British Cambrian to Ordovician Stratigraphy

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Chapter 14

Scotland: Ordovician of the Midland Valley Terrane

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INTRODUCTION

The Midland Valley Terrane shares faunal similarities with the Laurentian Craton but is regarded as a separate Ordovician terrane lying outboard of it. It is composed of Precambrian metamorphic rocks (Bluck, 1984), now covered by Silurian and Upper Palaeozoic sedimentary rocks, and is bounded to the north-west and south-east by 'sub-terranes' of ophiolitic and other rocks that were accreted in Ordovician times (Bluck *et al.*, 1992). The Highland Border Sub-terrane to the north-west is discussed in Chapter 13, with the Grampian Terrane; here we are concerned with the Tyrone–Girvan Sub-terrane, to the south-east.

The Ballantrae Complex, which forms the basement of the Lower Palaeozoic sequence in the Girvan area, consists largely of ultramafic rocks, now serpentinite, with basalts and minor sedimentary rocks of Arenig age. While being obducted onto the south-east margin of the Midland Valley Terrane (Stone and Smellie, 1988) during Llanvirn times, this ophiolitic com-

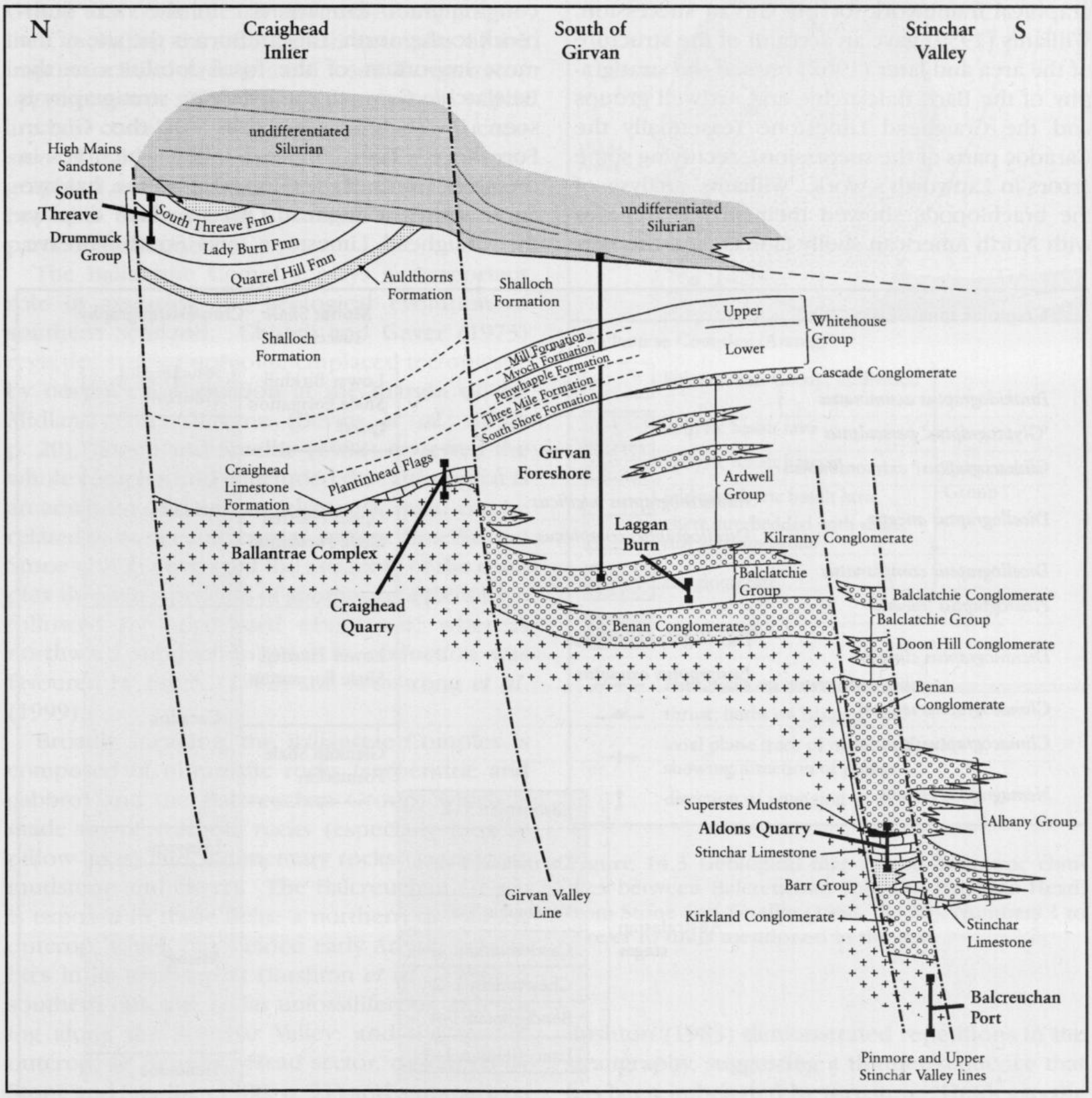

Figure 14.1 Schematic cross-section in the Girvan area to show the stratigraphical and structural relationships across the major south-facing growth faults. The GCR sites are shown in bold type. After Ingham (1992b, fig. 30.5).

plex was imbricated by thrusting, as shown at the Balcreuchan Port–Bennane Head site (see site report).

Deposition of the famous Girvan cover sequence commenced soon after, in later Llanvirn times, probably in a proximal fore-arc setting (Bluck, 1985). Extensional faults with large downthrows in a south-east direction produced half-grabens. The Ordovician transgresses north-west across this faulted basement, with overstep and great changes of thickness and facies (Figure 14.1).

Lapworth (1882) established the main stratigraphical framework for the Girvan succession. Williams (1959) gave an account of the structure of the area and later (1962) revised the stratigraphy of the Barr, Balclatchie and Ardwell groups and the Craighead Limestone (essentially the Caradoc parts of the succession), rectifying some errors in Lapworth's work. Williams' analysis of the brachiopods showed their strong affinities with North American shelly faunas, and this was confirmed by Tripp's work on trilobites (summarized in Tripp, 1993). Ingham (1978) has extended the study of the stratigraphy northwards, through the Whitehouse Group and Shalloch Formation (upper Caradoc and Ashgill series), and Harper (1982a, b) reviewed the stratigraphy of the Drummuck Group (higher Ashgill Series). There are references to the extensive literature on the Girvan succession under the various site descriptions.

In the southern fault-block, Aldons Quarry displays a part of the Barr Group, notably the Stinchar Limestone, lying between two major conglomeratic formations. In the next fault-block to the north, Laggan Burn is the site of the most important of the fossil localities in the Balclatchie Group. The overlying stratigraphy is seen in the long section on the Girvan Foreshore. The Craighead Inlier, which lies in the block north of the Girvan Valley line, has two famous sites: Craighead Quarry, which displays the Craighead Limestone, and South Threave,

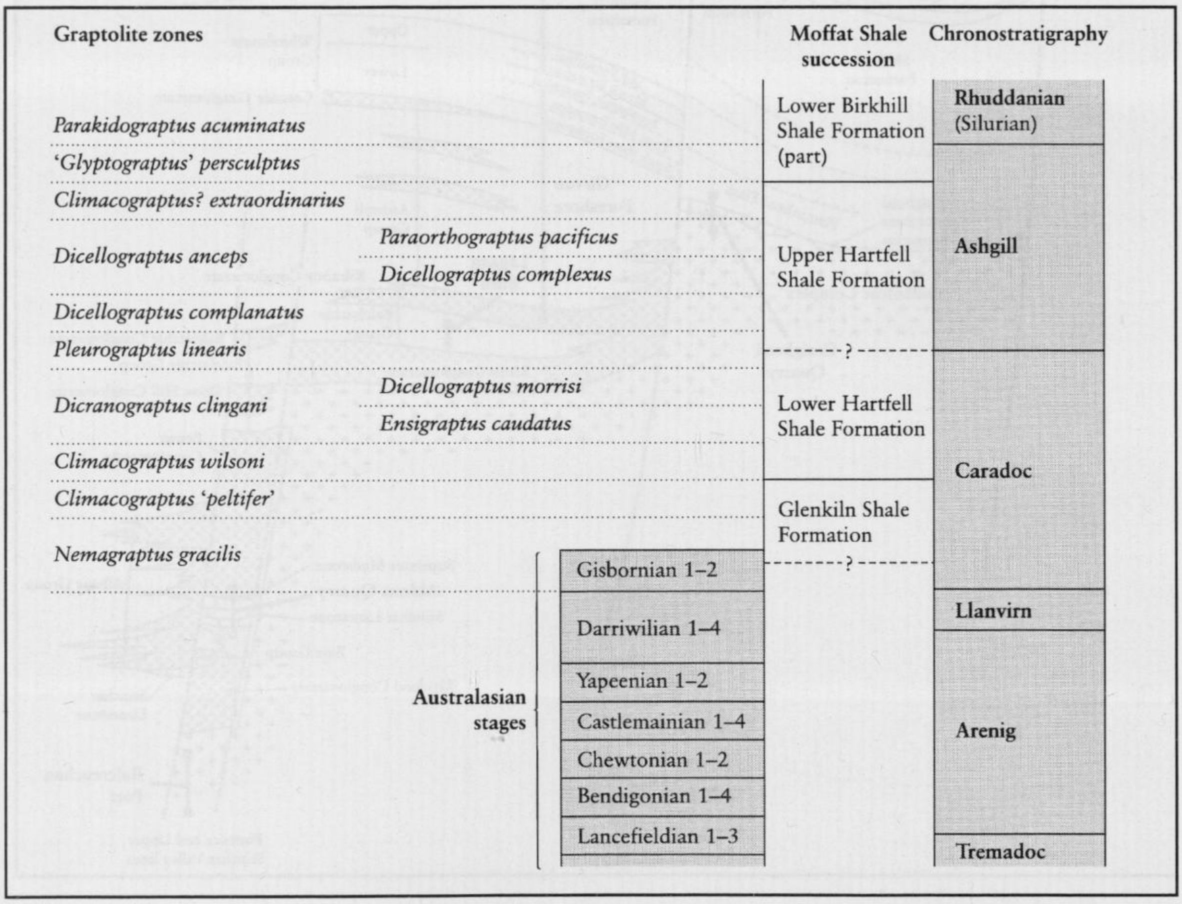

Figure 14.2 Ordovician graptolite zones used in Scotland, based on the graptolitic succession in the Moffat Shale Group, and supplemented for older rocks by reference to the Australasian standard stages. British standard chronostratigraphy is shown for comparison.

where the Lady Burn Starfish Beds are preserved.

BALCREUCHAN PORT–BENNANE HEAD (NX 0968 8750–NX 0910 8638)

Introduction

The sea-cliffs between Balcreuchan Port and Bennane Head expose local sedimentary units within the dominantly volcanic Balcreuchan Group that contain early and mid-Arenig graptolites, including the only British examples of the important basal Arenig zonal fossil *Tetragraptus approximatus.* These graptolite faunas, which are best correlated with the Australasian succession (Figure 14.2), not only give a biostratigraphical age for part of the Ballantrae Complex but also demonstrate structural repetition of parts of the sequence.

