold, showing strong refraction of the early cleavage between beds and plunging at 40–50° to 001°, is cut by the intense near-horizontal S2 crenulation cleavage and is effectively disguised. The mean orientation of the S2 crenulation cleavage is dip 7° east, strike 339° (N=7), with the π-axis for slaty cleavage and bedding plunging at 7° to 010° (N=16) (inset on Figure 25). The local dominance of one cleavage over the other, depending on the rock type, is graphically displayed by the metasiltstone and metamudstone units in the debrite at locality A (Figure 25). This has resulted in a striking contrast between metacarbonate and metasiltstone beds displaying a steeply dipping to vertical, spaced S1 cleavage, and adjacent units of black metamudstone characterized by a horizontal crenulation cleavage that has all but destroyed the earlier slaty cleavage (Figure 26c). The early spaced cleavage is axial planar (mean of fanned cleavage) to a south-plunging F1 anticline in the strongly cleaved metacarbonate bed immediately to the east of the debrite.

The debrite is crossed in part by a 15 cm-thick, folded, clastic dyke that has been affected by a steeply dipping S1 spaced cleavage continuous with that in the host rock. The fold plunges at 80–85°. The sides of the sandstone clasts in the debrite carry a horizontal set of corrugations that represent the intersection between S1 and the flat-lying crenulation cleavage (S2) (Figure 26a).

Apart from late, brittle structures, post-D2 structures are uncommon at this GCR site. However, in the deformed metamudstone at locality C (Figure 25), two later generations of crenulation cleavage are seen superimposed upon the S2 crenulation cleavage. The earlier of these has a dip of 50–60° south, strike 070°; and the later one dips at 30° north-east, strike 330°.

11.3 Interpretation

It could be argued, that graphitic and pyritous slaty metamudstones, and other lithologies more representative of the Easdale Slate Formation, are best seen in the less intensively deformed section at Cuan Point on Luing, 5.5 km north of Black Mill Bay. However, the sequence at the Black Mill Bay GCR site includes a debris flow deposit (debrite), which may be correlated with slump and slide deposits found a few kilometres to the west and south-west that constitute the Scarba Conglomerate, described by Anderton (1979) (see the *Lussa Bay* and *Kinuachdrachd* GCR site reports). That conglomerate formed because of the depositional basin margin becoming unstable during Easdale Slate times, and the debrite at Black Mill Bay, together with a few turbidite deposits, represents the more distant effects of that disturbance.

The rocks are affected by an early generation of strongly curvilinear, isoclinal folds (F1), linked with the development of slaty cleavage in mudstones and spaced cleavages in siliciclastic and carbonate rocks. These structures are temporally and geometrically related to the development of the F1 Loch Awe Syncline to the south-east, but fold vergence is difficult to demonstrate at Black Mill Bay due to the cleavage being at a small angle to, or parallel with, the bedding. In addition, a low-angle crenulation cleavage (S2) is strongly developed locally, to the extent that it overprints and reworks the slaty cleavage. This crenulation cleavage has a similar orientation to a much weaker fabric seen at Cuan Point, and that seen at an early stage of development at the *Fearnach Bay* GCR site. It is likely that it may also be correlated with the low-angle crenulation cleavage that commonly affects the slaty cleavage in metamudstones, and similar rocks found in the Easdale Subgroup on Jura, and reworks the earliest penetrative fabric in older strata at the *Camas Nathais* GCR site to the north (Treagus et al., 2013).

11.4 Conclusions

The Black Mill Bay GCR site provides a well-exposed coastal section across part of the Easdale Slate succession, which comprises black slaty metamudstone, making up the major part of the sequence, with units of metasiltstone and metasandstone, and horizons of metacarbonate lenses. Structurally, a wealth of minor structures and fabrics, resulting from varying degrees of interaction between two separate deformational episodes, are preserved within a relatively small area.

The feature that makes this site of wider interest is the preservation of a 4 m-thick debris flow deposit. A typical deposit of this type consists of a stratiform unit of matrix-supported clasts that vary greatly in size; these are enclosed in a muddy or silty matrix and are commonly accompanied by rafts and large blocks of sedimentary rock. Such flows originate at the basin margin and are capable of transporting detritus for long distances out into the basin.

The debris flow deposit at Black Mill Bay was deformed pervasively during the earliest deformation, which caused the formation of a slaty cleavage. As a result, pebbles and cobbles of sandstone, which were originally probably equidimensional or slightly elliptical in shape, have been deformed into a series of parallel rod-like shapes. This is in strong contrast to the debris flow deposit at the *Port Selma* GCR site (Treagus et al., 2013) where the boulders are little deformed and delicate sedimentary structures are preserved within the deposit.

The main value of this GCR site is to establish a link between other sites that represent the Easdale Subgroup, and to provide a benchmark for comparing the Easdale Slate succession on the mainland with rocks thought to be of equivalent age on Islay and Jura. Likewise, there are significant similarities between the geometries of the two sets of structures at Black Mill Bay, and those at the *Camas Nathais*, *Port Selma* and *Fearnach Bay* GCR sites.

12 CRAIGNISH POINT (NR 759 999–NM 765 005)

P.W.G. Tanner

12.1 Introduction

This GCR site is situated near the southern end of the Craignish peninsula, west of Aird, and consists of a narrow coastal outcrop of the Craignish Phyllite Formation (Easdale Subgroup), intruded by a thick metadolerite sill (Figure 27). These exposures are of national, verging on international, importance because of the presence of calcite pseudomorphs after gypsum that are not found elsewhere in the Dalradian Supergroup in such an excellent state of preservation, or exhibiting the same wide range of morphological types. The original gypsum crystals had twinned forms ranging in shape from butterflies to bow-ties (Figure 28) that are unique, and have not been reported previously from naturally occurring rocks or sediments worldwide. This occurrence is in contrast with the outcrop of the Craignish Phyllites elsewhere, where such features, if once present, are no longer preserved due to later deformation, metamorphism, and fluid flow (see the *Kilmory Bay* GCR site report).

Following early work by MacCulloch (1819), the 'Craignish Phyllites' were first mapped and named by Hill (1899) and Peach and Horne (1909). The Craignish peninsula was first mapped for the Geological Survey by H.B. Maufe in 1901, but it was Bailey (1913) who established the stratigraphical succession, which was subsequently confirmed by Allison (1941). The peninsula was later the subject of detailed sedimentological studies (Knill, 1959; Anderton, 1976) and structural studies (Knill, 1960). Lath-like pseudomorphs after gypsum were first reported from the country rocks beneath a metadolerite sill on Craignish Point by Anderton (1975). However, it was not until 1995 that the exceptional forms taken by the original twinned gypsum crystals were recognized by the author of this site report.

The sill-like nature of the basic meta-igneous bodies that are found in abundance throughout the Craignish Phyllites was first recognized by Jamieson (1860). Bailey (1913) noted that, in some cases, they are slightly transgressive, and that they are associated with 'remarkable contact alteration'. The sills, which were emplaced prior to the deformation and regional metamorphism of the country rocks, can be many tens of metres thick. They generally have highly sheared and altered margins and less deformed and metamorphosed interiors (Graham, 1976). Recent research has shown that the alteration is due to the infiltration of a CO_2-rich fluid from the country rocks during the regional metamorphism (Graham *et al.*, 1985; Skelton *et al.*, 1995).

The Craignish peninsula lies on the north-west limb of the Loch Awe Syncline and the rocks were mildly deformed and metamorphosed to the greenschist facies during the Grampian Event. This part of the peninsula has almost entirely escaped any later deformations, including the development of conjugate sets of kink bands for which the surrounding area is well known. It is cut by Palaeogene dykes belonging to the Mull Swarm.

12.2 Description

The Craignish Phyllites are clearly exposed on a narrow rock platform backed by small cliffs, with areas of clean, tidally scoured rock. They are overlain conformably by a metadolerite sill that runs parallel to the coast and forms a positive topographic feature. The phyllites consist of a well-bedded sequence of grey-green phyllitic metasandstone and metasiltstone, with characteristic orange-brown-weathering layers of metacarbonate rock of varying thickness. Sedimentary structures such as parallel lamination, cross-lamination, graded bedding, convolute folds, and water-escape structures are common and well preserved. The rocks dip at 50–55° to the south-east, and at low Spring tide a maximum thickness of 20 m of metasedimentary rock is exposed at any point along the coast, within the GCR site. Sedimentary logs of the sequence at four localities were given by Anderton (1975, figure 2, locations B–E).

Anderton (1975) carried out the first detailed sedimentological study of these rocks and identified four facies associations, namely:

1. Laminated silt/sand
2. Tabular sand facies.
3. Sheet sand facies.
4. Channel facies.

Facies 1 consists of finely laminated (0.1–2 cm) alternations of metasandstone and metasiltstone, and is host to most of the pseudomorphs. Facies 2, commonly found interbedded with Facies 1, is characterized by 5–40 cm-thick metasandstone beds, which are parallel-sided, have erosional bases, and commonly show sole markings, including flute marks. Parallel lamination is well developed in the metasandstones, and shows a transition to climbing ripples in some beds. Facies 3 consists of structureless metasandstones, over 5 cm thick, that lack the features of the Facies 2 beds; with a decrease in bed thickness it grades into Facies 1. In Facies 4, the metasandstones are coarser in grain size than those of the other facies, and have strongly discordant bases and an irregular cross-sectional geometry.

The pseudomorphs after gypsum were reported first from the Craignish Phyllites by Anderton (1975 plate 2, b and c) from his locality T2 (NM 761 002), which is within the area of this GCR site. The host rocks are grey-green phyllitic metasiltstones with thin, 1–2 cm-thick, orange-weathering carbonate bands and nodules, phyllitic calcsilicate rocks, laminated phyllitic metasandstone–metasiltstone units, and thicker metasandstone beds to 27 cm thick. The pseudomorphs are blade- and lath-shaped bodies 0.1–4.0 cm long, which are concentrated along certain bedding-parallel horizons that can be traced laterally for several metres. These horizons commonly occur at the interface between porous, coarse-grained metasandstone and an underlying finer grained, less permeable bed. Other localities with less well-preserved calcite pseudomorphs were reported by Anderton (1975).

Anderton likened the pseudomorphs to the ‘desert roses’ and isolated gypsum crystals found at the present day in tidal-flat environments in many places in the world, but failed to recognize the true geometry of the twinned crystals found, in particular, within the GCR site. There the pseudomorphs are preserved as cavities or impressions on the weathered rock surface. They vary from irregularly shaped pits 1–3 mm across, to randomly orientated acicular impressions from a few millimetres to over 3 cm long, to millimetre-sized cavities with a distinct bow-tie shape (Figure 28a), and centimetre-sized ‘butterfly’ forms (Figure 28b). All types of pseudomorph are most common on the bases of cross-laminated metasandstone beds that vary in thickness from 1–27 cm, and rarely contain nodular calcareous patches, and rare sediment rafts. It is particularly noticeable that different beds and bedding surfaces within the laminated phyllitic rocks are characterized by a particular size and form of pseudomorph. Thus, a horizon on which minute sub-millimetre-sized bow-ties are preserved is found adjacent to one on which only centimetre-sized butterflies are seen.

The precursor mineral to the pseudomorphs grew across and preserved the original sedimentary fabric of the rock, and this internal texture was inherited by the optically continuous calcite crystal that replaced it. In some cases, the pseudomorph displays areas, especially rims, that are clear of inclusions but it is not clear whether these inclusion-free areas formed during gypsum growth or during its replacement by calcite. Anderton (1976, figure 3) illustrated the situation where calcite pseudomorphs that grew along the interface between coarse silt and underlying silty clay, were all truncated at the base of the overlying bed. He concluded that, following the growth of the gypsum crystals across the bedding interface, less-saline fluid flowing through the more porous upper bed had caused dissolution of any parts of the gypsum crystals that had penetrated the upper bed, resulting in the observed truncation.

All of the metasedimentary rocks have been affected by orogenic deformation to some extent, as expressed locally in the field by the development of a penetrative, slaty cleavage in the thin metamudstone seams. This cleavage dips more steeply south-east than the bedding (Figure 27), in keeping with the location of the GCR site on the north-west limb of the Loch Awe Syncline.

12.3 Interpretation

In 1975, Anderton published the results of a detailed sedimentological study of the coastal strip that includes this GCR site, and concluded that the Craignish Phyllites in this part of the outcrop were deposited in a tidal-flat to shallow-marine environment. This interpretation, though prompted by the finely laminated, thinly bedded and fine-grained nature of the beds, was based largely upon the identification of gypsum in the rocks at Craignish Point, and thence by comparison with present day examples of similar gypsum-bearing sequences. Evidence or reasons to support the inference that the calcite pseudomorphs were derived specifically from the alteration of gypsum were not given, apart from there being a morphological similarity between the lath-like pseudomorphs and prismatic gypsum. Recent work by the author has confirmed that the precursor mineral could only have been gypsum, a finding which supports the environmental interpretation placed upon the four sedimentary facies by Anderton.

From the sedimentary logs and other field data, Anderton (1975) concluded that the tidal-flat sediments of the laminated Facies 1 were cut by meandering channels filled with the coarser sediments belonging to the channel Facies 4. The sheet (3) and tabular-sand (2) facies were more rapidly deposited, and Anderton suggested that the latter were flood-tide storm sediments deposited in a subtidal to low intertidal setting.

All of the features shown by the pseudomorphs indicate that the gypsum grew synchronous with, or shortly after, the sedimentation. This conclusion is supported by the observation that some of the pseudomorphs have been affected by pressure-solution corrosion associated with the development of the earliest cleavage in these rocks.

The excellent state of preservation of the pseudomorphs may be due to the shielding effect of (and contact metamorphism by?) the thick metadolerite sill that runs along the GCR site. The sill was emplaced before the regional deformation and metamorphism of the Dalradian rocks, and could have protected the gypsum-bearing rocks locally from the main effects of the Grampian deformation. An analogous situation is found locally at the *Kilmory Bay* GCR site, where sedimentary structures are well preserved in a narrow zone of slightly hornfelsed rock adjacent to a thick metadolerite sill (see Roberts, 1977c, locality 10).

12.4 Conclusions

The Craignish Point GCR site is one of those exceptional places where, despite the many pairs of eyes that have looked at the rocks since Jamieson first described them in 1860, there still remain new features to discover and interpret.

The main feature of the site is that it preserves valuable evidence that crystals of gypsum (hydrous calcium sulphate) grew in the muds and fine sands soon after they had been laid down in Neoproterozoic times, many millions of years before the rocks were intruded by an igneous body and involved in the Caledonian Orogeny. The fact that this mineral was able to crystallize from seawater signifies that there was a hot climate at that time. Combined with other field evidence, this suggests that the environmental setting was probably analogous to that found at the present day on tidal flats in regions such as the Persian/Arabian Gulf.

A 34 m-thick dolerite sill, which now overlies these rocks, protected them from much of the deformation that has affected the Craignish Phyllites throughout the rest of the outcrop (see the *Fearnach Bay* GCR site), so preserving the sedimentary structures, as well as the pseudomorphs.

The aspect that gives this site a possible international, status is the extraordinary and unique forms shown by the former gypsum crystals (now replaced atom-for-atom by calcite). They display bow-tie and butterfly shapes, which reflect their internal structure, that of two crystals which have grown simultaneously to form an asymmetrical cross. They are aesthetically pleasing forms, but fragile and easily destroyed. Current research is aimed at determining whether they could be used as a more precise guide to the climatic and other physical conditions that prevailed at the time of their growth.

This GCR site also provides a representative section for a part of the Craignish Phyllite Formation, which in combination with other data, including those from the *Black Mill Bay* and *Fearnach Bay* GCR sites, can be used to model the original sedimentary architecture of the Easdale Subgroup.

13 FEARNACH BAY (NM 838 130–NM 832 141)

P.W.G. Tanner

13.1 Introduction

Fearnach Bay is located at the head of Loch Melfort, some 11 km east-north-east of the *Black Mill Bay* GCR site on the Isle of Luing. The GCR site consists of a narrow strip of coastal exposures, divided into two parts by the estuary of the River Oude (Figure 29). The rocks belong to the Craignish Phyllite Formation (Easdale Subgroup), and consist mainly of grey-green, generally calcareous, phyllitic metamudstones and metasiltstones, with thin quartzite and metacarbonate beds. The strata are largely right-way up, dip at a moderate angle to the east, and were strongly folded on all scales, from microscopic to mesoscopic, during the main phase of deformation (D1). The effects of later deformation on these structures are minimal.

The section provides a well-exposed sequence of rock types that characterize the Craignish Phyllite, and displays in splendid detail the 3-dimensional geometry of the first generation of minor folds and cleavages. Minor fold vergence, cleavage-bedding relationships, and way-up structures all indicate that the strata lie on the north-western limb of the Loch Awe Syncline. This GCR site also presents a good example of cylindroidal fold geometry on a mesoscopic scale (Figure 29, inset), together with excellent examples of structural features such as cleavage refraction and cleavage fans, and sedimentary structures such as pseudo-ripple marks and ripple-drift lamination.

There is very little published work on the geology of this GCR site, apart from a comment in the original Geological Survey memoir (Peach *et al*., 1909); strain measurements made on a deformed basic sill (Borradaile, 1972b); and a brief mention in a field guide (Borradaile, 1977). The rock types closely resemble those at the *Port Cill Maluaig* and *Strone Point* GCR sites, but the structural styles at the three localities are completely different.

13.2 Description

The Craignish Phyllite Formation at Fearnach Bay consists largely of finely banded grey-green phyllitic metamudstone, with units of more-siliceous phyllitic metasiltstone up to 20 cm thick. The metamudstones and metasiltstones are commonly interbedded with thin beds of orange-brown-weathering metacarbonate rock, which vary from 2–6 cm in thickness, and have a characteristic etched appearance. In places, particularly in the north of the site around the pier, they are accompanied by beds of massive metacarbonate rock up to 20 cm thick, which show a gradational contact with the siliciclastic host rock. Beds of fine-grained, white quartzite from 15–50 cm thick occur throughout the sequence. South of locality A (NM 8350 1342) (Figure 29), the Craignish Phyllite becomes lithologically more monotonous; it is more siliceous and tougher, less well bedded, and with fewer metacarbonate and quartzite beds than farther north. Quartz-carbonate veins occur throughout the sequence.

Taken as a whole, the sequence becomes younger to the east. Ripple-drift cross-lamination is the main way-up indicator and occurs in units up to 3 cm thick at the base of thick, orange-brown metacarbonate beds (Figure 30a), and also in alternating sequences of ripple-drift structures and 1–3 cm-thick metacarbonate beds, forming stacks up to 0.5 m thick.

The structure consists of a number of asymmetrical early (F1) folds, usually in pairs, which have N–S-trending axial traces. They are accompanied by a penetrative slaty cleavage (Figure 30b) that is associated with a poorly developed stretching lineation, plunging to the east-north-east at around 30°. The cleavage shows marked refraction across the more-competent layers in the slaty metamudstone, and slight normal fanning in fold closures. Metre-scale mesoscopic folds are found throughout the section; in the north, in exposures around the pier, there is a set of at least five folds with overall vergence indicating a syncline to the east. Bedding in the middle limbs of these structures dips at 80°, and is overturned locally. The associated slaty cleavage dips at *c*. 31°, and the fold hinges plunge at *c*. 10° towards 002°. There is evidence for a preceding episode of layer-parallel extension, or boudinage.

Many of the beds east of the pier display patterns of lenticular, discontinuous, en-echelon, regularly spaced, pod-like structures on their top surfaces, which are 5–10 cm long and 4 cm deep. Bottom structures have been reported from this GCR site by Borradaile (1977), but those examples are pseudo- or tectonic ripples resulting from the development of small, doubly plunging, en-echelon, buckle folds on the surface of the bed.

South of the River Oude, the coastal section as far as locality A, runs parallel to the strike of both bedding and cleavage, but several natural cross-sections are seen. In two of these sections a deformed basic intrusion is seen to be concordant with bedding in the metasedimentary rocks, and shows some internal compositional layering. A 15 cm-thick bed of quartzite, with what appears to be a muddy top, occurs between it and the more-typical phyllitic country-rock. The sill can be traced around several fold closures at this locality, and contains a penetrative fabric, defined by flattened amygdales. This fabric is continuous with the slightly fanned, slaty cleavage in the adjoining rocks. Measurement of the strain, represented by deformed amygdales, carried out at two localities by Borradaile (1972b, locations 13 and 14), gave X/Y ratios of 2.87–2.91. Buckle folds, affecting beds that vary considerably in thickness and competence, give rise to a plethora of minor folds whose wavelengths show a marked positive correlation with the bed thickness.

The geometry of the tectonic structures at this GCR site is summarized by the stereographic projections in Figure 29. Because the cleavage in the northern section has a more-shallow dip than in the southern section, there is quite a large spread in the orientation of poles to the S1 slaty cleavage. The computed π-axis derived from a plot of poles to bedding for the whole site is [plunge 05°NE; trend, 020°; N (number of readings)=20]. This is almost coincident with the mean orientation for the calculated best-fit line of intersection of the slaty cleavage planes [plunge 04°NE; trend, 024°; N=10] and the mean orientation of bedding-cleavage intersections and minor fold hinges [plunge 06°NE; trend, 021°; N=9], and shows that on a major scale, the structures are almost perfectly cylindroidal. It also demonstrates the inherent symmetry of structures in rock.

A second tectonic fabric (S2) is present locally as a millimetre-spaced crenulation cleavage in slaty metamudstone layers, and generally dips at less than five degrees. It is associated with rare, centimetre-scale, late folds, which refold tight to isoclinal F1 folds and plunge at a low-angle to the north-north-east.

13.3 Interpretation

The Craignish Phyllite was laid down in a shallow-water environment, as witnessed at this GCR site by the preservation of abundant ripple-drift bedding at different levels in the sequence. The depositional environment was probably similar to the near-shore to intertidal settings in which gypsum-bearing sediments, preserved at the *Craignish Point* GCR site, were being deposited at the same time (Anderton, 1976). However, in the area of Fearnach Bay, the Craignish Phyllite originally consisted of somewhat calcareous muds and silts (now metamorphosed to chlorite-white mica-carbonate-bearing phyllitic metamudstones and metasiltstones) and this contrasts with its lateral equivalent at Craignish Point, 15 km to the south-west, where the formation was formed from interbedded sands and silts with subordinate muddy layers.

The Craignish Phyllite is correlated across the Loch Awe Syncline with the Ardrishaig Phyllite. Indeed, the Craignish Phyllite at Fearnach Bay has much more in common with the Ardrishaig Phyllite, as seen at the *Strone Point* and *Port Cill Maluaig* GCR sites, than with rocks of the same formation farther west (i.e. at the *Craignish Point* GCR site). This is because the rocks at the three easterly sites are at a higher metamorphic grade, and have been more pervasively deformed, than the same lithostratigraphical sequence farther west.

The fold structures at Fearnach Bay are of primary, D1, age and appear to be virtually unaffected by any later deformation. They may be correlated with D1 structures at the *Black Mill Bay* GCR site, with which they share a common geometry (compare the inset on Figure 29 of this report with the inset on Figure 25 of the *Black Mill Bay* GCR site report).

13.4 Conclusions

The Fearnach Bay GCR site occupies a crucial position on the north-western limb of one of the most fundamental structures of the South-west Grampian Highlands, the near-upright F1 Loch Awe Syncline. A train of metre-scale folds, accompanied by a penetrative cleavage, is virtually unaffected by later deformation making this a site of major national importance. The geometry of the minor structures, which include folds, cleavage, and lineations, is that of a perfectly cylindroidal structure plunging at *c*. 5° to the north-north-east. Cleavage dips more steeply than bedding on the long limbs of these folds, consistent with their position on the north-western limb of the regional-scale fold. The inspiration to be gained from seeing such beautifully preserved folds and related cleavages in three dimensions, in all of their intricate detail, enhances the value of the site considerably.

The Dalradian rocks at this GCR site were formed from muddy and calcareous sediments, laid down in a shallow-water environment, and represent a more highly metamorphosed and deformed part of the Craignish Phyllite than is seen at the *Craignish Point* GCR site. Hence, this site provides a lithostratigraphical link, between the Craignish Phyllite and its generally higher grade equivalent on the other limb of the Loch Awe Syncline, the Ardrishaig Phyllite.

Regional metamorphism (to lower greenschist facies) altered the mud-rich sedimentary rocks to chlorite-white mica-rich phyllitic rocks, and caused recrystallization of the less reactive rocks such as limestone and quartzite. After lithification, the sedimentary rocks were intruded by basic magma that crystallized to form several thin sheets, concordant with the bedding.

14 KILMORY BAY
(NR 698 756–NR 704 725)

J.L. Roberts and P.W.G. Tanner

14.1 Introduction

The coastline between Kilmory Bay and the Point of Knap, in the Knapdale area of Kintyre, provides a 4 km-long section through the rocks of the Ardrishaig Phyllite Formation and Crinan Grit Formation of the Argyll Group, preserved in the core of the Loch Awe Syncline. These rocks are extremely well exposed along the seaward edges of the raised beaches, which are a characteristic feature of this coastline. The only significant gap in exposure is caused by the Quaternary deposits around the head of Kilmory Bay.

The Kilmory Bay GCR site is of national importance, for providing excellent examples of the geometrical and kinematic relationships between major and minor structures in folded rocks (Roberts, 1959). Mesoscopic fold closures are exposed in three dimensions, and are accompanied by a great diversity of spaced and penetrative cleavages that form pronounced cleavage fans. The interrelationships between these structures remain to be fully explored. In addition, recent research has focussed upon the origin of the sedimentary dykes that are reasonably common in the Ardrishaig Phyllites at this site (Phillips and Alsop, 2003), and upon the effects of fluid flow during the regional metamorphism of the basic sills (Graham *et al*., 1983; Skelton *et al*., 1995)

The stratigraphy and structure of the area were established by J.S.G. Wilson of the Geological Survey, as reported by Peach *et al.* (1911). He used graded bedding in the Crinan Grits to show that this formation is younger than the Ardrishaig Phyllites, and recognized that, as the minor folds affecting the Crinan Grits plunge to the north-north-east, this formation must lie structurally above the Ardrishaig Phyllites (Figure 31) (see also Bailey, 1913).

Three major folds comprise the compound Loch Awe Syncline in Knapdale (see the *Port Cill Maluaig* GCR report, Figure 34). The most south-easterly of these folds, the Kilmory Bay Syncline is seen in its type area in Kilmory Bay as a plexus of 5 or more major closures (Figure 31). Bailey (1922) interpreted the Kilmory Bay Syncline as a secondary structure that had affected a stack of recumbent folds and intervening slides, formed during the primary deformation. However, more-recent work by Roberts (1959, 1974) has shown that at Kilmory Bay the rocks are affected by only one major deformation (D1), and that the Kilmory Bay Syncline is an early structure (F1), associated with the deformation that elsewhere produced early nappe-like structures. Roberts (1966a), provided a brief account of the sedimentological features of these rocks, and Roberts (1959), and Roberts and Sanderson (1974) discussed the origin of minor F1 folds with curved hinges.

14.2 Description

14.2.1 Stratigraphy

The Ardrishaig Phyllite Formation (informally referred to as the 'Ardrishaig Phyllites') is the oldest stratigraphical unit in the area. It lies on the south-east limb of the Kilmory Bay Syncline, and is exposed almost continuously along the seaward edge of the raised beach, which forms the coastline between Port Ban (NR 700 740) and the Point of Knap (NR 697 721). It consists typically of greenish-grey phyllitic metamudstones and metasiltstones, interbedded with beds of fine-grained quartzite and rare metalimestone, dipping steeply to the north-west (Figure 31). Beds of fine-grained quartzite are common locally on the coastline facing Glas Eilean. Ripple-drift bedding is developed in some of the more-silty layers, and sedimentary dykes, up to 25 cm thick, of fine-grained but rather impure quartzite, are found at a number of localities, including NR 696 731, where they trend east-north-east and cross-cut the bedding in the Ardrishaig Phyllites (Figure 32). Those at NR 700 743 have been described by Phillips and Alsop (2003), who presented evidence for some of these dykes being of post-D1 age. However, recent work by P.W.G. Tanner has identified features, which clearly indicate that they are all part of a linked system of pre-tectonic injections of mobilized water-saturated sandstone.

Groove and flute casts occur on the soles of fine-grained quartzite beds found immediately to the south-east of NR 696 731, and indicate that they were deposited by turbidity currents flowing from the north-west. Farther south, a sedimentary breccia, up to 2 m thick, is exposed in the cliffs backing the raised beach at NR 698 726. Lying in a matrix of sandy metalimestone, the fragments consist mostly of pale-coloured limestone, flattened parallel to the slaty cleavage, along with less-deformed pebbles of blue quartz, phyllitic metamudstone, and fine-grained quartzite (Peach *et al*., 1911).

The Ardnoe Member (formerly 'group') is the lowest division of the Crinan Grit Formation at Kilmory Bay. Its base is marked by a thick bed of massive fine-grained quartzite, which is exposed along the north-west side of Port Ban (NR 700 740). A dolomitic breccia occurs locally at the contact with the underlying Ardrishaig Phyllites, and is at the same stratigraphical level as the Shira Limestone (Figure 2). This bed is overlain by a sequence of schistose pebbly quartzites and fine-grained metaconglomerates, which make up the lowest division of the member. At Port Ban, the pebbly quartzites are coarser grained, and the bases of individual beds are commonly conglomeratic. Graded bedding, together with metre-scale cross-bedding in the upper parts of these beds, where they are exposed on the low headland at NR 699 741, show these rocks to be younger than the underlying Ardrishaig Phyllites (Peach *et al.,* 1911). The upper part of the member consists mostly of slaty metamudstones and fine-grained metalimestones, interbedded with fine-grained quartzites.

The main part of the Crinan Grit Formation (the 'Crinan Grits') crops out north of Kilmory Bay in the core and along the north-west limb of the Kilmory Bay Syncline (Figure 31). The base of the 'Crinan Grits' is marked by a massive bed of pebbly metaconglomerate, which is exposed on the coast opposite Eilean a' Chapuill at NR 696 747. Traced inland towards the east-north-east, this bed contains pebbles of blue and white quartz, feldspar, and dolomite, said to be the size of 'pigeons' eggs' (Peach *et al.*, 1911), and its base is markedly lobate, either as the result of load-casting, or syn-depositional erosion. This bed is overlain by massive beds of gritty meta-arenite, which were originally pebbly conglomerates and coarse-grained feldspathic sandstones. The pebbles consist of white and blue quartz, microcline, orthoclase, perthite, and oligoclase, listed in order of decreasing abundance. The pebbly metaquartzites are locally interbedded with thin layers of dark slaty metamudstone, and commonly show graded bedding, thus enabling the stratigraphical sequence to be determined. Cross-bedding is developed locally towards the tops of these graded beds, which represent attenuated Bouma sequences. These features are particularly well exposed along the rocky coast south of Port Liath (NR 698 757), where the beds are vertical and strike north-north-east on the north-west limb of the Kilmory Bay Syncline (Figure 31).

Both the Crinan Grits and the Ardrishaig Phyllites are intruded by sill-like bodies of basic meta-igneous rock that were folded and deformed, along with their Dalradian host rocks, during D1. The interiors of these basic sills commonly preserve relict igneous textures, whereas their margins are generally highly schistose. The original character of the metasedimentary rocks is best seen where they are protected from the effects of subsequent deformation, having been indurated ('baked') by contact metamorphism adjacent to the thicker sills. All of these rocks are affected by greenschist-facies metamorphism at chlorite grade, contemporaneous with the formation of the S1 slaty cleavage in the more-pelitic rocks.

14.2.2 Structure

The closure of the north-westerly syncline of the compound Kilmory Bay Syncline is seen to the north-west of Kilmory Bay at NR 696 747. There, the Crinan Grits dip moderately towards the north-north-east, and away from the Ardnoe Member that forms the headland. Traced north along the coast towards Port Liath (NR 689 757), these pebbly quartzites become vertical and trend north-north-east on the north-west limb of this syncline. The outcrop of the conglomeratic bed, where exposed on the coast opposite Eilean a'Chapuill (NR 697 749), defines the closure of the next anticline to the south-east, and part of the succeeding syncline. However, the south-east limb of this major syncline, and the closure of the major anticline to its south-east, are obscured by superficial deposits in Kilmory Bay. The closure of the following syncline is exposed to the south-east, between Kilmory Bay and Port Ban (NR 700 740), where beds of the Ardnoe Member lie in its core. All of these major F1 folds plunge at a moderately steep angle towards the north-east within axial planes that dip very steeply to the north-west.

The slaty cleavage (S1) developed in the metamudstone beds, strikes consistently north-east and dips at 60–80° to the north-west throughout the area, and is statistically axial planar to both the mesoscopic and major folds. The Ardrishaig Phyllites, with their extreme contrast in lithology, between bands of gritty quartzite up to 2 m thick, and interbedded units of phyllitic metasiltstone, give rise to an extraordinary range of cleavage refraction geometries. Slaty cleavage is represented by a shape- or spaced-cleavage in the coarser grained rocks. It typically shows cleavage refraction as it passes into the coarser grained beds, producing a strongly divergent cleavage fan about the fold hinges. Typically, a fibrous mineral lineation, which Clough (in Gunn *et al.*, 1897) termed the stretching direction, is developed on S1, and pitches steeply down-dip. The stretching lineation is commonly revealed by elongated rusty pyrite blebs.

The minor F1 folds in the Ardnoe Member are co-axial with the major folds that affect the overlying Crinan Grits; most of them plunge at moderate angles to the north-east (although some of them are curvilinear) within axial planes that dip very steeply towards the north-west. The exposures around NR 700 744, to the south of Kilmory Bay, show a spectacular series of very tight F1 folds affecting three beds of fine-grained quartzite. The anticlinal fold hinges are stripped bare by erosion to form a series of truncated whale-backs in the quartzite beds, plunging gently towards the north-east (Figure 33). At low Spring tides, the lowermost bed of fine-grained quartzite can be traced with scarcely a break around a complex series of minor F1 folds. The quartzite beds maintain approximately the same thickness normal to the bedding around the fold-hinges (Class 1C folds of Ramsay, 1967), whereas the intervening layers of less competent rock thicken into the fold cores to form Class 3 folds.

The minor F1 folds in the Ardrishaig Phyllites are coplanar with major and minor folds in the Crinan Grits. Their axial planes dip very steeply towards the north-west, parallel to the slaty cleavage in the metamudstones. However, their fold hinges are strongly curved within a fairly constant axial-plane orientation, giving rise to minor F1 folds plunging to either the north-east or south-west at moderately steep angles. Locally, the hinges of F1 folds change pitch through more than 90° within a short distance, forming curvilinear folds. Wherever graded bedding or ripple-drift bedding allows the stratigraphical order of the sedimentary beds to be determined, its relationship with the slaty cleavage, or its equivalent as a plane of grain flattening, shows that these D1 structures are all upward-facing. No evidence of an earlier, pre-D1, fabric has been noted.

14.3 Interpretation

The sedimentological features of the Ardrishaig Phyllites and the Crinan Grits have not been described in any detail from Kilmory Bay, and warrant further study. The Ardrishaig Phyllites probably represent tidal-flat deposits, like the Craignish Phyllites, their stratigraphical equivalent to the north-west of the Loch Awe Syncline (Anderton, 1975), whereas the graded beds of the Crinan Grits were evidently deposited by turbidity currents in deeper water.

Following the injection of sedimentary dykes, and the intrusion of dolerite sills, all of these rocks were affected by the first phase of the regional deformation (D1) under conditions of chlorite-grade metamorphism. The resultant slaty cleavage (S1) is axial-planar to a series of upward-facing major F1 folds with a north-east trend. This geometry is incompatible with the interpretation by Bailey (1922) that the Kilmory Bay Syncline is a later structure, superimposed upon a primary nappe-complex. Although the major F1 folds in the Crinan Grits generally plunge at a moderately steep angle, towards the north-east, the minor F1 folds in the Ardrishaig Phyllites typically have curved hinges, plunging to the south-west, as well as to the north-east. The curvilinear nature of these folds reflects the non-cylindroidal nature of the F1 fold-buckles as they formed, subsequently accentuated by the deformation (Roberts and Sanderson, 1974; cf. Roberts, 1959). This has caused the individual fold-hinges to rotate away from the position in which they were formed, at a high angle to the stretching direction, while undergoing a relative increase in their length. Typically, this gives rise to individual folds with curved hinges, pitching away from one another in opposite directions within a common axial plane.

14.4 Conclusions

The Kilmory Bay GCR site provides a representative cross-section through the upper part of the Argyll Group, from the Ardrishaig Phyllites (for which the complete sequence is exposed) into the overlying Crinan Grits. Graded bedding in the Crinan Grits can be used to determine that this formation is younger than the Ardrishaig Phyllites, as was first demonstrated by the Geological Survey in 1911, making this site one of historical interest. These two formations are folded by the compound Kilmory Bay Syncline, a major early fold, which is one of the three major folds that comprise the regionally important Loch Awe Syncline.

The rocks display a great variety of sedimentary and structural features, some of which are seldom seen with such clarity in the Dalradian, making this site of national interest. Graded bedding, accompanied by channelling and lateral facies changes, together with cross-bedding and cross-lamination, is found throughout the rock succession. Strain in the hinge-zones of the major folds is, in places, sufficiently low that the evidence for the origin of certain rather enigmatic sedimentary structures, such as sedimentary injections and dykes, is preserved in the more competent beds.

In addition, the clean, wave-washed exposures and 3-D nature of some parts of the coastal section, allow the relationships between major and minor fold structures, and a great variety of cleavage types, to be studied with exceptional precision. In the Ardrishaig Phyllites, the extreme contrast in lithology between beds of gritty quartzite, up to 2 m thick, and interbedded units of what was originally a somewhat silty mudrock, gives rise to an extraordinary range of cleavage refraction geometries. Superb examples of minor F1 folds are seen in the Ardnoe Member at the stratigraphical base of the Crinan Grits, with equally good examples of minor F1 folds with curved hinges being found within the Ardrishaig Phyllites.

15 PORT CILL MALUAIG (NR 722 700–NR 714 690)

J.L. Roberts and P.W.G. Tanner

15.1 Introduction

This relatively small GCR site is located along the seaward edge of the raised beach to the south-west of Port Cill Maluaig, on the east coast of Loch Caolisport in Knapdale (Figure 34). Minor geological structures are the main focus of attention, as the rocks all belong to the Ardrishaig Phyllite Formation and show very little overall variation in lithology. The 'Ardrishaig Phyllites', as previously known, are the uppermost formation of the Easdale Subgroup. They have been intruded by basaltic sills, and all of the rocks have undergone greenschist-facies regional metamorphism within the biotite zone.

The GCR site lies on the south-east limb of the F1 Ardrishaig Anticline (Figure 34), which is correlated with the Aberfoyle Anticline on the south-east side of the F4 Cowal Antiform to form part of an overall F1 structure that is generally referred to as the Tay Nappe. The site is located within the Knapdale Steep Belt (Roberts, 1974) and, in contrast to the other GCR sites in Knapdale, the rocks have been affected by *both* the D1 and D2 phases of the Grampian Event. These two phases of early deformation are closely related to one another: D1 resulted in the development of the slaty cleavage (S1), which was overprinted and virtually destroyed by the development of the later, closely spaced S2 fabric. Bedding in these rocks is inverted and, together with S1, dips steeply towards the north-west; it is cut by a penetrative S2 fabric which dips at a lower angle in the same direction (inset on Figure 34).

This site provides exceptional examples of minor F2 folds with strongly curvilinear fold hinges, which form miniature elongated basins and domes locally, where they affect thin beds of fine-grained quartzite. It also provides a lithological and structural contrast with the Ardrishaig Phyllites within the *Kilmory Bay* GCR site, which lie on the opposing, north-west limb of the Ardrishaig Anticline, and are dominated by early (D1) minor structures.

There is no published map that gives details of the geology of the area around, and including, the GCR site and the only description is in a field guide by Roberts (1977c). However, a 13.4 m-thick basic meta-igneous sill, exposed at the north end of the section, figured prominently in a study of variations in fluid flow during regional metamorphism across Knapdale (Skelton *et al*., 1995).

15.2 Description

The Ardrishaig Phyllites at this site consist of grey-green phyllitic metamudstone and metasiltstone, interbedded with fine-grained quartzite and uncommon metalimestone. The quartzite beds vary in thickness along their length and some are seen to die out within a few metres. A number of the thicker quartzite beds contain discontinuous, calcite-rich, layers or lenses.

Minor F2 folds are common. They are identified from the fact that they fold the following: (a) pre-existing slaty cleavage in metamudstone, or finely-spaced cleavage in metasandstone; (b) a penetrative fabric in the basic meta-igneous bodies; (c) a pre-existing striation lineation; and (d) in a few instances, early isoclinal folds. The minor F2 folds verge overall towards the north-west, and are associated, in the phyllitic rocks, with a penetrative, finely-spaced crenulation cleavage developed parallel to their axial surfaces. This cleavage forms the dominant fabric in the rock, dipping north-west at a moderately steep angle (30–60°), consistently shallower than the bedding (60–80°). A fibrous mineral lineation, plunging at 25–45° to the west-north-west, defines the D2 stretching direction.

The mesoscopic and minor F2 folds occur as Class 1C folds (Ramsay, 1967) where they affect the more-competent layers of fine-grained quartzite, rather than Class 3 folds, which are developed in the less-competent layers formed by the phyllitic rocks. Thus, the more-competent layers tend to maintain the same thickness, as they are traced around the fold hinges, while the less-competent layers thicken into the fold hinges, so that overall the folding is similar in style.