The Ballantrae Complex plays an important role in assessing the geological evolution of southern Scotland. Church and Gayer (1973) regarded it as an ophiolite emplaced tectonically by northward obduction at the margin of the Midland Valley Terrane (Bevins *et al.*, 1992, p. 20). Stone and Smellie (1988) reviewed the whole complex and concluded that although it is an amalgam of disparate elements, most can be related to an oceanic crustal setting. Smellie and Stone (1992) envisaged the assembly of the complex through a process of southward subduction followed by northward obduction, whereas northward subduction prior to obduction was favoured by Bluck (1992) and Armstrong *et al.* (1999).

Broadly speaking, the Ballantrae Complex is composed of ultramafic rocks (serpentine and gabbro) and the Balcreuchan Group, which is made up of volcanic rocks (especially basaltic pillow lavas) and sedimentary rocks (sandstone, mudstone and chert). The Balcreuchan Group is exposed in three belts: a northern or Pinbain outcrop, which has yielded early Arenig graptolites in its lowest part (Rushton *et al.*, 1986); a southern outcrop, so far unfossiliferous, extending along the Stinchar Valley; and the central outcrop, or Bennane Head sector, described by Stone and Smellie (1988, p. 51) and summarized below. The Bennane Head sector was formerly considered to be a conformable succession of great (kilometre-scale) thickness, but Stone and

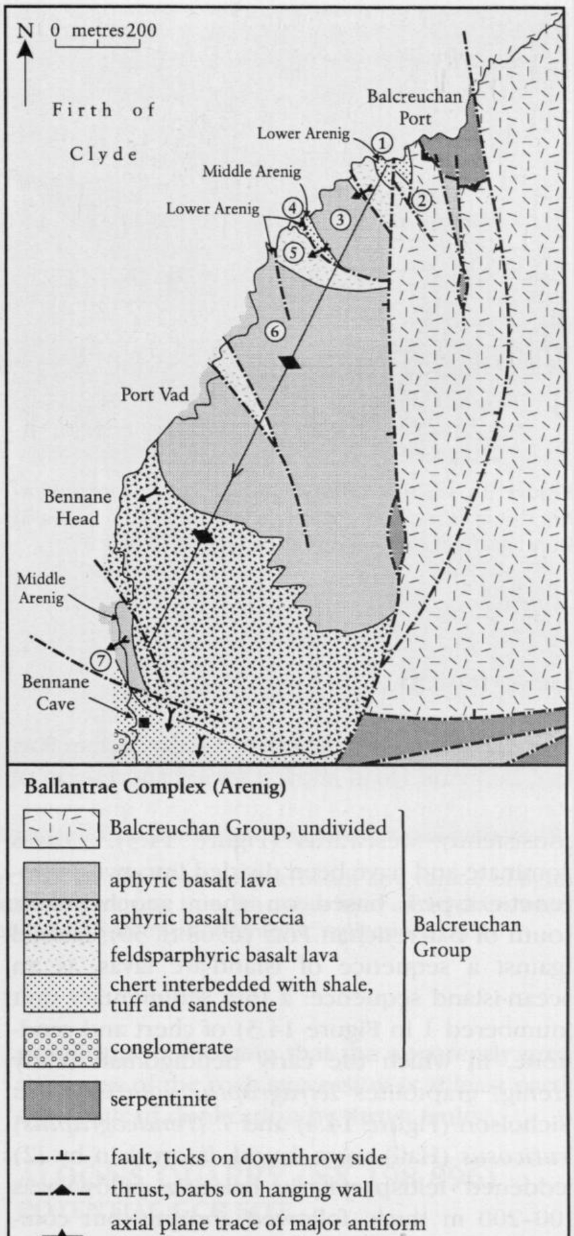

Figure 14.3 Geological map of the Ballantrae complex between Balcreuchan Port and Bennane Head, from Stone and Smellie (1988, fig. 16). Numbers 1 to 7 refer to units mentioned in the text.

Rushton (1983) demonstrated repetitions in the stratigraphy, suggesting a thinner sequence that has been imbricated by thrusting. Guides to the section are given by Bluck (1992) and Stone (1996), who refer to more detailed accounts of particular localities.

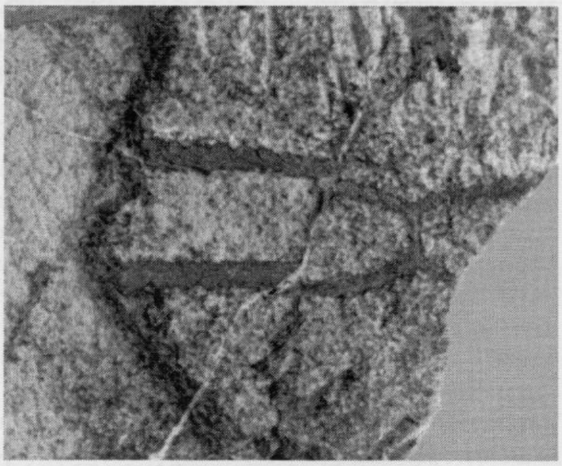

Figure 14.4 The graptolite *Tetragraptus approximatus* Nicholson, ×3, from sandstone unit 1 (basal Bendigonian, lower Arenig) of Figure 14.3.

Description

The coastal exposures between Balcreuchan Port and Bennane Head show a varied succession of steeply dipping rocks that strike NNW and young consistently westwards (Figure 14.3). Lavas dominate and have been divided into two petrogenetic types, based on their geochemistry. South of Balcreuchan Port (0968 8750), faulted against a sequence of island-arc lavas, is an ocean-island sequence: a thin sedimentary unit (numbered 1 in Figure 14.3) of chert and sandstone, in which the early Bendigonian (early Arenig) graptolites *Tetragraptus approximatus* Nicholson (Figure 14.4) and *T. (Pendeograptus) fruticosus* (Hall) were found, is overlain by (2) reddened feldsparphyric balsaltic pillow-lavas 100–200 m thick, followed abruptly but conformably by (3) unreddened aphyric pillow-basalts also 100–200 m thick. These are succeeded conformably by (4) a succession of conglomerate and tuffaceous sandstone, near the top of which a thin (1–2 cm) bed of laminated grey mudstone (at 0948 8737) contains many fragmentary Chewtonian (mid-Arenig) graptolites. Among these are *Didymograptus* cf. *protoindentus* and others listed by Stone and Rushton (1983, p. 301); their *'Acrograptus?'* was rightly assigned to *Paradelograptus* by Erdtmann *et al.* (1987) but wrongly identified with the latest Tremadoc species *P. onubensis* Erdtmann, Maletz and Gutierrez-Marco (see Rushton and Stone, 1988).

To the west of unit 4, a major fault introduces clastic sedimentary strata overlain conformably by (5) reddened feldsparphyric pillow-basalts identical to those of Unit 2, and at the top of these (0945 8731) a red chert bed (Figure 14.5) (Stone and Smellie, 1988, fig. 17) yielded *Tetragraptus approximatus,* indicating a late Lancefieldian or early Bendigonian age. These lavas are again succeeded by (6) aphyric basaltic lavas, considered to be a tectonic repetition of unit 3.

About 1 km to the south, just south of Bennane Head, aphyric lavas overlie thick basalt breccia and are succeeded by a unit (7) of sandstone, breccia and chert (0910 8638), at the base of which a dark-coloured bed of siliceous mudstone yielded a graptolite fauna of approximately Chewtonian age (Stone and Rushton, 1983, locality 5).

Interpretation

Although the rock succession faces uniformly westwards, giving the appearance of a thick, conformable sequence, the distribution of faunas is not consistent with a through succession because it shows alternations of early and mid-Arenig faunas. This suggests that the Balcreuchan Group succession is repeated by a series of thrusts: feldsparphyric basalts, overlying or containing early Arenig graptolites, are succeeded by aphyric basalts that contain or are overlain by mid-Arenig graptolite faunas. Thus, in the sequence outlined above, units 5 and 6 are considered to be a tectonic repetition of units 2 and 3. A further faulted repetition of the feldsparphyric lava is seen north of Port Vad, but there is no faunal evidence there.

According to this interpretation, the *T. approximatus* from unit 5 should be marginally younger than the species from unit 1; given the stratigraphical range of *T. approximatus* this is quite possible, though the implication in Stone and Rushton (1983, p. 300, 301) is that the fossils of unit 5 might be slightly the older. Similarly the present interpretation would demand that the fauna from unit 7 be slightly younger than that from unit 4, and again the biostratigraphical evidence is not precise enough either to contradict or to affirm the hypothesis (Stone and Smellie, 1988, p. 53, table 5). However, a part of the faunal succession, corresponding to the upper parts of the Bendigonian Stage, is unrepresented in the

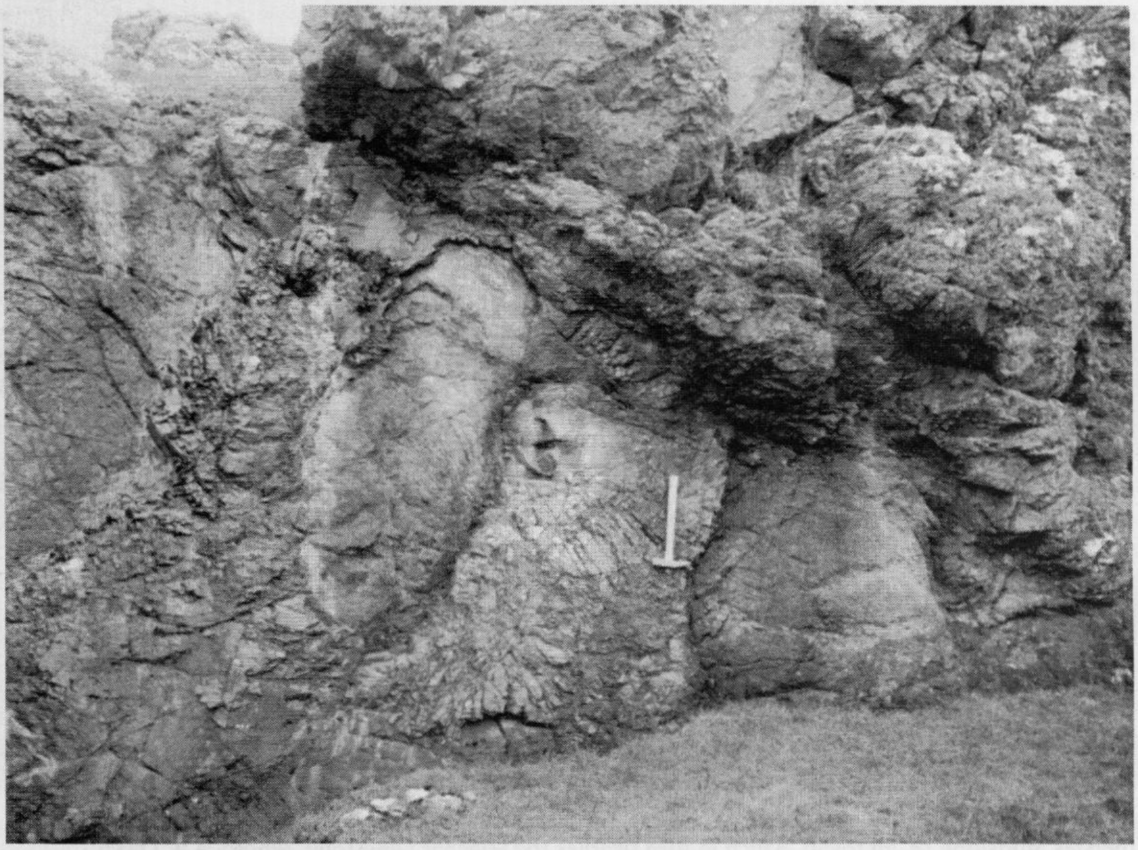

Figure 14.5 Gully 500 m south-west of Balcreuchan Port. Pillows of feldspar-phyric basalt lava (unit 5 of figure 14.3) dip steeply towards the observer and their upper surfaces protrude through a thin layer of red chert which contains *Tetragraptus approximatus*. (Photo: British Geological Survey photographic collection, D3587.)