The F2 fold hinges mostly plunge north-east at a moderately steep angle. However, some minor F2 folds have hinges that are strongly curved within their axial planes, so that their plunge passes from north-east through the horizontal to south-west within a short distance. Where two adjacent curvilinear minor folds run parallel to one another, the two fold trains are commonly 'out of phase', with plunge culminations in one, being adjacent to plunge depressions in the other, and nearest neighbours in the two fold trains plunging in opposing directions. Alternatively, adjacent minor folds affecting the same bed may plunge, sometimes steeply, in opposite directions (Figure 35). Excellent examples of curvilinear F2 fold-hinges are seen to the south-west of a thin Palaeogene basalt dyke at NR 717 697, giving rise to hump-backed exposures of fine-grained quartzite, all closely packed together.

The D2 deformation strongly affects, and overprints, the earlier S1 cleavage, which lies close to the bedding and is difficult to distinguish from the microcrenulation form of S2 in the field. Minor F1 folds are rarely seen in these rocks, probably due to the intensity of the D2 deformation. However, an area of reddened rocks, exposed on the raised beach 50 m to the north-east of the small beach at Port Mhoirich (NR 716 696), displays a series of minor, possibly F1 folds, affected by the F2 folding.

A gently dipping to horizontal crenulation cleavage locally affects the D2 structures and represents the late-stage deformation that is seen generally throughout Knapdale.

15.3 Interpretation

The Ardrishaig Anticline is a major fold structure in the South-west Grampian Highlands that can only be recognized on stratigraphical grounds, from the correlation of the Ardrishaig Phyllite Formation and Erins Quartzite Formation, within the Cowal Antiform to the south-east, with the equivalent Ardrishaig Phyllite Formation and Crinan Grit Formation to the north-west (Figure 34). The relative structural age of the Ardrishaig Anticline is a matter of inference, since the nature of the early (D1) structures within the Cowal Antiform, has been obscured by the intensity of the D2 deformation. Recognition of the age of the Ardrishaig Anticline, as an F1 fold, relies upon evidence from the equivalent Aberfoyle Anticline in the Highland Border region (see the *Ardscalpsie Point* and *Cove Bay to Kilcreggan* GCR site reports in Tanner et al., 2013b). Having concluded that the Ardrishaig Anticline is a D1 structure, it is then clear, that the north-westerly vergence displayed by the F2 folds on the lower limb of this fold at Port Cill Maluaig, corresponds to the same vergence shown by F2 folds on the lower limb of the Tay Nappe in the Aberfoyle Anticline on the south-east limb of the Cowal Antiform (for example at the *Cove Bay to Kilcreggan* GCR site).

The curved nature of the F2 fold hinges at Port Cill Maluaig reflects the non-cylindroidal character of the initial F2 fold-buckles, which can be interpreted as having been accentuated by the intensity of the D2 deformation (Roberts and Sanderson, 1974). Individual fold hinges change their direction of plunge in a regular manner, forming sinuous lines that lie in a plane. The well-developed stretching lineation lies in the same plane, bisecting the angle between opposing plunge directions (the 'apical angle'). This provides the clue as to how the originally horizontal bedding surfaces have been distorted to form basins and domes on a metre scale, by folding followed by progressive rotation of individual fold hinges towards the stretching direction. The reasons for this are discussed in the *Glen Orchy* GCR site report in Treagus et al. (2013), and examined in full in the *Strone Point* GCR site report in this paper.

15.4 Conclusions

The coastline south of Port Cill Maluaig exposes a representative cross-section through the Ardrishaig Phyllites on the south-east limb of the Ardrishaig Anticline, one of the major early (F1) folds in the South-west Grampian Highlands. The rocks consist of grey-green phyllitic metasiltstones and metamudstones, with beds of fine-grained quartzite and two thick sills of dark green, amphibolitic meta-igneous rock. The rocks are affected by two phases of regional deformation: the D1 phase produced an early cleavage lying very close to the bedding, presumably on the limbs of tight to isoclinal F1 folds, whilst the D2 phase resulted in development of a penetrative fabric, which virtually obliterated the evidence for the sedimentary and early structural history of these rocks.

The GCR site displays superb examples of minor F2 folds with strongly curved fold hinges. They are displayed at Port Cill Maluaig in three-dimensions with a perfection that is difficult to match from elsewhere in the Dalradian outcrop.

16 STRONE POINT (NN 113 088–NN 121 089)

P.W.G. Tanner

16.1 Introduction

One of the more-important major structures in the South-west Grampian Highlands is the Ardrishaig Anticline, an early fold whose axial trace passes just to the north of Inverary and continues to the south-west, parallel to the west coast of Loch Fyne. The significance of the Ardrishaig Anticline lies in the fact that it is folded south-eastwards over the Cowal Antiform to correlate with the Tay Nappe (Aberfoyle Anticline) in the Highland Border region. The actual closure of the Ardrishaig Anticline is not well exposed but its geometry is almost certainly mirrored by that of one of its satellite folds, the Strone Point Anticline, which is seen at Strone Point, 2 km east of Inverary (Figure 36). The hinge-zone and north-west limb of the Strone Point Anticline may be examined readily at this GCR site.

This GCR site is also valuable for providing an accessible section in which to examine the range in rock types, and structures, seen in the Ardrishaig Phyllite Formation south-east of the Loch Awe Syncline, as compared to those found in the equivalent Craignish Phyllite Formation on the north-west limb of the syncline, for example, at the *Fearnach Bay* GCR site.

The Strone Point section was first described for the Geological Survey by Hill (1905), who considered that the rocks there are representative of the facies shown by the Ardrishaig Phyllite 'Group' in the surrounding part of Cowal. Apart from reporting the presence of 'isoclinal folding', Hill (1905) gave no specific details of the structure. The only published account of the structural geometry is by Borradaile (1972b), who analysed in detail the mode of formation of the highly curvilinear minor folds that occur there. This GCR site provides an ideal opportunity to examine the geometry of these minor folds and their relationship to the regional stretching lineation.

16.2 Description

The Ardrishaig Phyllites are admirably exposed in the almost continuous rock exposure found on the narrow rock platform, backed by low cliffs a few metres high. The phyllitic metamudstones and metasiltstones that characterize the formation, are grey-green in colour, with a silvery or silky sheen, and contain beds of quartzite and metacarbonate rock. The quartzite beds are prominent, but few in number, and consist of fine-grained quartzite in uniform, non-graded units up to 2 m thick. The phyllitic rocks contain orange-weathering bands of metacarbonate rock, probably dolomitic, that are 20–50 cm thick, and are particularly common in the hinge-zone of the major anticline. There is also one small body of metadolerite, of the type commonly found in the Ardrishaig Phyllites elsewhere in the area.

The coastline east-north-east from Strone Point provides an excellent, slightly oblique, section through the north-west limb of the Strone Point Anticline (which includes a mesoscopic fold pair related to the major structure), and the hinge-zone, but the south-east limb lies beneath the loch. The closure of this fold, identified and named by Borradaile (1972b), is well exposed at NN 1180 0880, where it is marked by symmetrical folds of metre-scale wavelength, which affect interbanded phyllitic rocks and orange-coloured metacarbonate rock. Although no way-up evidence has been recorded from these rocks, the Strone Point fold is an upward-facing anticline based upon evidence of inverted graded in the adjoining Ben Lui Schists (Borradaile, 1972b).

An intensely developed, penetrative cleavage, seen as a spaced cleavage in the metacarbonate rocks, and a slaty cleavage in the metamudstones, is axial planar to the major fold. In the hinge-zone, it is associated with a zig-zag interdigitation of the two lithologies, resulting in a blurring of the original boundaries between the layers (Figure 37). The cleavage is very consistent in orientation (Figure 36, inset; Figure 38 c), and on the north-west limb of the fold it dips consistently more steeply to the north-west than the bedding. This is in agreement with the presence of the anticlinal hinge to the south-east, but appears at first sight to be in conflict with the observation that both S- and Z-shaped, congruous, tight to isoclinal minor folds occur on the same fold limb. However, these folds give a consistent sense of vergence to the south, when viewed in the vertical plane, with minor axial planes consistently dipping at a steeper angle to the north-west, than bedding. The change in the down-plunge minor fold pattern, is due to a randomly distributed variation about the horizontal in the plunge direction of the minor folds from north-east to south-west. Indeed, individual minor folds are strongly curvilinear, and change their plunge direction in a single exposure (Borradaile, 1972b, plate 2). This is particularly well seen in the quartzite beds, as illustrated by Voll (1960, figures 19 a and b) from just outwith the GCR site (Figure 38 a and b). Quartzite beds are thickened into bulbous shapes where they pass around minor fold closures, but are considerably thinned on the fold limbs.

An important feature of these rocks is the development of a down-dip stretching lineation on the slaty cleavage planes (Borradaile, 1972b), which is marked by a fine, silky striation lineation, first described by Clough (in Gunn *et al.*, 1897) from the Cowal peninsula. When plotted on the same stereographic projection as the poles to cleavage, the D1 fold hinges and bedding/cleavage intersection lineation lie on a great circle that is only at an angle of 04° to the mean orientation of the penetrative cleavage, and contains the stretching lineation (Figure 38 c). From a thin-section study of 40 deformed quartz grains in slaty metamudstone, Borradaile (1972b) confirmed that the lineation is parallel to the long axes of the grains, and hence represents the X direction.

Pyrite crystals that grew in the mudstone before deformation are commonly streaked-out parallel to the stretching lineation, a feature accentuated by their subsequent oxidation to form rusty-looking, commonly elliptical streaks on the cleavage plane. It is of historical interest that the Duke of Argyll published a paper in 1889 interpreting these artefacts as fossil annelid worm tubes.

16.3 Interpretation

The Ardrishaig Phyllites have been affected by a single ductile deformation phase (D1) that resulted in the formation of the Strone Point Anticline and its associated minor folds, spaced and slaty cleavages, and stretching lineation. The only evidence of later ductile deformation is given by open warps that locally affect the early cleavage in the hinge-zone of the major structure, and centimetre-spaced kink bands, which are common from Strone Point northwards along the west side of the headland.

The Strone Point Anticline is an upward-facing F1 structure, whose axial surface is inferred to dip north-west at 29°, parallel to the mean orientation of the associated penetrative cleavage. In the absence of bedding readings from the south-east limb, and with minor folds and bedding cleavage intersection lineations having orientations that vary in trend by 180° or more (Figure 38 c), there is a problem with determining its axis orientation. Within the hinge-zone of the major fold, a strong ?axial lineation plunges at 10–26° to the north, which would make the fold a sideways-closing structure. However, if the major fold mimics the behaviour of its minor satellites, and is strongly curvilinear, the orientation seen in one slice through the structure at Strone Point, is but a single snapshot of a structure that has an overall near-horizontal axis that trends north-east–south-west, and hence faces up to the south-east.

The Strone Point Anticline lies to the south-east of a major F1 fold of the same age, the Ardrishaig Anticline, which is considered to represent the Tay Nappe to the north of the later Cowal Antiform (Bailey, 1938; Roberts, 1966a). The presence of other major folds of the same age as the Ardrishaig Anticline in the Ardrishaig Phyllites is consistent with the recent interpretation of the Tay Nappe as a plexus of large fold closures, rather than a single major fold (Krabbendam *et al*., 1997).

An S1 slaty, to spaced cleavage, is dominant at this locality and is related to the formation of the Strone Point Anticline. Although Borradaile (1972b) stated confidently that the main cleavage was the first to form in these rocks, and is of D1 age, he also recorded the presence of a coplanar crenulation cleavage in a few instances. Further fabric analysis is needed to clarify this situation.

The significance of the curvilinear minor folds, and their relationship to the stretching lineation, is discussed in the *Glen Orchy* GCR site report in Treagus et al. (2013). The wide range in minor fold axis orientations at the Strone Point GCR site has resulted from the rotation of the originally horizontal, or slightly sinusoidal minor fold hinges, towards the orientation of the NNW-trending stretching lineation (the X direction of the strain ellipsoid), with increasing, but locally variable, amounts of strain. Only a single section through the major fold is available for study, so it is not known whether the major fold in this case is also curvilinear.

16.4 Conclusions

Strone Point is an excellent GCR site for demonstrating the techniques used for unravelling the geometry and evolution of a large fold structure, in this instance the Strone Point Anticline. It also provides a well-exposed and readily accessible representative section of the Ardrishaig Phyllite Formation to the south-east of the Loch Awe Syncline, which is stratigraphically equivalent to the Craignish Phyllite Formation to the north-west (see the *Fearnach Bay* and *Craignish Point* GCR site reports).

The main value of this locality lies in the fact that the Strone Point Anticline is of the same age as, and can act as a proxy for, the neighbouring but poorly exposed Ardrishaig Anticline. The axial trace of the latter major structure runs in a north-easterly direction a few kilometres to the north-west of Strone Point. This surrogate role is important, as the Ardrishaig Anticline is the north-western equivalent of the Tay Nappe, one of the largest fold structures in the South-west Grampian Highlands. Thus, the structures described from this GCR site may be compared in detail with the fabrics (such as cleavages) and minor fold structures found in the core of the Tay Nappe, for example at the *Cove Bay to Kilcreggan* GCR site, described in Tanner et al. (2013b).

This is also a valuable location for studying the mode of development of folds with highly curved hinges, and complements a similar study, in rocks of the Beinn Udlaidh Syncline at the *Glen Orchy* GCR site (Treagus et al., 2013), which were at the time much more deeply buried in the Earth's crust, and hence hotter.

17 KILCHRENAN BURN AND SHORE (NN 035215, NN 034227)

J.E. Treagus

17.1 Introduction

This GCR site, on the north-west side of Loch Awe, provides the best exposures of the Kilchrenan Conglomerate Member (formerly the Kilchrenan Boulder Bed), an important unit, which occurs near the top of the Argyll Group. More precisely, it is found near or at the top of the Tayvallich Slate and Limestone Formation and below the Tayvallich Volcanic Formation and Loch na Cille 'Boulder Bed' (see the *West Tayvallich Peninsula* GCR site report). The member is important for the light that it throws on the sedimentary environment of the Tayvallich Subgroup, but it is particularly important for information that it yields on the strain experienced by these rocks in the first phase of deformation. Its characteristics have been described briefly by Borradaile (1973, 1977).

The Kilchrenan Conglomerate Member is a thin, but locally continuous unit, confined to some 4 km outcrop length in the hinge-zone of the F1 Loch Awe Syncline. The metaconglomerate has only undergone weak deformation after D1, and comprises clasts of one dominant lithological type in a homogeneous matrix of another; these facts are important in its use for strain measurements. The exposures are around the village of Kilchrenan, to its south on the shore of Loch Awe and to its west in the Kilchrenan Burn. The only other outcrops of a metaconglomerate occupying a similar stratigraphical position are found east of Loch Awe, but those have not been described formally.

17.2 Description

This GCR site incorporates two localities for the Kilchrenan Conglomerate Member, a single bed, at most 30 m thick, which is otherwise poorly exposed. The Kilchrenan Burn exposes the member intermittently from NN 0335 2289 to NN 0342 2276, but the best exposures are seen in weathered rocks on the west bank near the former grid reference (Figure 39, locality A). The member here consists of a matrix of unbedded slaty metamudstone (once a carbonaceous silty mud) supporting elliptical clasts of gritty quartzite. In some beds the clasts are tightly-packed oblate spheroids (Figure 40), which typically have maximum lengths of some 20 cm and minimum lengths of some 5 cm, the latter being perpendicular to the slaty cleavage. The cleavage, which dips at low angles to the north-west (e.g. 030/16), dominates the matrix. Bedding is rarely evident, but appears to be slightly less steeply dipping to the west, than the cleavage.

The second locality consists of exposures on the shore of Loch Awe (Figure 39, locality B), which are best seen from NN 0351 2157 to NN 0340 2148, south-west of Struan, particularly in the low, moss-covered, crags away from the shoreline. The description of the member given above generally applies, but here angular black mudstone and rounded limestone clasts have also been incorporated into the conglomerate, and there is a range in clast sizes (long axes), from 20 cm down to 0.5 cm. There are rare clasts of granite, first noted by Kynaston and Hill (1908). Another feature here is the presence of a crenulation cleavage that post-dates the slaty cleavage and slightly deforms the clasts. Although the deformation has resulted in generally oblate-shaped clasts, they do show a direction of stretching, down-dip within the NW-dipping (e.g. 030°/27°) cleavage.

17.3 Interpretation

Very little comment has been made in the literature regarding the sedimentary character of the Kilchrenan Conglomerate or of its significance in terms of the depositional environment of the Tayvallich Subgroup. Kilburn *et al*. (1965) interpreted it as a slump conglomerate, and its position between slump breccias and conglomerates in the Tayvallich Slate and Limestone Formation below, and the breccias of the Loch na Cille 'Boulder Bed' in the Tayvallich Volcanic Formation above (see the *West Tayvallich*

Peninsula GCR site report), would support the interpretation of the deposition of the subgroup on an unstable shelf. The strong sorting of the clasts seen in the Kilchrenan Burn locality and their assumed high original sphericity, suggest a shallow water deposit, which has been transported to, and preserved in, deeper waters. Subsequent volcanicity and faulting supports the concept of increasing instability of the shelf (Anderton, 1985). The presence of rare granite clasts has important implications for the palaeogeography of the region and warrants further research.

Structurally, both localities are situated on the gentle west- to NW-dipping, south-eastern limb of the Loch Awe Syncline. Although bedding is not easily distinguished in these rocks, this structural context is supported by the observation of cleavage dipping more steeply than bedding, as is seen in the Kilchrenan Burn locality. However, according to the mapping of Borradaile (1973), the exposures on the shore of Loch Awe lie on the short limb of a parasitic fold, with cleavage dipping shallower than the overturned bedding (Figure 39). The cleavage in which the clasts are deformed is clearly the first slaty cleavage. Measurement of the clast shape should therefore give an indication of the strain experienced during D1, with the usual assumptions that the clasts were originally subspherical and that they will give a minimum value of the strain for the whole rock. Provisional strain ratios for the clasts give X:Y:Z average ratios of 1.5:1.23:0.54 for the quartzite clasts of the Loch Awe locality and up to 1.8:1.8:0.3 for the oblate shapes in the Kilchrenan Burn (Figure 40).

17.4 Conclusions

The Kilchrenan Burn and Shore GCR site is primarily of national importance for the study of pebbles in the Kilchrenan Conglomerate Member of the Tayvallich Slate and Limestone Formation. Conglomerates in which original rounded pebbles of one rock-type are not in contact with one another and sit in a uniform matrix, are extremely unusual and are of great importance to structural studies. The pebbles were deformed in the earliest deformation experienced by the Dalradian rocks of the South-west Grampian Highlands (D1) and the dimensions and orientation of the pebbles indicate the direction and strength of the forces that formed the mountain belt.

Of almost equal importance is the light that this unique sedimentary deposit can throw on the nature of the sedimentary basin in late Argyll Group time, particularly its depth, slope and stability. From the initial roundness of the pebbles and the very localized nature of the deposit, it has been suggested that the basin was on a shallow shelf, which became increasingly unstable with time, eventually resulting in the volcanicity and contemporaneous faulting seen in the overlying rocks.

18 WEST TAYVALLICH PENINSULA (NR 732 878–NR 690 803)

E.A. Pickett

18.1 Introduction

This large GCR site is on the west coast of the Tayvallich peninsula, which lies on the Argyll mainland, east of the Isle of Jura. It provides some of the best exposures of Neoproterozoic submarine extrusive rocks and associated reworked volcanic rocks in the British Isles, including spectacular pillow lavas and hyaloclastites. The site is of stratigraphical importance as it provides a well-exposed section through the Crinan Grit Formation, the Tayvallich Slate and Limestone Formation and the Tayvallich Volcanic Formation. The lower boundary of the Tayvallich Volcanic Formation is particularly well exposed. The southern end of the peninsula also displays the controversial Loch na Cille Boulder Bed which lies within the volcanic sequence.

This area has been a classical geological site since the early 20th century when B.N. Peach discovered the pillow lavas and so established the existence of extrusive igneous rocks in the Dalradian of the South-west Grampian Highlands (Peach, 1904; Peach *et al.*, 1911). His observations and interpretations of pipe amygdales and lava flow morphology were essential in establishing the stratigraphical sequence of the area. Elles (1935), in her study of the Loch na Cille Boulder Bed, disputed Peach's proposed stratigraphy but Allison (1941) conclusively vindicated the original interpretation. Wood (1964) described in detail structures observed in pillow lavas on the peninsula. Wilson and Leake (1972) carried out the first major geochemical study of a wide range of rocks from the Tayvallich peninsula (including lavas, intrusive rocks and sedimentary rocks) and Graham (1976) made further analyses of the meta-igneous rocks rocks as part of a wider study of metabasalts in the South-west Grampian Highlands. Recent geochemical studies of the Tayvallich lavas were carried out by Hyslop and Pickett (1999), Pickett *et al.* (2006) and Fettes *et al.* 2011 as part of investigations of Dalradian basic meta-igneous rocks and their tectonic significance. The most recent detailed study on the entire sequence was carried out by Gower (1977) who described a series of localities along the west coast of the peninsula. Much of the following description is based on his observations.

A feature of great importance within the site is a trachytic ('quartz keratophyre') intrusion that is believed to be contemporaneous with the extrusion and deposition of the volcanic and volcaniclastic rocks. This intrusion was dated by Halliday *et al.* (1989) who obtained a conventional multi-grain U-Pb zircon age of 595 ± 4 Ma, thus providing an age for the Tayvallich Subgroup and indicating that most of the Dalradian Supergroup is of Neoproterozoic age. Dempster *et al.* (2002) subsequently reported a U-Pb TIMS (Thermal Ionisation Mass Spectrometry) zircon age of 601

± 4 Ma from a tuff on the west coast of the Tayvallich peninsula at Port Bhuailteir (NR 688 810) (Figure 41). This date is within error of the earlier determination, and confirmed the age of the Tayvallich Volcanic rocks.

The structure of the area is dominated by the F1 Tayvallich Syncline, which plunges at 20 - 50° to the south-south-west and has an axial plane which dips to the east-south-east at 70 - 80°. This fold is an important component of the major Loch Awe Syncline. There is a strong axial planar slaty cleavage associated with the fold although subsequent deformation episodes have overprinted this cleavage with a crenulation cleavage locally. A stretching lineation plunges down the dip on the slaty cleavage surfaces.

18.2 Description

This large site is best considered as a number of separate sections (Figure 41):
(1) the axial zone of the syncline at Loch na Cille, (2) Rubha Riabhag to An Aird, (3) An Aird to Port an Sgadain, (4) Port an Sgadain to Port Bealach nan Gall, 5) the closure of the Tayvallich Syncline around the northern slopes of Barr na h-Iolaire.

18.2.1 Area 1: Loch Na Cille

This area is in the axial zone of the Tayvallich Syncline and contains the youngest rocks of the area, vertically dipping feldspathic metasandstones, which are exposed on the south-east limb of the syncline at NR 698 806. Mineralogically they are distinct from the older Crinan Grits in that they contain detrital epidote and more feldspar and mica. Gower (1973) proposed the name Kells Grit for these metasandstones, which have been correlated with the Loch Avich Grit of the Southern Highland Group farther north-east (Borradaile, 1973) (see the Loch Avich GCR site report).

The Kells Grit is underlain by a sequence of metalimestones and metabreccias containing clasts of igneous rock within a calcareous matrix. One of these metabreccias is the Loch na Cille Boulder Bed, which lies at the base of the metalimestone succession. It crops out down the centre of the peninsula of Rubha na Cille and is best exposed at the northern end (NR 688 803). It stratigraphically overlies pillow lavas that are exposed on the west coast and is in turn overlain by grey metalimestone containing lava fragments. The Loch na Cille Boulder Bed is particularly well exposed on the east shore of Rubha Fitheach, where fragments of pillow and vesicular lava are deformed and flattened within the main cleavage. The clasts are predominantly fragments of mafic meta-igneous rock and pebbles of pale-coloured felsic metavolcanic rock in a chloritic, calcareous or quartzose matrix. However, Elles (1935) also recorded the presence of quartzite, gneiss and schist and noted that many of the boulders are rounded. In a recent re-examination of the metabreccias, Prave (1999) also observed a range of clasts in beds towards the top of the unit, which he termed ‘extrabasinal’, including granitic rocks, schists, felsic volcanic rocks and quartzite.

18.2.2 Area 2: Rubha Riabhag to an Aird

North-eastwards along the coast from Rubha na Cille progressively older members of the Tayvallich Volcanic Formation are exposed. The lithologies include massive lava, excellently preserved pillow lava, pillow breccia and stratified and reworked hyaloclastite and volcaniclastic rocks. The hyaloclastites were first recognized by Gower (1977). The pillow lavas are particularly well exposed at NR 693 817 with pillows up to 3 m by 1 m in size (Figure 42). Stratigraphical way-up is well defined by the pillow morphology and by concentrations of feldspar crystals (up to 1 cm long) at the pillow bases. Many of the pillows also display concentric bands of vesicles towards their tops. Recent geochemical studies have shown that the pillow lavas have high-Fe-Ti tholeiitic compositions and were derived from a relatively enriched mantle source (Fettes *et* al., 2011).

Within the volcanic sequence is a distinctive 8 m-thick bed of 'porphyry breccia', described by Peach *et al.* (1911), which is composed of pink-orange trachytic boulders (up to 1 m across) within a tuffaceous matrix (NR 690 813). These boulders are lithologically similar to a trachytic 'feldspar porphyry' or 'quartz keratophyre' intrusion (over 16 m thick), which is exposed in the intertidal zone nearby (NR 695 822). The mineralogy of this intrusion was studied in detail by Peach *et al.* (1911). It contains tabular albite crystals up to 3 mm in length displaying chess-board twinning within a finer grained albite-rich groundmass containing quartz, epidote, white mica, chlorite and opaque minerals. Parts of the intrusion show a poorly developed mineral banding of alternating mafic and felsic layers parallel to the upper contact. This contact is concordant with the surrounding bedded volcanic rocks and a chilled margin is present locally (Gower, 1977). It is from this intrusion that zircons have provided a U-Pb age of 595 ± 4 Ma, one of only two reliable radiometric dates from the upper part of the Dalradian Supergroup (Halliday *et al.*, 1989).

18.2.3 Area 3: An Aird to Port An Sgadain

The small peninsula of An Aird is composed largely of a metabasaltic laccolith, which might have acted as a feeder to some of the overlying pillow lavas. The western side of the peninsula is composed of pillow lavas, overlain to the east by pillow breccias and hyaloclastites. The pillow lavas at this locality are excellently exposed and are the ones originally described by Peach (1904) and Peach et al. (1911). Graham (1976) described their petrology, noting a range of features including microphenocrysts of twinned plagioclase (now albite), 'trachytic' textures and amygdales. Northwards from An Aird, are pillow breccias and hyaloclastites (Gower, 1977). Thin rusty-weathering metalimestone lenses are also present and a distinctive dolomitic breccia occurs directly south-west of Port an Sgadain.

18.2.4 Area 4: Port An Sgadain to Port Bealach Nan Gall

At the southern end of this section, the base of the Tayvallich Volcanic Formation and its contact with the underlying Tayvallich Slate and Limestone Formation are very well preserved. Here the lava flows have pipe amygdales at their base and scoriaceous tops, commonly with rusty-weathering carbonate veins penetrating between the blocks of lava (Gower, 1977). Peach *et al*. (1911) used these exposures to demonstrate that the sequence here is the right way up and dips at 40° to the east. During its extrusion the lowest lava produced load structures and push folds in the underlying soft sediment. In places bulbous masses of lava became detached and isolated within the sediment (Wood, 1964). The Tayvallich Slate and Limestone Formation is very variable and includes dolomitic metalimestones, phyllitic rocks, thin-bedded and massive metalimestones and conglomeratic beds. The metalimestone beds contain numerous quartz clasts (up to 1.5 cm across). The formation exhibits a variety of sedimentary structures including grading, cross-bedding, channels and flute casts, possibly reflecting a turbiditic origin. At Port Bealach nan Gall, the quartzitic Crinan Grits are exposed beneath the metalimestones. At this locality the Crinan Grits comprise graded, very coarse-grained, locally conglomeratic metasandstone containing excellent examples of flute casts (50–60 cm long). Beds of metamudstone, one of which contains large carbonate nodules (up to 2 m in diameter), are also exposed.

18.2.5 Area 5: Barr Na H-Iolaire

The closure of the Tayvallich Syncline can be traced out by following the scarp that represents the base of the lavas around the northern slopes of Barr na h-Iolaire. Although the underlying metalimestone is largely obscured, the base of the Tayvallich Volcanic Formation can be traced around the minor folds associated with the closure of the syncline. In their detailed map of this area, Wilson and Leake (1972) showed the distribution of beds of meta-agglomerate within the Tayvallich Volcanic Formation. They described the distinctive geochemical composition of one meta-agglomerate, the 'Barbreack Agglomerate', which they found to be much more siliceous than the pillow lavas and to contain very high levels of Nb, Zr, U, Th, La and Ce.

18.3 Interpretation

The sequence preserved along the west coast of the Tayvallich peninsula is interpreted as recording a period of rapid subsidence and basin deepening associated with active rifting along a continental margin during late-Dalradian times (Anderton, 1985). The Crinan Grit, which is the oldest formation at this GCR site, was interpreted by Anderton as the result of turbidite deposition in submarine fan channels.

The overlying Tayvallich Slate and Limestone Formation is also largely turbiditic. The orientation of cross-bedding and flute casts suggests current directions from the south and south-east (Gower, 1977). Anderton (1985) interpreted the abrupt change from clastic to carbonate sedimentation as the result of a relatively sudden re-organization of the palaeogeography. This stopped or diverted the clastic input and the sediment-starved shelves began to accumulate carbonate-rich deposits. Erosion and reworking of the carbonates generated turbiditic deposits in adjacent basins.

The overlying Tayvallich Volcanic Formation indicates a period of magmatism caused by eventual rupturing of the continental crust within the widening rift (Anderton, 1985). Wood (1964) used the orientation of push folds in underlying metasedimentary rocks to determine that lavas at the base of the section flowed northwards into soft sediments. Extrusion of the volcanic pile was largely submarine, as indicated by the pillow lavas and hyaloclastites, and many of the lavas are extensively spilitized, probably reflecting sea-floor hydrothermal processes that occurred soon after extrusion. Graham (1976) interpreted the geochemistry of the lavas and associated intrusions as indicating initial continental rifting preceding ocean-floor spreading. Recent work has confirmed that the lavas have enriched characteristics, typical of within-plate ocean-island basalts (OIB) but also found on extensional plate margins where thinning of the continental lithosphere prior to rupturing results in basin formation and relatively low degrees of decompression melting of the underlying mantle (Fettes *et al*., 2011). Geochemical evidence of crustal contamination has been found in some of the Tasyvallich lavas, though not in those from the Tayvallich peninsula.

The trachytic intrusion exposed at the GCR site is geochemically related to the extrusive rocks and probably represents part of the subvolcanic feeder system (Graham, 1976). Lithologically similar trachytic blocks occur as clasts in overlying volcanic breccias, supporting geochemical evidence that the intrusion is cogenetic with the volcanic rocks and hence is a suitable subject for radiometric dating of the volcanism.

Reworking of volcanic material by sedimentary processes produced a variety of volcaniclastic rocks, which are intercalated with the extrusive rocks. The Loch na Cille Boulder Bed towards the top of the Tayvallich sequence was originally interpreted by Peach *et al*. (1911) as a tectonic breccia or 'crush-conglomerate'. Various other origins were later proposed, including a glacial origin (Elles, 1935), a porphyritic lava flow including xenoliths of 'acidic' boulders (Allison, 1941) and a hyaloclastite resulting from a submarine fissure eruption (Gower, 1977). Hyslop and Pickett (1999) interpreted the unit as being deposited from debris flows and forming part of the overall Tayvallich volcanic-volcaniclastic sequence. Conversely, Prave (1999) revived the glaciogenic interpretation of Elles (1934), citing the presence of extrabasinal clasts, many of them rounded, of granite, schist, felsic volcanic rock and quartzite in beds towards the top of the unit. These observations, coupled with the stratigraphical proximity of the Loch na Cille Boulder Bed to the *c.* 595 Ma trachytic intrusion, led Prave to suggest that the boulder bed is evidence for a Varangerian glaciation (*c.* 620–590 Ma) in the Dalradian of Scotland (see Stephenson et al., 2013a). On balance it would seem that there is good evidence for some form of volcaniclastic deposition, but that the higher beds with the extrabasinal clasts merit further investigation.

18.4 Conclusions

The West Tayvallich Peninsula GCR site preserves an excellently exposed succession that passes stratigraphically up from the Crinan Grit Formation, through the Tayvallich Slate and Limestone Formation and the Tayvallich Volcanic Formation to the Loch na Cille Boulder Bed and, at the top of the sequence, the Kells Grit. These formations comprise some of the most distinctive and persistent stratigraphical markers of the Dalradian terrane and hence are valuable for correlation purposes. In addition to its stratigraphical significance, the site is of national importance for its wide range of extrusive volcanic rocks and associated volcaniclastic sedimentary rocks, formed during rifting of continental crust in the Neoproterozoic. A variety of igneous and sedimentary processes can be demonstrated and are invaluable in current studies involving reconstructing the tectonic regime and environments in which the higher parts of the Dalradian succession were deposited. The site exhibits minor structures associated with the Tayvallich Syncline, an important component of the major F1 Loch Awe Syncline that controls outcrop patterns over a wide area of the South-west Grampian Highlands.

A trachytic intrusion and a stratiform tuff from this site have yielded concordant U-Pb (zircon) ages of *c.* 600 Ma. These are the only reliable radiometric dates from the upper part of the Dalradian and are therefore critical in establishing a chronostratigraphical framework for the Dalradian Supergroup as a whole.

The site has been a classic locality for teaching and research, since at least 1911, and it was here that pillow lavas, erupted underwater, were first recognized and described in the Dalradian of Scotland. The study of these exceptional volcanic rocks in terms of their geochemistry and depositional setting continues today.

19 SOUTH BAY, BARMORE ISLAND (NR 868 714–NR 872 702)

J.L. Roberts and P.W.G. Tanner

19.1 Introduction

Barmore Island is situated a few kilometres north of Tarbert, on the east side of the Kintyre peninsula. It is connected to the mainland by a narrow isthmus (Figure 43). The coast immediately south of the isthmus provides a well-exposed and unique cross-section through the Dalradian rocks of Knapdale and North Kintyre, which includes the critical contact between the Argyll and Southern Highland groups. This rugged coastline also displays the effects of glacial scouring by Pleistocene ice-sheets, flowing southwards along Loch Fyne.

The sequence begins with the Stonefield Schist Formation that lies at the top of the Crinan Subgroup and appears to be conformable with the overlying Loch Tay Limestone Formation, which here represents the Tayvallich Subgroup. Towards the south-east, these rocks pass stratigraphically upwards, with no discernable break, into the Southern Highland Group, which comprises the Glen Sluan Schist Formation, the Green Beds Formation, and the Beinn Bheula Schist Formation. The Loch Tay Limestone forms one of the most important marker horizons for lithostratigraphical correlation within the Dalradian Supergroup. It is equivalent to the Tayvallich Slate and Limestone Formation, which lies in the core of the Loch Awe Syncline farther to the north-west.

This GCR site lies adjacent to the major F4 Tarbert Monoform, which separates the Knapdale Steep Belt to the north-west from the inverted rocks of the Cowal Antiform to the south-east. This setting is comparable with that of the *Portincaple* GCR site (Tanner et al., 2013b), which is located on the closure of the Highland Border Downbend (F4) between the Cowal Antiform and the Highland Border Steep Belt. The regional metamorphic grade reached by the rocks in the two areas is however different: those at Portincaple are barely in the biotite zone, whereas those at Barmore Island are in the garnet zone. A detailed structural analysis has not been made of the rocks of this site and they warrant further study.

Following descriptions of the general geology by the Geological Survey (Peach *et al*., 1911) and by McCallien (1925), some of the structural features were described by Roberts (1966b, 1974, 1977c). A notable early study of the origin of the 'green beds' was carried out by Phillips (1930), and the petrography of the Loch Tay Limestone has been investigated in considerable detail by Gower (1973) and Graham *et al.* (1983).

19.2 Description

19.2.1 Stratigraphy

The Stonefield Schists occur at NR 806 714 as garnetiferous mica schists, interbedded with quartz-mica schist and schistose gritty metasandstone. The bedding is approximately vertical and strikes north-east, with graded bedding in one exposure showing that the sequence youngs to the south-east. A transition zone some 6 m wide separates the Stonefield Schists from the Loch Tay Limestone. Within this transition zone, thin, weathered, calcareous bands appear, become thicker up-sequence and are replaced progressively by beds of dark-grey sugary metalimestone (up to 7 cm thick) separated by thin beds of dark metametamudstone.

The Loch Tay Limestone is about 75 m thick in this section, and occurs typically as a grey crystalline metalimestone (containing some dolomite) with a granular texture, interbedded with minor amounts of dark schistose metamudstone. It has a banded appearance due to differential weathering of the centimetre-scale layers, some of which are slightly more micaceous, whereas others are more quartzose. Graded bedding in the more-quartzose layers is revealed by the transition from a quartz-rich metalimestone at the base of the bed to an increasingly carbonate-rich rock at the top. Such grading shows younging to the south-east, so the beds are inverted. A carbonate metabreccia, in which highly deformed fragments of metalimestone are flattened in a plane parallel to the steep bedding and stretched down dip, is developed close to the south-east margin of the formation. Pinch-and-swell structure commonly affects the more-quartzose layers, as well as quartz-plagioclase veins (Figure 44). The metalimestone is affected by a system of linked, listric faults associated with thick bodies of haematite-stained fault breccia. Two thick sills of basic meta-igneous rock, now garnet-biotite amphibolite, occur within the outcrop of the Loch Tay Limestone.

The Glen Sluan Schist Formation is exposed immediately to the south-east of the Loch Tay Limestone at NR 868 710. There is a sharp contact between orange-weathering metacarbonate rock and the stratigraphically younger micaceous schist, which contains numerous thick quartz lenses. The Glen Sluan Schists consist largely of quartzose mica schist, which is interbedded with minor amounts of schistose pebbly metasandstone towards its contact with the Green Beds Formation. Albite is commonly developed as conspicuous porphyroblasts in the more-pelitic layers, and can be distinguished from detrital feldspar in the more-psammitic layers by the fact that the porphyroblasts appear undeformed in hand specimen.

Individual 'green beds' occur within the succession from the Glen Sluan Schist Formation at NR 869 710 to the Beinn Bheula Schist Formation south of Sgeir Port a' Ghuail (Figure 43). Where they form a dominant proportion of the succession, they define the Green Beds Formation. They occur typically as massive chlorite-epidote-biotite schists, interbedded with epidotic metaconglomerates, quartz-mica schists, and albite schists. The bedding in the 'green beds' is defined by very regular, parallel-sided, alternating fine- and coarse-grained layers, which vary in colour from green to dark greenish grey, commonly with a speckled appearance (possibly due to biotite). The layers vary in thickness from 1–20 cm and their distinctive greenish colour is due to the presence of chlorite and epidote. Locally, individual beds pass downwards into metaconglomerate (schistose pebbly grit) with detrital grains of quartz and feldspar. Graded bedding and small-scale channelling are well developed locally in schistose gritty metasandstones interbedded with the green-coloured beds. They show overall younging towards the south-east, but some beds clearly young in the opposite direction, suggesting that early (F1) folds are present in the section.

The Green Beds Formation passes upwards into the Beinn Bheula Schist Formation, which is exposed at the south-east end of the section. The latter consists of a very thick sequence of garnetiferous mica schists, biotite schists, quartz-mica schists, albite schists, and schistose gritty metasandstones containing detrital grains of quartz, often of a bluish hue, together with pink or white oligoclase feldspar.

19.2.2 Structure

The rocks at this GCR site were deformed during the D1–D4 phases of Caledonian deformation. No F1 folds have been observed but there is an early schistosity (S1), lying subparallel to bedding. Locally, both bedding and S1 are deformed by tight F2 folds, giving rise to 'strain-bands' (Clough, in Gunn *et al.*, 1897) and minor folds that plunge steeply north-east and verge towards the north-west. Typically, the F2 folds have an intense cleavage developed parallel to their axial planes, which affects the earlier S1 schistosity. The 'strain-bands', or S2 spaced cleavage domains as they are now known, are typically developed in the schistose gritty metasandstones.

L3 linear structures trend north-east, and are generally horizontal, but there is a 500 m-wide zone between NR 871 705 and NR 872 700 where these F3 fold hinges plunge more steeply towards the north-north-east. F4 folding affects the rocks to the south-east of the Loch Tay Limestone, giving rise to alternating zones of steeply dipping and flat-lying rocks. Typically the F4 folds have axial planes dipping at a moderately steep angle towards the south-east, parallel to a crenulation cleavage, while their fold hinges plunge at less than 10° to the north-east.

19.3 Interpretation

Stratigraphically, the Loch Tay Limestone can be correlated with the Tayvallich Slate and Limestone Formation, which crops out in the core of the Loch Awe Syncline, farther to the north-west (see the *West Tayvallich Peninsula* GCR site report; Figure 34). These formations mark a change in sedimentation from the pebbly quartzites and pebble metaconglomerates, typical of the upper parts of the Argyll Group, into the pebbly metagreywackes of the overlying Southern Highland Group. Such a change in lithology is not accompanied by any corresponding change in the mode of deposition, since graded bedding is a characteristic feature of this part of the Dalradian sequence, both above and below the Loch Tay Limestone. Thus, there is no sedimentological evidence for a profound break in the succession, or orogenic unconformity, between the Argyll Group and the Southern Highland Group.