Bennane Head sector, and it may be that there is a non-sequence in the stratigraphy. The obvious level for such a non-sequence is the change from feldsparphyric basalts (units 2 and 5) to aphyric basalts (units 3 and 6), which would accord with Lewis' idea (in Stone and Rushton, 1983, p. 300) that the reddened condition of the feldsparphyric basalts was caused by long exposure on the sea floor.

Conclusions

The coast between Balcreuchan Port and Bennane Head exposes part of the Ballantrae Complex, a fragment of ancient sea floor that has been driven by plate-tectonic processes onto a continental margin now underlying the Midland Valley of Scotland. Graptolites found at some of the coastal exposures include the only British examples of the important zonal species *Tetragraptus approximatus* and are especially significant in showing that the apparently great thickness of the rock succession is at least partly the result of duplication by thrust faults.

ALDONS QUARRY (NX 198 896)

POTENTIAL GCR SITE

Introduction

Although not a confirmed GCR site at the time of writing, Aldons Quarry is described as a potential site because it is of regional importance in the succession of the Girvan district from a stratigraphical and palaeoenvironmental point of view and is internationally important palaeontologically. The site is the type locality for a large number of fossil species of markedly Laurentian aspect. It also provides both sedimentological and palaeoecological evidence for the profound effects of basement faulting in the accumulation and distribution of sediment in the Ordovician

Figure 14.6 The south-east face of Aldons Quarry showing the Benan Conglomerate overlying the thin Superstes Mudstone (<2m thick), which in turn overlies the Stinchar Limestone. (Photo: A.W. Owen.)

of the Midland Valley Terrane.

The abandoned quarry at Aldons (Figure 14.6), 7 km south of Girvan, exposes the Stinchar Limestone, one of two limestone formations in the Ordovician of the Girvan district, and the overlying Superstes Mudstone and Benan Conglomerate. When viewed in its wider context, the succession at Aldons helps demonstrate the significance of basement faulting during the Ordovician, including progressive northward overlap by the sedimentary cover sequence over the eroded Ballantrae Complex across a series of major NE–SW faults (Figure 14.1). Aldons Quarry lies less than 1 km to the north-west of one such, the Stinchar Valley Fault.

In his classic work on the Girvan succession (when considering the Stinchar Limestone – part of his 'Stinchar calcareous series'), Lapworth (1882, p. 573) provided the first detailed description of Aldons Quarry. A further brief description was given by Peach and Horne (1899, p. 495), who disputed the faulted contact between the Stinchar Limestone and the underlying Ballantrae Complex postulated by Lapworth and suggested that it may be an unconformity, a view subsequently endorsed by Williams (1962), Ince (1984) and Ingham (1992a). Williams (1962) provided a modern description of the Aldons brachiopods, and Tripp (1967, 1976) described the trilobite faunas. Most recently, Ingham (1992a, p. 393) described and interpreted the site in a field guide to the Girvan district. The lithological divisions and their thicknesses given below are largely taken from that work.

Description

Aldons Quarry lies on the southern limb of a large fold known as the Aldons Anticline, with the beds in the main quarry dipping fairly gently to the ESE. However, in the smaller, south-eastern, quarry the dip is reversed as the beds are folded around a NE-plunging syncline truncated against a NE–SW fault (British Geological Survey, 1988b).

In the north-west part of the main quarry, spilites of the Ballantrae Complex are overlain by a 1.5 m thick conglomerate, with angular clasts almost entirely of spilite. Some 17 m of dark-green pebbly sandstones overlie this conglomerate and are succeeded by 1.5 m of grey cobbly limestones with sandstone partings, followed by 1.5 m of cobbly and pebbly limestone. Many of the limestone cobbles are nodules of the calcareous alga *Girvanella,* which also coats most of the litho- and bioclasts. The following 6 m of cobbly limestone and 28 m of grey nodular and platy limestone are also rich in *Girvanella*. The Stinchar Limestone is capped by over 12 m of thinly bedded, grey, platy limestone and calcareous mudstone yielding a rich shelly fauna. In addition to calcareous algae, the Stinchar Limestone at Aldons contains, especially in its upper part, a diverse shelly fauna, including trilobites (Tripp, 1967, 1993), brachiopods (Williams, 1962), gastropods (Reed, 1920; Longstaff, 1924), ostracods and echinoderms (Peach and Horne, 1899, p. 690). Bergström (1990, p. 24, fig. 3) extracted a sparse conodont fauna, probably belonging in the *Pygodus anserinus* Zone, from an unspecified level in the upper part of the formation. He was able to identify the base of this zone in the middle of the Stinchar Limestone in the section at Benan Burn (Bergström, 1990, p. 6).

The Stinchar Limestone is overlain by the richly fossiliferous Superstes Mudstone: up to 1.8 m of sheared mudstone with calcareous nodules, seen on the south-east wall of the main quarry (Figure 14.6). Elsewhere, the Superstes Mudstone contains a graptolite fauna indicative of the lower part of the basal Caradoc *Nemagraptus gracilis* Zone (Rushton *et al*., 1996b, p. 23). The Superstes Mudstone is overlain by the Benan Conglomerate, the base of which shows slickensides. Although some tectonic movement has clearly occurred on this surface, Ingham (1992a, p. 395) considered that most of the Superstes Mudstone was removed by channelling prior to the deposition of the Benan Conglomerate, leaving only the basal part of the mudstone formation. To complicate matters, large blocks of the Benan Conglomerate have slumped down the quarry face, partially covering the Superstes Mudstone outcrop and obscuring the site whence Tripp (1976) had recovered an exceptionally diverse trilobite fauna.

Interpretation

The sedimentary units exposed at Aldons Quarry form part of the Barr Group, the full succession of which extends from the middle Llanvirn Kirkland Conglomerate through the Confinis Formation and its equivalents up into the Stinchar Limestone, ending with the thick (up to 640 m) Benan Conglomerate of early Caradoc age (Figure 14.1). Ince (1984) interpreted the two conglomerate units as fan complexes and the Stinchar Limestone as an intervening fan-abandonment phase. All but the uppermost part of this succession is older than the lowest parts of the cover sequence in the block to the north, where the uppermost part of the Benan Conglomerate overlies the Ballantrae Complex (Figure 14.1). That area was therefore not drowned until well into the early Caradoc, and the area to its north was exposed until the mid-Caradoc (see the Craighead Quarry site report). Although the lower beds above the Ballantrae Complex at Aldons may be equivalent to part of the Confinis Formation (Ingham, 1992a, p. 394), the lowest parts of the Barr Group are absent at Aldons, indicating the effect of basement faults within the one major fault block (see Ingham and Tripp, 1991, fig. 3). Tectonic instability is further demonstrated by the episode of deep channelling prior to the deposition of the Benan Conglomerate in the Aldons area (Williams, 1962; Ingham, 1992a). Thus, whereas around Benan Burn, 5 km to the north-east of Aldons, the Superstes Mudstone is about 40 m thick, its uppermost parts interfingering with the Benan Conglomerate (Ince, 1984, p. 230), in Aldons Quarry less than 2 m of Superstes Mudstone is present, and a few hundred metres to the north the Benan Conglomerate rests directly on the Ballantrae Complex.

The faunas of the Stinchar Limestone and Superstes Mudstone are particularly illuminating. Their palaeobiogeographical affinities are wholly Laurentian (Williams, 1962; Bergström, 1990; Tripp, 1993), indicating the location of the Midland Valley Terrane on the 'North American' side of the Iapetus Ocean. The trilobite fauna from the upper part of the Stinchar Limestone is very similar to that of the platy upper Stinchar Limestone elsewhere and comprises 27 species (Tripp, 1967). It represents a fairly shallow-shelf assemblage, assigned by Ingham and Tripp (1991) to the illaenid–cheirurid type of association, although Tripp (1993) considered it to be a deeper-water fauna than the illaenid–cheirurid association of the lower Stinchar Limestone.

Trilobites are by far the most abundant elements of the fauna of the Superstes Mudstone at Aldons. The whole fauna was described most recently by Tripp (1976), who also reviewed taxa described previously by Reed, Lamont and Begg. The fauna is remarkably diverse, comprising 69 species belonging to 52 genera. Twenty-one species have their type locality at Aldons, and Tripp (1993, fig. 4) showed the broad taxonomic composition of the fauna, based on 3261 specimens. That 5% of these specimens are referable to the genus *Nileus* led Ingham and Tripp (1991) to assign the fauna to a 'borderline *Nileus* association', indicating a deepening from the environment of deposition of the Stinchar Limestone. They assigned 42% of the trilobites in the Superstes Mudstone at Craigneil, some 6.5 km to the south-west of Aldons, to *Nileus*, thus indicating a fully developed *Nileus* association there. The deeper water indicated by the trilobite fauna at Craigneil is also explained in terms of fault-induced subsidence (Ingham and Tripp, 1993, fig. 3).

Conclusions

The rock succession at Aldons Quarry and the changes in water depth indicated by its fossils help to demonstrate the importance of basement faulting in the Girvan district during the Ordovician. This included the progressive northward extension of sedimentation through time over the eroded Ballantrae Complex, across a series of major NE–SW faults. Aldons is also the type locality for a large number of fossil species, all of which have very strong affinities to those of North America, indicating the greater proximity during the Llanvirn and early Caradoc of the Midland Valley Terrane to the low-latitude Laurentian plate than to the Avalonian microplate, which included England and Wales.

LAGGAN BURN (NX 202 945–NX 206 946, NX 204 947–NX 206 947 AND NX 209 943)

Introduction

Rocks of the lower Balclatchie Group exposed in a tributary to Laggan Burn are particularly significant for their fossil content. In particular, the graptolites preserved in three dimensions were the basis of Bulman's classic study (1944–1947) of rhabdosome development and are associated with a diverse conodont fauna of the *Amorphognathus tvaerensis* Zone.