The Green Beds Formation occurs at the same stratigraphical level as the Loch Avich Lavas Formation, which crops out farther to the north-west within the Loch Awe Syncline (see the *Loch Avich* GCR site report). The 'green beds' occur as finely laminated rocks, passing imperceptibly into graded beds of schistose gritty metasandstone, suggesting that they were deposited by turbidity currents. Their composition suggests a volcanic origin and J.B. Hill (in Peach *et al.*, 1911) suggested that they were derived from the weathering of basic igneous rocks. Their volcaniclastic origin has been confirmed by the regional petrographical and geochemical study of Pickett *et al.* (2006).

The GCR site lies on the steep, NW-dipping, overturned, south-eastern limb of the major, upward-facing F1 Ardrishaig Anticline and forms part of the Knapdale Steep Belt. The S2 spaced cleavage and minor folds verge to the north-west as a 'symmetry-constant continuation' of the earlier D1 deformation, here represented only by an S1 schistosity (Voll, 1960; Roberts, 1974). In a short distance to the south-east, the inverted beds become less steeply inclined as the Ardrishaig Anticline is folded over the broad F4

Cowal Antiform, and the minor F4 folds and SE-dipping S4 crenulation cleavage seen at this site are related to the Tarbert Monoform, a major F4 structure developed on the north-western limb of the Cowal Antiform.

19.4 Conclusions

The South Bay, Barmore Island GCR site provides a representative cross-section through the Dalradian rocks of the uppermost Argyll Group and the Southern Highland Group in Knapdale and North Kintyre. The exposures show clearly that the contact between the two groups is conformable, with no evidence of a structural break, or orogenic unconformity.

The Loch Tay Limestone Formation is exposed over the full width of its outcrop, allowing it to be compared with its stratigraphical equivalent to the north-west, namely the Tayvallich Slate and Limestone Formation. The site also provides an excellent section through the Green Beds, which are otherwise poorly exposed in the South-west Grampian Highlands. Their composition and finely-laminated nature suggests that they were originally volcaniclastic deposits, which were subsequently reworked by turbidity currents. They may be correlated with pillow lavas at Loch Avich, to the north-west. This GCR site also provides typical examples of the structural features that developed in response to three distinct phases (D1, D2 and D4) in the deformation history of the Dalradian rocks in the South-west Grampian Highlands.

20 LOCH AVICH (NM 957174–NM 952155)

E.A. Pickett

20.1 Introduction

This GCR site lies at the north-eastern end of Loch Avich, west of Loch Awe. It contains the type locality for the Loch Avich Lavas Formation and shows a complete section through the underlying gritty metasandstones and metamudstones of the Loch Avich Grit Formation. The uppermost part of the Tayvallich Volcanic Formation, which underlies the Loch Avich Grit Formation, is also present in the northern part of the site. The Loch Avich Grit and the Loch Avich Lavas are the youngest observed Dalradian rocks in the core of the Loch Awe Syncline and form the lower part of the Southern Highland Group. Hence the lavas are of great significance in the tectono-magmatic evolution of the Dalradian basin(s).

The Loch Avich Grit Formation has long been recognized and was first described by Hill (1905) and Bailey (1913). The outcrop of the Loch Avich Lavas Formation was originally classed as 'epidiorite' (Hill, 1905) and lavas (Bailey, 1913) and was not distinguished from the older Tayvallich Volcanic Formation. It has only relatively recently been recognized and described as a separate formation lying above the Loch Avich Grit Formation (Borradaile, 1972a). This discovery was especially important as the lavas represent the only known extrusive volcanic rocks in the Southern Highland Group. Several samples from the Loch Avich Lavas Formation were analysed geochemically and compared with lavas from the Tayvallich Volcanic Formation by Borradaile (1973) as part of his investigation of the structure and stratigraphy of the northern Loch Awe district. The Loch Avich lavas were the subject of recent research by Pickett *et al.* (2006) into the origin of the volcaniclastic Green Beds, with which they have been correlated stratigraphically, and were also included in the regional geochemical synthesis of Dalradian volcanism by Fettes *et al.* (2011).

20.2 Description

Around Loch Avich, the Tayvallich Volcanic Formation and the overlying Loch Avich Grit Formation lie within the core of the Kilchrenan Syncline (Figure 45), which is part of the major F1 Loch Awe Syncline. A complete section through the Loch Avich Grit Formation is preserved in the Allt Mór burn, north-west of the hill of An Cnap, where its observed thickness has been calculated as 650 m (Borradaile, 1973). Elsewhere in the Loch Awe area it attains a thickness of 1100 m. The formation typically comprises chloritic and feldspathic gritty metasandstones, which show graded bedding, together with green and green-grey metamudstones (Borradaile, 1973). The metasandstones are laterally discontinuous on a large scale and exhibit evidence of channelling. They contain angular grains of K-feldspar, some plagioclase, quartz, detrital epidote and opaque minerals in a chloritic matrix. Black slaty metamudstones, black calcareous metamudstones and detrital volcanic material occur as lenses within the metasandstones. Good exposures of typical lithologies can be observed near the burn junction at NM 954 165, north of An Cnap. Slightly calcareous black metamudstones occur at the top of the formation and can be observed by the roadside at the east end of Loch Avich in the southern part of the GCR site (NM 951 155). These rocks display NW-dipping bedding as well as slaty and crenulation cleavages.

The overlying Loch Avich Lavas Formation is represented only by a small outcrop preserved in the core of the Kilchrenan Syncline, on the hill of An Cnap, north of Loch Avich, at NM 954 158 (Figure 45). The formation consists of an observed thickness of 300–500 m of greenschist-facies pillow lavas with no significant sedimentary intercalations (Borradaile, 1973). Recent geochemical studies have indicated that the Loch Avich lavas are tholeiitic and have basaltic andesite to andesitic compositions (Pickett *et* al., 2006; Fettes *et* al., 2011). The south-western end of the lava outcrop terminates within the synclinal fold closure, where the lavas directly succeed black calcareous metamudstones at the top of the Loch Avich Grit Formation.

The following description of the lavas is based on field observations made by Pickett (1997) and Hyslop and Pickett (1999). Well-preserved pillow lavas are present in the central part of the outcrop, whereas more homogeneous lavas are exposed along the south-eastern margin. The pillows are 1–1.5 m wide and are separated by 5 cm-thick epidotic rims of formerly glassy pillow rinds. The asymmetrical pillow shapes indicate that they are the right way up (Figure 46). The pillow cores are generally porphyritic, whilst the margins are fine grained and display flow structures. Mineralized and chloritized vesicles are common. Several pillows display concentric rims of vesicles, which have been infilled by quartz in places, producing a ‘gritty’ appearance. The lavas are generally fine grained and are altered to a pale buff to light greenish grey colour. Many display a foliation, especially away from the central part of the outcrop. Small pockets of green slaty metamudstone are intercalated with the pillows locally.

The structure of the area is dominated by the Kilchrenan Syncline whose axial trace trends north-east–south-west through the southern part of the GCR site, across the hill of An Cnap (Borradaile, 1973). The north-west limb of the syncline, on which most of the site lies, is overturned, with bedding dipping at *c.* 40–75° to the north-west. On this limb, the south-west-striking S1 slaty cleavage dips at *c.* 40–50° to the north-west.

20.3 Interpretation

The Loch Avich Grit Formation was interpreted by Borradaile (1973) as a sequence of turbiditic deposits that, together with the overlying Loch Avich Lavas Formation, was generated in a subsiding deep marine basin during rifting of a continental margin during late-Dalradian times (Anderton, 1985). The Loch Avich lavas are interpreted as representing the final phase of a period of extensive volcanism (that also generated the Tayvallich Volcanic Formation; see the *West Tayvallich Peninsula* GCR site report), which accompanied the lithospheric stretching and rifting. They constitute the youngest expression of volcanism in the Dalradian and are generally regarded as a source of the volcaniclastic detritus in the green beds that occur at a comparable stratigraphical level throughout much of the Southern Highland Group outcrop (Pickett *et al.*, 2006).

Borradaile (1973) suggested that the Loch Avich lavas were fed by some of the sills that occur below the lavas of the Tayvallich Volcanic Formation, although there is no direct field evidence to corroborate this. He interpreted the Loch Avich lavas as being comagmatic with the Tayvallich volcanic rocks and its sill-feeders, the Loch Avich lavas representing a new phase of submarine volcanism. However, the geochemistry of the Loch Avich lavas does exhibit some suble differences from that of the underlying Tayvallich volcanic rocks (Hyslop and Pickett, 1999; Pickett *et al.*, 2006). Both show evidence of mixing of enriched and depleted components of their mid-ocean-ridge type mantle source and the Loch Avich Lavas in particular show signs of crustal contamination (Fettes *et al.*, 2011).

20.4 Conclusions

The Loch Avich GCR site is the type locality for the Loch Avich Lavas Formation, the only known extrusive volcanic rocks in the Southern Highland Group and the highest in the Dalradian succession. The complete section extends from the top of the

Tayvallich Volcanic Formation, through the Loch Avich Grit Formation to the base of the Loch Avich Lavas Formation.

The Loch Avich Grit Formation exhibits a range of metasedimentary rocks, which are valuable for the interpretation of the depositional environments in latest Neoproterozoic time. The Loch Avich Lavas Formation is well exposed and displays good pillow forms with many relict igneous features. These lavas are the subject of current geochemical studies associated with research into the origin of the widespread volcaniclastic Green Beds with which they have been correlated stratigraphically. The section is critical for studies of Dalradian stratigraphy and in reconstructing the depositional environment and tectono-magmatic setting of the uppermost part of the Dalradian Supergroup.

21 BUN-AN-UILT, ISLAY (NR 295 692–NR 29 694)

C.A. Bendall

21.1 Introduction

The rocks of Islay may be separated into four major divisions, namely the Rhinns Complex, Colonsay Group, Bowmore Sandstone Group, and Dalradian Supergroup. The boundaries between these units are tectonic and poorly exposed, and partly because of this, correlation of the Rhinns Complex, the Colonsay Group and the Bowmore Sandstone Group with rocks elsewhere in Scotland has proved equivocal. Of interest here is the Bowmore Sandstone Group and its relationship to the Dalradian rocks. The boundary between these two units is a tectonic break known as the Loch Skerrols Thrust. This structure was first recognized and described by Wilkinson (1907) who noted the existence of mylonitic rocks at the junction between the two units. Bailey (1917) alluded to the presence of a tectonic break on stratigraphical grounds, because the Bowmore Sandstone rocks appear to lie within the western limb of the Islay Anticline and are not repeated on the eastern limb.

For much of its length, the thrust is not exposed and its presence is inferred from a change in lithology and by the local strain increase apparent in nearby exposures. The only locality where the thrust is actually exposed is at Bun-an-uillt on the east side of Loch Gruinart. Here the thrust is manifested by a shear-zone with intensely foliated rocks (mylonites) that separates the Jura Quartzite of the Dalradian Argyll Group to the south from the Bowmore Sandstone to the north.

The interpretation and significance of the Loch Skerrols Thrust is by no means resolved and, consequently, nor is the stratigraphical status of the Bowmore Sandstone. The latter, which shows no significant signs of metamorphism, has been variously correlated with the Torridonian (Wilkinson, 1907; Green, 1924; Peach and Horne, 1930; Stewart, 1969), the Moine (Roberts, 1974), or the Dalradian Crinan Grit Formation (Fitches and Maltman, 1984).

21.2 Description

Whereas the stratigraphy and structure of the Dalradian rocks of Islay are reasonably well understood, the same cannot be said for the Bowmore Sandstone Group. It is generally poorly exposed, but is assumed to be bounded by the Loch Skerrols Thrust to the east and the Loch Gruinart Fault to the west. It has been described by Stewart (1969) and Fitches and Maltman (1984) as consisting of monotonous grey-brown feldspathic sandstones, with indistinct bedding and poorly developed tectonic fabrics. The group was divided into two by Amos (1960): the Laggan Sandstone Formation overlain by the Blackrock Grit Formation. The Laggan Sandstone Formation consists of fine- to medium-grained sandstones with thin siltstones and mudstones, and the Blackrock Grit Formation consists mainly of coarse-grained sandstones with pebbly bands.

The area around Loch Gruinart is low lying and exposure inland is very poor. Exposure of the thrust is limited to a thin strip along the eastern shoreline of the loch (NR 2950 6930, Figure 47), where it separates the Jura Quartzite Formation from the Blackrock Grit Formation. There are two outcrops of the Jura Quartzite along the shoreline. This is due to the shallow dip of the thrust (see below) and later faulting. South of the thrust at NR 2947 6919, the Jura Quartzite rocks are white, medium-grained quartzites, which have a somewhat shattered appearance. Bedding is difficult to identify and the planar surfaces in the rock are most likely to be tectonic foliation surfaces, as they contain a stretching lineation. The Loch Skerrols Thrust is not a simple planar boundary but a zone of intensely deformed and recrystallized rocks (Figure 48), which Fitches and Maltman (1984) referred to as the Loch Skerrols Shear-zone. The intensity of the foliation increases in the Jura Quartzite as the thrust (shear-zone) is approached, as indicated by its closer spacing. The foliation surfaces generally have shallow dips and a well-developed stretching lineation, which generally plunges towards 110° but with a variable amount of plunge due to later folding. The later folds are upright open structures that have hinges trending approximately east–west. However, these are only minor folds with wavelengths of a few tens of centimetres.

Immediately north of the shear-zone are greenish weathering impure feldspathic sandstones, which belong to the Blackrock Grit Formation. They also have a fabric, but this fabric becomes less intense northwards away from the shear-zone. The foliation surfaces are more micaceous than those in the Jura Quartzite and the rocks have an upright crenulation cleavage striking about 200°. Unlike the quartzites they do not show an obvious stretching lineation. The exposure ends a few tens of metres north of the shear-zone. About a hundred metres farther north, just west of Bun-an-uillt house, there is prominent headland that consists of shattered white quartzite. This appears to be Dalradian and was interpreted by Fitches and Maltman (1984) as lying adjacent to a later fault, not the Loch Skerrols Thrust. The Loch Skerrols Thrust is cut by several later faults such as this one, and these faults, along with later folding, probably explain the outcrop pattern of the thrust at the GCR site.

21.3 Interpretation

As emphasised by Fitches and Maltman (1984), the interpretation of the Loch Skerrols Thrust is vital to any consideration of the stratigraphical affinity of the Bowmore Sandstone. Early workers (see introduction) had considered that the Bowmore Sandstone could be correlated with either the Torridonian or the Moine rocks of the Northern Highlands, which presumably would imply that the Loch Skerrols Thrust is a structure analogous to the Moine Thrust. Fitches and Maltman concluded, however, that the thrust is a re-activated normal fault that developed into a shear-zone during the same deformation event that produced the Islay Anticline. Because the strain associated with the thrust diminishes considerably towards Tallant (NR 330 590), some 11 km south-south-east of this GCR site, and Laggan Bay, they also concluded that there might be stratigraphical continuity between Dalradian rocks on the north-western limb of the Islay Anticline, and the Bowmore Sandstone. The Bowmore Sandstone was thought to be 'laterally equivalent to the Crinan Grits', being the shallow-water correlative of the deeper water grits.

A provenance study of clasts in the Bowmore Sandstone has revealed various gneisses and pegmatites of Lewisian type (Saha, 1985). In particular, distinctive blue quartz that is characteristic of Scourian granulite-facies gneisses is present, as it is in the Colonsay Group and the Dalradian rocks of north-east Islay. The Blackrock Grit Formation also contains pebbles of chert, jasper and ferruginous sandstone indicative of non-metamorphic or low-grade sedimentary rocks (e.g. Torridonian) in the source area.

Saha (1989) also studied the variation in strain associated with the Loch Skerrols Thrust, and concluded that the thrust is a break-thrust that developed on the overturned north-western limb of the Islay Anticline. He drew no conclusions as to the stratigraphical affinity of the Bowmore Sandstone. However, it is implicit in his structural model that it must be Dalradian and it would be reasonable to reach the same conclusion as Fitches and Maltman (1984), namely that it correlates with the Crinan Grit Formation. In this case the older Jura Quartzite would have been thrust over the younger Bowmore Sandstone (=Crinan Grits). Finally, it should be stressed that there is as yet no consensus as to the precise significance of the Loch Skerrols Thrust as a major tectonic structure, nor to the stratigraphical affinity of the Bowmore Sandstone, and it has even been argued that the lithologies could be consistent with the Grampian Group (Stephenson and Gould, 1995).

21.4 Conclusions

The Bun-an-uilt GCR site includes the only exposure of the Loch Skerrols Thrust, one of the more enigmatic structures of the Scottish Caledonides, and hence is of great national importance. However, due to poor exposure its tectonic significance and the relationship between the rocks that lie above and below it are poorly understood. The Jura Quartzite lies above the thrust, and the Blackrock Grit Formation of the Bowmore Sandstone Group lies below. The tectonic significance of the thrust is therefore important in defining the stratigraphical status of the Bowmore Sandstone Group, which has been variously correlated with the Torridonian, the Moine or the Dalradian. The most recent interpretations have suggested that the thrust is not a major tectonic boundary (such as the Moine Thrust) and, therefore, that the Bowmore Sandstone may be the lateral equivalent of rocks belonging to the Upper Argyll Group of the Dalradian.

22 KILCHIARAN TO ARDNAVE POINT, ISLAY (NR 185 587–NR 298 740)

C.A. Bendall

22.1 Introduction

Isolated from the rest of the South-west Grampian Highlands by the Loch Gruinart Fault, rocks belonging to the Colonsay Group crop out in western Islay and on the islands of Oronsay and Colonsay. On Islay they form a continuous outcrop occupying the northern half of the Rhinns of Islay (Figure 49). This GCR site includes an almost continuous section along the west coast of the Rhinns, from Kilchiaran to Ardnave Point. Also included within this site is a coastal exposure of the meta-igneous basement rocks that form the southern part of the Rhinns of Islay. Their contact with the Colonsay Group is a zone of high strain.

The Colonsay Group was first described by Wilkinson (1907), and more recently by Stewart (1969), Stewart and Hackman (1973), Fitches and Maltman (1984), Bentley (1988) and Muir *et al*. (1995). The group is 5.5 to 6 km thick. On Islay, the lower part consists of a series of low-grade metasedimentary rocks, which are predominantly gritty metasandstones and metamudstones. These rocks have been subjected to several phases of deformation, which have resulted in a series of major upright folds trending north-east–south-west. The upper part of the group is exposed only on Oronsay and Colonsay. Stewart and Hackman (1973) proposed a tentative correlation between the upper part of the Islay succession and the lower part on Oronsay, but Bentley (1988) thought it possible that up to a kilometre of intervening strata is covered by sea between Islay and Oronsay.

None of the above authors drew any firm conclusions as to the stratigraphical correlation of the Colonsay Group with other major units in the Scottish Highlands. Stewart (1969) concluded that it could not be correlated reliably with any other stratigraphical unit, but Stewart and Hackman (1973) tentatively suggested a correlation with the Appin Group (Dalradian) of the Lochaber area. Fitches and Maltman (1984) did not rule out its correlation with the Dalradian, but they did have reservations on structural criteria. Bentley (1988) suggested that the Colonsay Group–Appin Group correlation is unlikely on geochronological grounds (see below). He also ruled out a correlation with the Torridonian on structural and tectonic criteria, and with the Moine Supergroup on geochronological grounds, but proposed a tentative correlation with the Iona Group.

The basement rocks of the Rhinns Complex (Muir, 1990; Muir *et al.*, 1994a), are now known to be younger than was thought by early workers such as Wilkinson (1907), who assumed that this series of amphibolite-facies metagabbros and metasyenites were part of the Lewisian Gneiss Complex. Subsequent investigations have yielded an age of 1782 +/- 5 Ma (Marcantonio *et al.*, 1988), and although this correlates well with the tectonothermal reworking of the Lewisian during the Laxfordian Event (Mendum *et al.*, 2009), stable isotopes indicate that the gneisses of the Rhinns Complex are derived dominantly from juvenile mantle material, which is not known to be associated with the Laxfordian Event. Consequently they are now believed to be part of an extensive Palaeoproterozoic orogenic province in the North Atlantic region (Dickin, 1992; Muir *et al.*, 1992). They cannot therefore be correlated with any other rock units in Scotland. They are too old to be Moine or metamorphosed Torridonian and they are too young to be Lewisian.

22.2 Description

The basement rocks of the Rhinns Complex are not particularly well exposed, and the best exposures occur on the west coast of the Rhinns. They consist predominantly of metagabbros and metasyenites, interpreted as an alkaline igneous complex that has been subjected to multiphase deformation and amphibolite-facies metamorphism (Muir *et al.,* 1992). The metasyenite is well exposed along the coast where it appears as a pink feldspathic foliated rock, with thin schistose amphibolite sheets; good examples of these may be found about 1.5 km south-west of Kilchiaran at NR 185 591. Towards the boundary with the overlying Colonsay Group the fabric intensifies, becoming mylonitic at the boundary (the Kilchiaran Shear-zone or Bruichladdich Slide). The position of the boundary is easily identified by the distinct change in lithology from the sheared feldspathic gneiss to a gritty metasandstone (the Eilean Liath Grit), with an intense mylonitic fabric. For the most part, the actual contact between the two lithologies is not exposed but lies within a deeply eroded gully. However, at NR 1878 5933, 1 km south-west of Kilchiaran, the contact is exposed at low tide (Figure 50). At this locality the shear-zone strikes at *c.* 040°, but the strike varies inland due to folding (see Figure 49).

The Colonsay Group on Islay was mapped by Stewart and Hackman (1973), who identified ten formations that are essentially a series of gritty metasandstones, metamudstones and metagreywackes (Table 1). They described the Eilean Liath Grit, the Rubha Gàidhealach Grit and the Crosprig Grit as coarse feldspathic sandstones. Cross-bedding was identified in both the Rubha Gàidhealach Grit and the Crosprig Grit, and conglomeratic facies with pebbles up to 4 cm in size were recognized in the Crosprig Grit.

There is good exposure of the Eilean Liath Grit along the coast south-west of Kilchiaran and the overlying Kilchiaran Phyllite is well exposed at Kilchiaran Bay (NR 201 599). The phyllite is a mudstone with thin silty bands, which has been deformed and metamorphosed and now has a strong slaty cleavage. A thin bed of possible volcaniclastic origin has been identified near the top of the formation by Batchelor (2011). The overlying formation is the

Rubha Gàidhealach Grit, which is exposed on the headland at NR 198 601. The overlying Rubha na h-Àirde Mòire Phyllite is fine grained at the base where the cleaved metamudstone has been quarried for slate; however, it grades upwards into flaggy fine-grained metasandstones. These are exposed around the headland of Rubha na h-Áirde Mòire (Figure 49) where they occupy the core of a large, kilometre-scale syncline. Above the Rubha na h-Àirde Mòire Phyllite are the Cosprig Grit and the Kilchoman Phyllite. The Kilchoman Phyllite consists of grey metamudstones with calcareous bands; graded beds have been observed in this unit (Stewart and Hackman, 1973). Muir *et al.* (1995) re-examined these rocks and concluded that the Crosprig Grit and the Kilchoman Phyllite are not separate formations but are simply the Rubha Gàidhealach Grit and the Kilchiaran Phyllite repeated by upright folding (Table 1).

They did not, however, re-examine the upper four formations; these were described by Stewart and Hackman only. The Smaull Greywacke consists of a sequence of graded metagreywacke units, some of which are be quite coarse grained, with grain sizes of up to 2–3 mm. This grades upwards into the Sanaigmore Phyllite, which is a dark-grey metamudstone with silty calcareous bands. Above this, is the Sanaig Greywacke, which consists of graded metagreywacke. The youngest Colonsay Group formation on Islay is the Ardnave Formation, which consists of a thick sequence of metamudstones and fine-grained laminated metagreywackes.

The structure of the Colonsay Group was described in detail by Fitches and Maltman (1984). They identified four stages of deformation on both Islay and Colonsay, which they numbered D1 to D4; these numbers relate to the Colonsay Group only. The first phase, D1, is a grain-alignment fabric, which is sub-parallel to bedding. D2 is expressed by a strong stretching lineation developed in metasandstones, and by close to isoclinal, recumbent to reclined minor sheath folds. These folds have axial planar crenulation and pressure-solution cleavages. D3 is the phase of deformation that produced most of the mapped folds. These are fairly upright, gently NE-plunging folds with wavelengths up to several hundred metres, and axial planar crenulation cleavages. D4 is represented by chevron folds and kink bands, and associated crenulation cleavages. The axial planes to D4 folds are upright and strike east–west.

On Islay the dominant phase of deformation is D3; all the folds shown on Figure 49 are F3 folds. Minor structures of more than one generation can be observed in most exposures of phyllitic rock, for example, two crenulation cleavages, one steep and the other flat lying, are present in the Kilchiaran Phyllite near Kilchiaran. Minor folds are ubiquitous in the coarser grained horizons.

Two thin lamprophyre dykes intrude the Kilchiaran Phyllite at Kilchiaran Bay; these have a tectonic fabric and consequently they were intruded at least prior to some of the deformation.

Associated with this deformation is low-grade metamorphism. Chlorite, white mica, and rare biotite have been identified in Colonsay Group rocks (Fitches and Maltman, 1984), indicating that the rocks were subjected to greenschist-facies metamorphism.

22.3 Interpretation

It is now generally accepted that the basement to the Colonsay Group, namely the Rhinns Complex, is not Lewisian but is Palaeoproterozoic. There are no rocks of comparable age in Scotland, but rocks similar in age *and* lithology are found on Inishtrahull off the north coast of Ireland (Muir *et al*., 1992). It is possible that the Rhinns Complex is a unique terrane in the British Isles, and may possibly be linked to the Ketilidian Belt of south Greenland (Stone *et al.,* 1999). Alternatively, it is possible that it forms the basement to the Dalradian Supergroup over much of its outcrop. Much, therefore, depends on the tectonic significance of the Loch Gruinart Fault, which is not exposed.

Although the nature of the contact between the Rhinns Complex and the Colonsay Group is tectonic (the Kilchiaran Shear-zone or Bruichladdich Slide), the Colonsay Group almost certainly forms the cover to the Rhinns Complex basement. The contact shear-zone was interpreted as a sheared unconformity by Wilkinson (1907) and subsequently by Bentley (1988), on account of the presence of a 'basal conglomerate' close to the boundary. However, Stewart and Hackman (1973) disputed this, as they did not detect any facies changes close to the shear-zone, and observed that the five lowest units of the Colonsay Group are truncated against the basement. They therefore interpreted the contact as a zone of high strain and a tectonic break, which they referred to as the Bruichladdich Slide. Muir *et al*. (1995) suggested that the contact is somewhat more complex than the term 'slide' implies, involving tectonic interleaving of Colonsay Group and basement rocks, and renamed it the Kilchiaran Shear-zone. The Kilchiaran Shear-zone/Bruichladdich Slide is folded around F3 folds and hence is either a D1 or D2 structure.

The lowest 800 m of the Colonsay Group succession on Islay has been interpreted as representing delta-top sheet sands and interdistributary muds, whereas the upper part suggests deeper water, delta-slope turbidites. The sediments were derived from the west, from a hinterland of deformed high-grade gneisses with a sedimentary cover (Stewart and Hackman, 1973). Saha (1985) pointed out that the source area could not have been very distant, as the feldspar clasts are angular and fresh. The presence of clasts of blue quartz has been taken to suggest granulite-facies rocks, although the local Rhinns Complex basement is neither granulite facies nor contains blue quartz; a more likely source would be the Lewisian Gneiss Complex of the Hebridean Terrane.

Correlation of the Colonsay Group with other Highland rocks would greatly aid interpretation of the significance of the Loch Gruinart Fault, and the relationship of this west Islay terrane with other Highland terranes. For example, if the Colonsay Group should prove to be an integral part of the Dalradian Supergroup, then the Loch Gruinart Fault would not be a terrane boundary, and the Rhinns Complex could form the basement to the Dalradian elsewhere. However, the earlier, D1 and D2 structures in the Colonsay Group, which are also present in the Rhinns Complex, have no obvious counterparts in the Dalradian of eastern Islay or in the South-west Grampian Highlands; it is the later D3 and D4 structures that can be correlated most readily with those of the Islay Anticline (Fitches and Maltman, 1984; Bentley, 1988). Hence, the Colonsay Group does not appear to have the same tectonic history as the Dalradian. This would imply that the west Islay terrane is unrelated to other terranes in Scotland. Indeed Rogers *et al.* (1989) suggested that it was the docking of this terrane with the Grampian Terrane that initiated the tectonic activity in the Dalradian rocks that is generally referred to as the Grampian Event.

Establishing an age for the Colonsay Group has proved elusive. Bentley (1988) dated some appinitic intrusions on Colonsay, which he interpreted as post-dating the early deformation and pre-dating the late deformation. From $^{40}Ar/^{39}Ar$ stepwise heating methods on hornblende, he suggested that the best estimate of the age of these intrusions is *c*. 600 Ma. This implied that the Colonsay Group is older than 600 Ma, as is some of the deformation that has affected it. However, this date is now believed to be a result of excess argon, and a U-Pb date of 439 ± 9 Ma, derived from zircons in one of the intrusions by ion-microprobe (SHRIMP) is currently accepted as the crystallization age (Muir *et al*., 1997). Furthermore, the intrusion is now considered to have been emplaced after all main phases of deformation and hence the Colonsay Group and its deformation pre-date *c*. 440 Ma. This does strengthen the case for correlating the Colonsay Group with part of the Dalradian, although the difficulties in matching their detailed structural histories remains a problem.

The Colonsay Group is currently interpreted as a sequence of low-grade metasedimentary rocks that were deposited sometime in the Neoproterozoic. These rocks were laid unconformably on a Palaeoproterozoic basement in an intracratonic basin setting, and were possibly deformed during a Neoproterozoic orogenic event(s) that is not recognized in Dalradian rocks. However, recent research suggests that tectonism could have affected at least part of the Dalradian prior to the Grampian Event (Tanner and Bluck, 1999). Hence it may yet be shown that the Colonsay Group does indeed have structural and stratigraphical affinities with the Dalradian rocks of the central Grampian Highlands and this interpretation has been strengthened by U-Pb ages of detrital zircons, which are comparable with the Grampian Group (McAteer *et al*., 2010).

22.4 Conclusions

The continuous section from Kilchiaran to Ardnave Point, on the north-western coast of the Rhinns of Islay, provides excellent exposures of the lower part of the Colonsay Group, arguably the most enigmatic sequence of metasedimentary rocks in the Grampian Terrane. Its stratigraphical affinities are uncertain; the most obvious lithological correlations are with the Grampian Group and lowest Appin Group of the Dalradian. However, rocks of the Colonsay Group record four distinct phases of deformation, including an early event that cannot be recognized in undoubted Dalradian rocks nearby, suggesting that they might belong to a separate west Islay terrane, having a different tectonic history to the main Dalradian outcrop.

The contact of the group with meta-igneous basement rocks of Palaeoproterozoic age is also exposed at this GCR site. The contact is sheared and mylonitic in places and the original relationship between the Colonsay Group and the Rhinns Complex, which is like no other basement in Scotland, has been a matter of some debate.

The age of the Colonsay Group and its relationship to its Palaeoproterozoic basement have profound implications for the identification of the diverse geological terranes that came together during the Caledonian Orogeny to form the Scottish Highlands. Hence, they might provide a vital link in understanding the complex inter-relationships between the Neoproterozoic rocks of North America, Greenland and north-west Europe, and are potentially of international importance.

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Figure 1 Map of the South-west Grampian Highlands showing subgroups of the Dalradian Supergroup, the axial plane traces of

major folds, the line of section A–B on Figure 3 and the locations of the GCR sites included in this paper. Only areas described in this regional paper are ornamented.
GCR sites: 1 Garvellach Isles, 2 Caol Isla, Islay, 3 Rubha a'Mhail, Islay, 4 Kilnaughton Bay, Islay, 5 Lussa Bay, Jura, 6 Kinuachdrach, Jura, 7 Surnaig Farm, Islay, 8 Ardbeg, Islay, 9 Ardilistry Bay, Islay, 10 Black Mill Bay, Luing, 11 Craignish Point, 12 Fearnach Bay, 13 Kilmory Bay, 14 Port Cill Maluaig, 15 Strone Point, 16 Kilchrenan burn and shore, 17 West Tayvallich peninsula, 18 South Bay, Barmore Island, 19 Loch Avich, 20 Bun-an-Uillt, Islay, 21 Kilchiaran to Ardnave Point, Islay.
Abbreviations: AA Ardrishaig Anticline, BF Bolsa Fault, IA Islay Anticline, KBS Kilmory Bay Syncline, KSZ Kilchiaran Shear-zone, LAS Loch Awe Syncline, LGF Loch Gruinart Fault, LST Loch Skerrols Thrust, PBF Pass of Brander Fault, TF Tyndrum Fault, TS Tayvallich Syncline.

Figure 2 Stratigraphical columns (not to scale) showing lateral correlations between members and formations of the Dalradian Supergroup in the South-west Grampian Highlands. A the islands of Islay, Jura and the Garvellachs, B the Loch Awe Syncline, C the Ardrishaig Anticline, core and south-east limb, D and E rocks of uncertain affinity on Islay and Colonsay, and those forming the basement to the Dalradian Supergroup.
GB Great Breccia, DB Disrupted Beds.

Figure 3 True-scale cross-section showing the location of GCR sites included in this paper (numbered as on Figure 1), the correlation between stratigraphical sequences, and major structures, across the South-west Grampian Highlands. Line of section A–B is shown on Figure 1. (Cross-section: P.W.G. Tanner.)

Figure 4 Facsimile copy of part of the geological map of Islay published by E.B. Bailey (1917).

Figure 5 Map of the Garvellach Isles, Firth of Lorn, after Spencer, (1971).

Figure 6 Tillite bed containing large exotic clasts of pink granite, from the north end of Garbh Eileach, Garvellach Isles. Hammer shaft is 47 cm long. (Photo: P.W.G. Tanner.)

Figure 7 Map of the shore section north of Caol Isla distillery, Isle of Islay. Adapted from Fairchild, (1991).

Figure 8
(a) Casts of sand-filled dewatering cracks seen in relief on the base of a metasandstone bed from Leac Thiolastaraidh, north of Caol Isla, Isle of Islay (NR 4297 7037).
(b) Negative print taken from an acetate peel of a typical dewatering crack from Leac Thiolastaraidh. The illustration shows a sandstone bed (s) overlying a layer of mudrock (m), both units having been cut by the upward injection of a sand-filled dewatering crack. Following exposure to erosion at the Earth's surface, the mudrock layer lying beneath the sandstone might be eroded away, leaving the sandstone infill (c) as a cast protruding from the base of the bed, as in Figure 8a.

(Photos: P.W.G. Tanner.)

Figure 9 Map of the coastal section at the Rubha a'Mhail, Isle of Islay, after Fairchild, (1991). The outline map (a) shows the locations of detailed sections (b) and (c).

Figure 10 Stromatolite bodies from Member 3 of the Bonahaven Dolomite Formation, north-east of Port a'Chotain, Rubha a'Mhail GCR site, Isle of Islay.
(a) Domal stromatolite bioherms at Bagh an da Dhorius, NR 410 788. Hammer shaft (arrowed) is 47cm long.
(b) Large bioherm at NR 407 789. Hammer shaft is 47 cm long.
(Photos: P.W.G. Tanner.)

Figure 11 Map of the area around the Kilnaughton Bay, Islay GCR site, south-east Islay.

Figure 12 Stratigraphical log of the pebble beds in the upper part of the Scarba Conglomerate Formation from NR 3479 4440–3492 4464, on the north side of Carraig Fhada, Kilnaughton Bay, Isle of Islay.

Figure 13 Rosettes and blades of kyanite, largely pseudomorphed by kaolinite and pyrophyllite (Burgess et al., 1981), lying on a bedding plane at a low angle to the S1 cleavage in the Jura Quartzite at Kilnaughton Bay, Isle of Islay. Scale is in cm/mm. (Photo: P.W.G. Tanner.)

Figure 14 Map of the area around the Lussa Bay GCR site, Isle of Jura.

Figure 15 A representative, 55 cm-thick, pebbly unit from the Scarba Conglomerate Formation at Lussa Bay, Isle of Jura, showing poorly developed graded bedding with rip-up clasts of metamudstone. Beds young to the right of the photo (south-east). Spirit level (top left) is 5 cm long. (Photo: P.W.G. Tanner.)

Figure 16 Map of the area around the Kinuachdrachd GCR site, Isle of Jura (after BGS 1:50 000 Sheet 36, Kilmartin, 2003 and Anderton, 1977).

Figure 17 Refracted S1 cleavage cutting near-horizontal bedding close to the hinge-zone of a mesoscopic F1 fold, in metasandstone beds, viewed to the north-east, Kinuachdrachd, Isle of Jura. Spirit level is 5 cm long. (Photo: P.W.G. Tanner.)

Figure 18 Map of the area around the Surnaig Farm GCR site, south-east Islay, showing the 'sandstone dykes' locality.

Figure 19 A folded sedimentary dyke (viewed to the west), within the Laphroaig Quartzite Formation, 300 m south-west of Surnaig Farm, south-east Islay (NR 3982 4525). The dyke is between 40 cm and 50 cm wide and the spirit level (centre) is 5 cm long. (Photo: P.W.G. Tanner.)

Figure 20 Map of the area around the Ardbeg GCR site, south-east Islay, showing the stilpnomelane locality.

Figure 21 Photomicrograph (in plane-polarized light) of the stilpnomelane-bearing metamafic sill on the foreshore 400 m east of Ardbeg Distillery at NR 4185 4625. Radiating clusters of stilpnomelane can be seen overgrowing actinolite, albite, quartz, and epidote. The field of view is 6 mm. (Photo: A. Condron.)

Figure 22 Map of the area around the Ardilistry Bay GCR site, south-east Islay.

Figure 23 Topographic expression of sills of metamafic rock at Ardilistry Bay, south-east Islay, viewed looking south-east from Locality X on Figure 22. (Photo: P.W.G. Tanner.)

Figure 24 Schematic vertical section through the metapyroxenite-bearing sill at Ardilistry Bay, south-east Islay.

Figure 25 Map of the area around the Black Mill Bay GCR site. A–D, localities mentioned in the text. Inset: An equal-area stereographic projection of poles to bedding, slaty cleavage (S1), and crenulation cleavage (S2), together with the best-fit line (π-girdle) containing the poles to bedding and cleavage. The nearly horizontal π-axis, gives the mean orientation of the related major fold axis.

Figure 26 A gravity-flow deposit, or debrite, at locality A on Figure 25 (NM 7311 0875), Black Mill Bay GCR site. The scale is 5 cm long.
(a) A near-vertical face approximately parallel to S1, showing deformed clasts of sandstone in a silty matrix.
(b) A horizontal, plan-view section through the deformed clasts shown in (a).
(c) An illustration of lithological control on cleavage development at locality A. The near-vertical S1 cleavage dominates in metacarbonate rock (M) and in the debrite (D), whereas the S2 crenulation cleavage is more strongly developed in the intervening black pelite (P) and gives rise to a near-horizontal parting in this lithology. A sedimentary dyke (S), now folded and cleaved, cuts the debrite and the pelite.
(Photos: P.W.G. Tanner.)

Figure 27 Map showing the outline geology of the Craignish Point GCR site.

Figure 28
(a) Weathered-out cavities in metasandstone, previously occupied by calcite pseudomorphs of bow-tie gypsum, Craignish Phyllite Formation, Craignish Point. The bow-ties are 3–6 mm across.
(b) Pseudomorphs of butterfly-twinned gypsum lying on a bedding plane in the Craignish Phyllite Formation, Craignish Point. The pseudomorphs are up to 5 cm across.
(Photos: P.W.G. Tanner.)

Figure 29 Map of the area around the Fearnach Bay GCR site, Loch Melfort. A, locality mentioned in the text.
Inset: Equal-area stereographic projections of poles to bedding, together with minor D1 fold hinges, and slaty cleavage (S1) (see text for explanation).

Figure 30
(a) Cross-lamination at the base of a massive bed of metacarbonate rock in the Craignish Phyllite Formation, NM 8336 1406, Fearnach Bay, Loch Melfort. Scale is 5 cm long.
(b) The contact between a basic sill (B) and phyllitic semipelite (P) folded by an upright F1 syncline at locality A (NM 8350 1342), Fearnach Bay, Loch Melfort (Figure 29). The fanned cleavage in the phyllite contrasts with the axial planar cleavage in the metadolerite sill (M). A thin band of quartzite (Q) occurs at the contact. Hammer shaft is 60 cm long.
(c) Intense folding of sandy metacarbonate layers, and cleavage refraction in the intervening metapelite, within the Craignish Phyllite Formation, a short distance north of locality A (NM 8350 1342), Fearnach Bay, Loch Melfort (Figure 29). The bar scale is 5cm long.
(Photos: P.W.G. Tanner.)

Figure 31 Preliminary map of the area around the Kilmory Bay GCR site with geological boundaries taken from Roberts (1977c).

Figure 32 Panoramic view of a train of F1 folds with fanned spaced cleavages, plunging north-north-east, Crinan Grit Formation (Ardnoe Member), Kilmory Bay (NR 700 743). (Photo: P.W.G. Tanner.)

Figure 33 En-echelon segmented sedimentary dyke (centre) parallel to spaced axial planar cleavage, Ardrishaig Phyllite, Kilmory Bay (NR 697 728). (Photo: P.W.G. Tanner.)

Figure 34 Map of Knapdale and north Kintyre (based on Roberts, 1977c), showing outcrops of the main Dalradian units and locations of GCR sites: 1 West Tayvallich Peninsula, 2 Kilmory Bay, 3 Port Cill Maluaig, 4 South Bay, Barmore Island. AA Ardrishaig Anticline, KBS Kilmory Bay Syncline, TS Tayvallich Syncline. Inset shows the geology of the Port Cill Maluaig GCR site (3).