This site was first noted by Lapworth (1882, p. 591), who commented on the existence of graptolites and brachiopods 'in a state of exquisite preservation'. The beds here were subsequently noted by Peach and Horne (1899, p. 512) and described in more detail by Pringle (in Bulman, 1944–1947). The regional geological setting is summarized by Floyd (1999). Bergström (1971, 1990) extracted a conodont fauna, remarkable for both its diversity and the abundance of elements, belonging to the *Baltoniodus gerdae* Subzone of the *Amorphognathus tvaerensis* Zone, which provide the best correlation of this part of the Girvan succession with the international chronostratigraphical schemes. Diverse brachiopod and trilobite faunas known from the site indicate a deep-water setting for the lower Balclatchie Group here.

Description

Laggan Burn and its tributaries north of Dalfask farm reveal several exposures of the lower Balclatchie Group (Figure 14.7). The stream-

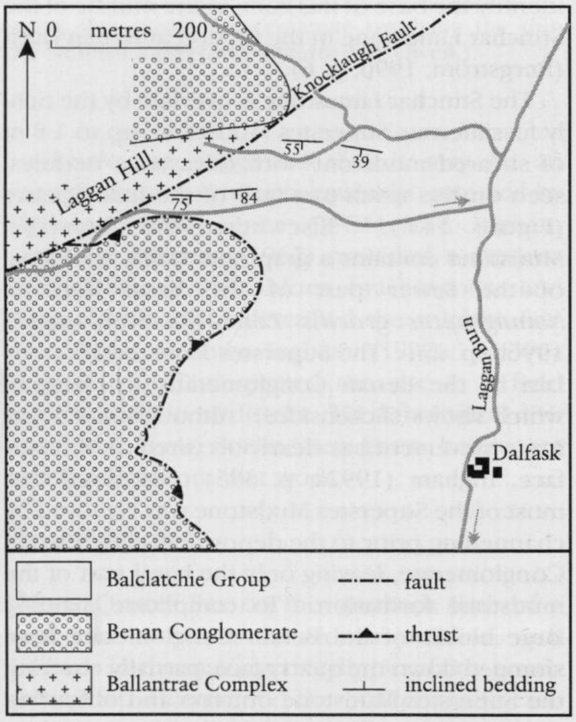

Figure 14.7 Geological map of the area near Dalfask, partly after Harper and Owen (1986, fig. 1). The tributary of Laggan Burn yielding the fossil faunas lies immediately north of the thrust which brings the Benan Conglomerate over mudstones of the Balclatchie Group.

bed and sides of the steep gorge (between 2033 9457 and 2057 9460) expose rusty-weathering blue-grey mudstones, siltstones with rarer pebbly horizons, thin limestones and limestone nodules (now very rare). These beds are vertical or dip steeply south and graded bedding shows that they young to the north. On the upper part of the southern bank of the stream (2045 9458), the Benan Conglomerate is thrust over the Balclatchie Group – a boundary that can be traced southwards with some certainty for at least 350 m. Pringle (in Bulman, 1944–1947, pp. i–iii) excavated parts of the tributary section and provided a sketch section and simple log of the beds present there. The banks of the stream are, at the time of writing, overgrown and it is difficult to determine the precise structural and stratigraphical relationship between the various small exposures of the Balclatchie Beds. It is clear, however, that the fault at the base of the Benan Conglomerate is a much lower-angled structure than that shown beneath the 'Balclatchie Grit' (probably a finer lithology within the conglomerate) on Pringle's section. Its southward extension approximately parallels the contours.

Bulman (1944–1947) extracted from certain limestone nodules a diverse graptolite fauna preserved in full relief and showing fine ultrastructural details. Graptolites are also present in the siltstones, where they retain partial relief and in some instances are current-orientated. Bergström (1971, 1990) obtained an abundant and diverse conodont fauna from a limestone bed in the section, and conodonts and scolecodonts also occur in the nodules. A low-diversity association of in-situ brachiopods and trilobites was described by Harper and Owen (1986) from 204 946, and more diverse brachiopod (Williams, 1962) and trilobite (Tripp, 1980a) faunas are known from a little farther east (206 946).

Interpretation

Bulman's study (1944–1947) of the three-dimensional graptolites from Laggan Burn was a seminal work in the study of graptolite ultrastructure and colony development. He described 17 species or subspecies of graptoloids and dendroids, of which five were new. For most species he described a complete set of growth stages, from prosicula to mature rhabdosome, and, together with observations from serial sections, this enabled the recognition of mode of development and proximal growth of several problematic genera. James (1965) described in detail the development of a species of *Dicellograptus* (probably *D. salopiensis* Elles and Wood – see Hughes, 1989, p. 29) from this locality. Although the species present are not stratigraphically very diagnostic, Rushton (in Floyd, 1999) attributed them to the *peltifer* Zone.

The conodont fauna described by Bergström (1971, 1990, pp. 3, 8–10) is the most diverse such fauna known from the Ordovician of the Girvan district (comprising 11 identifiable form taxa, together with several of uncertain affinity) and has by far the greatest abundance of any Girvan Ordovician fauna, yielding several hundred elements per kilogram, contrasting with fewer than 10 elsewhere. The conodont elements are well preserved but rather broken and, in common with others in the district, have a very low Conodont Alteration Index (1.5–2.5), which contrasts with values in excess of 5 elsewhere in Scotland. The fauna is dominated by elements of *Amorphognathus tvaerensis* Bergström, which (together with *Protopanderodus liripipus* Kennedy *et al.* and *Belodina compressa* (Branson and Mehl)) indicates a level low in the *Baltoniodus gerdae* Subzone of the *Amorphognathus tvaerensis* conodont Zone. Bergström (1971, p. 114) argued that an assignment of Bulman's graptolite fauna to the lower *Diplograptus multidens* graptolite zone (equivalent to the Scottish *peltifer* Zone) would be consistent with this and the known ranges of the graptolites. A correlation with the Harnagian Substage of the Burrellian Stage in the standard Anglo-Welsh Caradoc succession is thus indicated.

Although the conodont fauna and certain graptolites have a widespread distribution, the brachiopods and trilobites emphasize the Laurentian affinities of the Ordovician shelf faunas of Girvan, and thus the palaeogeographical position of the Midland Valley Terrane. Williams (1962, p. 26) listed 16 species and subspecies of brachiopod, and Tripp (1980, table 1) listed 18 species of trilobite. Both authors indicated the strong Appalachian affinities of many lower Balclatchie Group taxa. In particular, Tripp (1980a, p. 135) noted that, as with the nearby exposures at Dalfask, the fauna from the tributary to Laggan Burn includes a large proportion of specimens of *Porterfieldia*, *Robergiella*, *Ampyxina* and *Raymondella* that are very close to or conspecific with forms from the Liberty Hall/Athens facies of the Edinburg Limestone in Virginia. Shaw and Fortey (1977, p. 422) considered the latter to be a lower-slope biofacies. A deep-water setting was confirmed by Harper and Owen (1986), who described an in-situ association of two new species, the brachiopod *Onniella williamsi* Harper and the trilobite *Diacanthaspis (D.) trippi* Owen, from siltstones associated with the limestone nodules in the tributary.

Conclusions

Laggan Burn is internationally significant for its fossil faunas. Graptolites preserved in full relief show very fine details of their skeletal structure, and their study in the 1940s was an important step forward in understanding the biology and classification of these members of the Early Palaeozoic plankton. Conodonts occur in far greater numbers than at any other Ordovician site in the Girvan district and enable this part of the succession to be tied to the standard divisions of Ordovician time. The benthic invertebrates (brachiopods and trilobites) show that the lower Balclatchie rocks here were deposited in deep water on the Laurentian (North American) side of the Iapetus Ocean and differ significantly from contemporary faunas from England and Wales.

GIRVAN FORESHORE (NX 147 931–NX 178 961)

Introduction

The spectacular exposures along the Girvan foreshore provide a wealth of sedimentological, structural and palaeontological information indicative of a tectonically active, deep-water environment and are thus crucial to the understanding of the Midland Valley Terrane in the British Caledonides. The site is the type locality for several Caradoc to lower Ashgill lithostratigraphical units and for some magnificently preserved deep-water trilobite species. The shelly and graptolite faunas in the upper part of the section are important for understanding the international correlation, especially of the base of the Ashgill Series.

The succession between Kennedy's Pass and Craigskelly on the outskirts of Girvan, extending for 4.5 km along the foreshore, provides exposures of the lower Caradoc to lower Ashgill cover-sequence above the obducted Ballantrae Complex (Figure 14.8). The site contains the type localities for the Kilranny Conglomerate, the Ardwell Group, the Whitehouse Group (with many of its constituent formations) and the Shalloch Formation. It is also the type locality for a number of deep-water trilobite genera and species. It is thus important nationally, for establishing the depositional and plate-tectonic environment of this segment of the British Caledonides, and internationally, for the understanding of tectonic and palaeobiogeographical processes operating along the Laurentian margin of the Iapetus Ocean. Moreover, the faunas of the Whitehouse Group have provided the best evidence hitherto for the positioning of the graptolite zones in relation to the shelly-based definition of the base of the Ashgill Series (Fortey *et* al., 1991, 1995).

Dr J.K. Ingham (University of Glasgow) has produced very detailed maps of most of the Girvan Foreshore, and these were published in simplified form in a field guide to the Girvan district (Ingham, 1992b; Bluck and Ingham, 1992a). Ingham has also provided overviews of the succession and its significance (1978, 1992a); in collaboration with Dr D.A.T. Harper, he has also formally subdivided the Whitehouse Group (Harper, 1984). The geology of the area was summarized by Cameron *et al.* (1986), and detailed sedimentological (Hubert, 1966; Bluck, 1983) and faunal (Harper, 1979, 1984–1989; Williams, 1987; Bergström, 1990; J.K. Ingham, in prep.) studies have clarified the palaeoenvironmental and tectonic history of the site.