Figure 35
(a) Minor F2 folds showing strongly curved fold-hinges, which plunge in opposing directions, Port Cill Maluaig. Hammer shaft is 47 cm long.
(b) Mesoscopic and minor F2 folds from Port Mhoirich (Port Cill Maluaig GCR site), viewed to the north-east. Note the control of bed thickness on the wavelength of the folds. Hammer shaft is 47 cm long.
(Photos: P.W.G. Tanner.)

Figure 36 Map of the area around the Strone Point GCR site, showing the position of the Ardrishaig and Strone Point anticlines, linked by an inferred syncline (modified from Borradaile, 1970). The inset map shows the detailed geology of the Strone Point GCR site.

Figure 37 Strongly folded and cleaved layers of orange-brown metacarbonate rock (C) and grey-green phyllitic metamudstones (P) define rather open S-folds on the lower part of the hinge-zone of the Strone Point Anticline at Strone Point (NN 1183 0884). The penetrative S1 cleavage dips at a shallow angle to the north-west, the direction of view being to the south-west. Solid lines highlight the trace of the bedding. Hammer shaft is 47 cm long. (Photo: P.W.G. Tanner.)

Figure 38 Sketch of typical curvilinear folds at Strone Point, based on part of figure 19 of Voll (1960). The geometry of the folds is illustrated by the equal-area stereographic projection, reproduced from figure 2a of Borradaile (1970), augmented by data collected by P.W.G. Tanner.

Figure 39 Map of the hinge-zone of the F1 Loch Awe Syncline at Kilchrenan, showing the principal exposures of the Kilchrenan Conglomerate Member of the Tayvallich Slate and Limestone Formation (after Borradaile 1973, 1977).

Figure 40 The Kilchrenan Conglomerate in exposures on the bank of the Kilchrenan Burn. The clasts are of quartzite in a gritty, muddy matrix. Coin is 2 cm diameter. (Photo: J.E. Treagus.)

Figure 41 Simplified map of the West Tayvallich peninsula. Numbers refer to sections described in the text. Modified after BGS 1:50 000 Sheet 28E (Knapdale, 1996). Additional information from Elles (1935), Wilson and Leake (1972) and Gower (1977).

Figure 42 Basaltic pillow lavas in the Tayvallich Volcanic Formation showing concentric bands of vesicles, coast of An Aird (NR 7020 8370). Hammer shaft is 37 cm long. (Photo: BGS No. P 219459, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Figure 43 Map of the coastal section between Barmore Island, Loch Fyne and East Loch Tarbert; outcrops of basic meta-igneous rock omitted (after Roberts, 1977c, with additional data).

Figure 44 Typical Loch Tay Limestone lithology of thinly bedded metalimestone interbedded with dark grey metamudstone. A strongly boudinaged quartzofeldspathic vein occupies the centre of the photograph. NR 8683 7123, South Bay, Barmore Island. Hammer shaft is 60 cm long. (Photo: P.W.G. Tanner.)

Figure 45 Map of the area north-east of Loch Avich that includes the outcrop of the Loch Avich Lavas Formation (after Borradaile, 1977).

Figure 46 Basaltic andesite pillow lavas at An Cnap, Loch Avich, viewed to the south-east (NM 9544 1586). Hammer shaft is 35 cm long. (Photo: E.K. Hyslop, BGS No. P 726591.)

Figure 47 Map of the Loch Skerrols Thrust on the east side of Loch Gruinart, Isle of Islay showing the Bun-an-Uillt GCR site (after Fitches and Maltman, 1984).

Figure 48
(a) The main exposure of cataclastic rocks within the Blackrock Grit Formation, below the Loch Skerrols Thrust, NR 2950 6930, *c.* 300 m south-west of Bun-an-Uilt, Islay. Scale is 5 cm long.

(b) Possible stretching lineation in the Jura Quartzite, above the Loch Skerrols Thrust (NR 2947 6919). Scale is 5 cm long. (Photos: P.W.G. Tanner.)

Figure 49 Map of north-western Islay showing outcrops of the Colonsay Group and its basement of Rhinns Complex, modified after Stewart and Hackman (1973) and Muir *et al.* (1995).

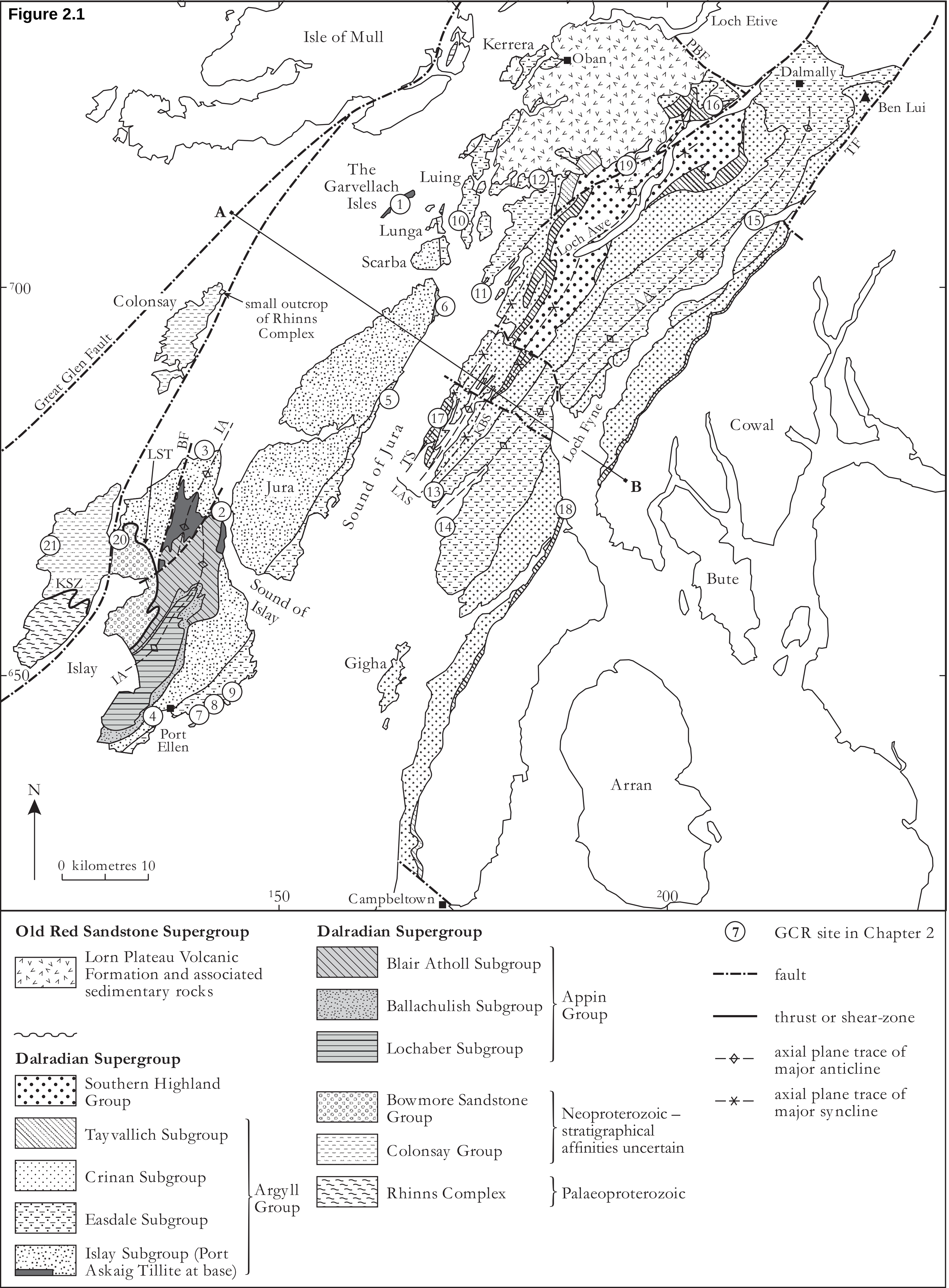
Figure 50 Topographical expression of basement–cover contact *c.* 1 km south-west of Kilchiaran Bay, north-west Islay. Gritty metasandstones of the Eilean Liath Grit Formation of the Colonsay Group to the right of the inlet are separated from highly sheared feldspathic gneisses of the Rhinns Complex to the left by the Kilchiaran Shear-zone, which controls the line of the inlet. Inset shows the strongly sheared rocks in the contact zone; spirit level is 5 cm long. (Photos: P.W.G. Tanner.)

Table 1 Stratigraphical sequences for the lower part of the Colonsay Group according to Stewart and Hackman (1973) and Muir *et al.* (1995).

Stewart and Hackman (1973)	**Muir *et al.* (1995)**
Kilchoman Phyllite	(Rubha na h-Airde Móire Phyllite -repeated through folding)
Crosprig Grit	(Rubha Gaidhealach Grit- repeated through folding)
Rubha na h-Airde Móire Phyllite	Rubha na h-Airde Móire Phyllite
Rubha Gaidhealach Grit	Rubha Gaidhealach Grit
Kilchiaran Phyllite	Kilchiaran Phyllite
Eilean Liath Grit	Eilean Liath Grit

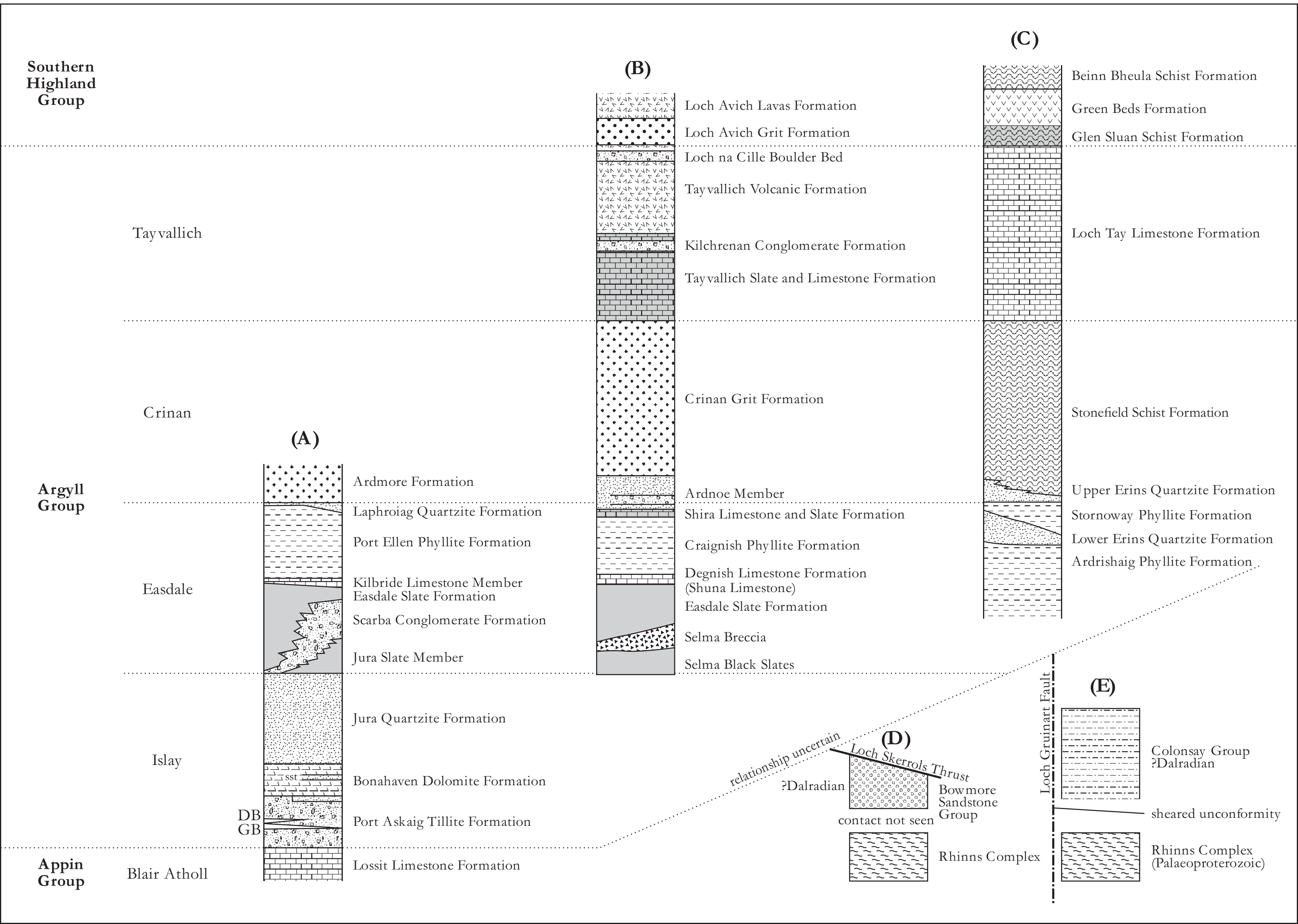
Table 2.1 Stratigraphical sequences for the lower part of the Colonsay Group according to Stewart and Hackman (1973) and Muir *et al.* (1995).

Figure 2.1



Isle of Mull
Kerrera
Oban
Loch Etive
PBF
Dalmally
Ben Lui
TF
The Garvellach Isles
Luing
Lunga
Scarba
Colonsay
small outcrop of Rhinns Complex
Great Glen Fault
Loch Awe
Loch Fyne
Cowal
Jura
Sound of Jura
Sound of Islay
Islay
Gigha
Bute
Arran
Port Ellen
Campbeltown
LST
BF
IA
KSZ
TS
LAs
KBS
AA
A
B
700
650
150
200
N
0 kilometres 10
Old Red Sandstone Supergroup
Lorn Plateau Volcanic Formation and associated sedimentary rocks
Dalradian Supergroup
Southern Highland Group
Tayvallich Subgroup
Crinan Subgroup
Easdale Subgroup
Islay Subgroup (Port Askaig Tillite at base)
Argyll Group
Dalradian Supergroup
Blair Atholl Subgroup
Ballachulish Subgroup
Lochaber Subgroup
Appin Group
Bowmore Sandstone Group
Colonsay Group
Neoproterozoic – stratigraphical affinities uncertain
Rhinns Complex
Palaeoproterozoic
7 GCR site in Chapter 2
fault
thrust or shear-zone
axial plane trace of major anticline
axial plane trace of major syncline

Figure 2.2



Southern Highland Group
Argyll Group
Appin Group
Tayvallich
Crinan
Easdale
Islay
Blair Atholl
(A)
Ardmore Formation
Laphroiag Quartzite Formation
Port Ellen Phyllite Formation
Kilbride Limestone Member
Easdale Slate Formation
Scarba Conglomerate Formation
Jura Slate Member
Jura Quartzite Formation
sst
Bonahaven Dolomite Formation
DB
GB
Port Askaig Tillite Formation
Lossit Limestone Formation
(B)
Loch Avich Lavas Formation
Loch Avich Grit Formation
Loch na Cille Boulder Bed
Tayvallich Volcanic Formation
Kilchrenan Conglomerate Formation
Tayvallich Slate and Limestone Formation
Crinan Grit Formation
Ardnoe Member
Shira Limestone and Slate Formation
Craignish Phyllite Formation
Degnish Limestone Formation
(Shuna Limestone)
Easdale Slate Formation
Selma Breccia
Selma Black Slates
(C)
Beinn Bheula Schist Formation
Green Beds Formation
Glen Sluan Schist Formation
Loch Tay Limestone Formation
Stonefield Schist Formation
Upper Erins Quartzite Formation
Stornoway Phyllite Formation
Lower Erins Quartzite Formation
Ardrishaig Phyllite Formation
relationship uncertain
(D)
Loch Skerrols Thrust
?Dalradian
Bowmore Sandstone Group
contact not seen
Rhinns Complex
Loch Gruinart Fault
(E)
Colonsay Group
?Dalradian
sheared unconformity
Rhinns Complex
(Palaeoproterozoic)

Figure 2.3

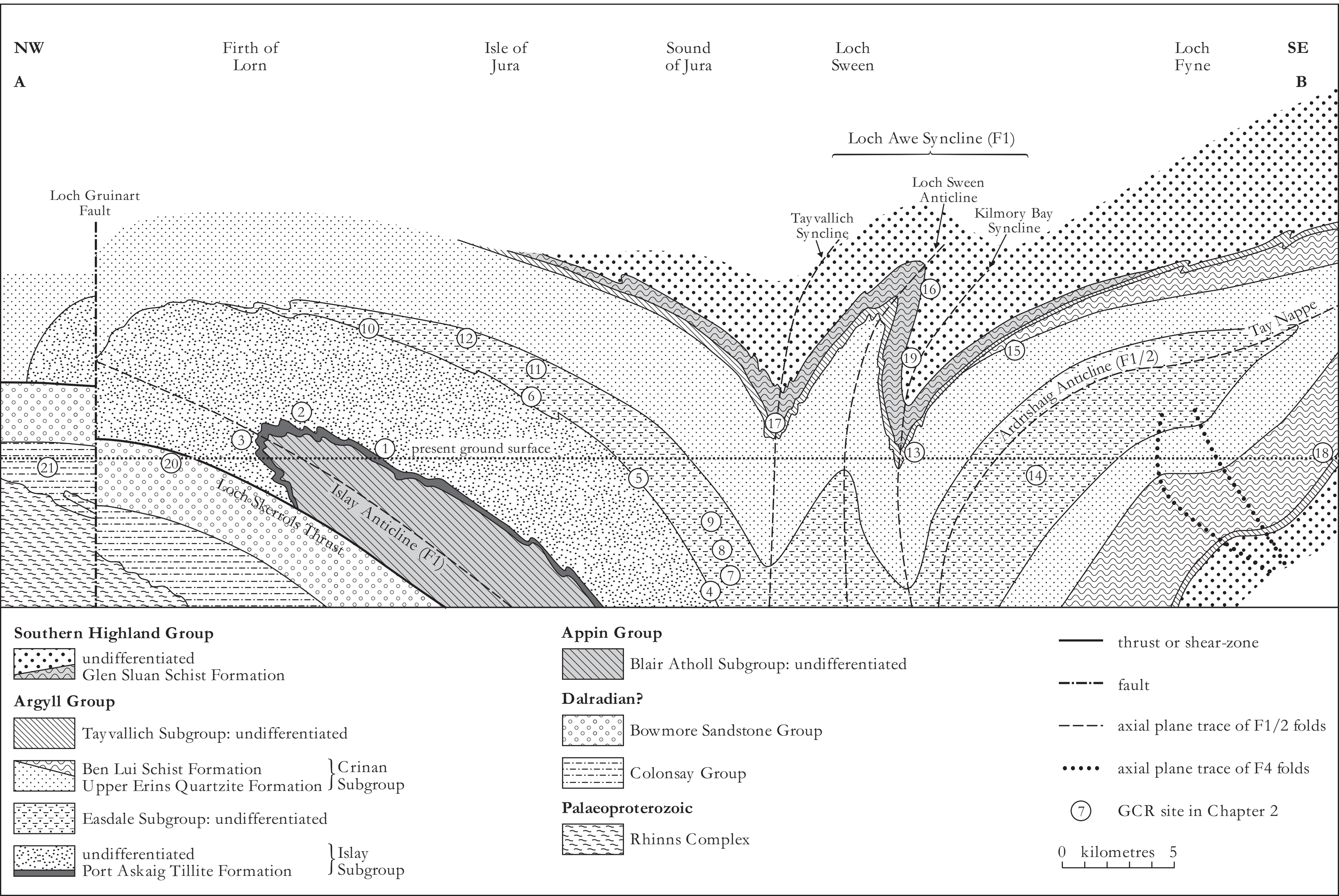
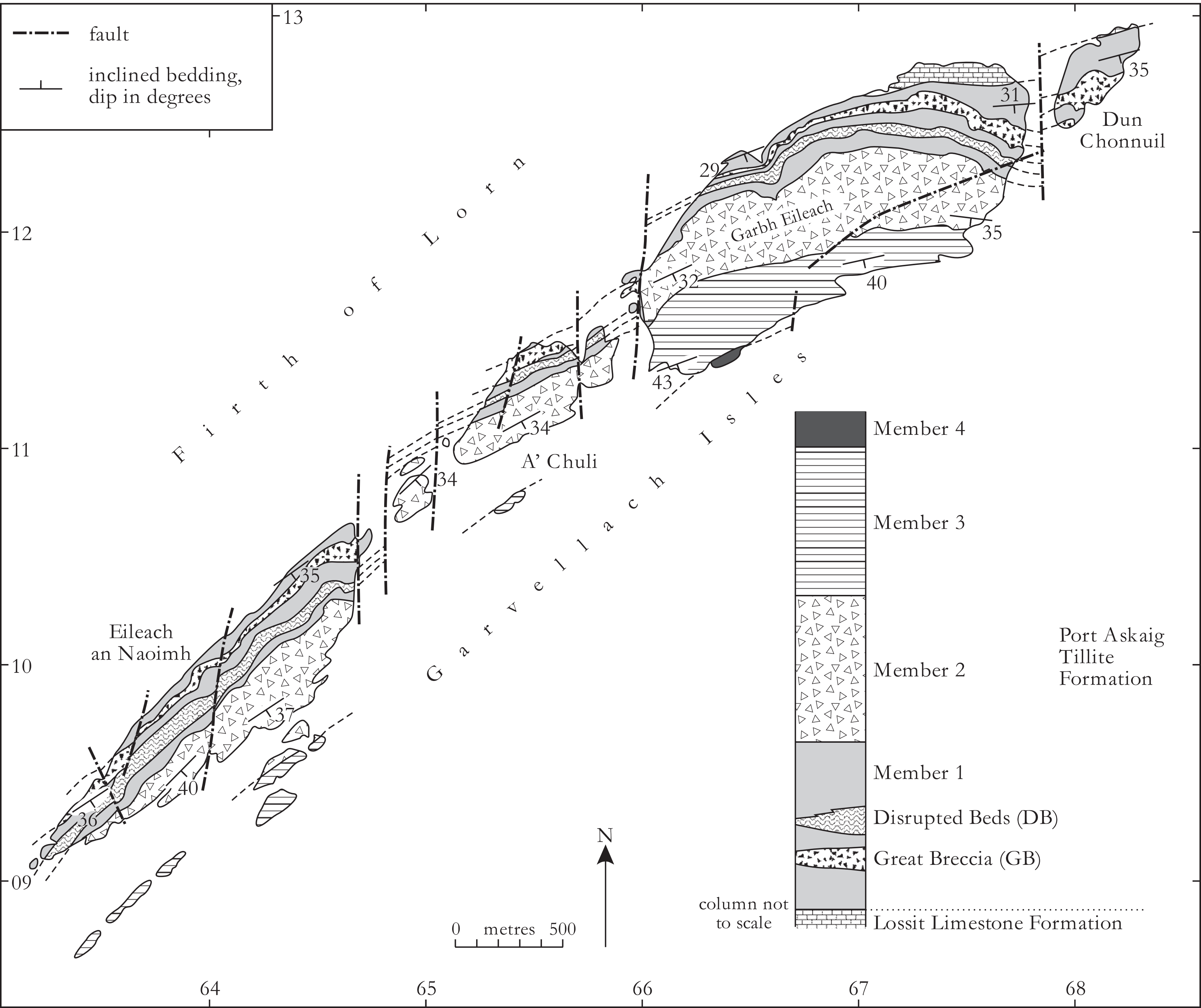

NW
A
Firth of Lorn
Isle of Jura
Sound of Jura
Loch Sween
Loch Fyne
SE
B
Loch Awe Syncline (F1)
Loch Gruinart Fault
Tayvallich Syncline
Loch Sween Anticline
Kilmory Bay Syncline
Tay Nappe
Ardrishaig Anticline (F1/2)
present ground surface
Loch Skerrols Thrust
Islay Anticline (F1)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Southern Highland Group
undifferentiated
Glen Sluan Schist Formation
Argyll Group
Tayvallich Subgroup: undifferentiated
Ben Lui Schist Formation
Upper Erins Quartzite Formation
Crinan Subgroup
Easdale Subgroup: undifferentiated
undifferentiated
Port Askaig Tillite Formation
Islay Subgroup
Appin Group
Blair Atholl Subgroup: undifferentiated
Dalradian?
Bowmore Sandstone Group
Colonsay Group
Palaeoproterozoic
Rhinns Complex
thrust or shear-zone
fault
axial plane trace of F1/2 folds
axial plane trace of F4 folds
7 GCR site in Chapter 2
0 kilometres 5

Figure 2.5



fault
inclined bedding, dip in degrees
Firth of Lorn
Garvellach Isles
Eileach an Naoimh
A' Chuli
Garbh Eileach
Dun Chonnuil
N
0 metres 500
Member 4
Member 3
Member 2
Member 1
Disrupted Beds (DB)
Great Breccia (GB)
column not to scale
Lossit Limestone Formation
Port Askaig Tillite Formation
13
12
11
10
09
64
65
66
67
68
35
31
29
35
32
40
43
34
34
35
37
40
36

Figure 2.7

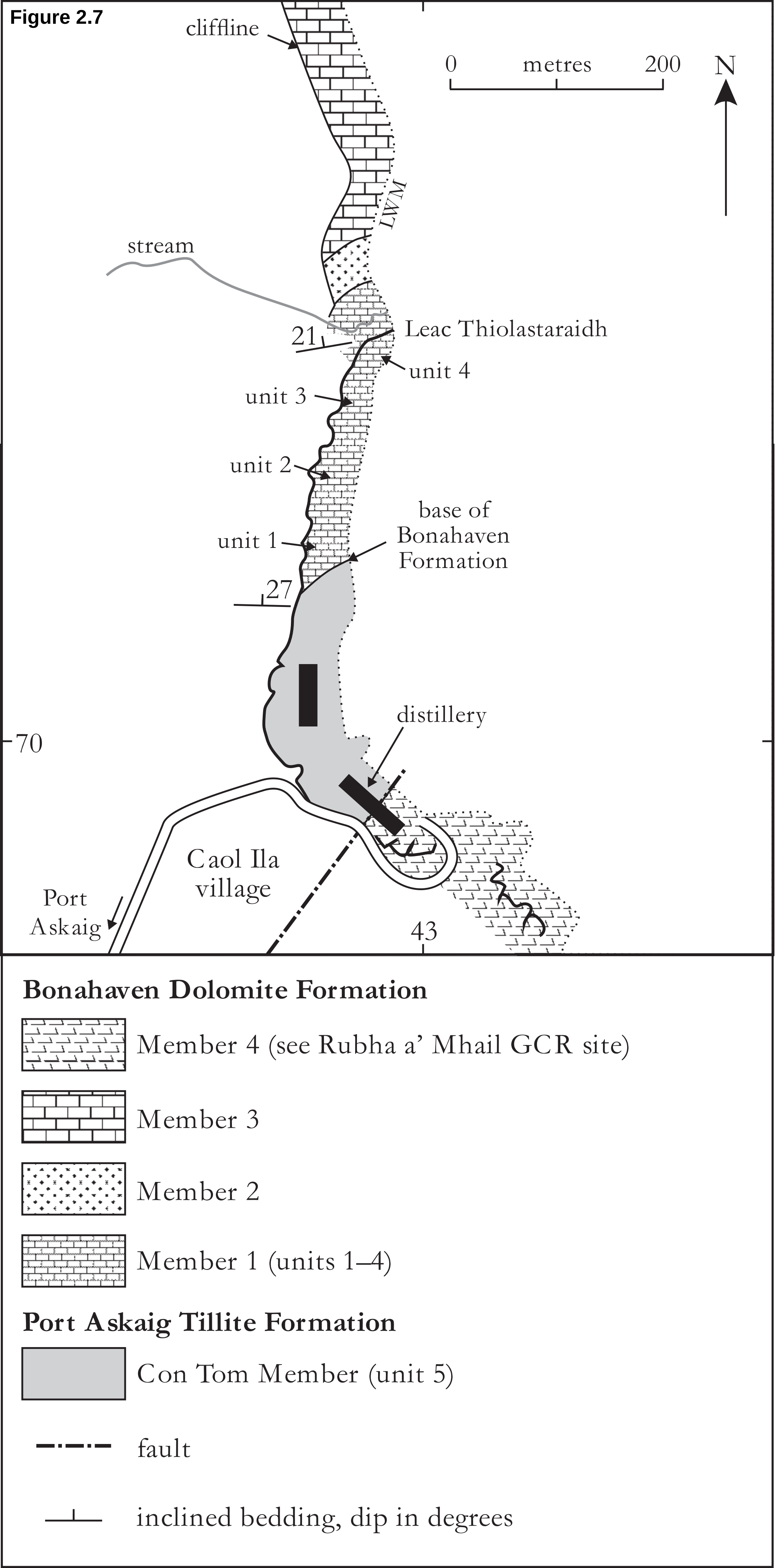
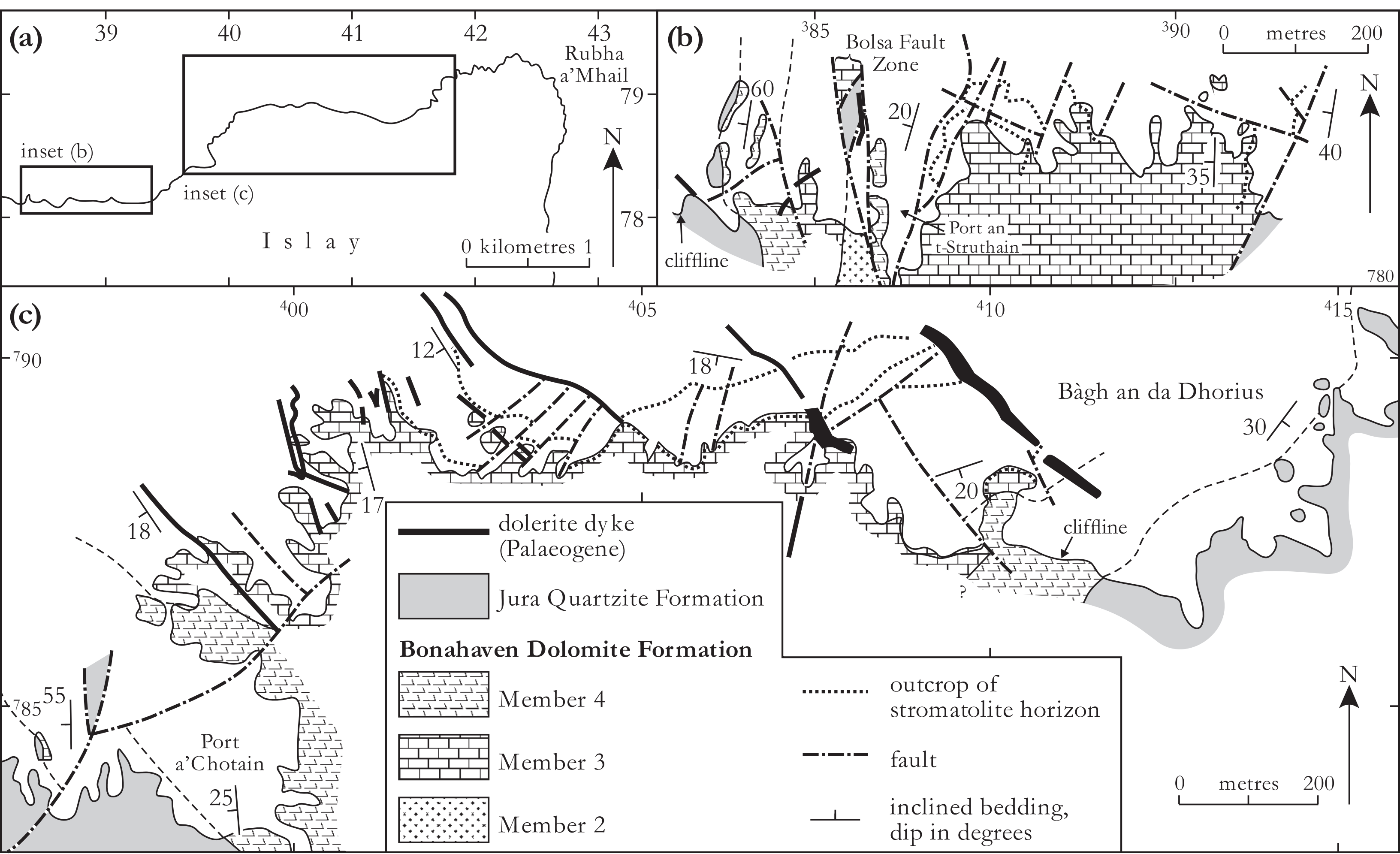

cliffline
0 metres 200
N
LWM
stream
Leac Thiolastaraidh
21
unit 4
unit 3
unit 2
unit 1
base of Bonahaven Formation
27
distillery
70
Caol Ila village
Port Askaig
43
Bonahaven Dolomite Formation
Member 4 (see Rubha a' Mhail GCR site)
Member 3
Member 2
Member 1 (units 1–4)
Port Askaig Tillite Formation
Con Tom Member (unit 5)
fault
inclined bedding, dip in degrees

Figure 2.9



(a)
39
40
41
42
43
Rubha a'Mhail
79
78
inset (b)
inset (c)
N
I s l a y
0 kilometres 1
(b)
385
390
0 metres 200
Bolsa Fault Zone
60
20
40
35
N
cliffline
Port an t-Struthain
780
(c)
400
405
410
415
790
12
18
17
18
20
30
Bàgh an da Dhorius
cliffline
?
785
55
Port a'Chotain
25
N
0 metres 200
dolerite dyke (Palaeogene)
Jura Quartzite Formation
Bonahaven Dolomite Formation
Member 4
Member 3
Member 2
outcrop of stromatolite horizon
fault
inclined bedding, dip in degrees

Figure 2.11

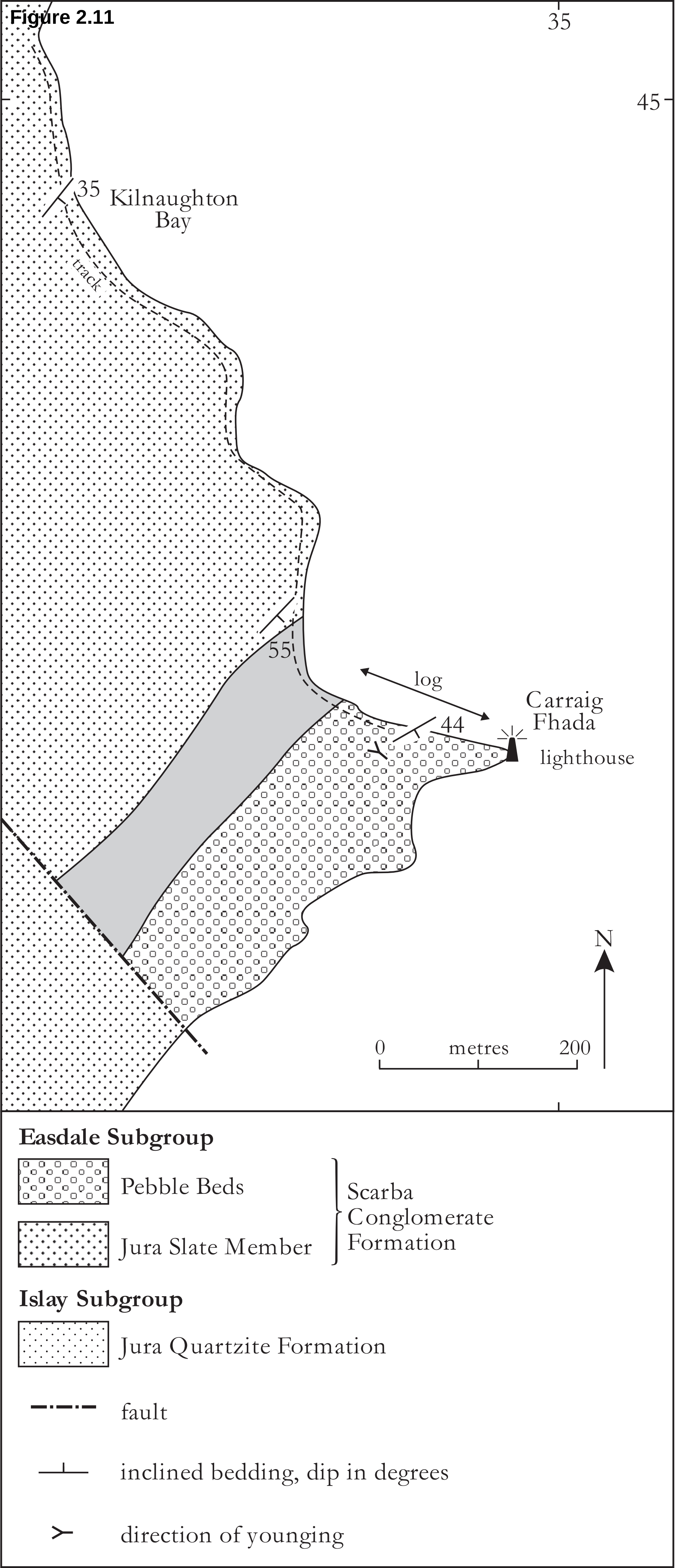
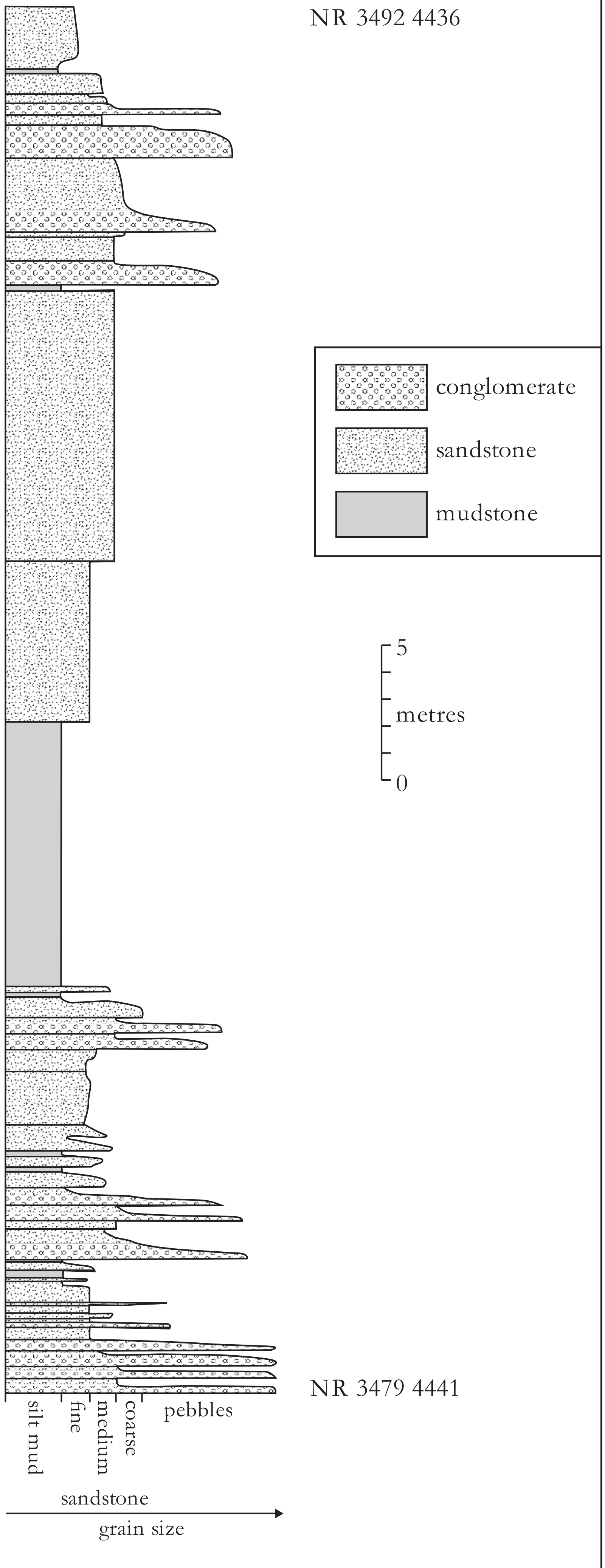

35
45
35
Kilnaughton
Bay
track
55
log
44
Carraig
Fhada
lighthouse
N
0
metres
200
Easdale Subgroup
Pebble Beds
Jura Slate Member
Scarba
Conglomerate
Formation
Islay Subgroup
Jura Quartzite Formation
fault
inclined bedding, dip in degrees
direction of younging

Figure 2.12



NR 3492 4436
conglomerate
sandstone
mudstone
5
metres
0
NR 3479 4441
silt mud
fine
medium
coarse
pebbles
sandstone
grain size