The base of the cover sequence above the eroded Ballantrae Complex at Girvan is markedly diachronous and becomes progressively younger northwards across a series of syndepositional listric faults. The Girvan Foreshore site lies on the block between the Pinmore and the Girvan Valley faults (Ingham, 1992b, fig. 30.5) (Figure 14.1), in which the base of the succession is marked by the lower Caradoc Benan Conglomerate. The Ordovician succession extends up to the Cautleyan and is overlain by the strongly diachronous base of the local Silurian succession. In the block to the north of the Girvan Valley Fault, exposed in the the Craighead Inlier, the lower part of the cover sequence is the Craighead Limestone (see the Craighead Quarry site report), which is equivalent to a level high in the Ardwell Group in the

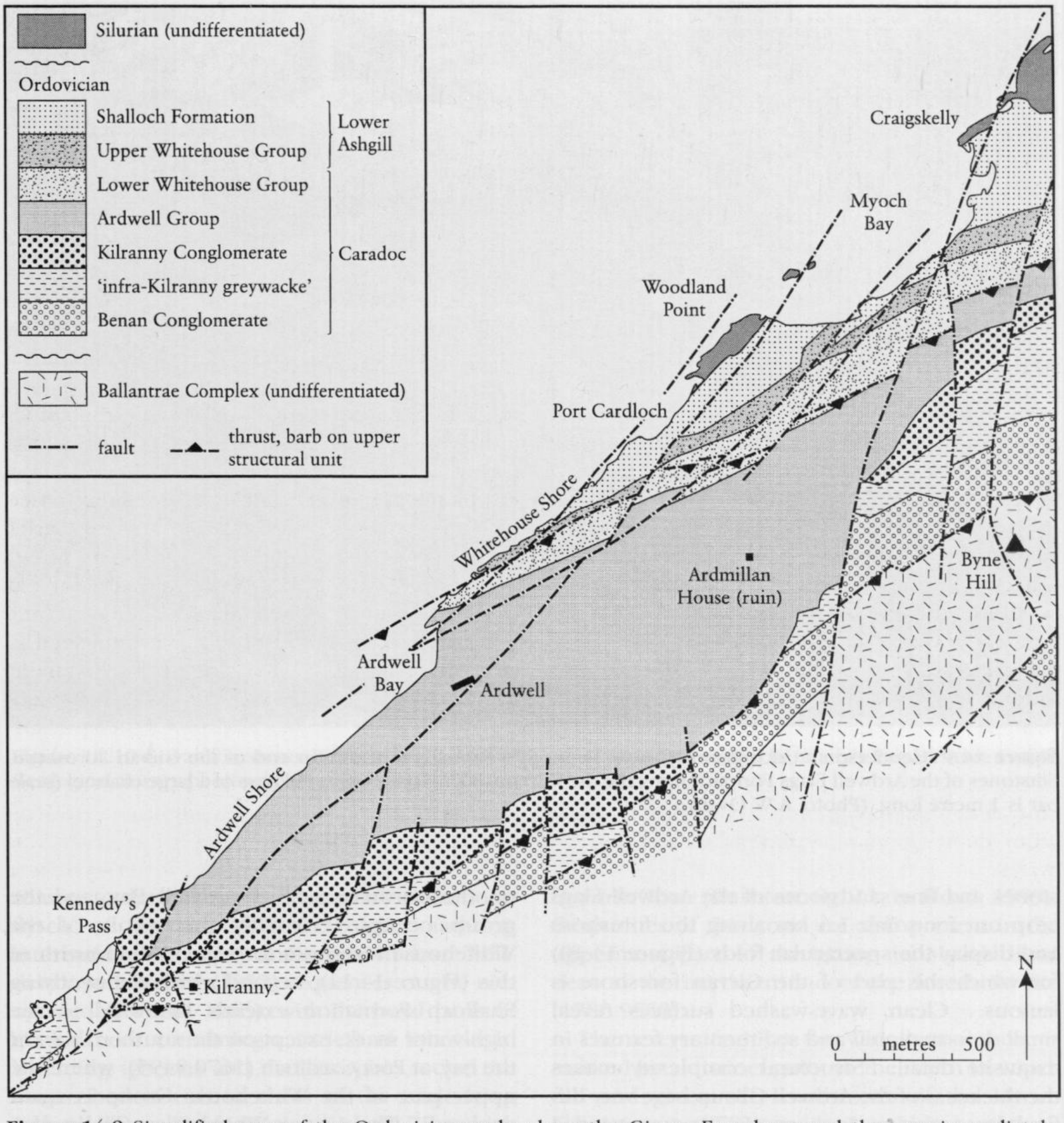

Figure 14.8 Simplified map of the Ordovician rocks along the Girvan Foreshore and the area immediately inland, after Bluck and Ingham (1992a, fig. 28.1a, b).

foreshore section (Figure 14.1). The uppermost Caradoc and lower Ashgill in the Craighead Inlier are cut out by faulting, but the Shalloch Formation can be recognized, and the overlying sequence extends much higher in the Ashgill (see the South Threave site report).

Description

At the southern end of the site, at Kennedy's Pass, the lower Caradoc Kilranny Conglomerate is in faulted contact with igneous rocks of the Ballantrae Complex and crops out along the foreshore for about 250 m. It is rich in igneous clasts and is underlain by siltstones and fine sandstones (the 'Infra-Kilranny Greywackes' of Williams, 1962), seen in a cleft in the raised cliff near the northern end of the conglomerate outcrop. The Kilranny Conglomerate is overlain (at 1490 9330) by siltstones of the Ardwell Group at 'Henderson's unconformity' (Figure 14.9) (see Henderson, 1935), which has been re-identified as the base of a channel cut in the conglomerates (Ingham, 1978, p. 168). The mudstones, silt-

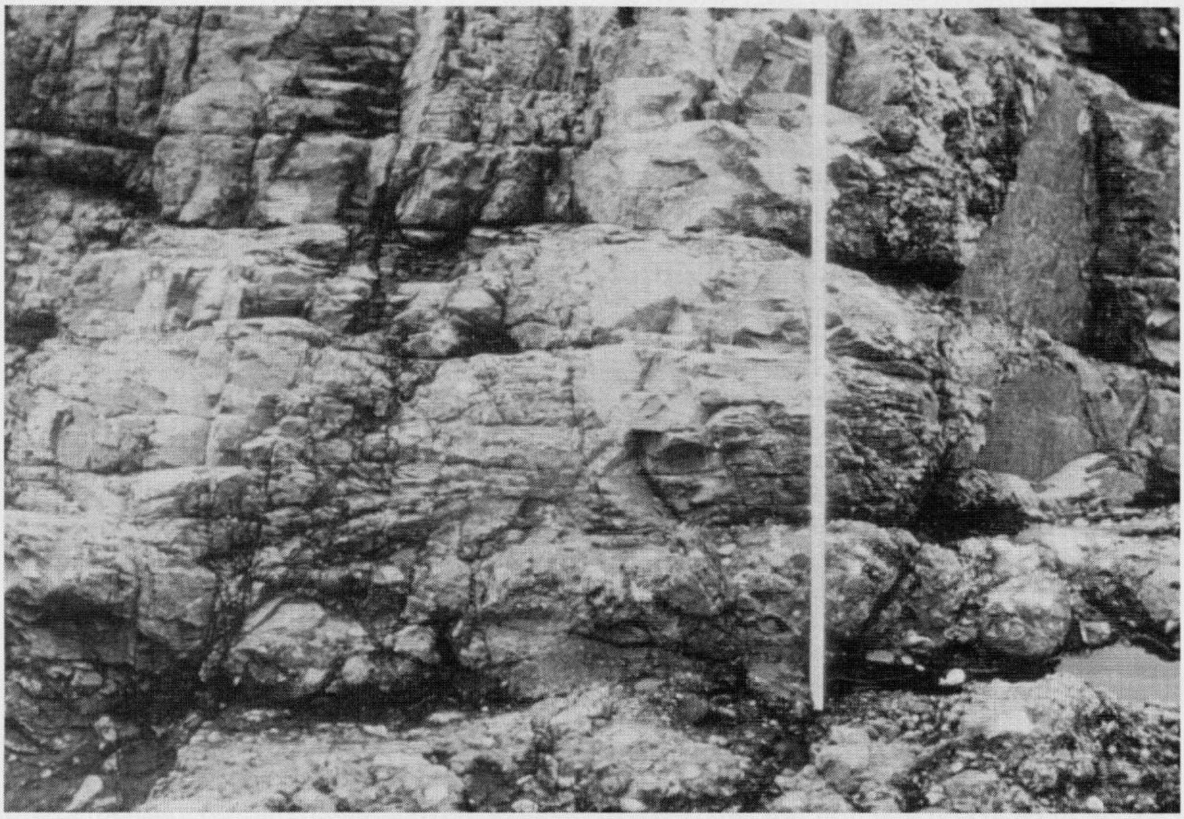

Figure 14.9 'Henderson's Unconformity' near Kennedy's Pass at the southern end of the Girvan Foreshore. Siltstones of the Ardwell Flags Formation overlie the Kilranny Conglomerate at the base of a large channel (scale bar is 1 metre long. (Photo: A.W. Owen.)

stones and fine sandstones of the Ardwell Flags crop out for some 1.6 km along the foreshore and display the spectacular folds (Figure 14.10) for which this part of the Girvan foreshore is famous. Clean, wave-washed surfaces reveal small deformational and sedimentary features in exquisite detail. Structural complexity makes the thickness of the Ardwell Group here very difficult to estimate; Ingham (1978) suggested a thickness in excess of 1200 m, whereas Cameron *et al.* (1986) gave about 750 m, but they agree that the formation thickens to about 1400 m inland. The sandstones and shales of the uppermost part of the group are exposed on the outer part of the foreshore near Ardwell Farm and lie between branches of a dextral wrench fault extending from Kennedy's Pass. The shales contain graptolites of the *Dicranograptus clingani* Zone (Ingham, 1992b), and these beds are thought to be equivalent to the thick Cascade conglomerates, sandstones and shales in Penwhapple Burn, 8 km to the north-east.

The base of the Whitehouse Group is exposed on the northern side of Ardwell Bay, and the group occupies virtually the whole of the Whitehouse foreshore for some 350 m north of this (Figure 14.11), beyond which the overlying Shalloch Formation extends landward to the high-water mark, except on the southern part of the bay, at Port Cardloch (1670 9495), where the upper part of the Whitehouse Group is again exposed. The Upper Whitehouse Group also crops out on the foreshore a further kilometre towards Girvan, in Myoch Bay. The lithologically varied Whitehouse Group is almost vertical and strikes approximately NE–SW, but the outcrop patterns of its constituent formations are disrupted by numerous faults of varying magnitudes. Meticulous mapping of this part of the site by Dr J.K. Ingham has done much to elucidate the succession, and his field guide (Ingham, 1992b) provides a far fuller picture than it is possible to give here and is in itself a succinct summary of this important section.

The South Shore Formation at the base of the Lower Whitehouse Group marks an abrupt

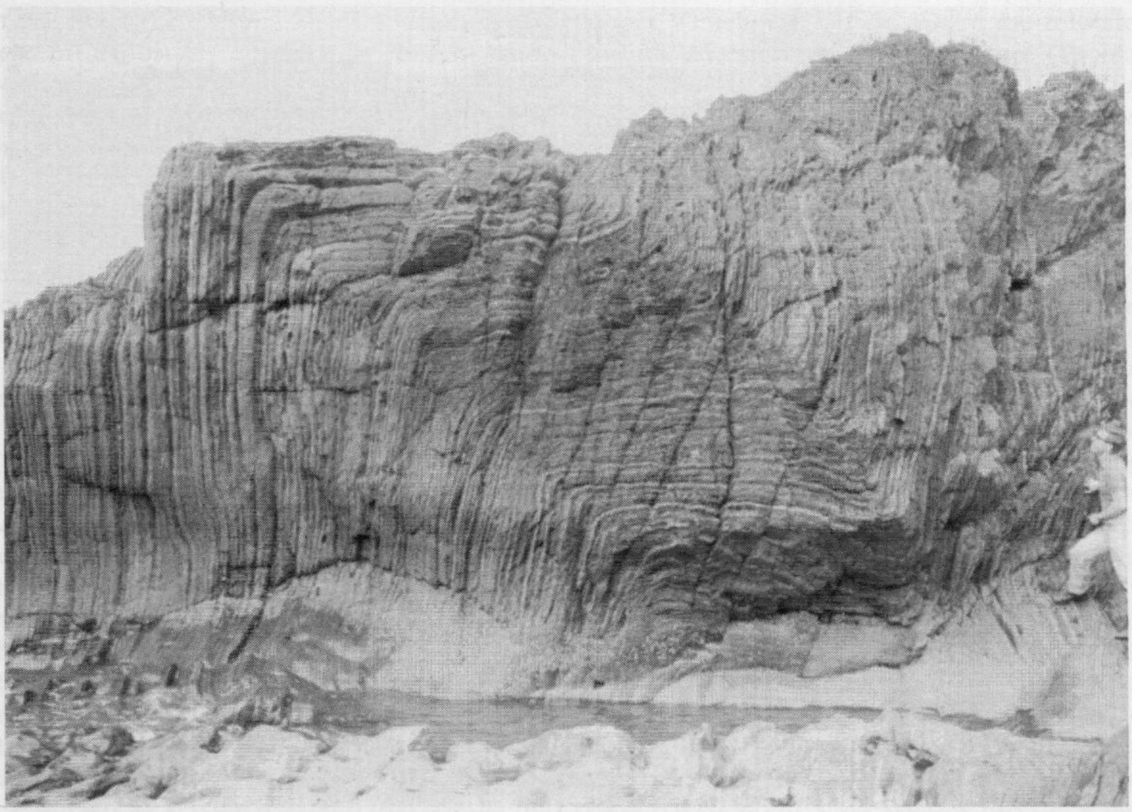

Figure 14.10 Girvan foreshore. Box-fold in the Ardwell Formation, north-east of Kennedy's Pass. (Photo: British Geological Survey photographic collection, D1563.)

change to detrital, sandy limestones ('limestone flysch' of Ingham, 1978 and earlier authors) interbedded with grey and green shales. Well-developed Bouma (1962) sequences can be recognized (Hubert, 1966), with the basal parts of graded beds containing a variety of lithoclasts, including igneous and metamorphic rocks; the lowest bed is rich in clasts of the underlying Ardwell Flags. The formation is about 75 m thick and has yielded conodonts indicative of the *Amorphognathus superbus* conodont zone (Bergström, 1990). It grades up into the Three Mile Formation (Figure 14.11): more than 45 m of alternating grey-green shales and thin but very persistent grey sandstones, with fine-scale sedimentary structures clearly displayed on wave-washed surfaces. A major, strike-parallel reverse fault cuts out the Penwhapple Formation (the upper unit of the Lower Whitehouse Group) from the foreshore area, but it is seen in Penwhapple Burn, where it mostly comprises siltstones, fine sandstones and mudstones, the latter including graptolites of the *Pleurograptus linearis* Zone (Rushton, fig. 11, in Floyd, 1999). Graptolites of this zone are also present in the uppermost part of the group in Myoch Burn near to the northern end of the foreshore site (1780 9550).

The reverse fault on the Whitehouse shore is marked by a distinct gully, to the north of which red and green silty mudstones of the Myoch Formation are exposed. A pebbly sandstone near the base of this lowest formation of the Upper Whitehouse Group is seen near low-water mark and contains cross-bedding indicating currents flowing from the north-west (Hubert, 1966). Red mudstones within the formation locally contain a rich deep-water fauna dominated by atheloptic trilobites and are latest Caradoc to earliest Ashgill in age. There is an abrupt change to the overlying grey and green banded shales of the lower part of the Mill Formation on the Whitehouse Shore, where the lowest horizons indicate the mixing of partly consolidated sediment on an unstable slope. The Mill Formation on the Whitehouse shore comprises a

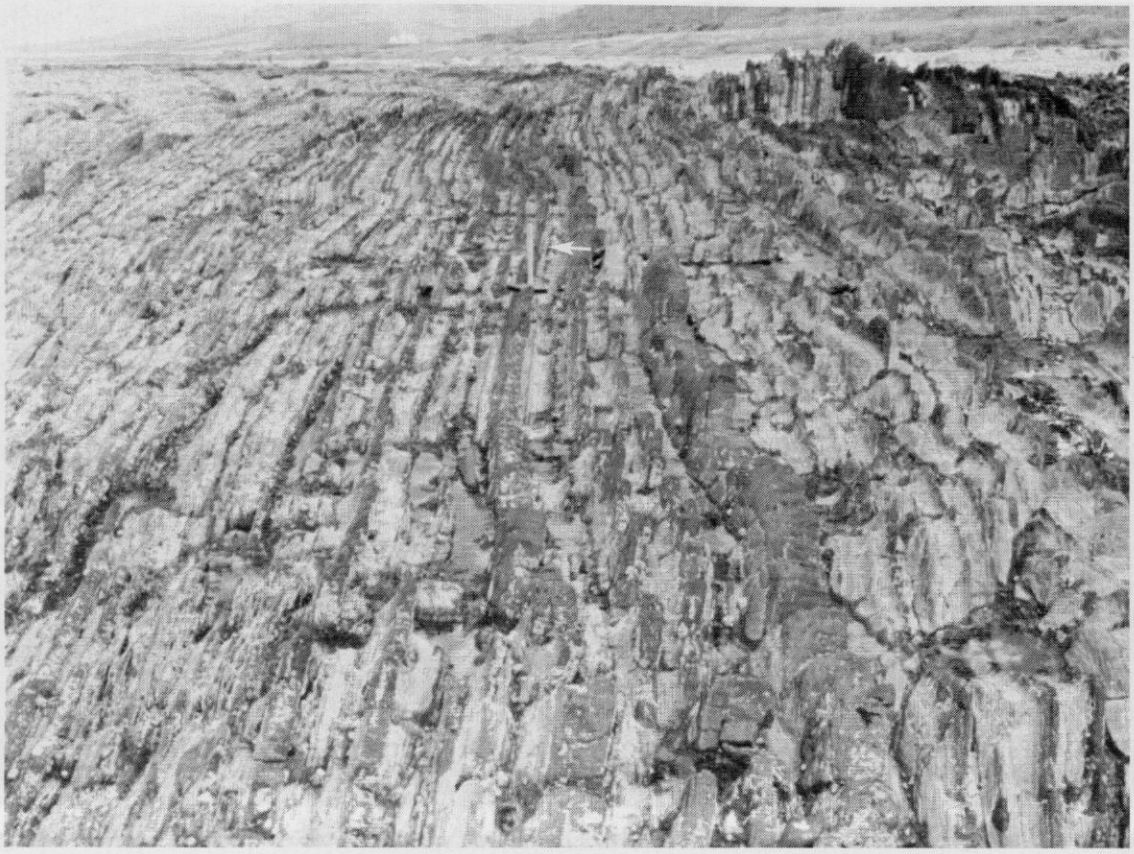

Figure 14.11 Girvan foreshore west of Ardmillan, looking ENE. Steeply dipping fine-grained turbidites of the Three Mile Formation (Lower Whitehouse Group), younging to the left. Hammer (arrowed) above centre for scale. (Photo: British Geological Survey photographic collection, D3527.)

lower shale unit, containing graptolites of the *Dicellograptus complanatus* Zone (Williams, 1987) and transported deep-water trilobites, overlain by a siltstone–sandstone member. The upper Whitehouse Group exposure in Myoch Bay, 1.5 km to the north-east, is structurally complex but is more complete and includes units not seen on the Whitehouse shore (Ingham, 1992b). These include a sandstone–shale channel-fill unit in the Myoch Formation and, in the lower part of the Mill Formation, a coarsening-upwards sequence of shales overlain by calcareous siltstones, succeeded by a channel-fill conglomerate. The shales include a graptolitic horizon indicative of a level close to the *linearis–complanatus* zonal boundary (Williams, 1987). The conglomerate contains a large number of mudclasts, together with more exotic clasts, set in a matrix that also contains shelf brachiopods and trilobites indicative of an early Ashgill age (Thomas *et al.*, 1984, p. 39, Ingham, 1992b, p. 412).

The base of the Shalloch Formation is seen both on the Whitehouse shore and in Myoch Bay and is marked by a lead-grey mudstone, 1 m thick, overlain by over 200 m of alternating sandstone and shale beds, with a few graded limestones. Graptolitic horizons near the base and top of the formation indicate respectively the *complanatus* and *anceps* graptolite zones (Ingham, 1978), and a limestone 117 m above the base of the formation has yielded one of the richer conodont faunas in the Girvan district, indicative of the *Amorphognathus ordovicicus* conodont zone (Bergström, 1990).

The upper part of the Ordovician succession (upper Cautleyan to Hirnantian) is missing, and the Shalloch Formation is overlain with slight (about 8°) unconformity at Woodland Point (1695 9530) by calcareous sandstones of the lower Llandovery Woodland Formation. These contain brachiopods and graptolites of the *Monograptus cyphus* Zone and are overlain on the headland by the quartz-rich conglomerates of the Scart Formation. There is a substantial gap in exposure, covered by beach sand, between the highest outcrops of the Shalloch Formation in Myoch Bay and at Craigskelly, at the northern end of the site, where another Llandovery conglomerate, the Craigskelly Conglomerate, crops out. The exposures at Horse Rock, to the immediate north of the site, show that this conglomerate, dominated by acid igneous rocks, overlies the Shalloch Formation and is in turn overlain by the Woodland Formation.

Interpretation

The succession along the Girvan Foreshore indicates the existence of a deep-water, tectonically active environment of deposition along the southern edge of the Midland Valley Terrane throughout Caradoc and early Ashgill times. Moreover, whilst some of the igneous clasts in the Kilranny Conglomerate were derived from the Ballantrae Complex, others were derived from the unroofing of intrusions not much older than the sedimentary succession that now contains them (Longman *et al.*, 1979; Bluck, 1983). The Girvan succession was therefore considered by Bluck (1983) to represent a proximal fore-arc environment (see also Bluck and Ingham, 1992a).

The 'cascade' folds in the Ardwell Flags are complex (see Williams, 1959; Ramsay, 1976; Williams and Spray, 1979) and were once thought to be tectonic in origin. However, their restriction to this part of the stratigraphy and the recognition of sand-flows in some fold closures (Bluck, in Ingham, 1978, p. 169) suggest that they are syn-sedimentary features reflecting downslope movement from the north-west.