Figure 2.14

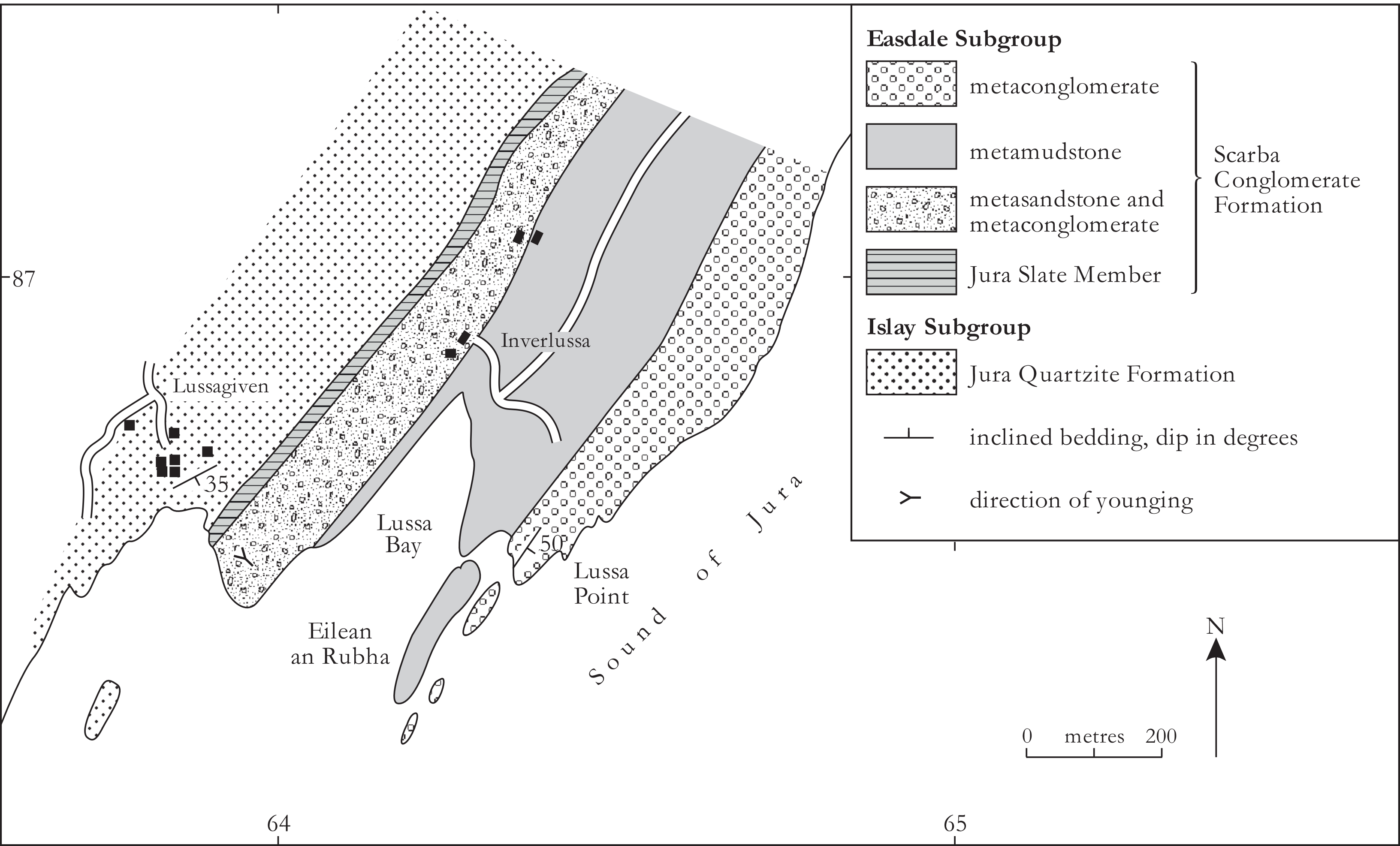
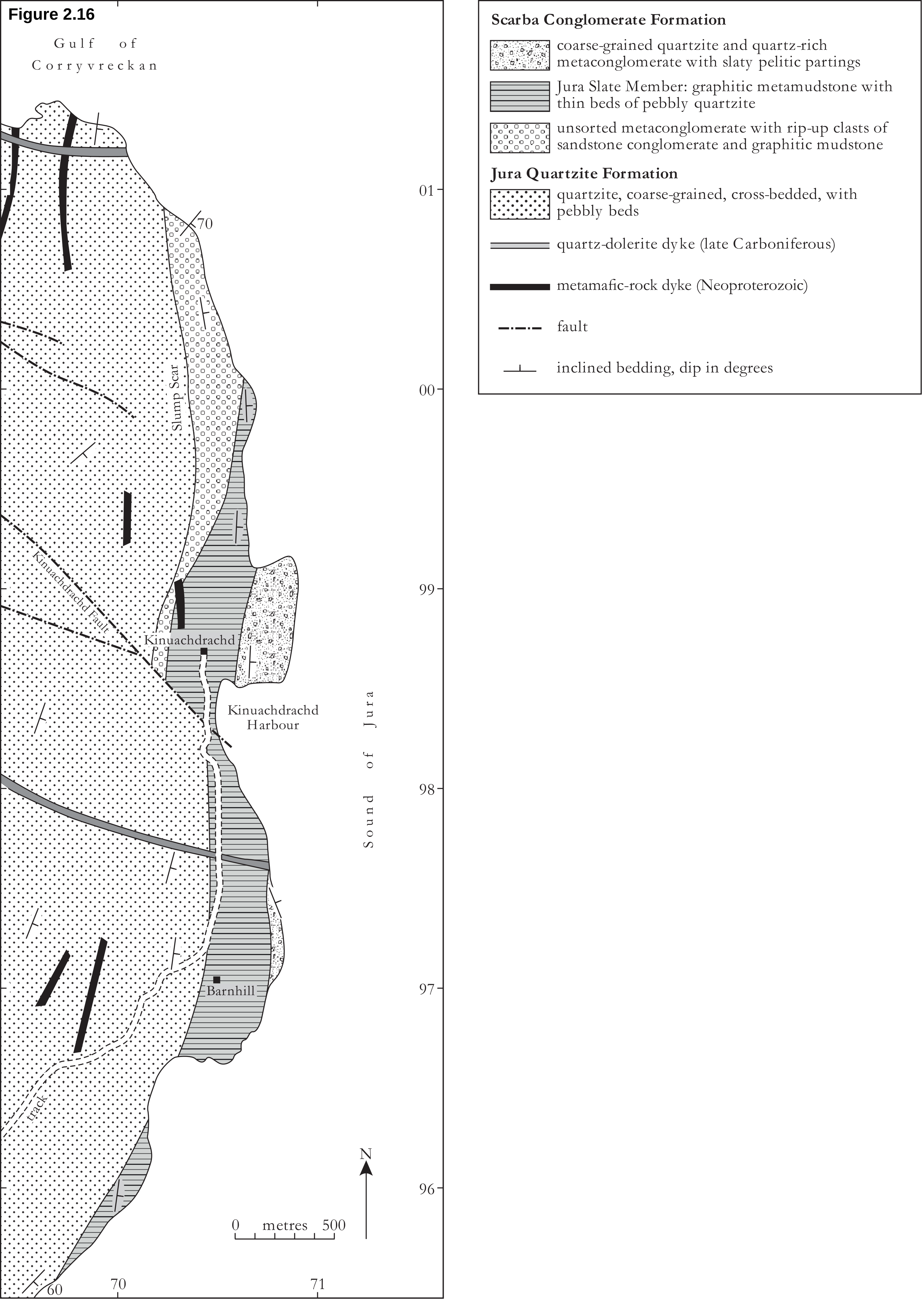
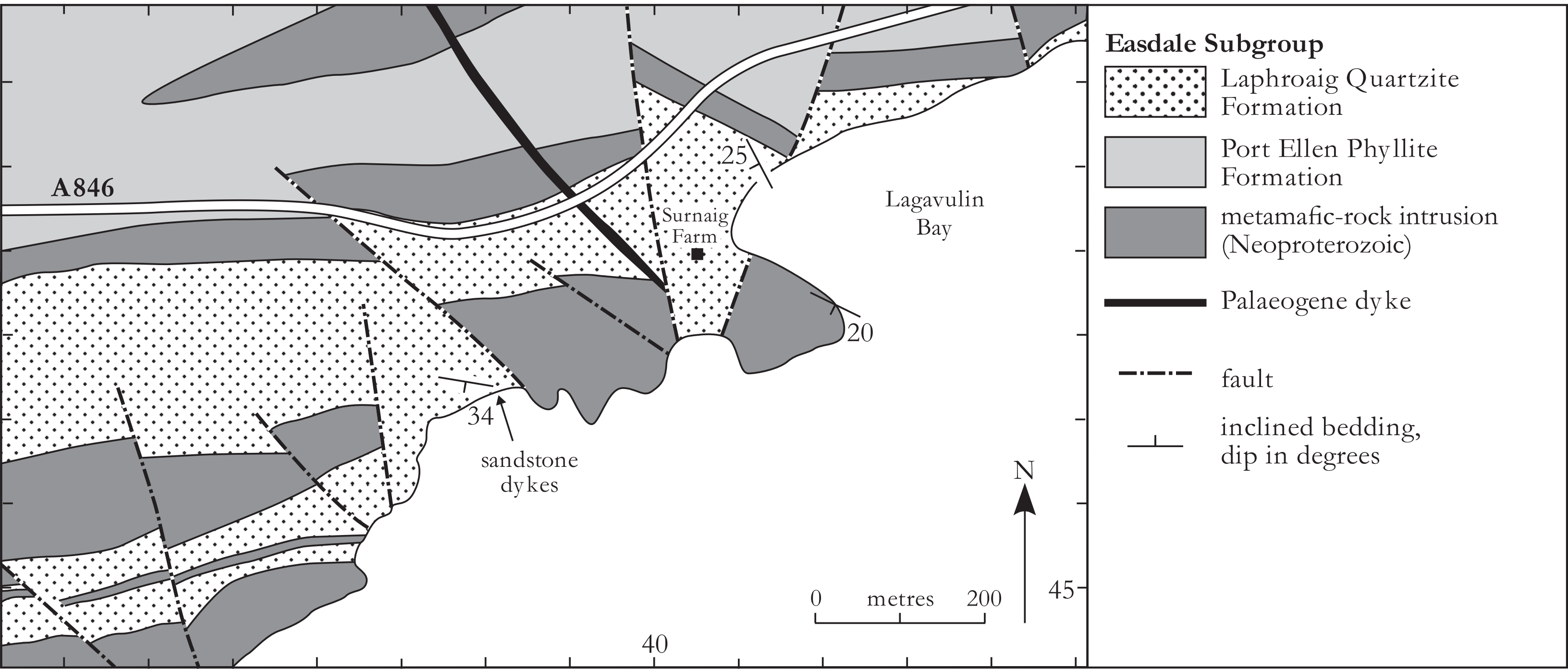

Easdale Subgroup
metaconglomerate
metamudstone
metasandstone and metaconglomerate
Jura Slate Member
Scarba Conglomerate Formation
Islay Subgroup
Jura Quartzite Formation
inclined bedding, dip in degrees
direction of younging
Lussagiven
Inverlussa
Lussa Bay
Lussa Point
Eilean an Rubha
Sound of Jura
35
50
87
64
65
N
0 metres 200

Figure 2.16



Gulf of Corryvreckan
Slump Scar
70
Kinuachdrachd Fault
Kinuachdrachd
Kinuachdrachd Harbour
Barnhill
track
Sound of Jura
N
0 metres 500
01
00
99
98
97
96
60
70
71
Scarba Conglomerate Formation
coarse-grained quartzite and quartz-rich metaconglomerate with slaty pelitic partings
Jura Slate Member: graphitic metamudstone with thin beds of pebbly quartzite
unsorted metaconglomerate with rip-up clasts of sandstone conglomerate and graphitic mudstone
Jura Quartzite Formation
quartzite, coarse-grained, cross-bedded, with pebbly beds
quartz-dolerite dyke (late Carboniferous)
metamafic-rock dyke (Neoproterozoic)
fault
inclined bedding, dip in degrees

Figure 2.18



A846
Surnaig Farm
Lagavulin Bay
25
20
34
sandstone dykes
N
0
metres
200
45
40
Easdale Subgroup
Laphroaig Quartzite Formation
Port Ellen Phyllite Formation
metamafic-rock intrusion (Neoproterozoic)
Palaeogene dyke
fault
inclined bedding, dip in degrees

Figure 2.20

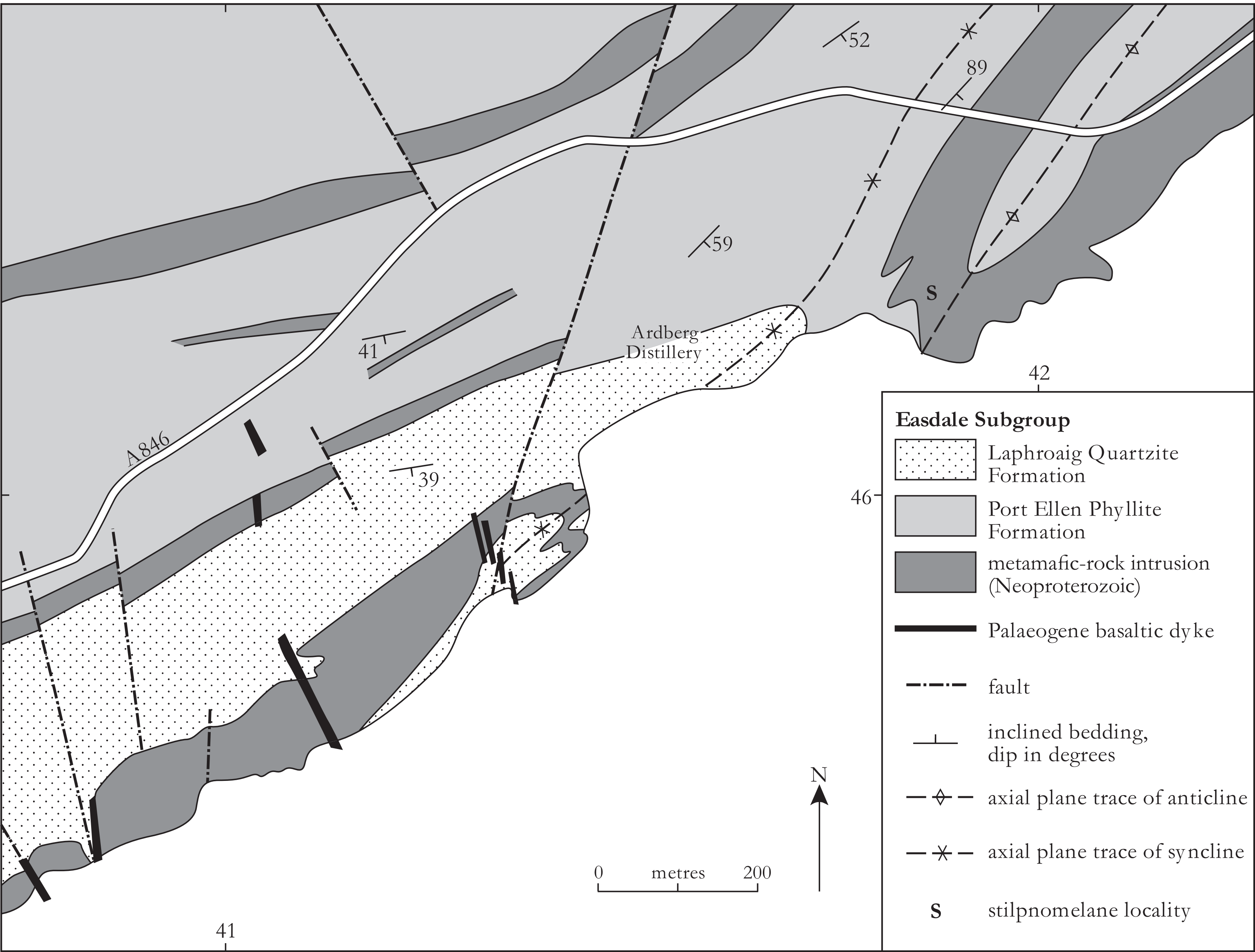
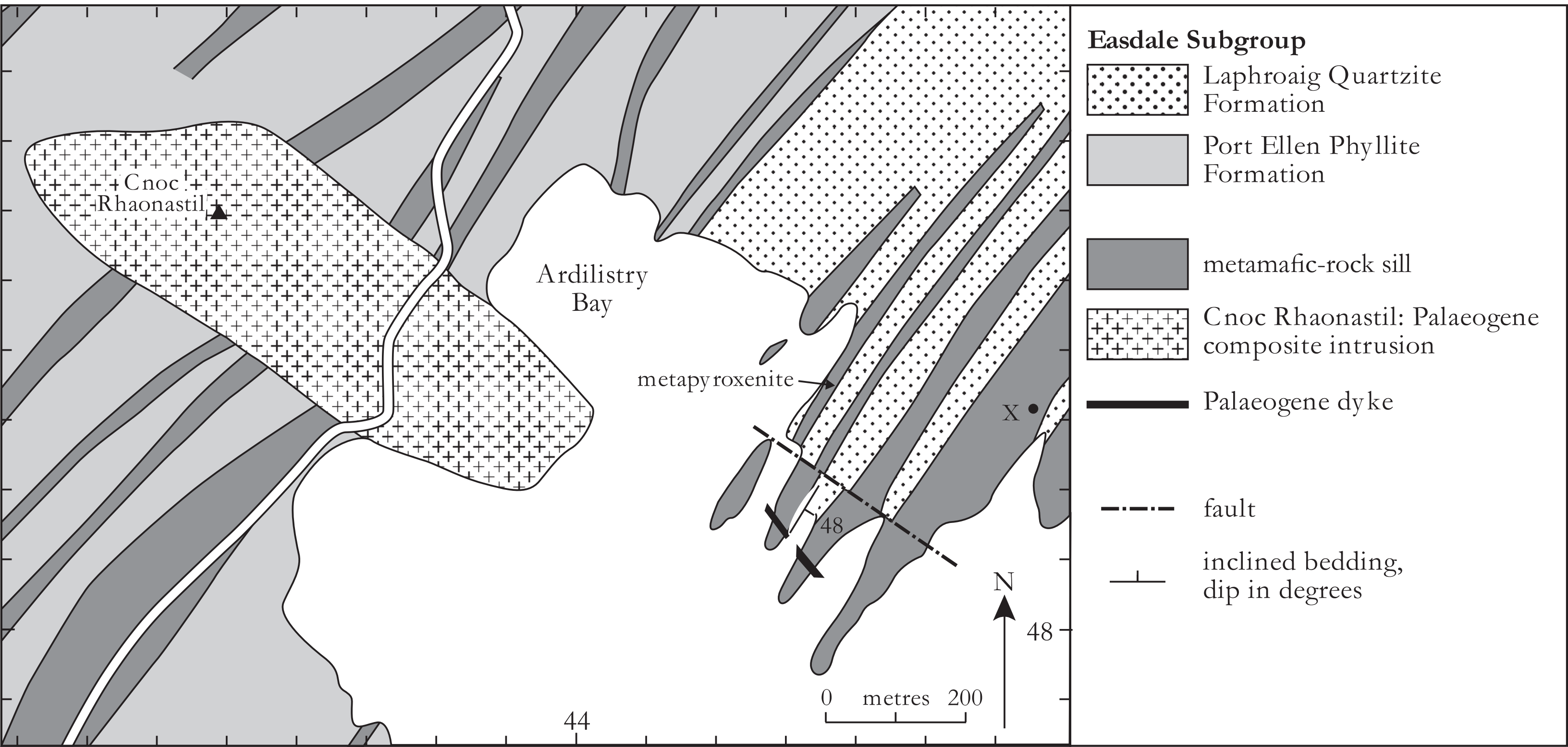

52
89
59
41
39
Ardberg Distillery
A846
S
42
46
41
Easdale Subgroup
Laphroaig Quartzite Formation
Port Ellen Phyllite Formation
metamafic-rock intrusion (Neoproterozoic)
Palaeogene basaltic dyke
fault
inclined bedding, dip in degrees
axial plane trace of anticline
axial plane trace of syncline
S
stilpnomelane locality
N
0 metres 200

Figure 2.22



Cnoc
Rhaonastil
Ardilistry
Bay
metapyroxenite
X
48
N
48
0 metres 200
44
Easdale Subgroup
Laphroaig Quartzite Formation
Port Ellen Phyllite Formation
metamafic-rock sill
Cnoc Rhaonastil: Palaeogene composite intrusion
Palaeogene dyke
fault
inclined bedding, dip in degrees

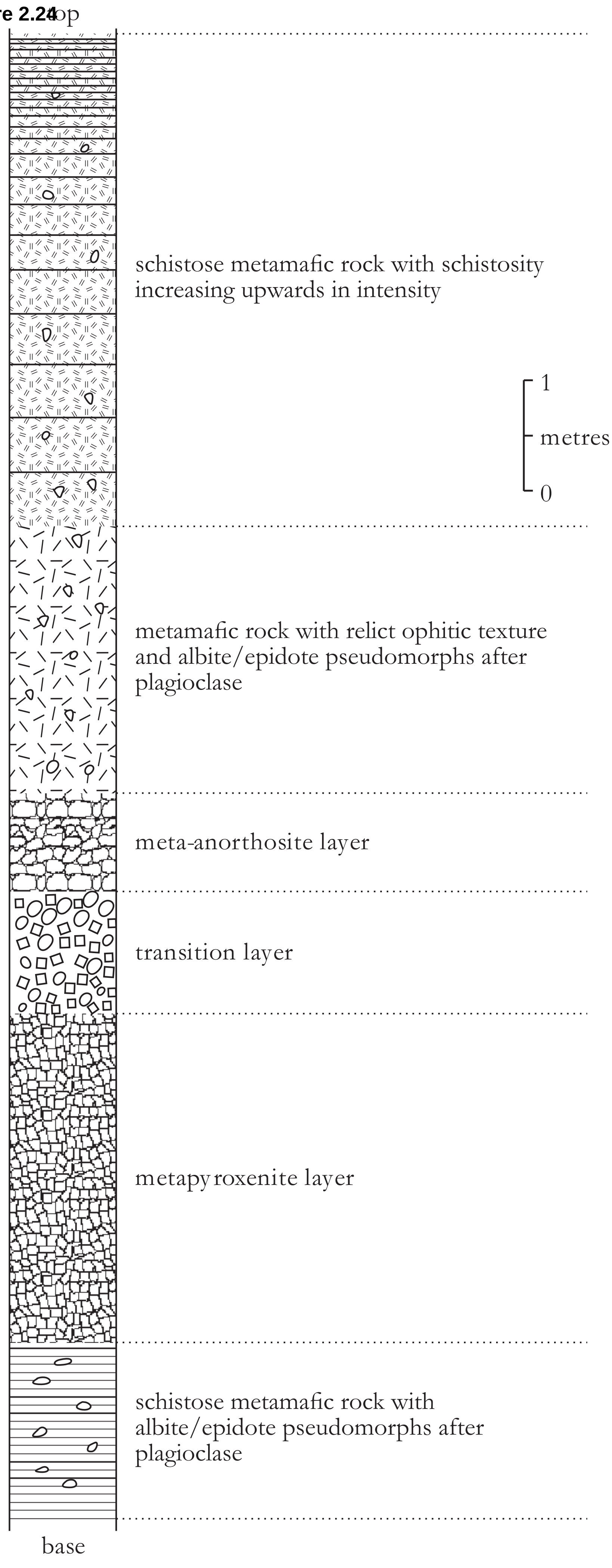
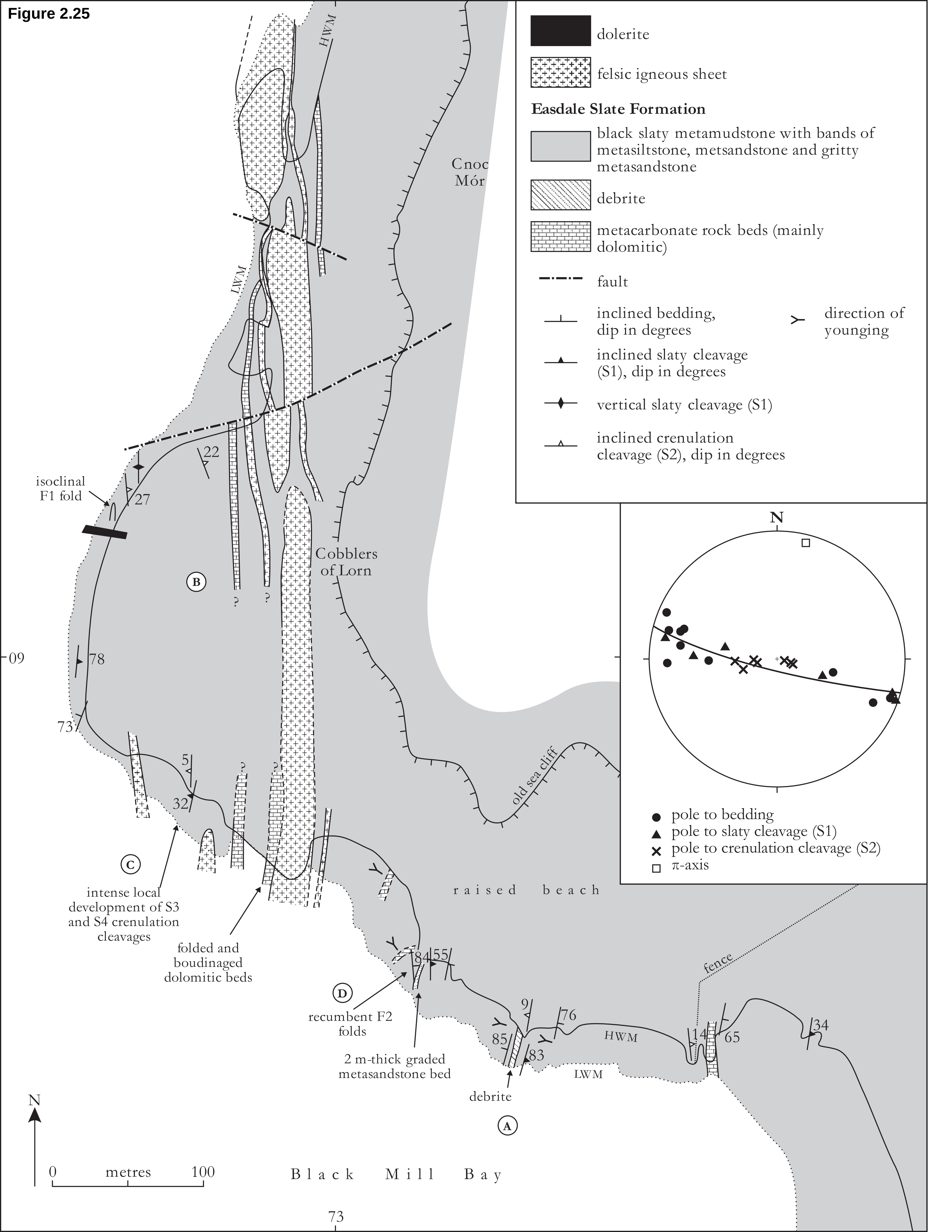

top
schistose metamafic rock with schistosity increasing upwards in intensity
1
metres
0
metamafic rock with relict ophitic texture and albite/epidote pseudomorphs after plagioclase
meta-anorthosite layer
transition layer
metapyroxenite layer
schistose metamafic rock with albite/epidote pseudomorphs after plagioclase
base

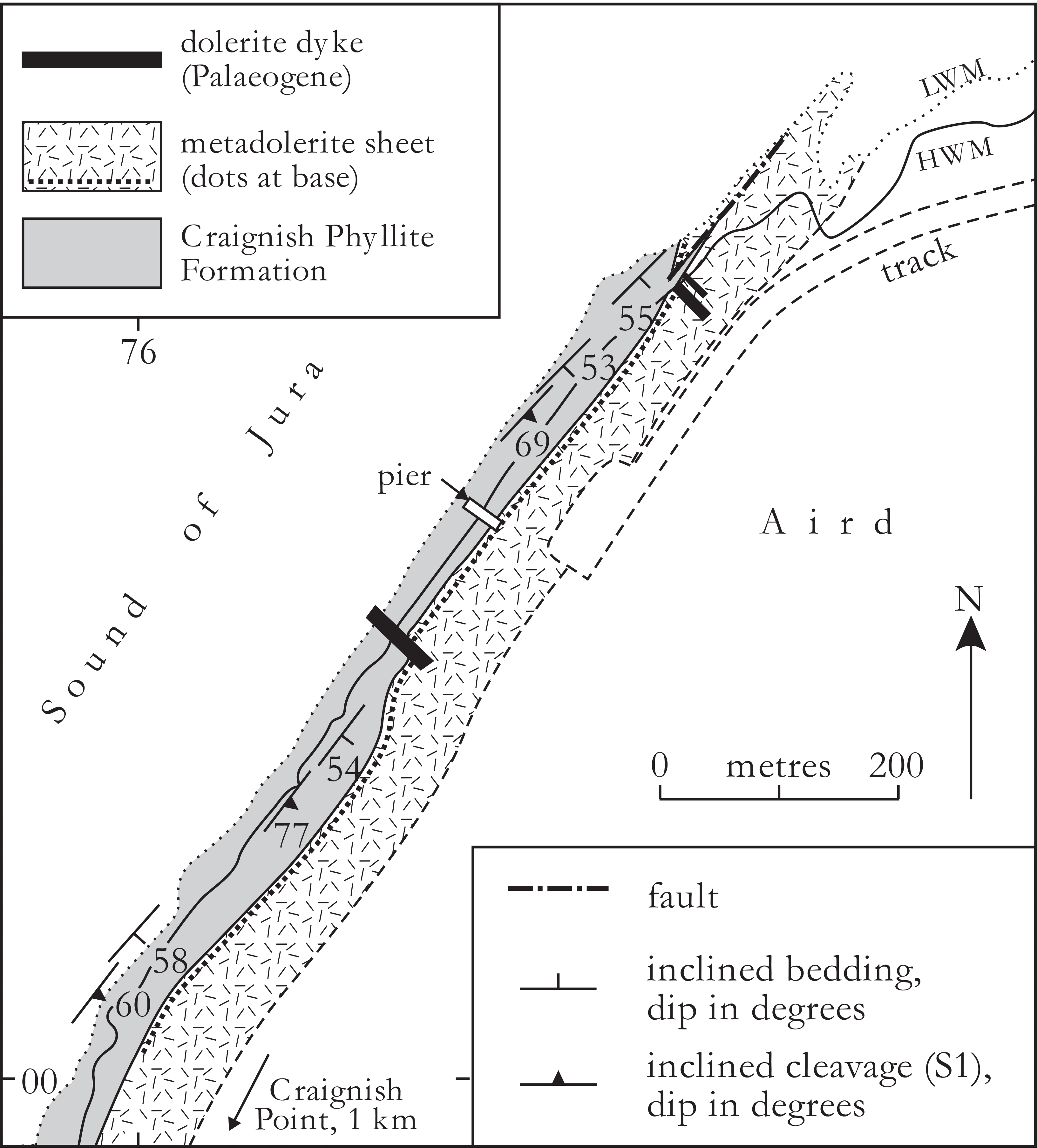
Figure 2.24

Figure 2.25



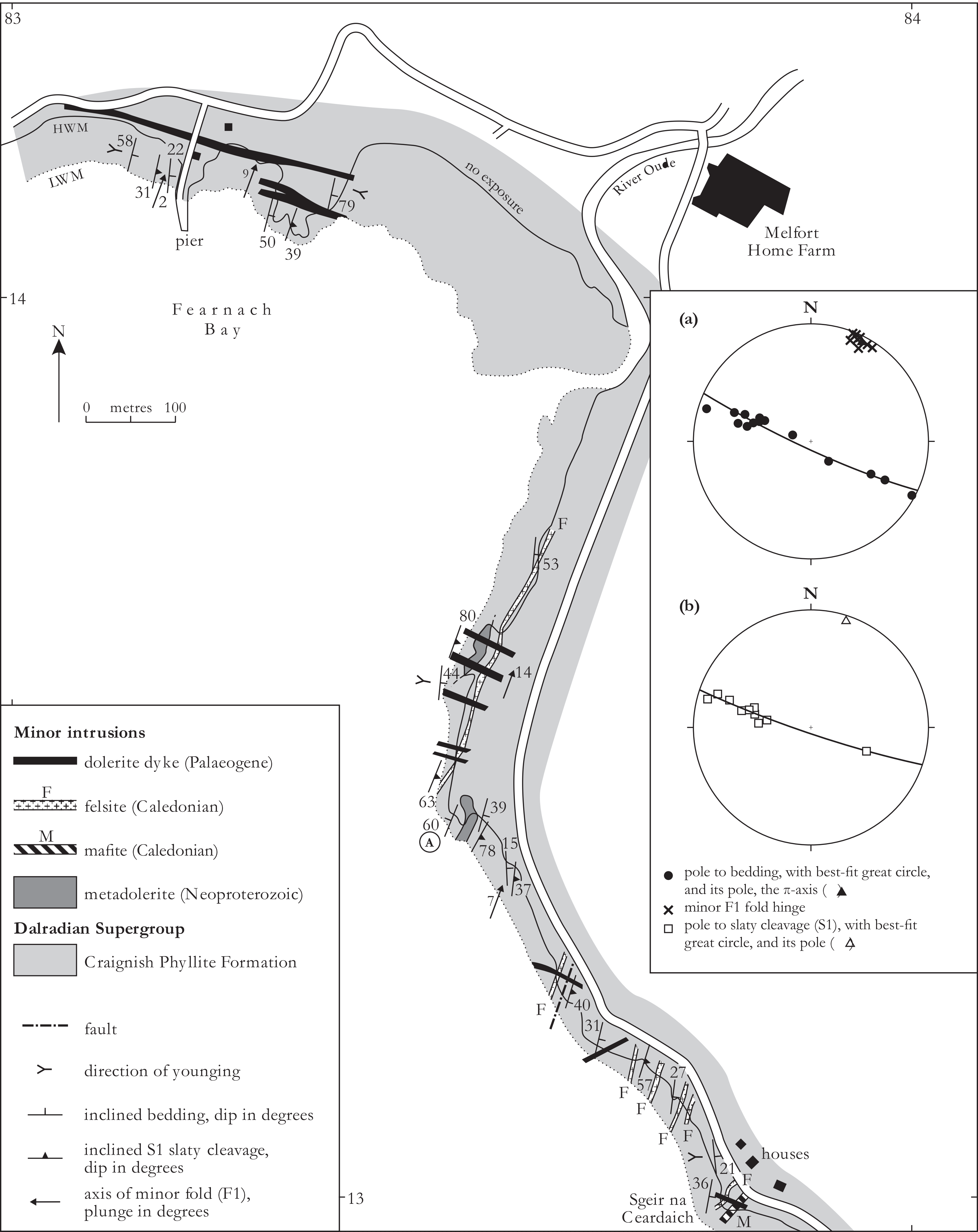
dolerite
felsic igneous sheet
Easdale Slate Formation
black slaty metamudstone with bands of metasiltstone, metsandstone and gritty metasandstone
debrite
metacarbonate rock beds (mainly dolomitic)
fault
inclined bedding, dip in degrees
direction of younging
inclined slaty cleavage (S1), dip in degrees
vertical slaty cleavage (S1)
inclined crenulation cleavage (S2), dip in degrees
pole to bedding
pole to slaty cleavage (S1)
pole to crenulation cleavage (S2)
π-axis
N
HWM
LWM
Cnoc Mór
Cobblers of Lorn
old sea cliff
raised beach
fence
Black Mill Bay
isoclinal F1 fold
intense local development of S3 and S4 crenulation cleavages
folded and boudinaged dolomitic beds
recumbent F2 folds
2 m-thick graded metasandstone bed
debrite
A
B
C
D
09
73
0 metres 100

Figure 2.27



dolerite dyke
(Palaeogene)
metadolerite sheet
(dots at base)
Craignish Phyllite
Formation
76
Sound of Jura
LWM
HWM
track
55
53
69
pier
Aird
N
54
77
0 metres 200
58
60
00
Craignish
Point, 1 km
fault
inclined bedding,
dip in degrees
inclined cleavage (S1),
dip in degrees

Figure 2.29



83
84
14
13
HWM
LWM
58
22
31
2
pier
9
50
39
79
no exposure
River Oude
Melfort
Home Farm
Fearnach
Bay
N
0 metres 100
F
53
80
44
14
63
60
A
39
78
15
37
7
F
40
31
F
57
27
F
F
F
21
F
36
houses
Sgeir na
Ceardaich
M
(a)
N
(b)
N
pole to bedding, with best-fit great circle, and its pole, the π-axis ( )
minor F1 fold hinge
pole to slaty cleavage (S1), with best-fit great circle, and its pole ( )
Minor intrusions
dolerite dyke (Palaeogene)
F
felsite (Caledonian)
M
mafite (Caledonian)
metadolerite (Neoproterozoic)
Dalradian Supergroup
Craignish Phyllite Formation
fault
direction of younging
inclined bedding, dip in degrees
inclined S1 slaty cleavage, dip in degrees
axis of minor fold (F1), plunge in degrees

Figure 2.31

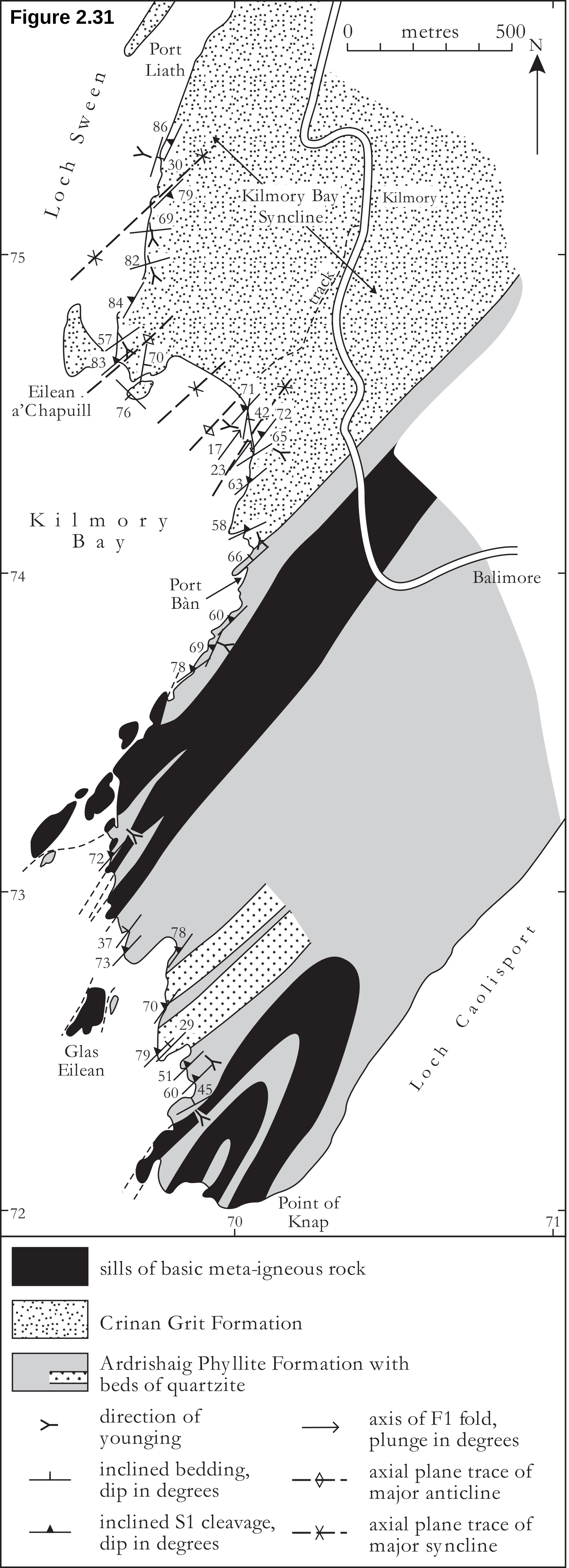
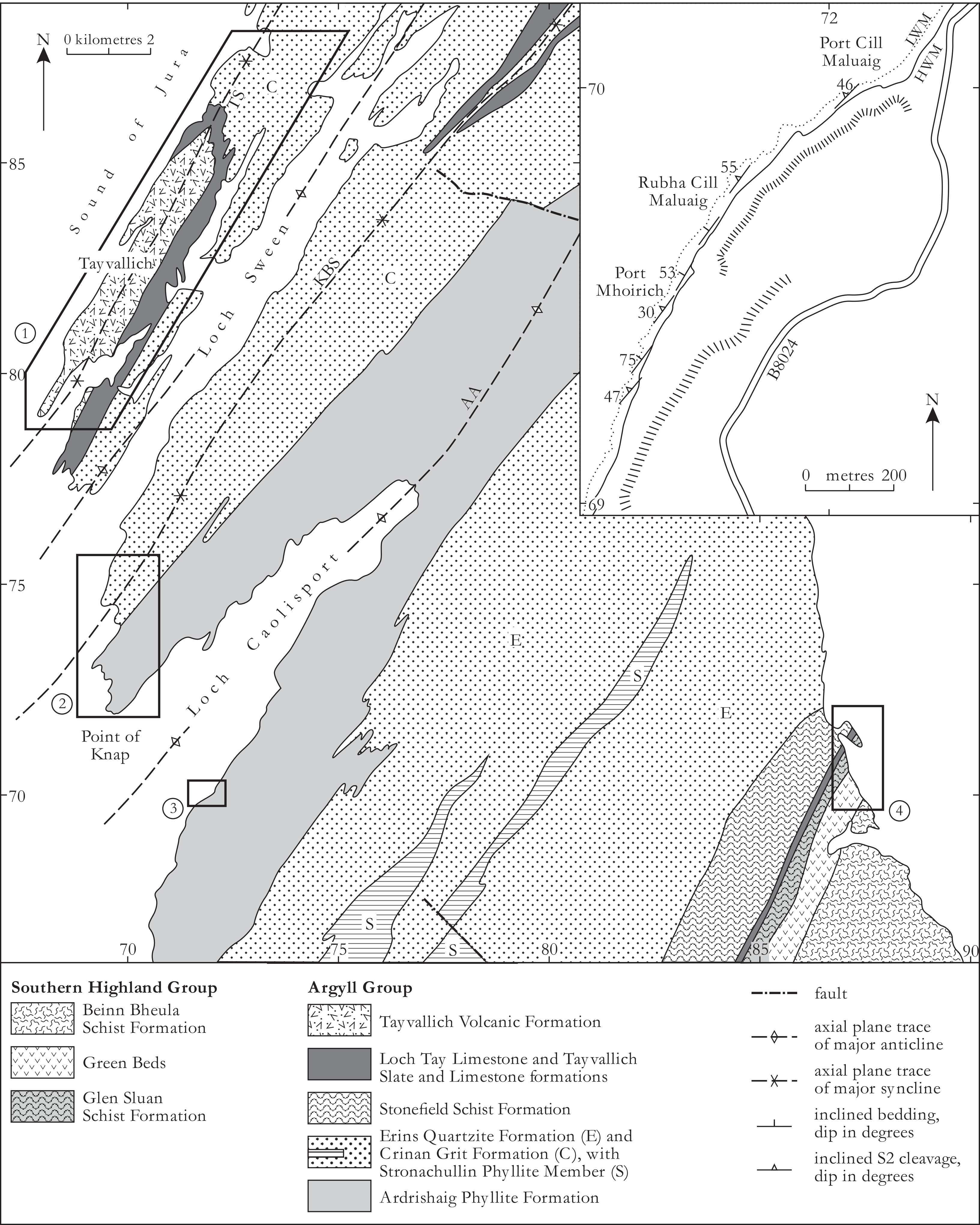
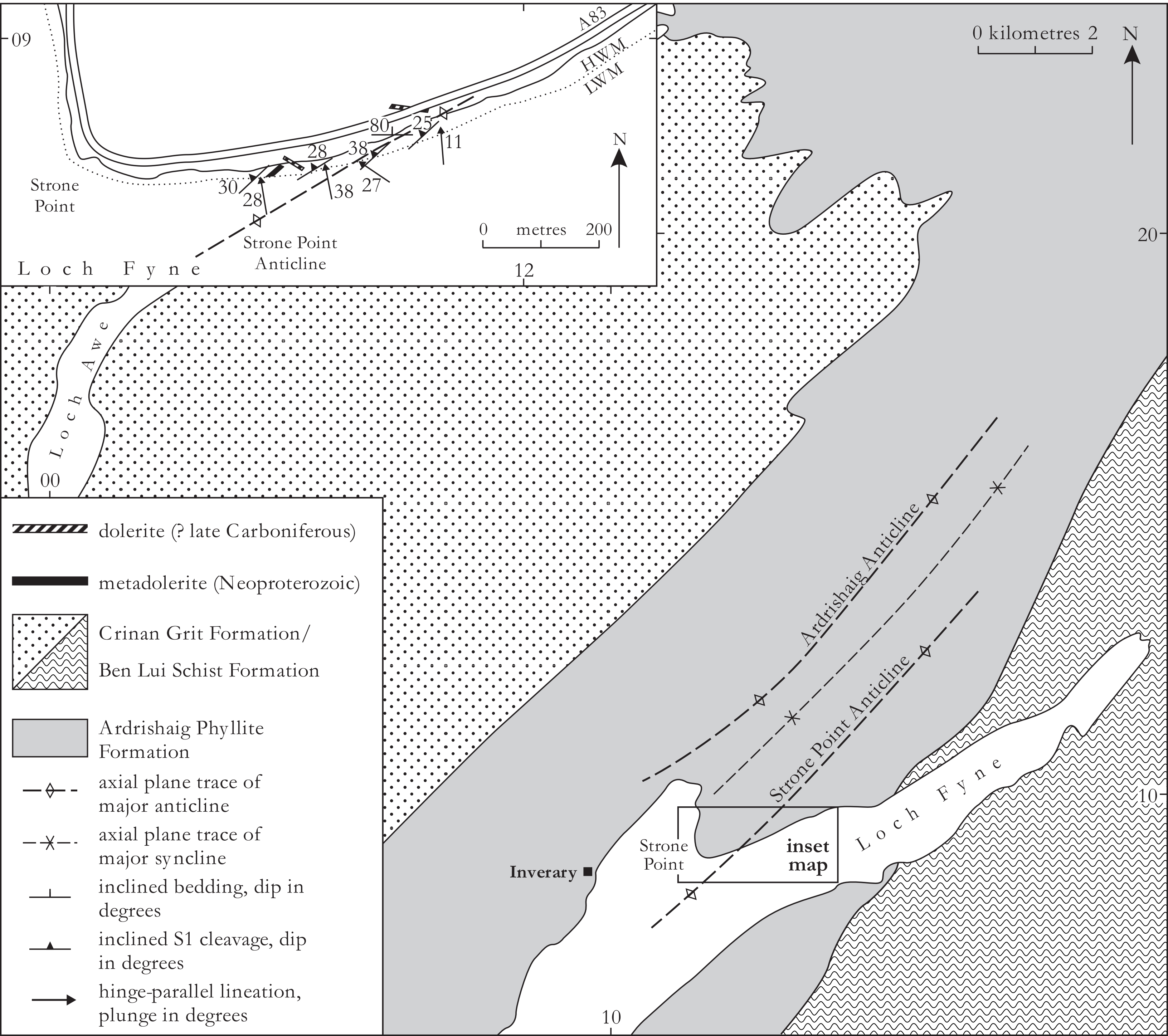