The Bouma sequences of the South Shore Formation indicate deposition by turbidity flows, and the overlying Three Mile Formation is regarded as a more distal turbidite succession ('sandstone flysch') (see Ingham (1978)). Bioclasts in the South Shore Formation include the trinucleid trilobite *Tretaspis ceriodes*, a typical member of latest Caradoc shelf faunas in the Anglo-Welsh area, Scandinavia and even China (Ingham, 1978, 1992b; Owen, 1987). Its occurrence at Girvan provides an indication not only of the age of the South Shore Formation but also of the extent to which the faunal provincialism of the earlier part of the Ordovician had broken down by the late Caradoc. This is also seen in the composition of the deep-water faunas of the upper Whitehouse Group, where the trilobites include an extremely diverse mixture (Thomas *et al.*, 1984, p. 40; Ingham, 1992b, p. 402) of the large-eyed, pelagic species (mostly cyclopygids) and small-eyed or blind benthic taxa, a typical atheloptic assemblage (Fortey and Owens, 1987). This deep-water biofacies was previously restricted to mesopelagic and outer-shelf to upper-slope environments on the margins of Gondwana and Avalonia, except for a brief incursion of two taxa into the Girvan area in the early Caradoc (Ingham and Tripp, 1991; Rushton *et al.*, 1996b). Whittard (1952b) and Owen and Ingham (1996) have described some of the trilobite species of the upper Whitehouse Group, and Dr Ingham (in prep.) is working on several widely distributed taxa. The brachiopod fauna is also of deep-water aspect and is an example of the widespread *Foliomena* fauna (Harper, 1979, 1984).

The association of graptolites and early Ashgill shelly faunas in the lower part of the Mill Formation at Myoch Bay is valuable for wider correlation of the base of the Ashgill Series. The absence of the lower part of the Mill Formation on the Whitehouse shore and the mixing of partly consolidated sediment in the lowest horizons of the formation present there are probably the result of local down-slope failure of part of the sediment pile (Ingham, 1992b, fig. 30.2). The channel-fill mudclast conglomerate in Myoch Bay also indicates down-slope transport and the sandstone flysch of the Shalloch Formation indicates a distal environment, well supplied with siliceous sediment. The removal of the upper part of the Ordovician was probably by submarine slope failure or channelling, reflecting continued tectonic instability.

Conclusions

The Girvan Foreshore is a classic site in British geology. It contains spectacular structures and sedimentary features that, together with some magnificently preserved deep-water fossils, indicate an unstable deep-water environment during the Caradoc and early Ashgill divisions of the Ordovician. This information plays a crucial part in understanding the British segment of the Caledonian–Appalachian mountain belt. Moreover, the relative levels of certain shelly and graptolitic faunas are important in the international understanding of the correlation of the base of the Ashgill Series.

CRAIGHEAD QUARRY (NS 232 012, NS 234 014)

Introduction

Craighead Quarry is of international significance. Richly fossiliferous, it is the type locality for numerous species. It shows a complex development of limestone types and an unconformable surface of considerable relief between the Ballantrae ophiolite and its overlying sedimentary cover sequence. Not only is this a rare insight into such a surface, but its mid-Caradoc age is crucial to the understanding of the Ordovician development of the southern edge of the Midland Valley Terrane.

The quarry complex at Craighead, north of Girvan, is the type and only major outcrop of the Craighead Limestone Formation. The formation can be seen to overlie the Ballantrae Complex (Figure 14.1) and comprises a variety of lithologies not seen elsewhere in the Girvan succession. The site is unique in the British Isles in showing in detail the transgression of a sedimentary succession over the highly irregular topography of an ophiolitic basement. The Craighead Limestone Formation was originally correlated with the only other major limestone formation in the Ordovician of the Girvan district, the Stinchar Limestone (Lapworth, 1882). With the study of the fossils, this view became less widely held from the early 1930s onward, culminating in Williams' (1962) correlation of the Craighead Limestone with part of the Ardwell Group, south of Girvan. This significantly younger age is important in interpreting the history of the Midland Valley Terrane, in that it helps demonstrate the progressive northward transgression of the Ordovician cover sequence above the ophiolite across a series of fault-bounded blocks. Graptolites and trilobites enable correlation with the middle Caradoc of the Anglo-Welsh area and the upper Mohawkian of eastern North America respectively.

Description

This site comprises a large abandoned quarry complex west of Craighead farm and three smaller quarries to the south-west (Figure 14.12). Williams (1962, p. 48, pl. 4) published maps and measured sections of the quarries that formed the basis of those produced by Tripp (1980b), Bergström (1990) and Ingham (1992c).

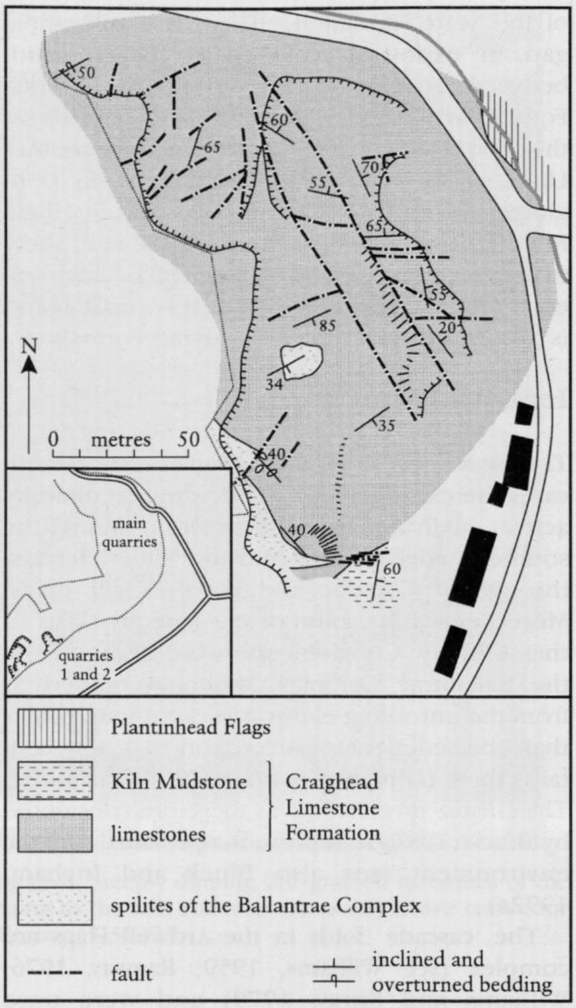

Figure 14.12 Simplified geological map of Craighead Main Quarry, after Williams (1962, pl. 4) and Ingham (1992c, fig. 31.1). Inset map shows the position of the two smaller quarries to the south-west (see Williams, 1962 for details).

Williams' work remains definitive, although Ingham (1992c) provided a more recent synthesis as part of a field excursion guide to the Craighead Inlier. The quarries expose the Craighead Limestone Formation and its unconformable relationship to the underlying spilites and cherts of the Ballantrae Complex. The formation is overlain by fine-grained greywackes of the Plantinhead Flags, which crop out in the stream section to the immediate east of the site.

Lithofacies interrelationships within the Craighead Formation are complex, especially in its lower parts, above the highly irregular unconformity surface. Interpretation is hindered by folding and faulting, making detailed correlation

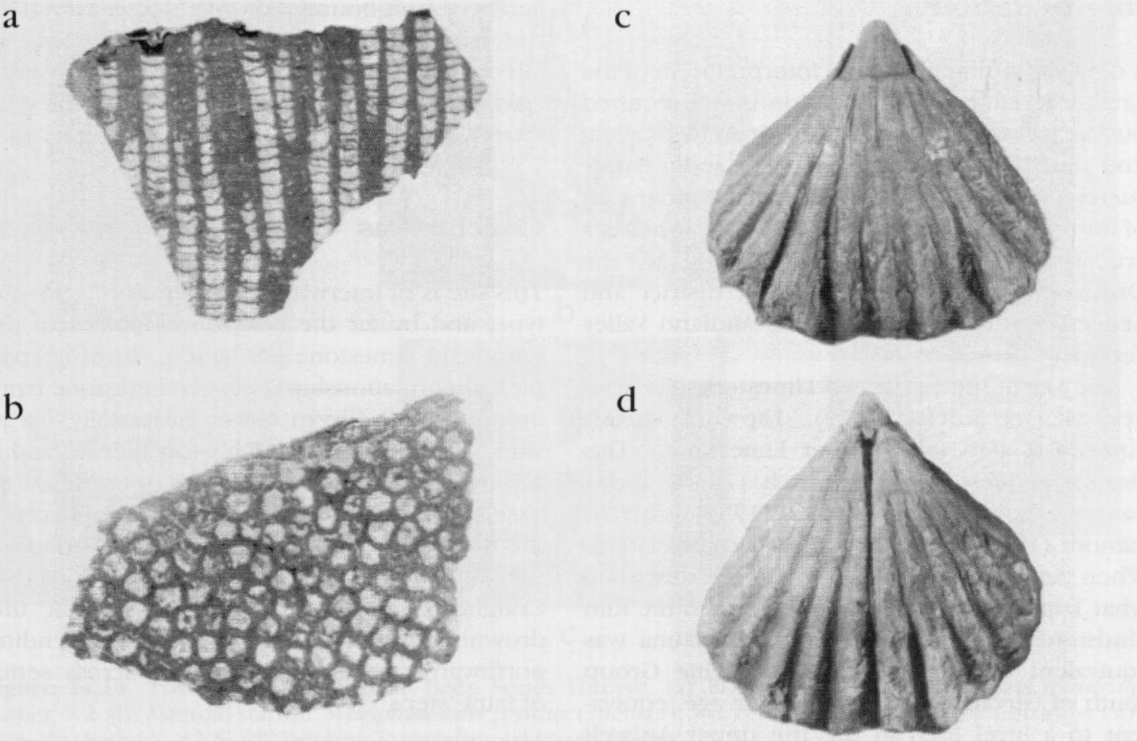

Figure 14.13 Fossils from the Craighead Limestone, Craighead Quarry. (a, b) *Lyopora favosa* M'Coy, × 2. (c, d) *Rostricellula lapworthi* (Davidson), ×3.

between quarry faces very difficult. The complicated basal relationships of the formation are best seen along the west faces of the south-west part of the main quarry. Here, the upper parts of a marked topographical high in the underlying Ballantrae Complex are overlain by conglomeratic limestones rich in the calcareous alga *Girvanella*, whereas to the south, away from the high, the basal parts of the Craighead Formation comprise conglomerates containing clasts of spilite, serpentinite and jasper, and are overlain by rubbly limestones. Some limestones in the formation are conglomeratic, others nodular, yet others contain an appreciable siliciclastic component. Many contain *Girvanella*, and some are crinoidal or otherwise bioclastic. Williams (1962) provided an outline of the distribution of the different lithologies and their likely lateral correlation within and between the quarries.

In addition to the variety of limestone types, the Craighead Formation includes two mudstone intercalations. The lower one, the Sericoidea Mudstone Member, is exposed above the ramp leading down the western side of the main quarry complex, and the upper one, the Kiln Mudstone Member, occurs at the southern end of the main quarry by (and beneath) the ruined kiln, and also in the quarries to the south-west. Evidence from these latter exposures shows that the Kiln Member lies within the higher limestones of the Craighead Formation.

Many of the lithologies of the Craighead Formation are richly fossiliferous, and the unit has provided the type material for a great many species. In particular, 43 species of brachiopod and 28 of trilobite have their type material from the Craighead quarries. Reed (1935) published extensive lists of brachiopods (Figure 14.13c, d), trilobites, bivalves, gastropods, corals (Figure 14.13a, b) and graptolites from the quarries, but his lists do not differentiate between faunas from the limestones and those from the two mudstone intercalations. The diverse brachiopod (Williams, 1962) and trilobite (Tripp, 1954, 1980b) faunas have received modern monographic revision. Both are strongly Laurentian in aspect and show marked differences between the limestone and mudstone. Tripp's list (1980b) also shows significant differences between the two mudstone faunas.