0 metres 500
N
Port Liath
Loch Sween
Kilmory Bay Syncline
Kilmory
track
Eilean a'Chapuill
Kilmory Bay
Port Bàn
Balimore
Glas Eilean
Loch Caolisport
Point of Knap
75
74
73
72
70
71
86
30
79
69
82
84
57
83
70
76
71
42
72
65
17
23
63
58
66
60
69
78
72
37
73
78
70
29
79
51
60
45
sills of basic meta-igneous rock
Crinan Grit Formation
Ardrishaig Phyllite Formation with beds of quartzite
direction of younging
inclined bedding, dip in degrees
inclined S1 cleavage, dip in degrees
axis of F1 fold, plunge in degrees
axial plane trace of major anticline
axial plane trace of major syncline

Figure 2.34



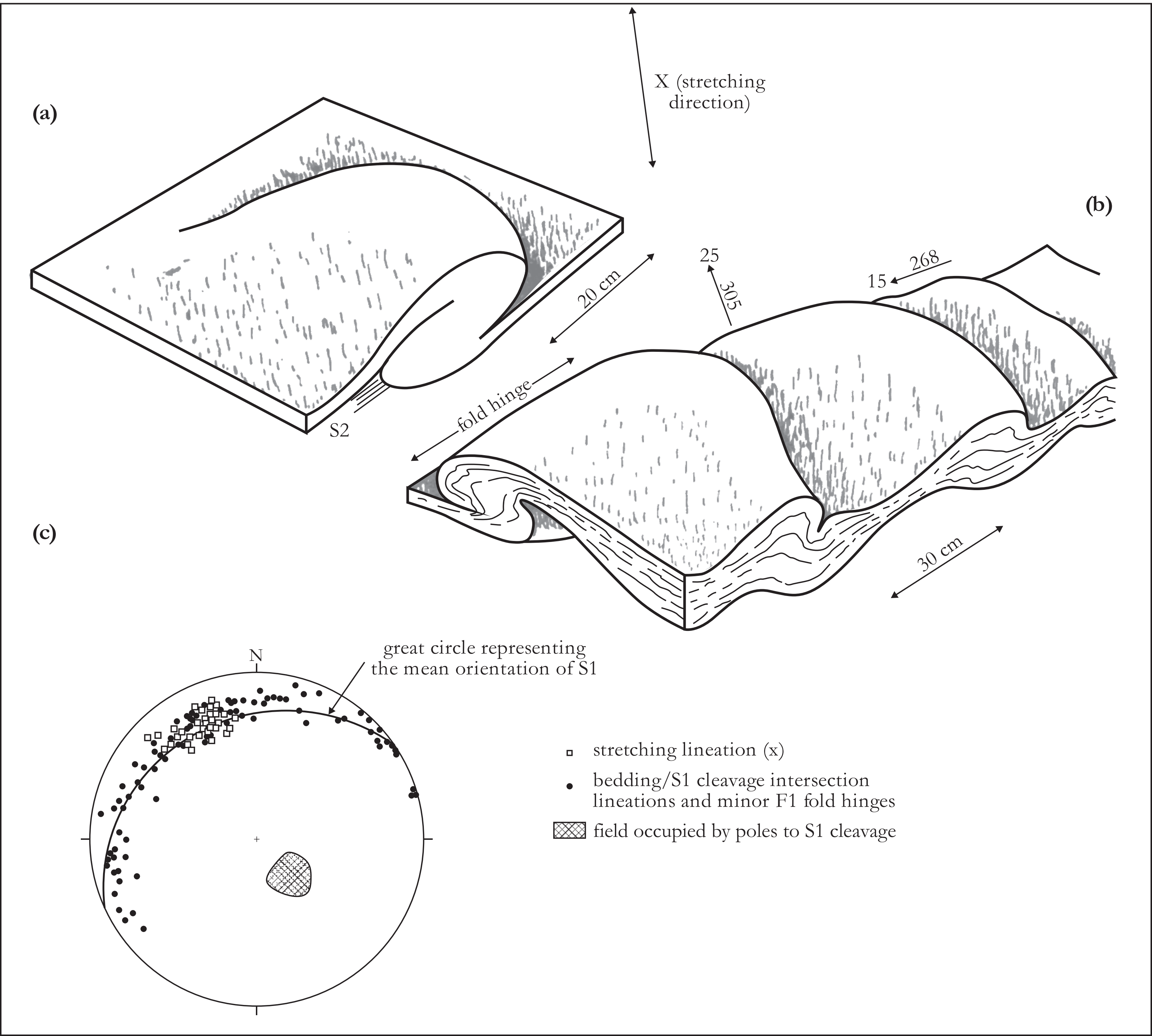
N
0 kilometres 2
Sound of Jura
TS
C
Tayvallich
Loch Sween
KBS
C
AA
Loch Caolisport
Loch
E
S
E
S
S
Point of Knap
1
2
3
4
85
80
75
70
70
75
80
85
90
72
Port Cill Maluaig
LWM
HWM
70
46
55
Rubha Cill Maluaig
Port Mhoirich
53
30
75
47
B8024
N
0 metres 200
69
Southern Highland Group
Beinn Bheula Schist Formation
Green Beds
Glen Sluan Schist Formation
Argyll Group
Tayvallich Volcanic Formation
Loch Tay Limestone and Tayvallich Slate and Limestone formations
Stonefield Schist Formation
Erins Quartzite Formation (E) and Crinan Grit Formation (C), with Stronachullin Phyllite Member (S)
Ardrishaig Phyllite Formation
fault
axial plane trace of major anticline
axial plane trace of major syncline
inclined bedding, dip in degrees
inclined S2 cleavage, dip in degrees

Figure 2.36



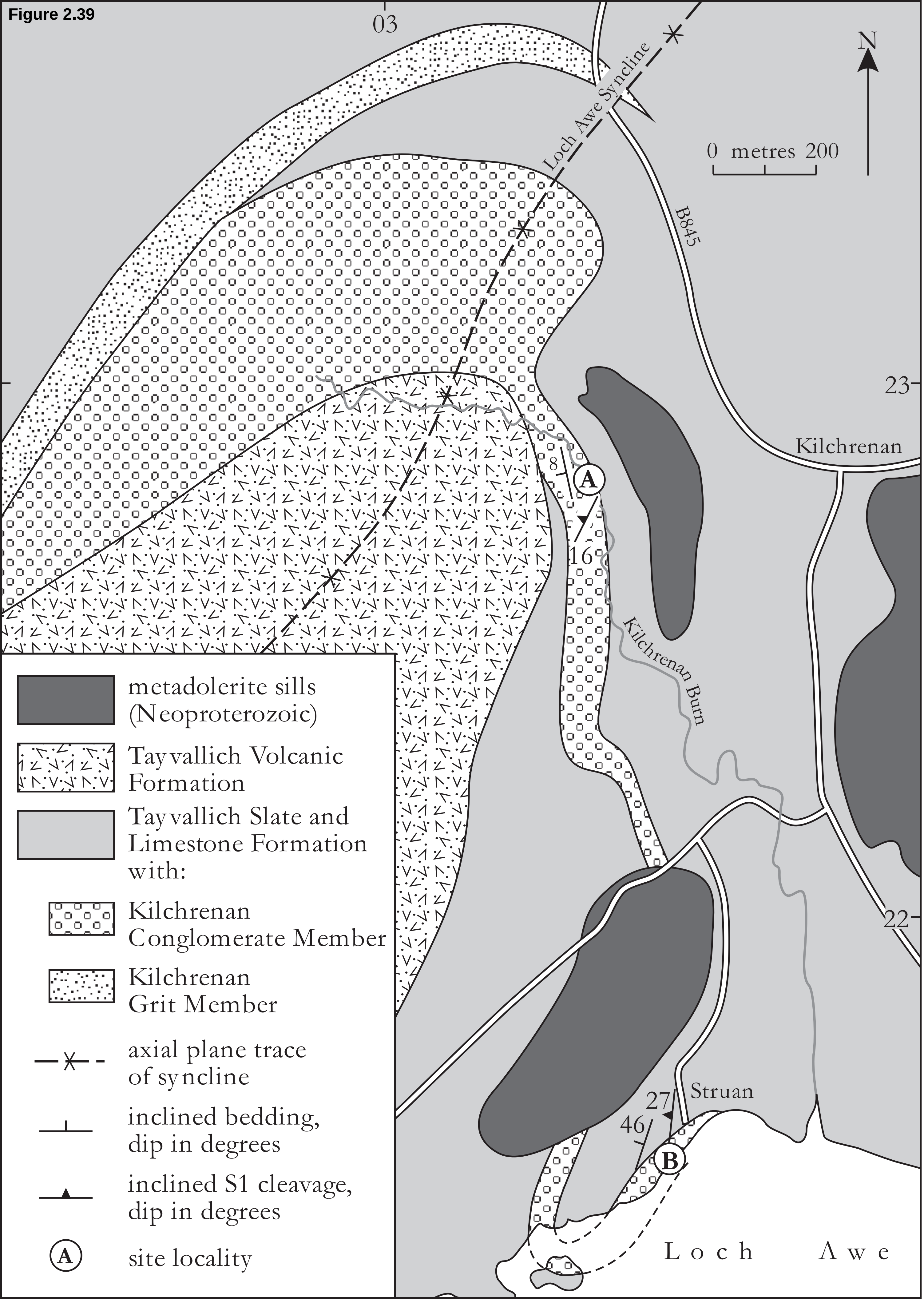
09
A83
HWM
LWM
80
25
11
28
38
30
28
38
27
Strone Point
N
0 metres 200
Strone Point Anticline
Loch Fyne
12
0 kilometres 2
N
20
Loch Awe
00
Ardrishaig Anticline
Strone Point Anticline
Loch Fyne
10
Strone Point
inset map
Inverary
10
dolerite (? late Carboniferous)
metadolerite (Neoproterozoic)
Crinan Grit Formation/
Ben Lui Schist Formation
Ardrishaig Phyllite Formation
axial plane trace of major anticline
axial plane trace of major syncline
inclined bedding, dip in degrees
inclined S1 cleavage, dip in degrees
hinge-parallel lineation, plunge in degrees

Figure 2.38



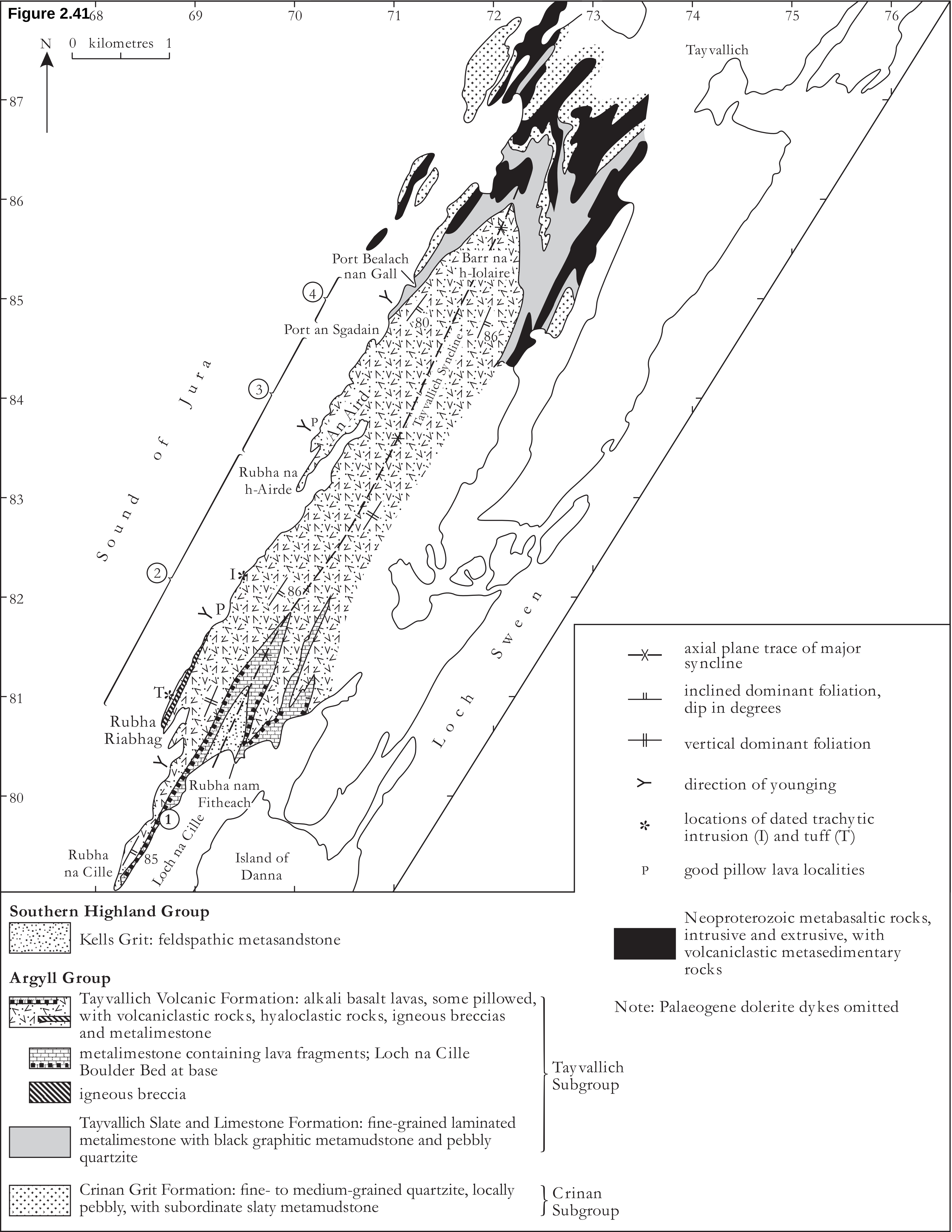
(a)
X (stretching
direction)
(b)
20 cm
25
305
268
15
S2
fold hinge
30 cm
(c)
N
great circle representing
the mean orientation of S1
stretching lineation (x)
bedding/S1 cleavage intersection
lineations and minor F1 fold hinges
field occupied by poles to S1 cleavage

Figure 2.39



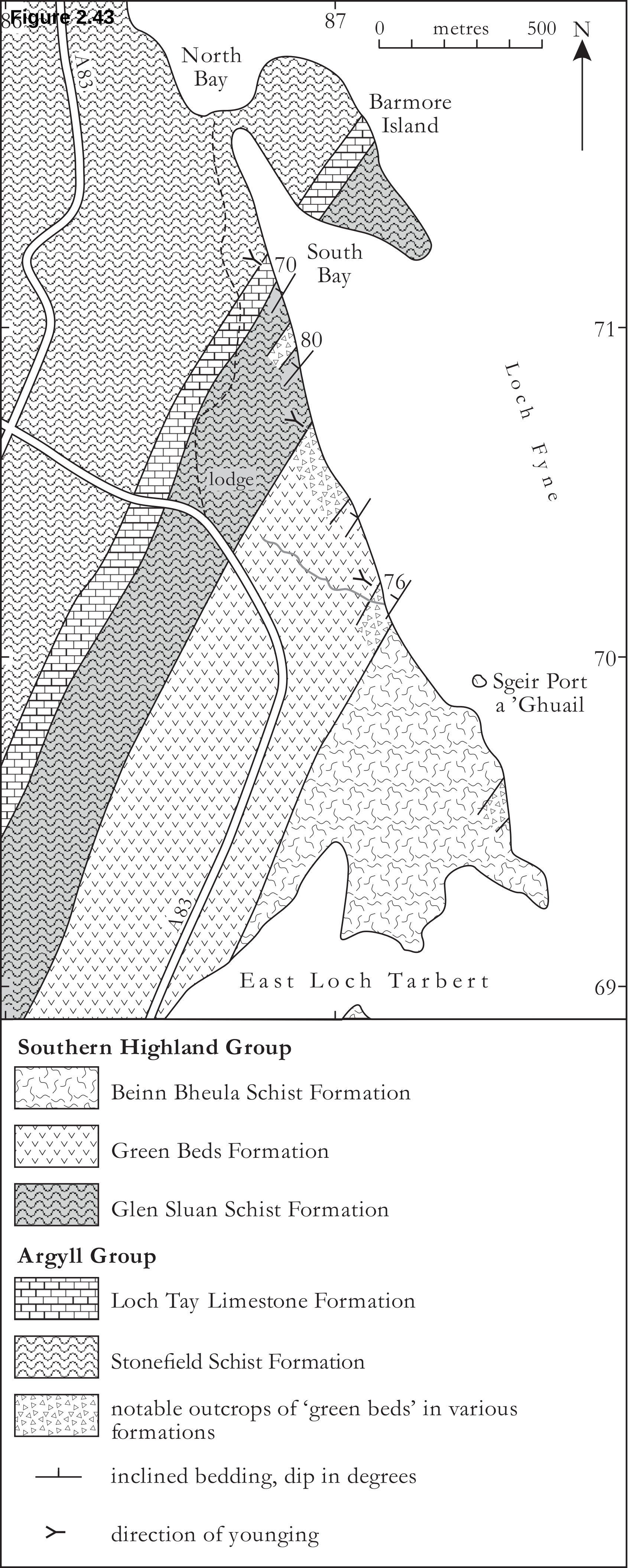
03
23
22
N
0 metres 200
Loch Awe Syncline
B845
Kilchrenan
Kilchrenan Burn
Struan
Loch Awe
A
B
8
16
27
46
metadolerite sills (Neoproterozoic)
Tayvallich Volcanic Formation
Tayvallich Slate and Limestone Formation with:
Kilchrenan Conglomerate Member
Kilchrenan Grit Member
axial plane trace of syncline
inclined bedding, dip in degrees
inclined S1 cleavage, dip in degrees
site locality

Figure 2.41



68
69
70
71
72
73
74
75
76
87
86
85
84
83
82
81
80
N
0 kilometres 1
Tayvallich
Port Bealach nan Gall
Barr na h-Iolaire
Port an Sgadain
80
86
Tayvallich Syncline
An Aird
Sound of Jura
Rubha na h-Airde
I
86
P
T
Rubha Riabhag
Rubha nam Fitheach
Loch na Cille
Rubha na Cille
85
Island of Danna
Loch Sween
1
2
3
4
axial plane trace of major syncline
inclined dominant foliation, dip in degrees
vertical dominant foliation
direction of younging
locations of dated trachytic intrusion (I) and tuff (T)
good pillow lava localities
Southern Highland Group
Kells Grit: feldspathic metasandstone
Argyll Group
Tayvallich Volcanic Formation: alkali basalt lavas, some pillowed, with volcaniclastic rocks, hyaloclastic rocks, igneous breccias and metalimestone
metalimestone containing lava fragments; Loch na Cille Boulder Bed at base
igneous breccia
Tayvallich Slate and Limestone Formation: fine-grained laminated metalimestone with black graphitic metamudstone and pebbly quartzite
Tayvallich Subgroup
Crinan Grit Formation: fine- to medium-grained quartzite, locally pebbly, with subordinate slaty metamudstone
Crinan Subgroup
Neoproterozoic metabasaltic rocks, intrusive and extrusive, with volcaniclastic metasedimentary rocks
Note: Palaeogene dolerite dykes omitted

Figure 2.43



87
0
metres
500
N
North Bay
Barmore Island
A83
South Bay
70
80
71
Loch Fyne
lodge
76
70
Sgeir Port a 'Ghuail
A83
East Loch Tarbert
69
Southern Highland Group
Beinn Bheula Schist Formation
Green Beds Formation
Glen Sluan Schist Formation
Argyll Group
Loch Tay Limestone Formation
Stonefield Schist Formation
notable outcrops of 'green beds' in various formations
inclined bedding, dip in degrees
direction of younging

Figure 2.45

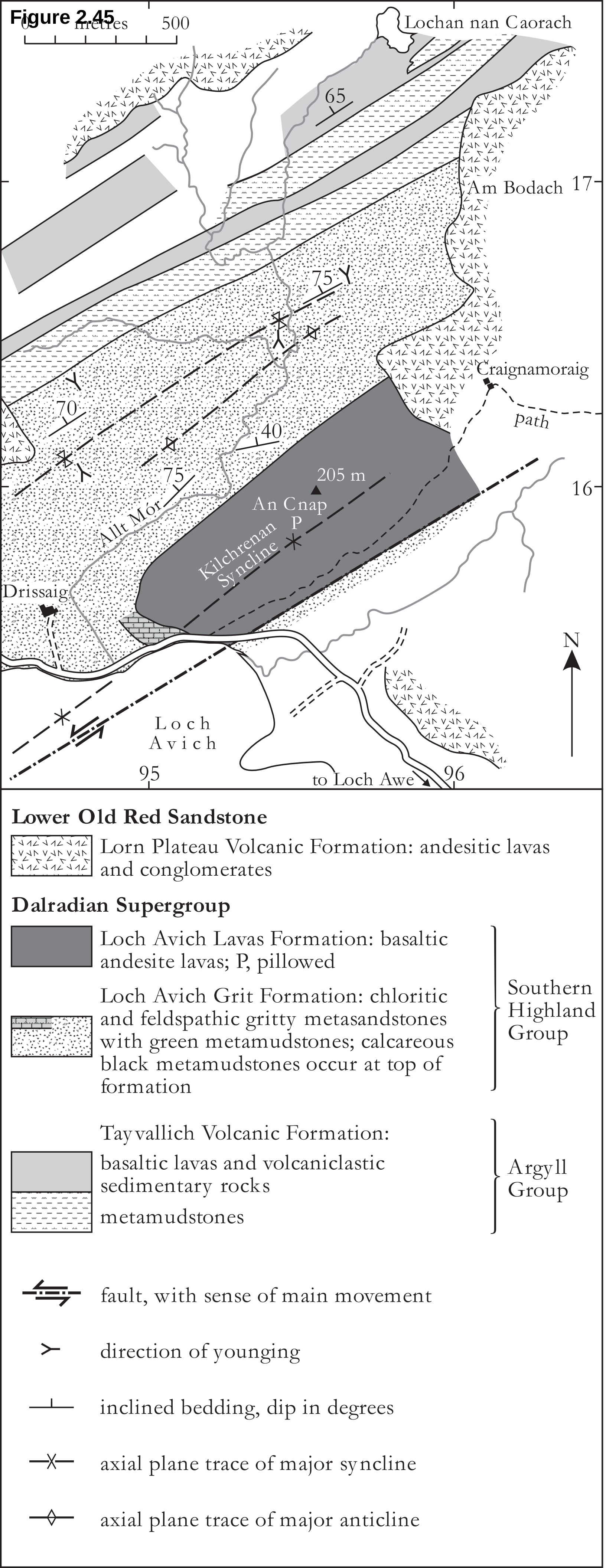
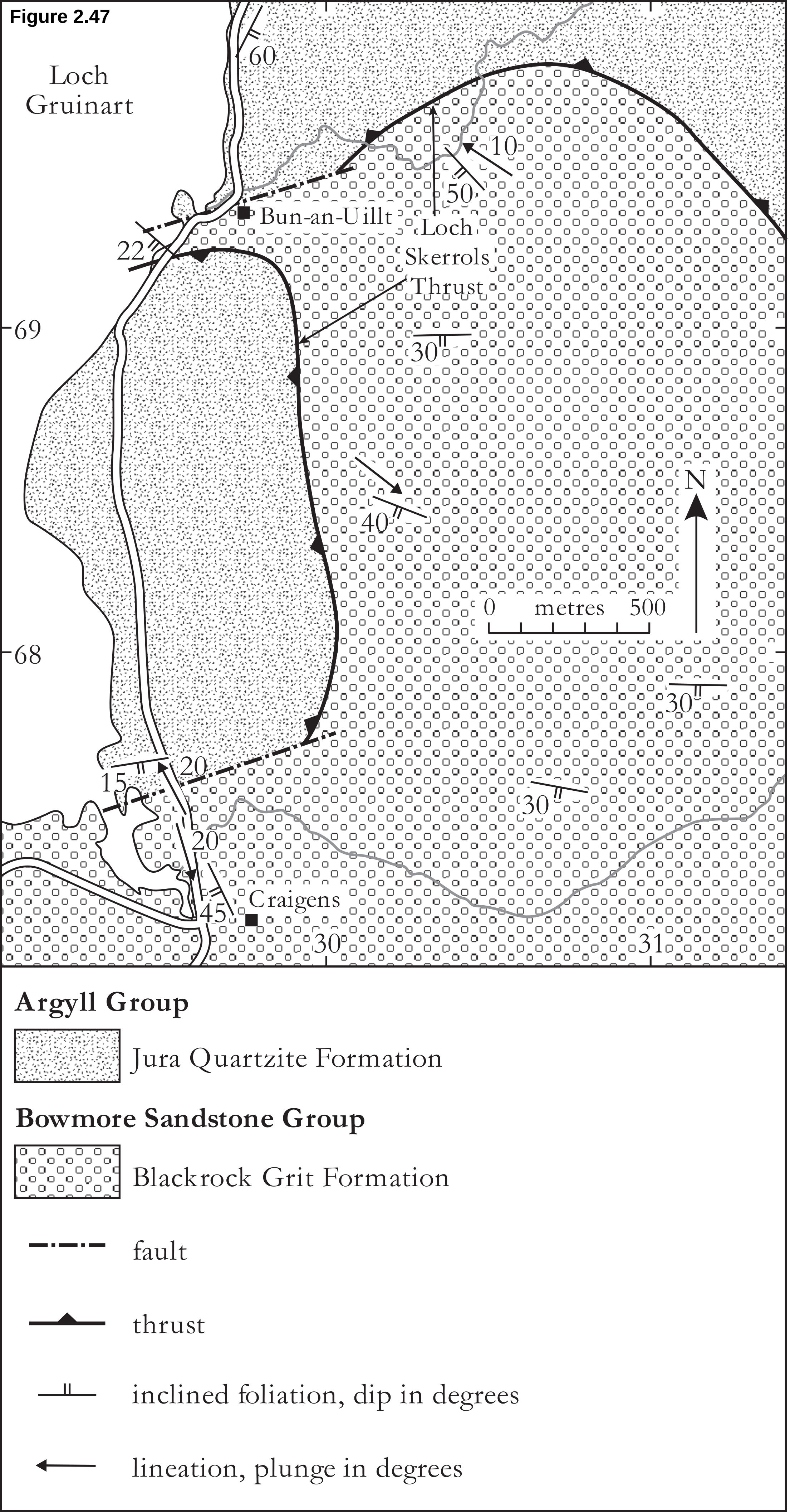

0
metres
500
Lochan nan Caorach
65
17
Am Bodach
75
70
Craignamoraig
path
40
205 m
An Cnap
P
Kilchrenan Syncline
75
Allt Mór
16
Drissaig
N
Loch Avich
95
to Loch Awe
96
Lower Old Red Sandstone
Lorn Plateau Volcanic Formation: andesitic lavas and conglomerates
Dalradian Supergroup
Loch Avich Lavas Formation: basaltic andesite lavas; P, pillowed
Loch Avich Grit Formation: chloritic and feldspathic gritty metasandstones with green metamudstones; calcareous black metamudstones occur at top of formation
Southern Highland Group
Tayvallich Volcanic Formation:
basaltic lavas and volcaniclastic sedimentary rocks
metamudstones
Argyll Group
fault, with sense of main movement
direction of younging
inclined bedding, dip in degrees
axial plane trace of major syncline
axial plane trace of major anticline

Figure 2.47



Loch Gruinart
60
10
50
Bun-an-Uillt
Loch Skerrols Thrust
22
69
30
40
N
0 metres 500
68
30
20
15
30
20
45
Craigens
30
31
Argyll Group
Jura Quartzite Formation
Bowmore Sandstone Group
Blackrock Grit Formation
fault
thrust
inclined foliation, dip in degrees
lineation, plunge in degrees

Figure 2.49

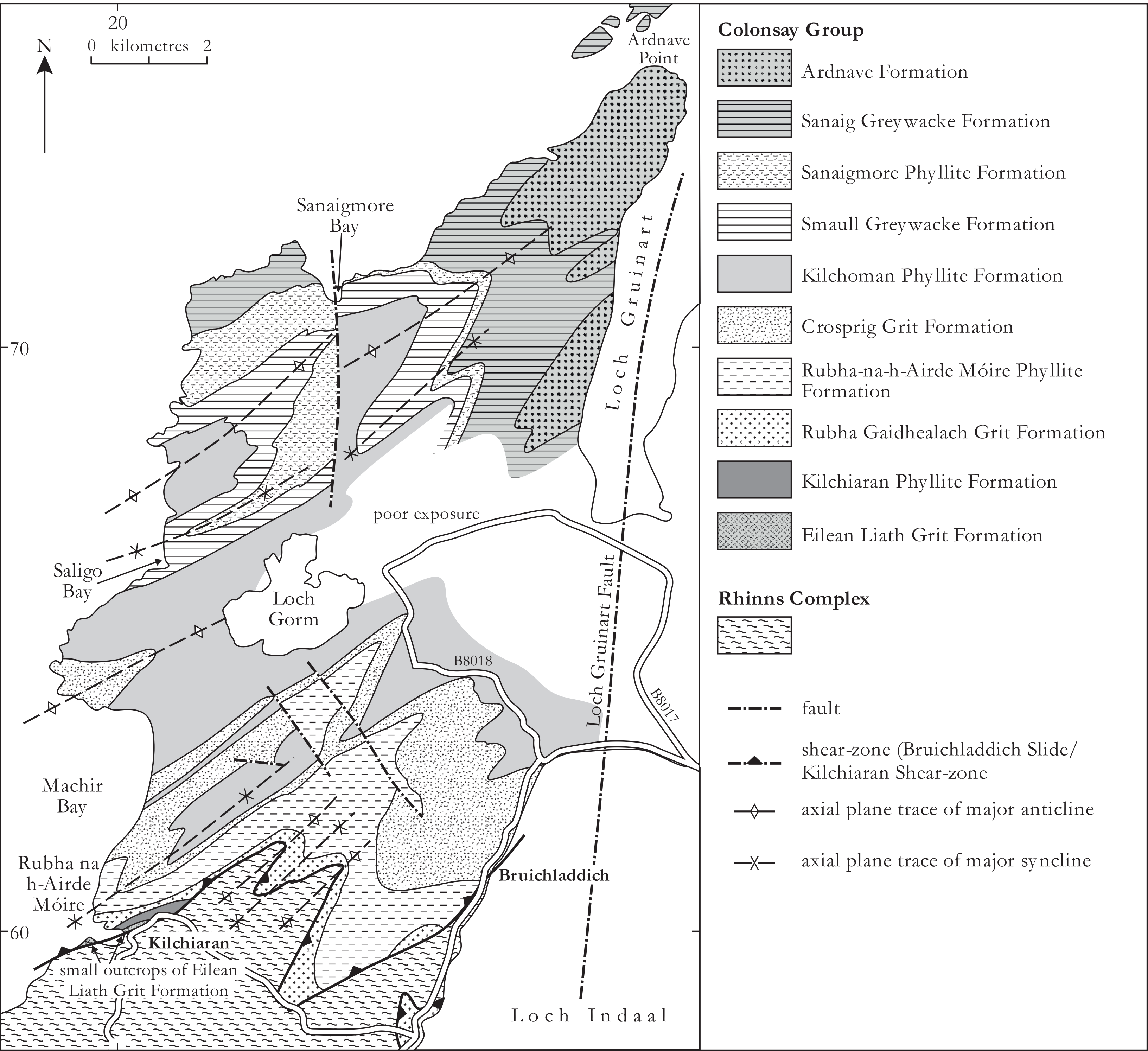

20
N
0 kilometres 2
70
60
Ardnave Point
Sanaigmore Bay
Saligo Bay
Loch Gorm
poor exposure
Machir Bay
Rubha na h-Airde Móire
Kilchiaran
small outcrops of Eilean Liath Grit Formation
Bruichladdich
B8018
B8017
Loch Gruinart
Loch Gruinart Fault
Loch Indaal
Colonsay Group
Ardnave Formation
Sanaig Greywacke Formation
Sanaigmore Phyllite Formation
Smaull Greywacke Formation
Kilchoman Phyllite Formation
Crosprig Grit Formation
Rubha-na-h-Airde Móire Phyllite Formation
Rubha Gaidhealach Grit Formation
Kilchiaran Phyllite Formation
Eilean Liath Grit Formation
Rhinns Complex
fault
shear-zone (Bruichladdich Slide/ Kilchiaran Shear-zone
axial plane trace of major anticline
axial plane trace of major syncline

Figure 2.4 colour

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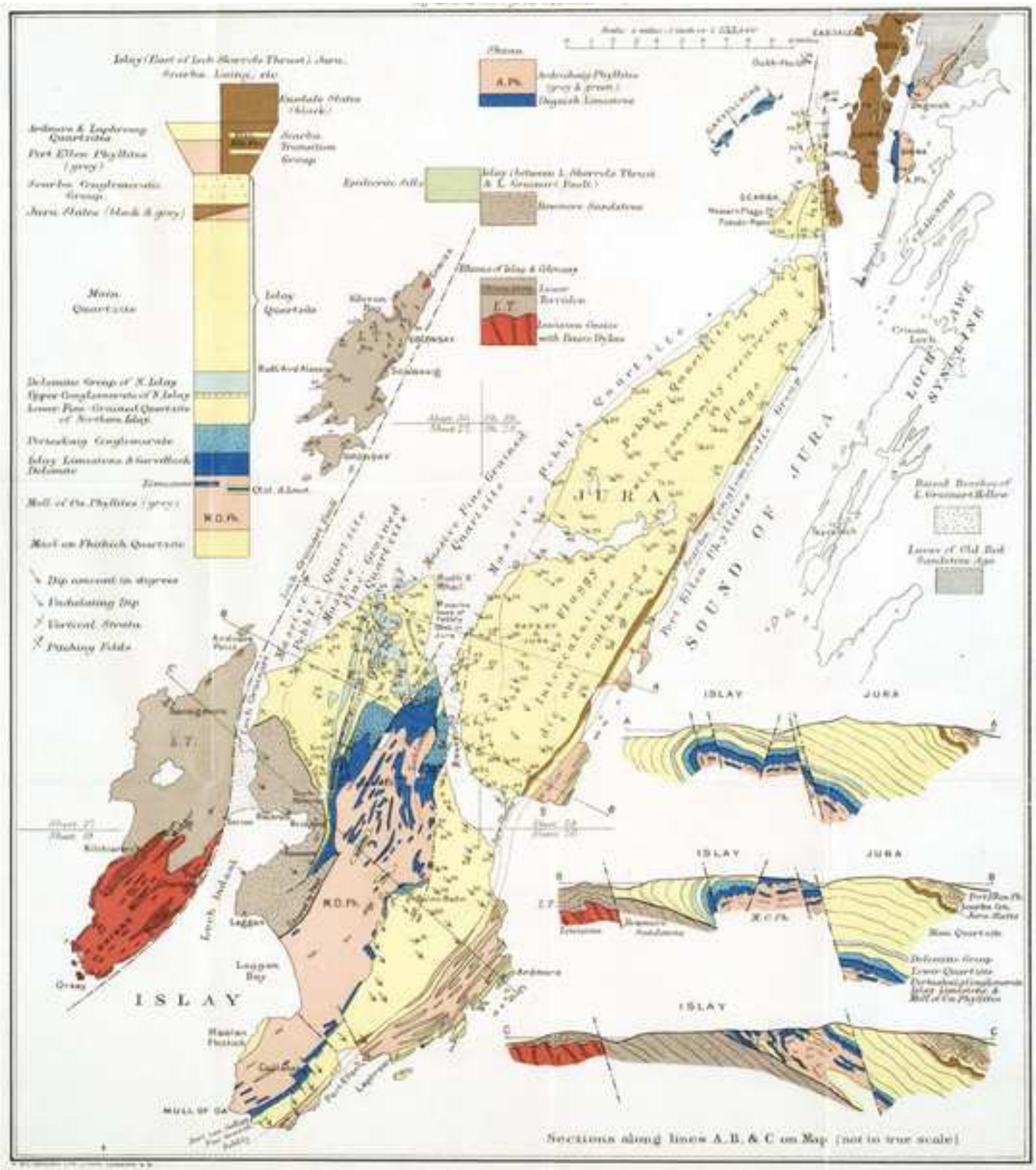

Figure 2.6 colour

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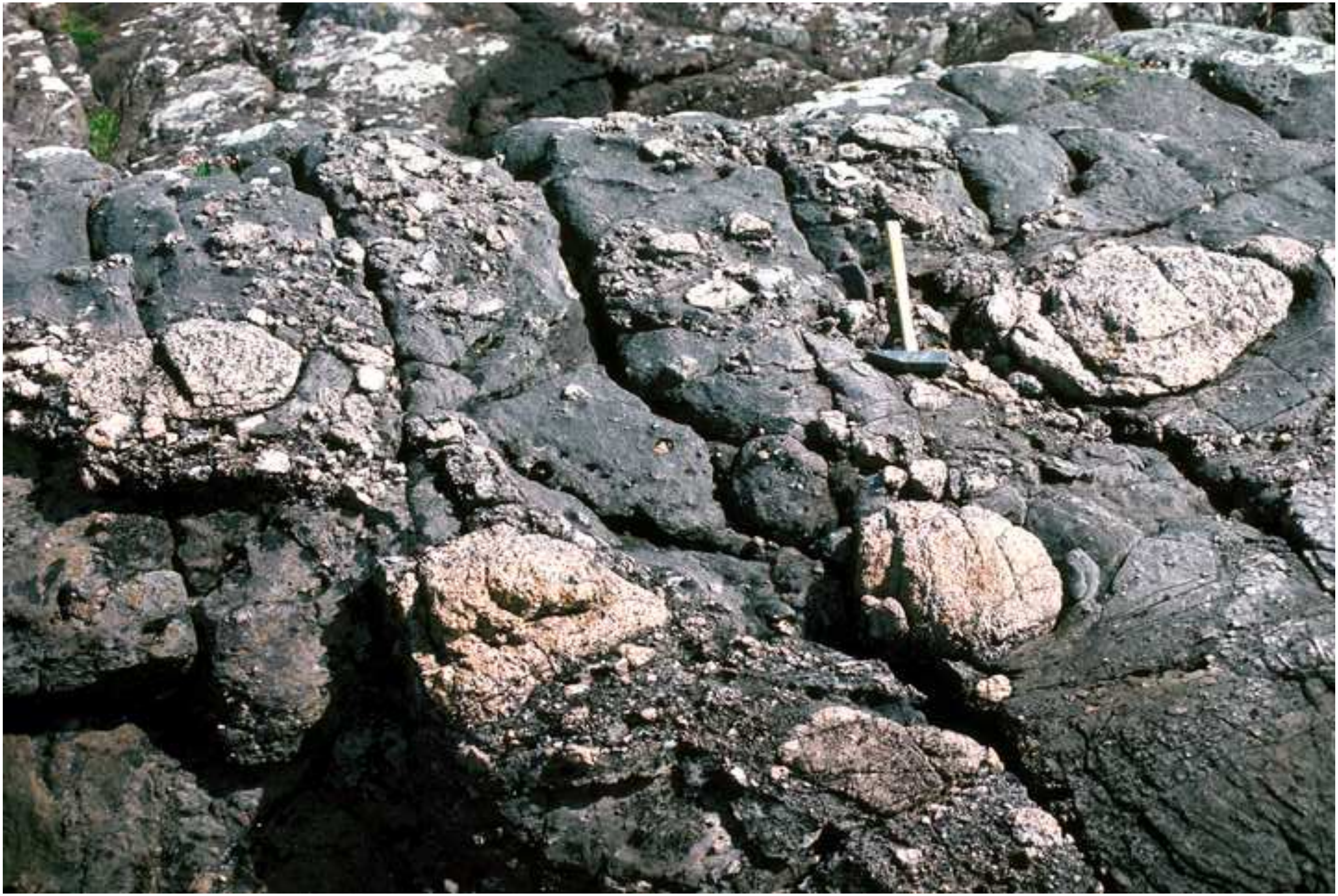

Figure 2.8a
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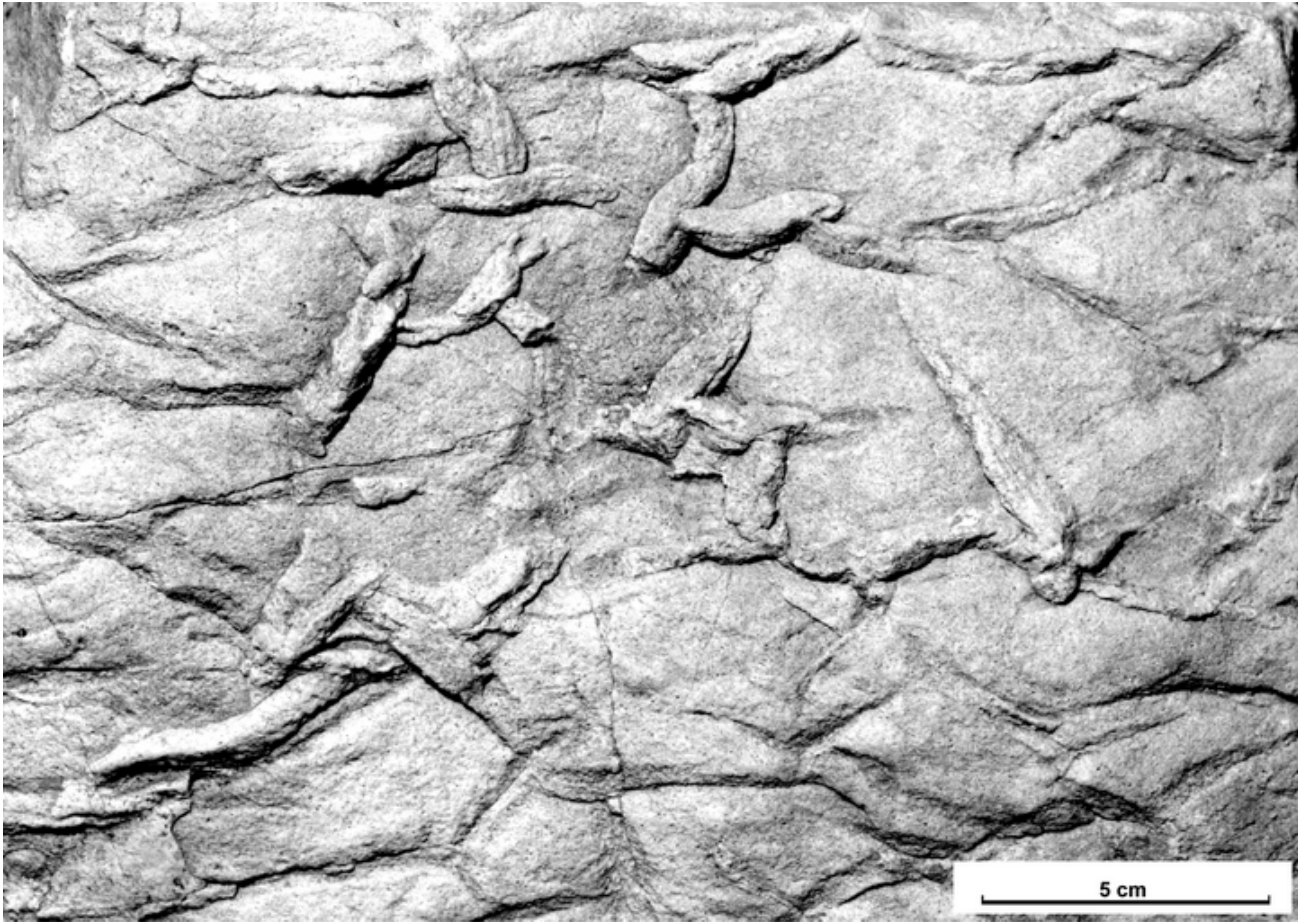

Figure 2.8b
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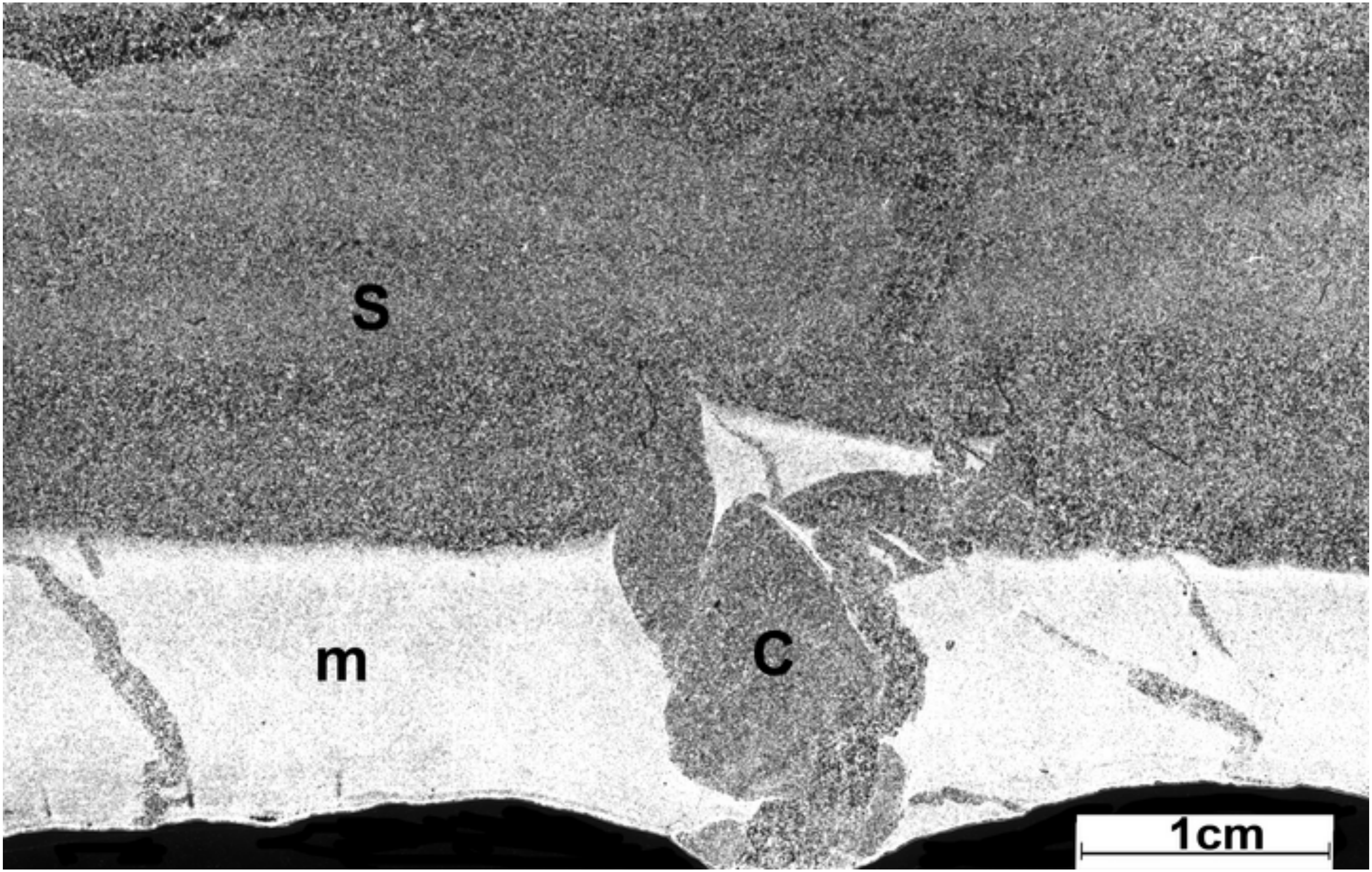

Figure 2.10a
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Figure 2.10b colour
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Figure 2.13 colour
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Figure 2.15 colour

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Figure 2.17 colour

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Figure 2.19 colour
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Figure 2.21
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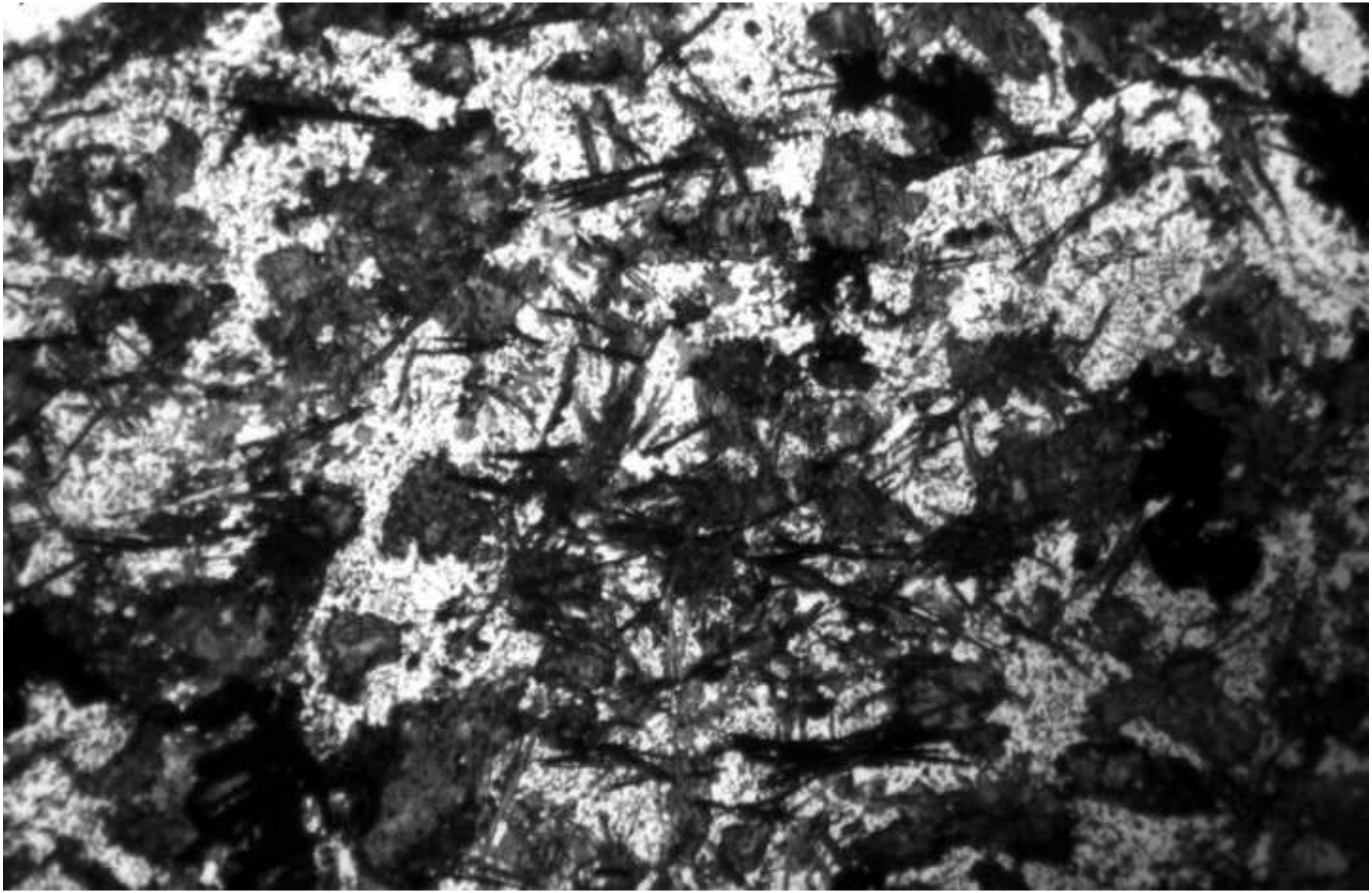

Figure 2.23 colour
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Figure 2.26a colour
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Figure 2.26b colour
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Figure 2.26c colour
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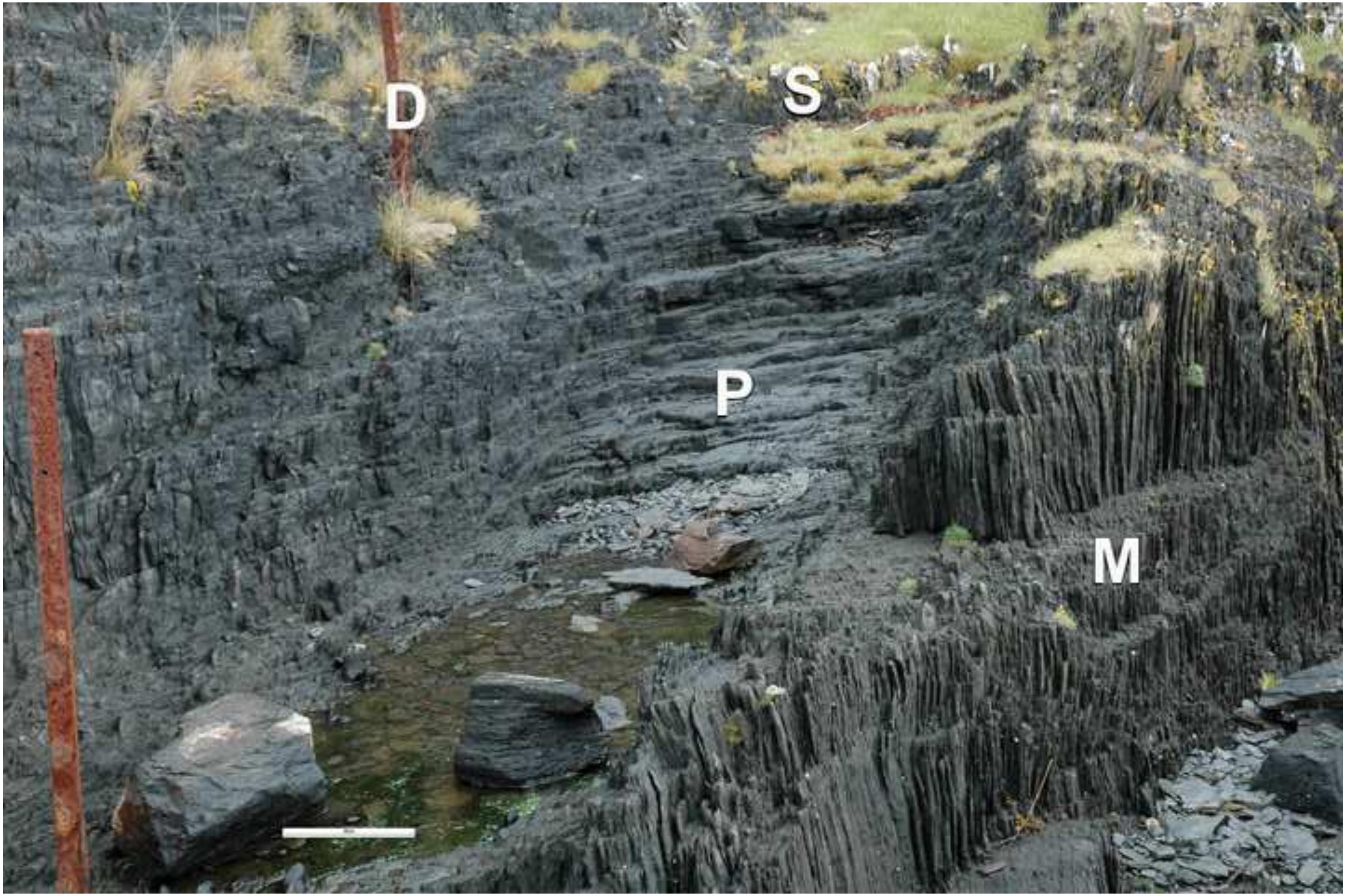

Figure 2.28a colour
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Figure 2.28b colour

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Figure 2.30a colour

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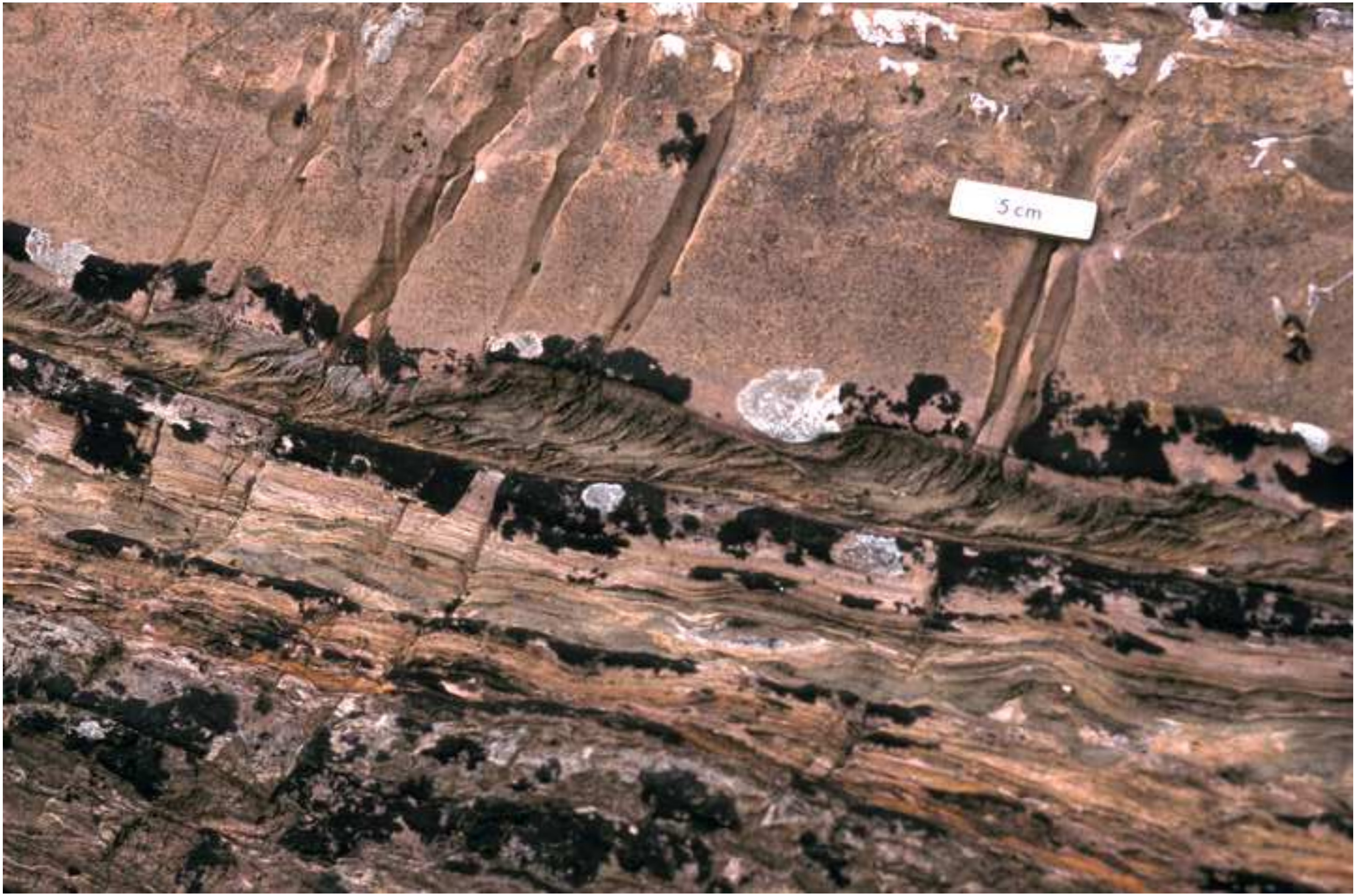

Figure 2.30b colour
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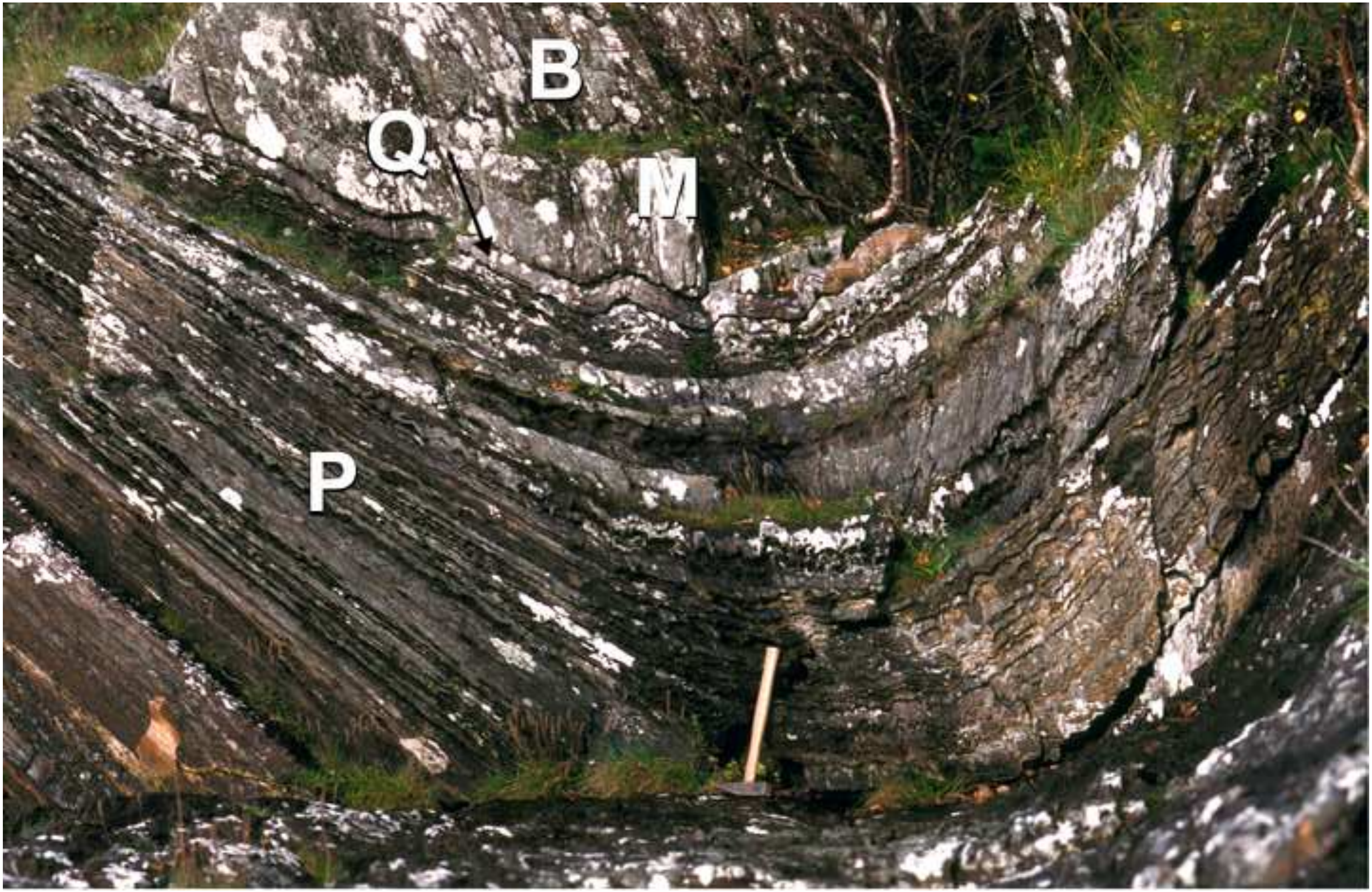

Figure 2.30c colour
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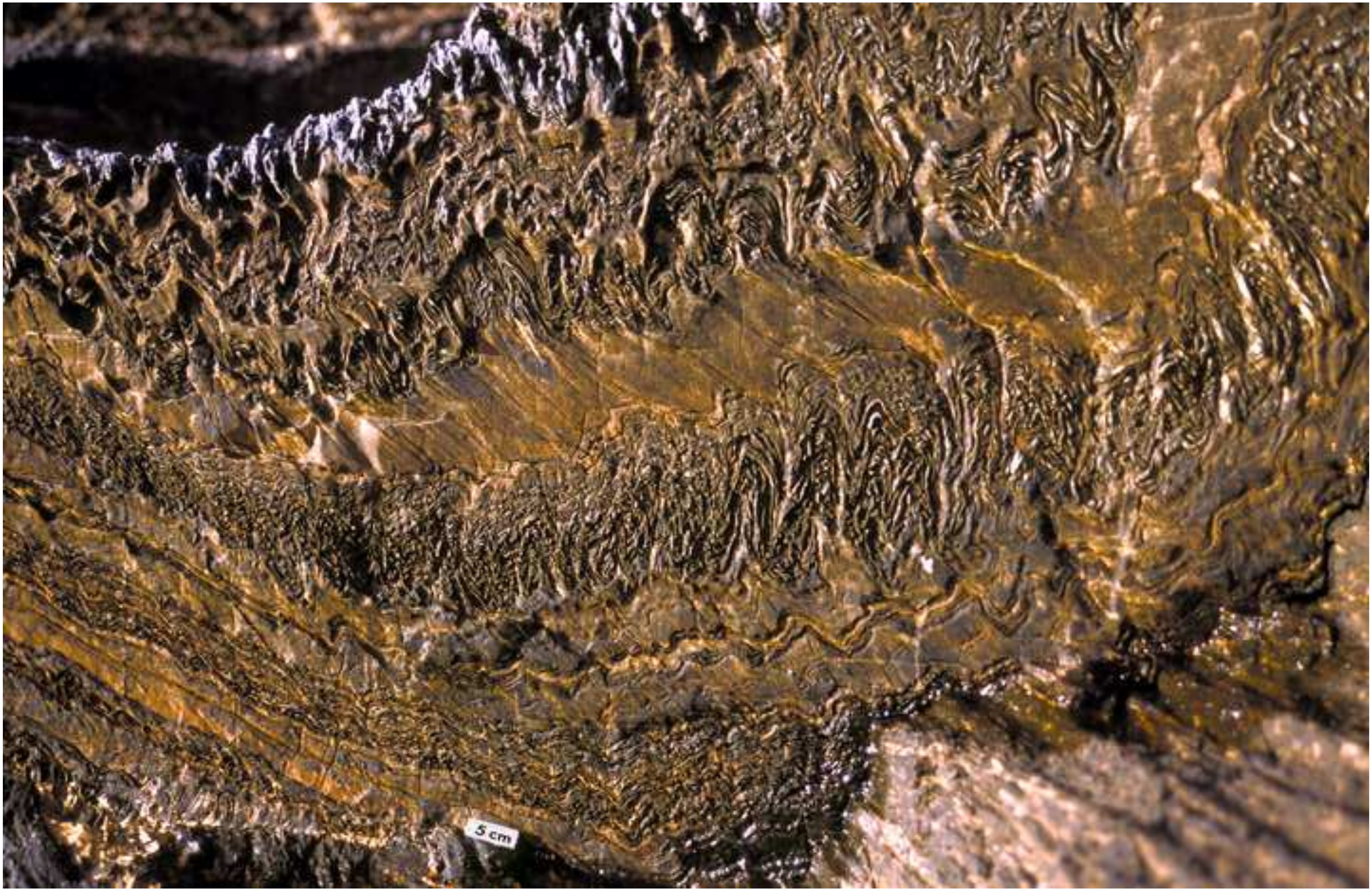

Figure 2.32 colour
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Figure 2.33 colour

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Figure 2.35a colour
Click here to download high resolution image

Figure 2.35b colour
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Figure 2.37 colour

Click here to download high resolution image

Figure 2.40 colour

Click here to download high resolution image

Figure 2.42 colour

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Figure 2.44 colour
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Figure 2.46 colour

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Figure 2.48a + b colour

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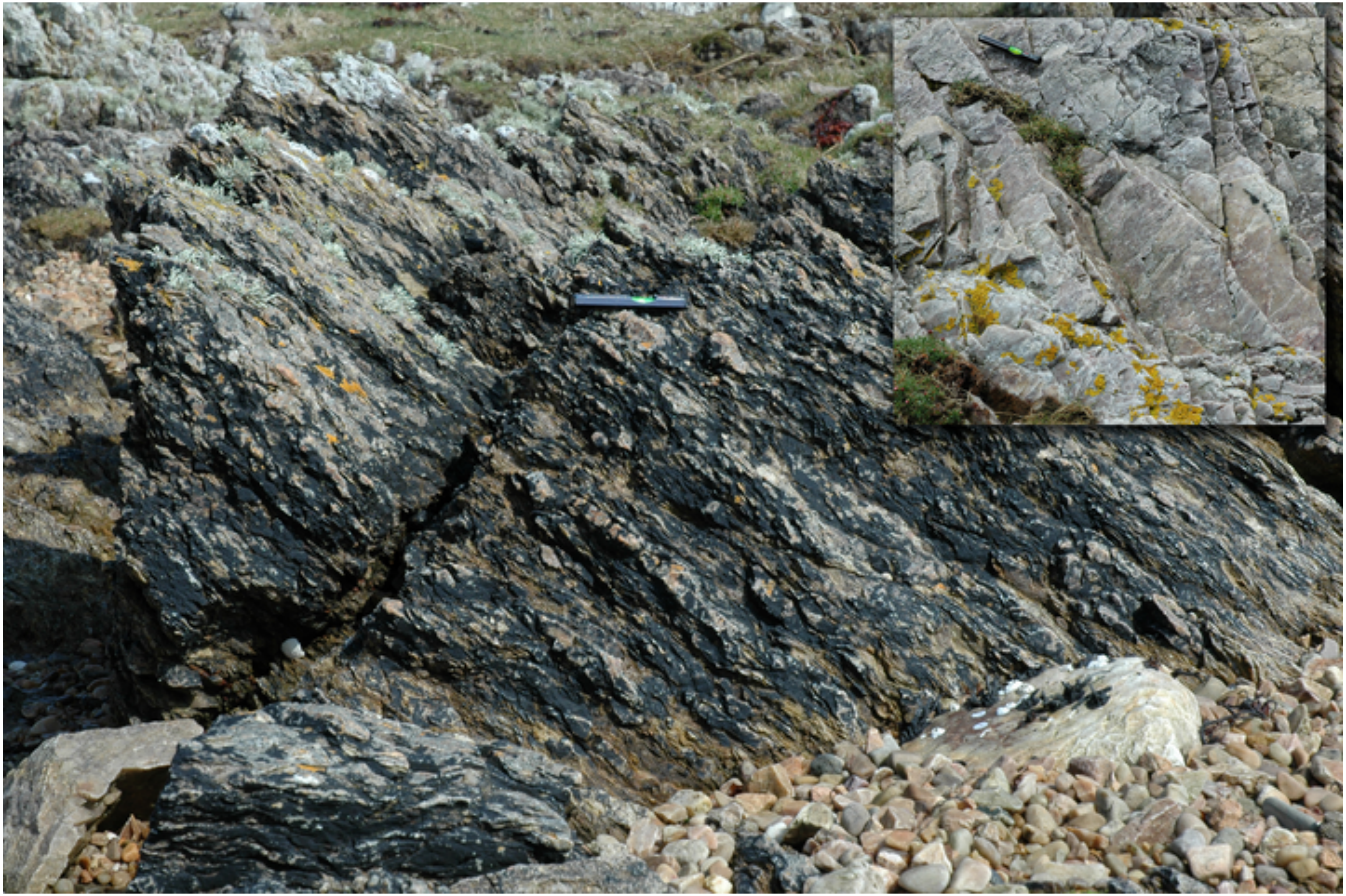

Figure 2.50 colour

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Figure 2.4 B&W

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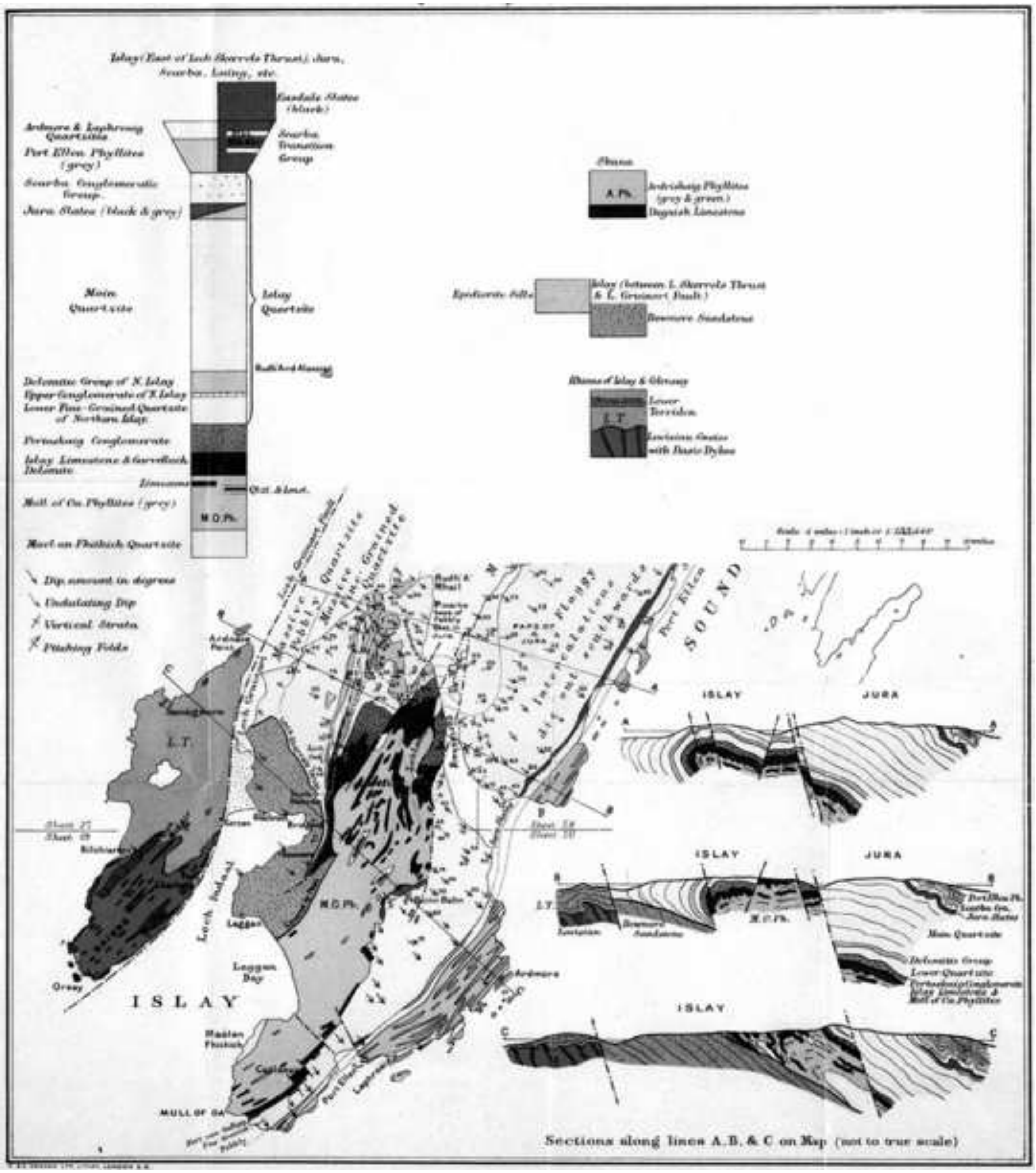

Figure 2.6 B&W
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Figure 2.10b B&W

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Figure 2.13 B&W

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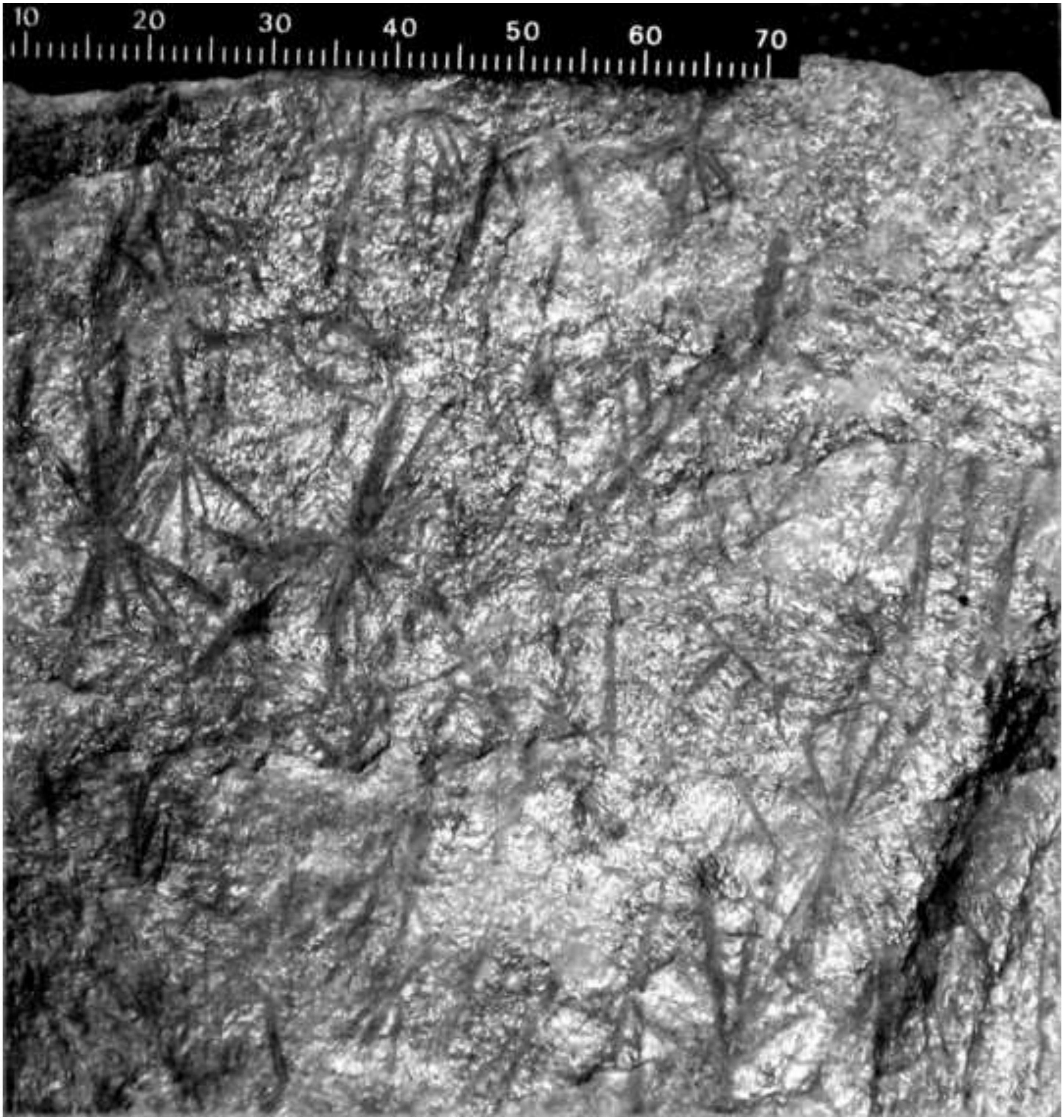

Figure 2.15 B&W

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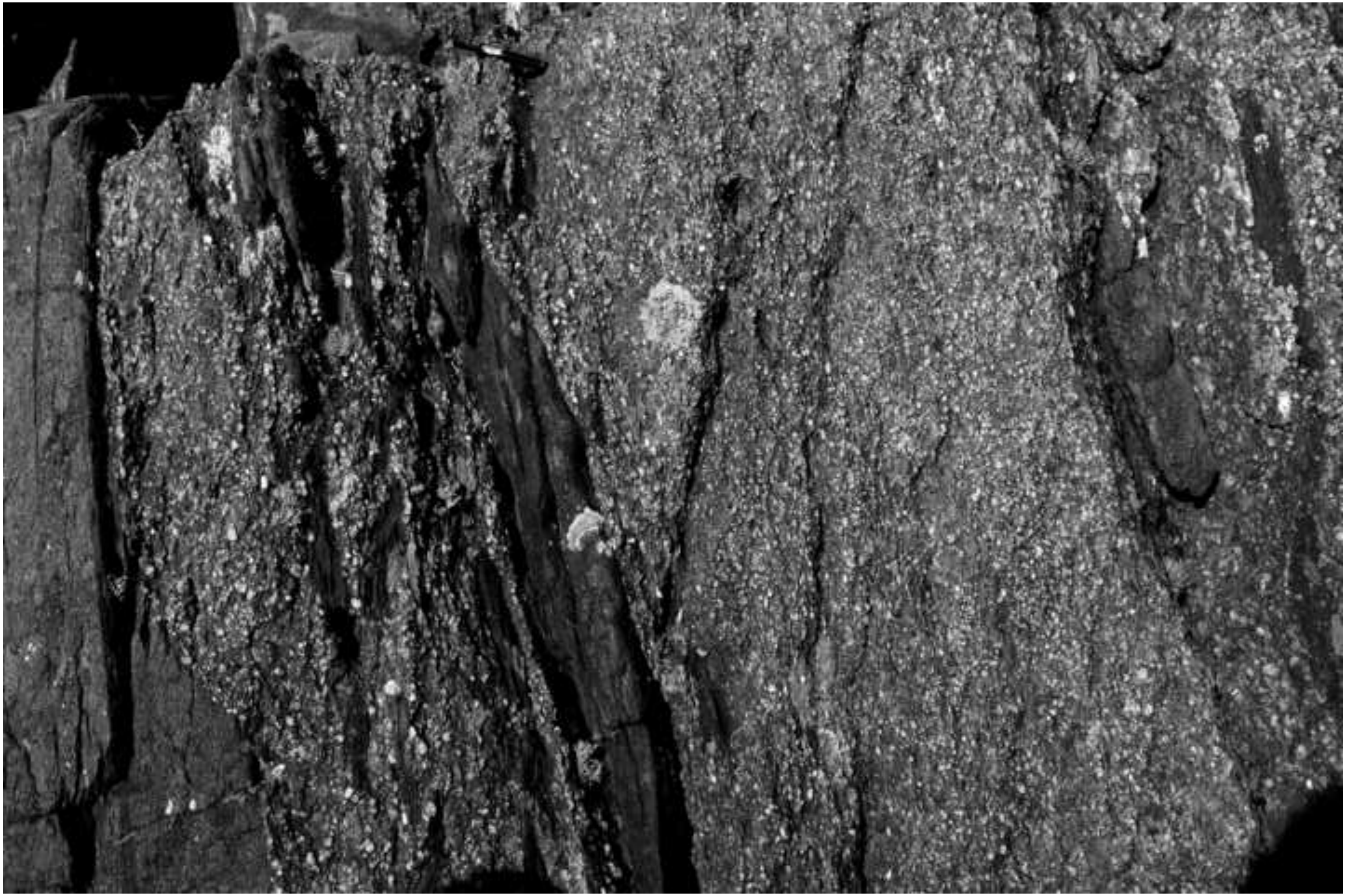

Figure 2.17 B&W
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Figure 2.19 B&W
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Figure 2.23 B&W
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Figure 2.26a B&W

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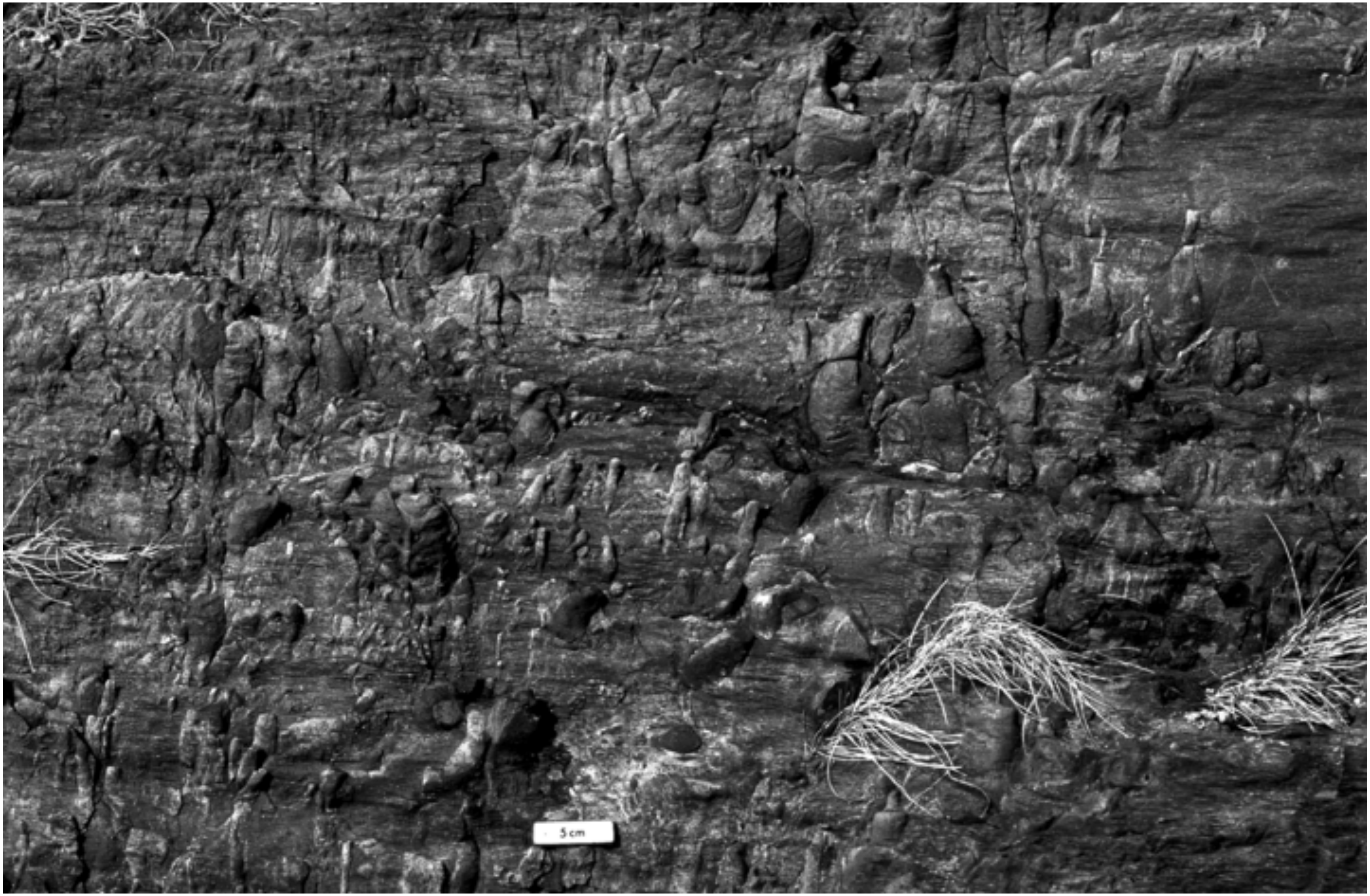

Figure 2.26b B&W

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Figure 2.26c B&W
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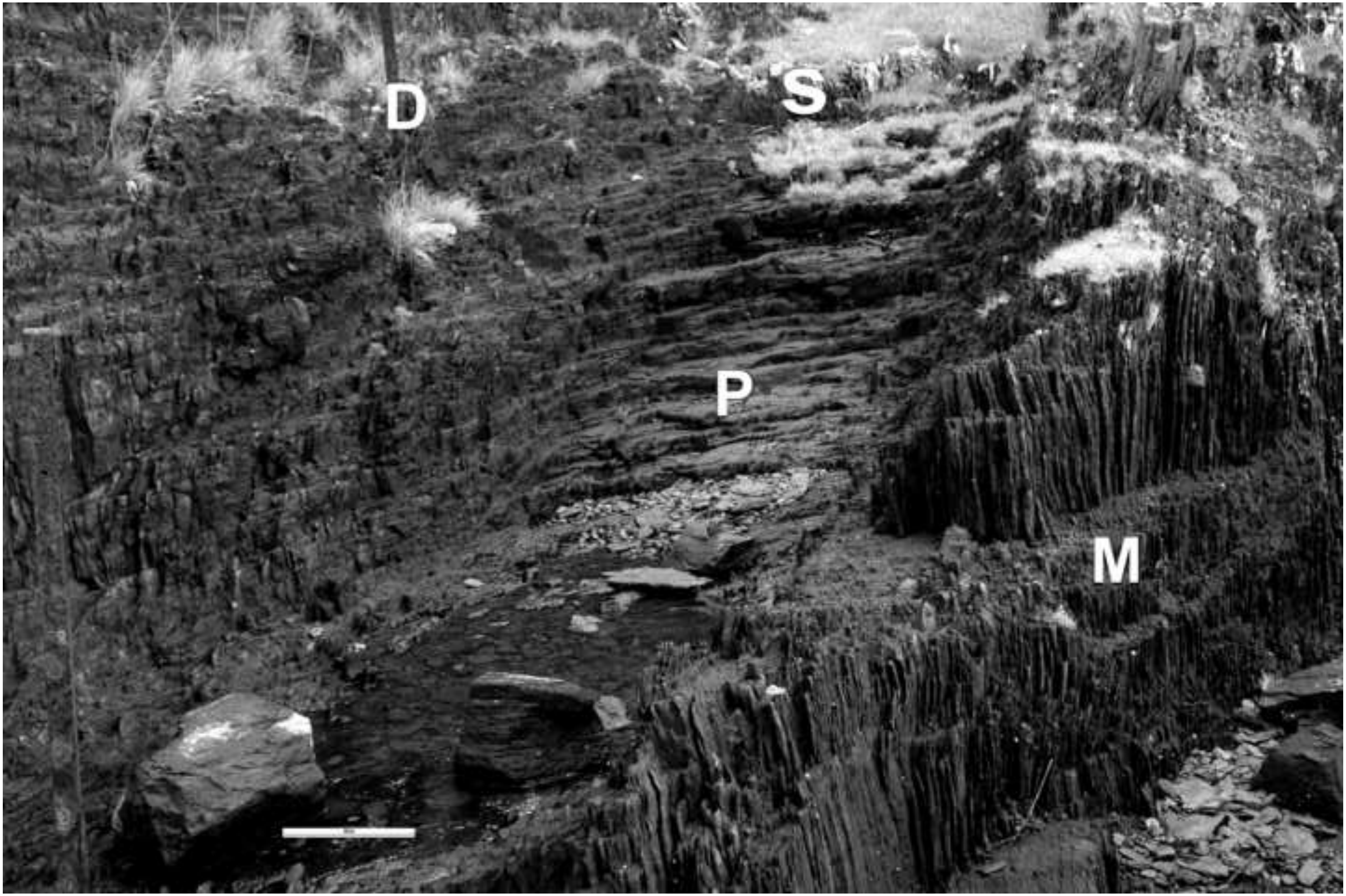

Figure 2.28a B&W

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Figure 2.28b B&W
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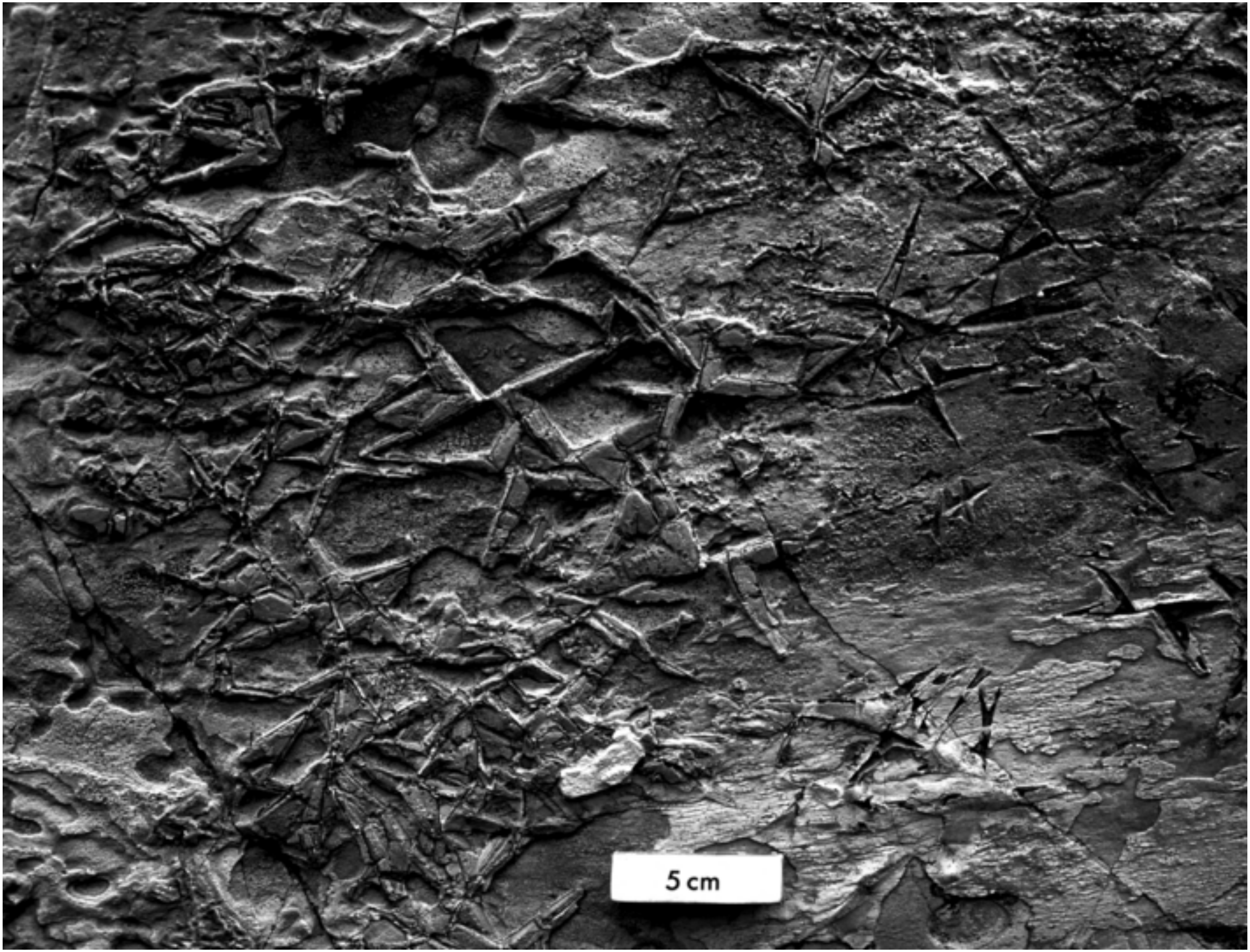

Figure 2.30a B&W

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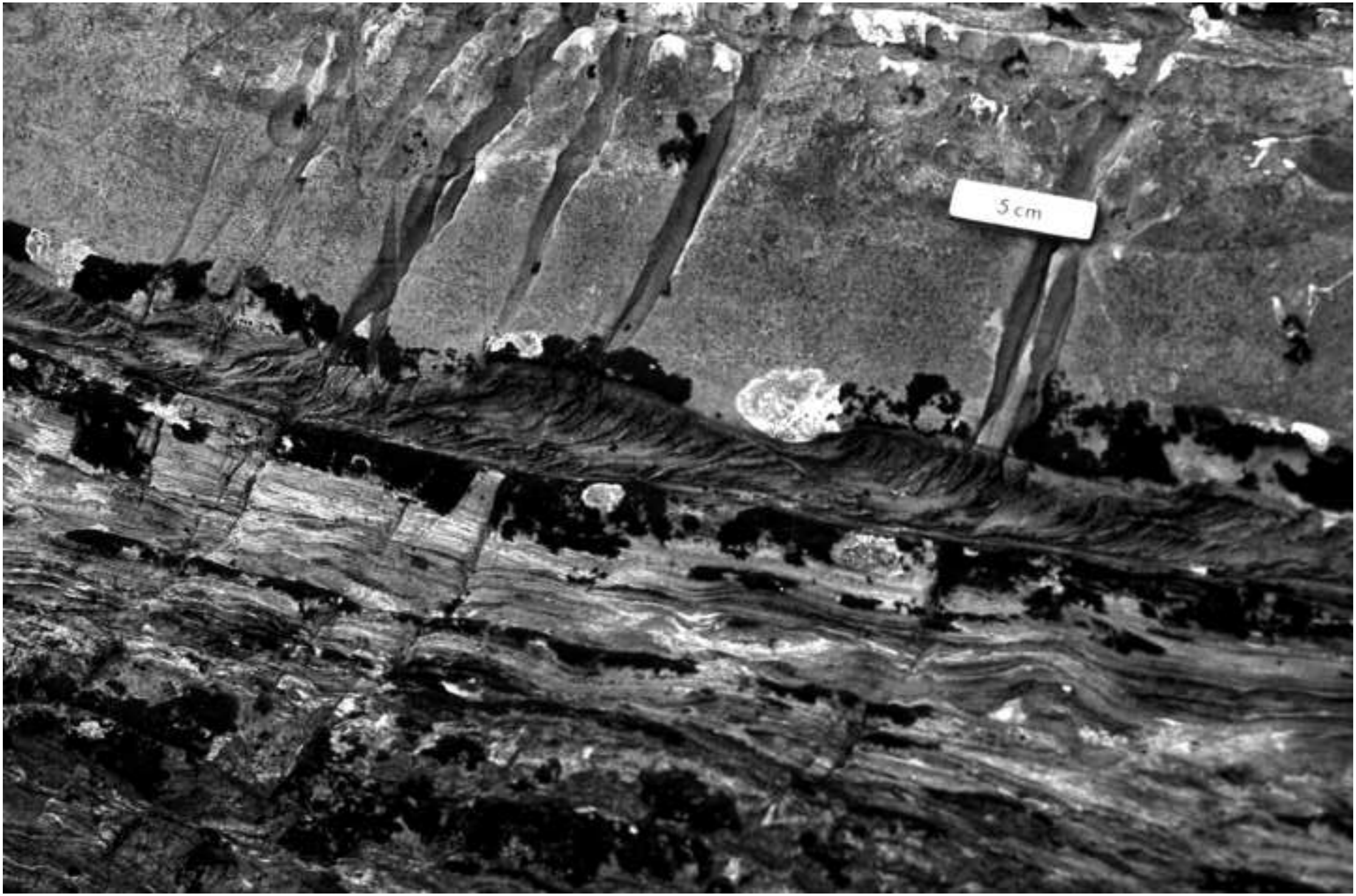

Figure 2.30b B&W

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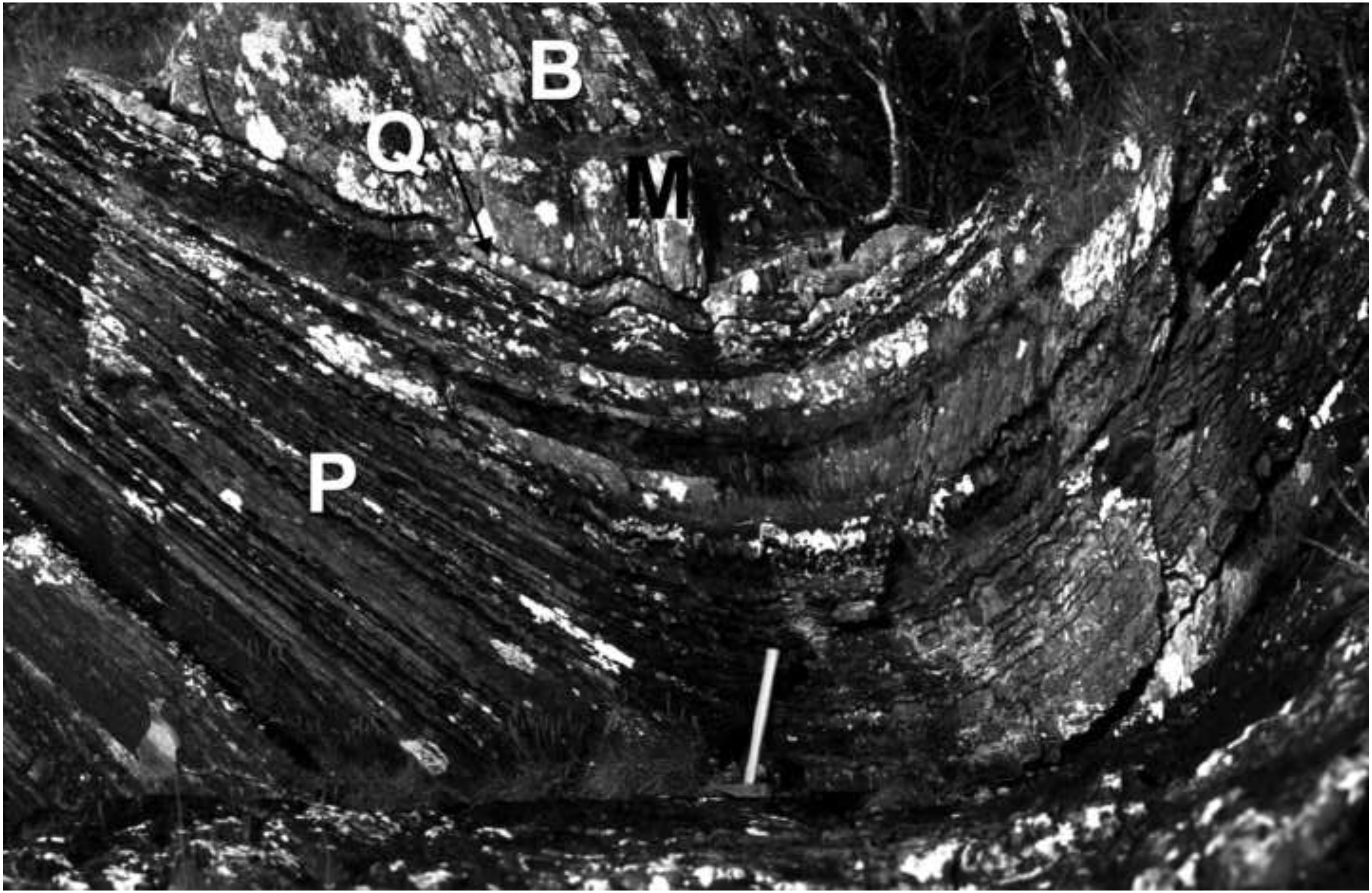

Figure 2.30c B&W

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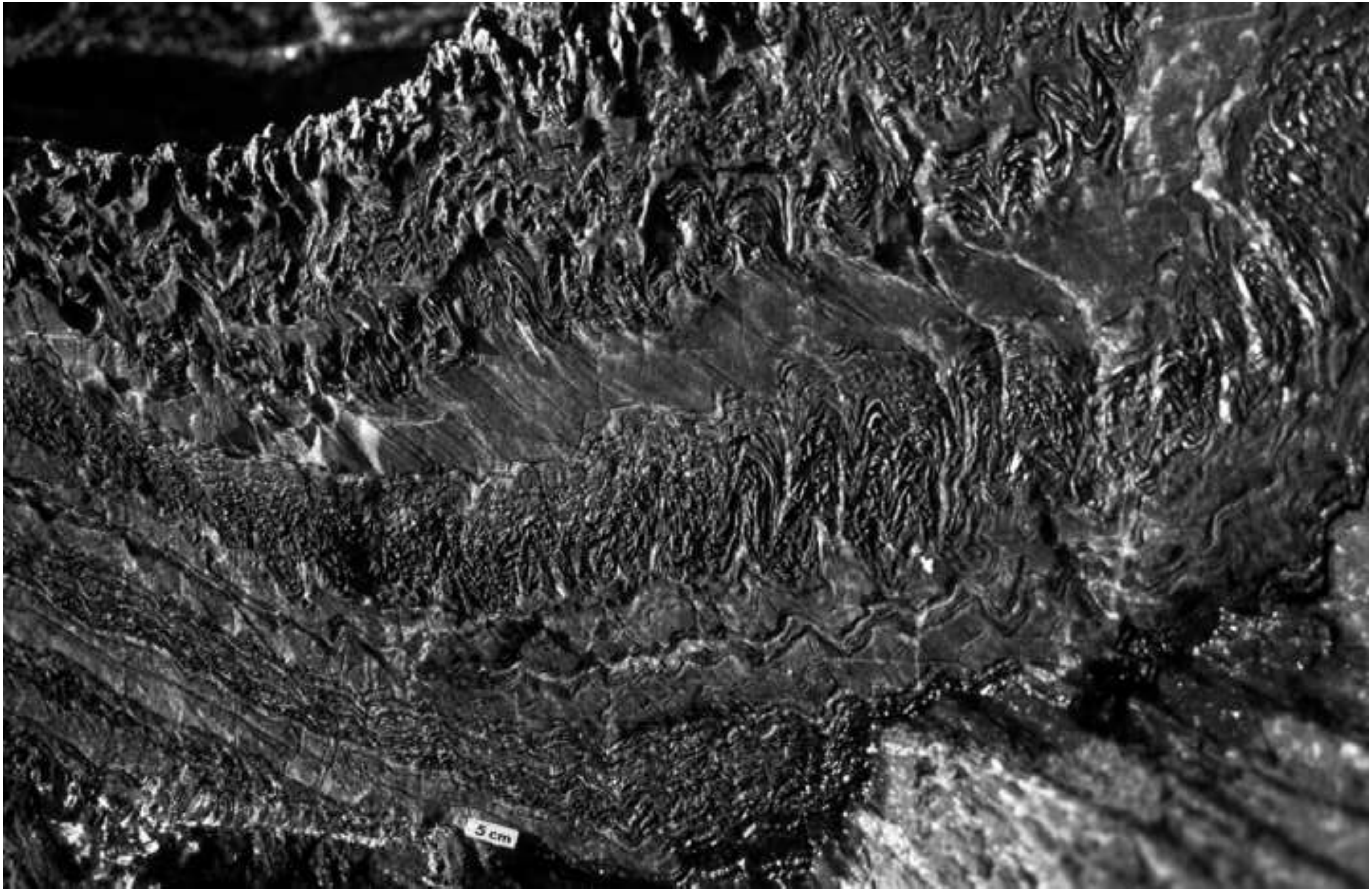

Figure 2.32 B&W

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Figure 2.33 B&W

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Figure 2.35a B&W
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Figure 2.35b B&W
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Figure 2.37 B&W

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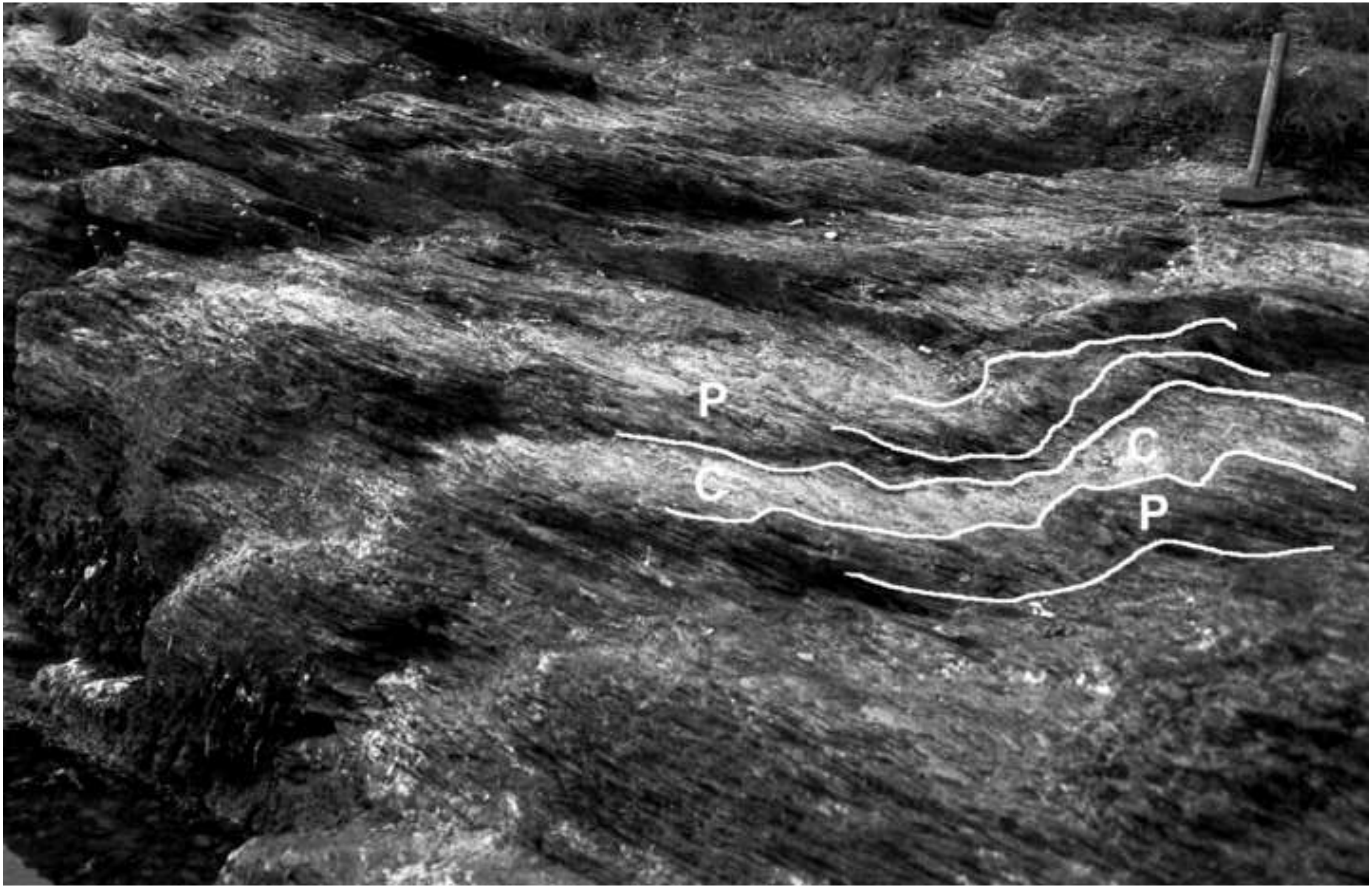

Figure 2.40 B&W

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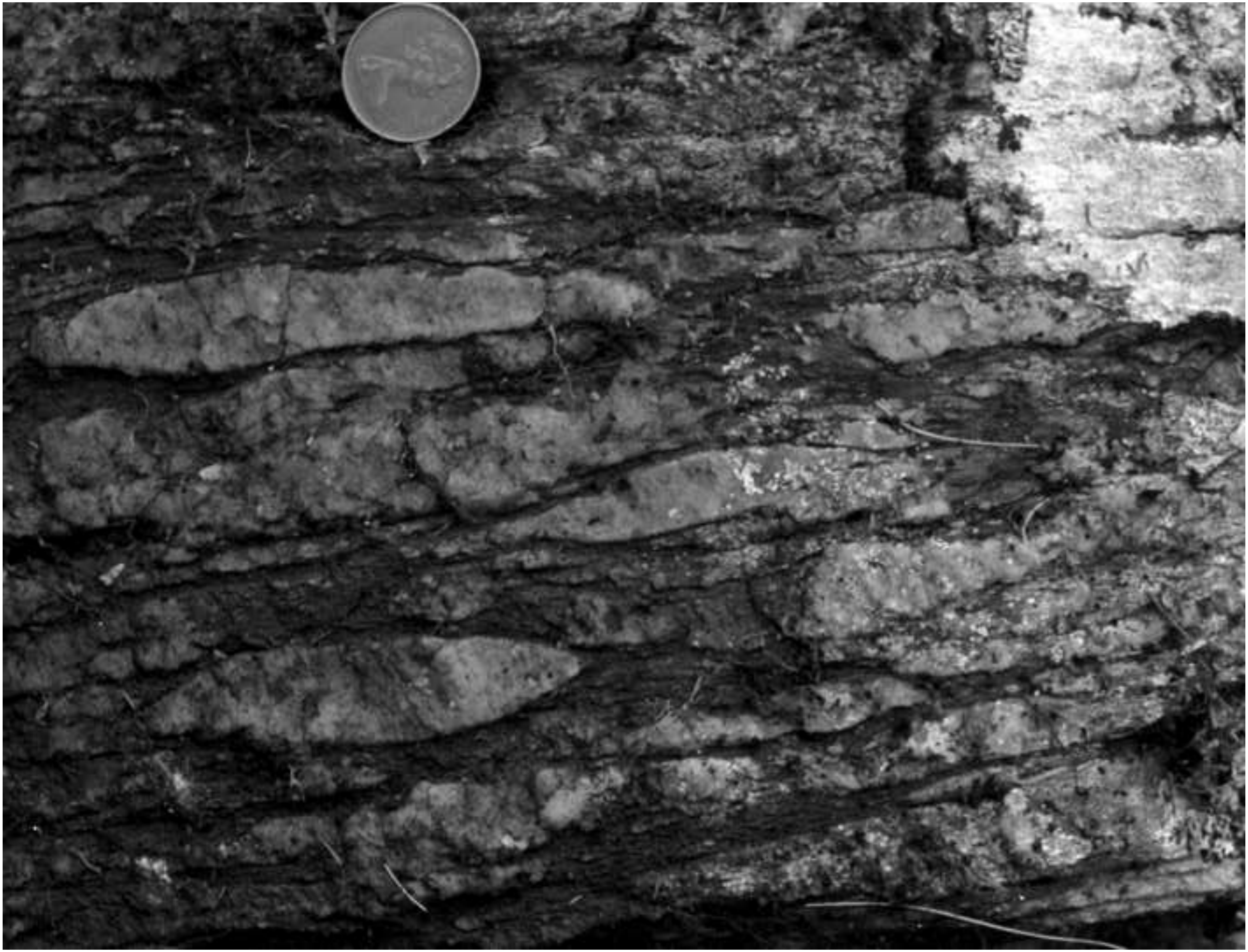

Figure 2.42 B&W

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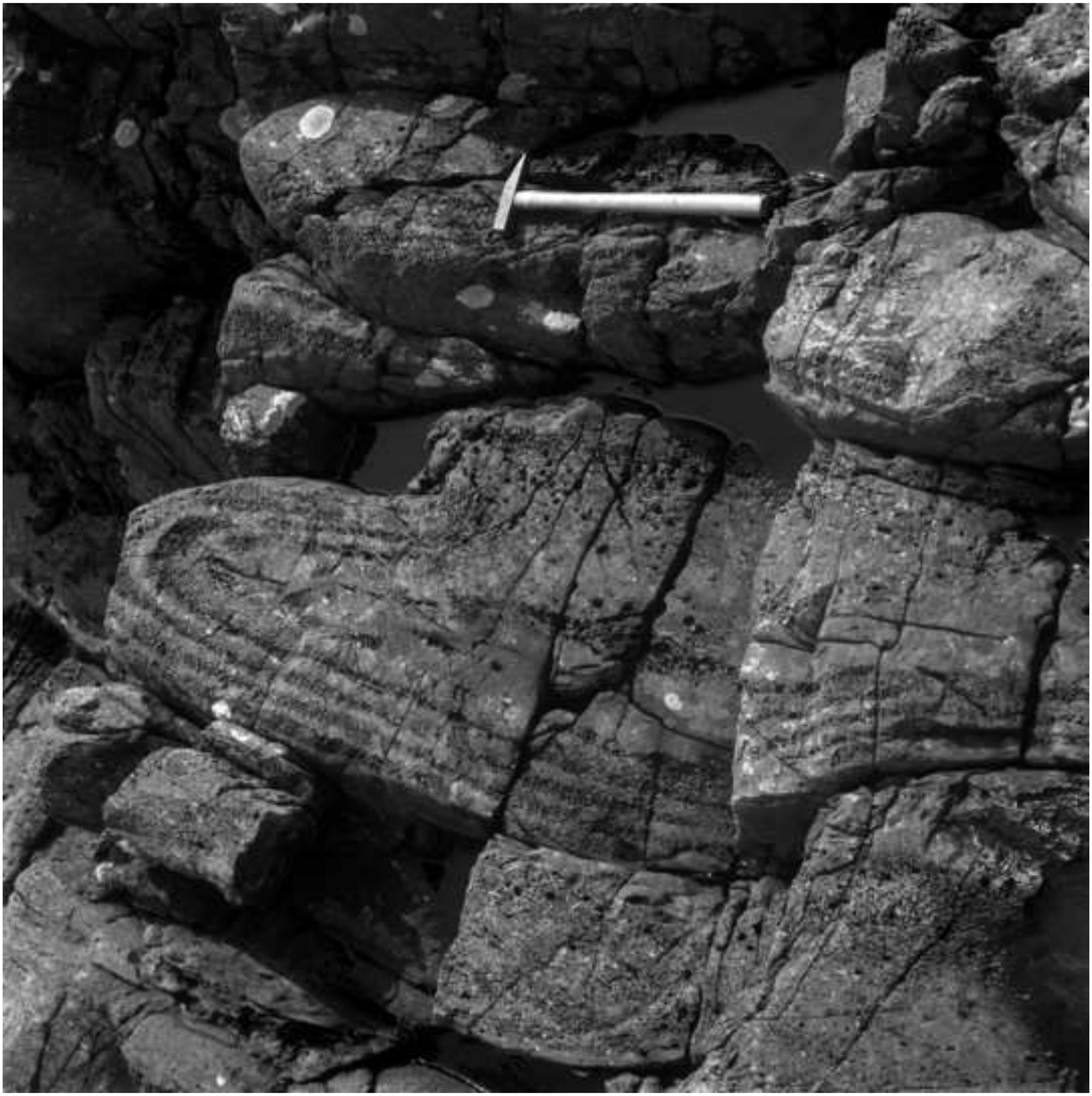

Figure 2.44 B&W

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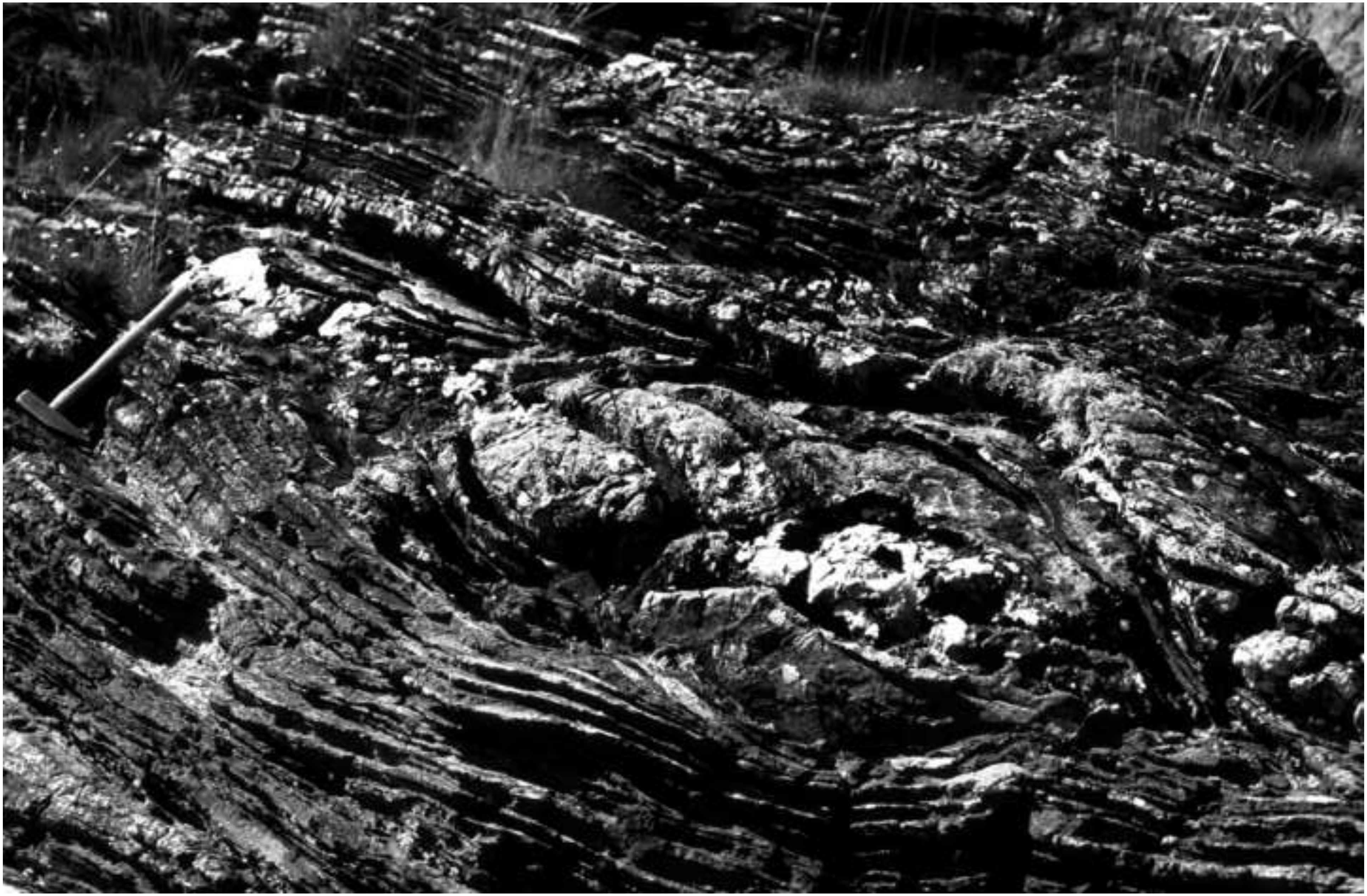

Figure 2.46 B&W

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Figure 2.48a + b B&W
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Figure 2.50 B&W

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