Interpretation

A detailed sedimentological interpretation of the Craighead Limestone Formation is still required but the formation is unique in Britain in showing fine details of transgression of a sedimentary succession over the highly irregular topography of an ophiolitic basement. Moreover, it holds a crucial place in the understanding of the Ordovician history of the Girvan district and hence the southern edge of the Midland Valley Terrane.

The age of the Craighead Limestone has been debated (see Sinclair, 1949). Lapworth (1882) equated it with the Stinchar Limestone. This view was questioned by Ulrich (1930) and a younger age suggested by Reed (1935), whereas Lamont (1935) favoured the earlier correlation. When Anderson and Pringle (1946) described what Tripp (1954) subsequently termed the Kiln Mudstones, they considered that its fauna was equivalent to those of the Balclatchie Group south of Girvan. An even younger age, equivalent to a level high in the the upper Ardwell Group, was suggested by Williams (1962, p. 61), but a slightly lower level within the upper Ardwell group was subsequently indicated by Ingham (1978, p. 173) and has become the accepted view.

A graptolite fauna from the Sericoidea Mudstone identified by Rickards (in Tripp, 1980b, p. 147) indicates a level low in the *Dicranograptus clingani* Zone (mid-Caradoc), and shelly fossils in the limestones indicate a basal Shermanian age in terms of the former eastern North American chronostratigraphy (Ingham, 1992c, p. 422); this chronostratigraphy has since been revised by Leslie and Bergström (1995). The limestones of the main quarries have yielded few conodonts, but a sample from the topmost limestone below the Kiln Mudstone in Quarry 1 of Williams (1962) contained a fauna that Bergström (1990, p. 11) considered is probably within the *Amorphognathus superbus* Zone but which might be from the *A. tvaerensis* Zone. As with the shelly fossils, the conodont fauna is primarily Laurentian in affinity, although Bergström commented on the absence of certain taxa that elsewhere are commonly associated with those occurring in his sample.

The relatively young age of the Craighead Formation extends the model of the progressive northward transgression of the Ordovician cover sequence above the Ballantrae ophiolite across a series of fault-bounded blocks that is evident in the main Lower Palaeozoic outcrop south of Girvan. In this instance it reflects the transgression over the Girvan Valley line during the mid-Caradoc.

Conclusions

This site is of international importance. It is the type, and by far the best, development of the Craighead Limestone Formation, showing complex inter-relationships between limestone types unique in the Girvan Lower Palaeozoic succession. The formation is richly fossiliferous and is the type locality for many fossil species. At its base, it shows with unique clarity the effects of the drowning of an irregular, eroded surface of the Ballantrae ophiolite. The age of the Craighead Limestone demonstrates that this drowning was a progressive event extending northwards across the Girvan area, across series of fault 'steps'.

SOUTH THREAVE (NS 251 038)

Introduction

The upper Drummuck Group east of South Threave includes the world-famous Lady Burn Starfish Beds, which contain a Rawtheyan shelly fauna of unrivalled diversity and excellence of preservation. The wealth of taxonomic literature on the many phyla represented in the fauna gives it international significance beyond that due its stratigraphical age and palaeogeographical position.

This site exposes some of the youngest Ordovician rocks in the Girvan area. The Lady Burn Starfish Beds, known only from this site, provide the fullest census of Rawtheyan neritic benthos from the Laurentian margin and include the most diverse trilobite fauna of that age from anywhere in the world. They are also regarded as an echinoderm Lagerstätte, comprising the 'most diverse and important echinoderm fauna in the British Ordovician' (Donovan *et al.*, 1996) and include a fully studied fauna of the controversial calcichordates, which share both echinoderm and chordate features.

South Threave lies within the Craighead Inlier, in the most northerly part of the Girvan district (see the Craighead Quarry site report),

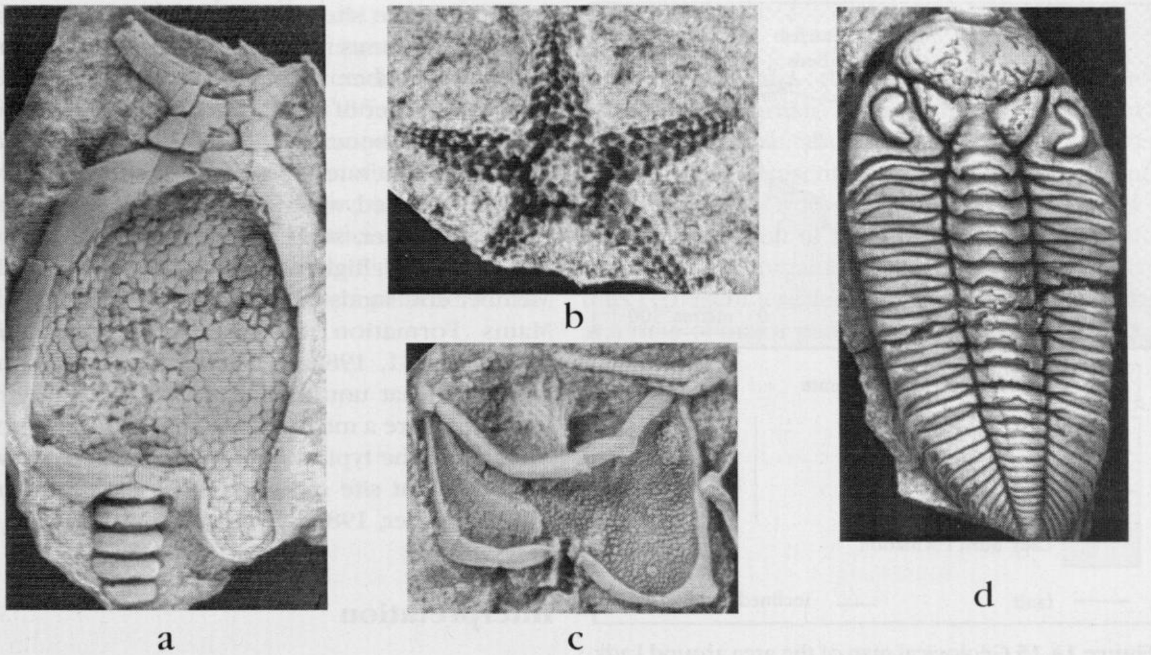

Figure 14.14 Fossils from the Starfish Beds, South Threave. (a) Rhombiferan cystid *Pygecystis quadrata* Bather, ×2. (b) Asteroid starfish *Mesopalaeaster primus* (Spencer), ×4. (c) Cornute calcichordate *Scotiaecystis curvata* (Bather), ×1.5. (d) Trilobite *Toxochasmops bisseti* (Reed), ×1.5.

where the Ordovician succession extends to much higher levels beneath the Llandovery unconformity than in the area to the immediate south of Girvan (see the Girvan Foreshore site report). It is the type area for the uppermost formation of the Drummuck Group, the South Threave Formation, of late Rawtheyan age.

Harper (1982a) re-mapped a substantial part of the Craighead Inlier and established a formal lithostratigraphy within the Drummuck Group of Lapworth (1882), thus building on the work of Lamont (1935). Harper divided the upper Drummuck Group into the Lady Burn and South Threave formations. The base of the latter was defined to the immediate south-west of the site, and the formation was subdivided into, in ascending order, the Farden, Cliff and Waterfall members. The last two of these have their principal exposures within the site, and the upper part of the Farden Member, including the Starfish Beds (see also Harper, 1982b), is exposed only here. The site is also included in a field guide to the Girvan district (Ingham, 1992c). The faunas of the Starfish Beds were made famous by the Gray family's extensive collections, made at the end of the 19th century and during the early decades of the 20th and now largely housed in the Natural History Museum, London (Cleevely *et al.*, 1989). The Starfish Beds were studied in detail by Begg (1946) and re-excavated by Harper (1982b). The abundant and well-preserved shelly fossils (Figure 14.14) have been the subject of a multitude of monographic studies, and the numerous illustrations of shelly fossils from the Starfish Beds in the recent guide to British upper Ordovician fossils (Harper and Owen, 1996) are testimony to their diversity, importance and fine state of preservation.

Description

The site comprises a section of Threave Glen, through which the Lady Burn flows, some 500 m ENE of South Threave Farm. The beds dip to the north at 35°, and lower horizons within the upper Drummuck Group are exposed in the burn and adjacent fields between the farm and the site (Figure 14.15).

The upper part of the 40 m thick Farden Member of the South Threave Formation is exposed in the banks of the Lady Burn at the western end of the site, where the grey-green silty mudstones and siltstones typical of the member are interbedded with green sandstones,

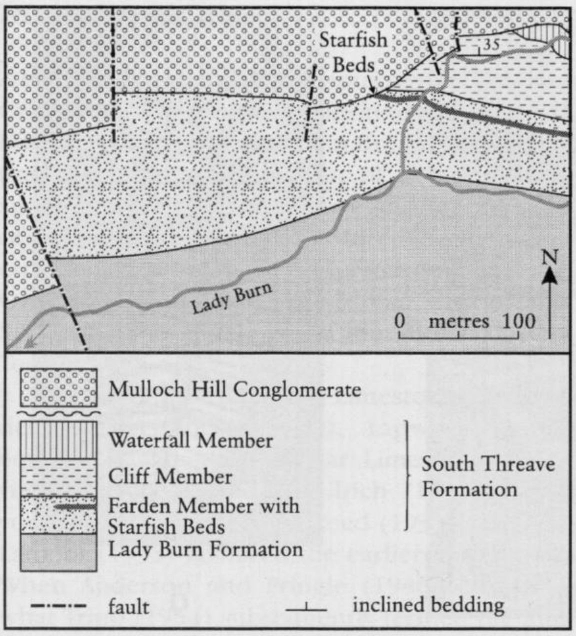

Figure 14.15 Geological map of the area around Lady Burn, east of South Threave farmhouse showing divisions of the upper Drummuck Group, after Harper (1982b, fig. 11). Note the marked overstep of the Mulloch Hill Conglomerate, the local base of the Silurian.

including the Starfish Beds. Harper (1982a, b) described three such beds, 10–25 cm thick, in his excavations on the south-east side of the river. He considered the lowest to be the horizon intensively sampled by the Gray family but was unsure as to how his three beds equated with the four discussed by Begg (1946), or even whether the latter author was referring to individual beds or fossiliferous horizons within beds.

The well-bedded green mudstones at the top of the Farden Member are succeeded by massive, blue-grey siltstones and silty mudstones of the Cliff Member. Within this 10 m thick unit, shells (including enrolled trilobites) are commonly found in concentric bands around mud 'nodules' suggesting entrainment during down-slope movement. Harper (1982a) noted that similar features are also seen in the Glenmard Member of the Quarrel Hill Formation in the lower Drummuck Group. Floyd *et al.* (1999) figure a specimen of the graptolite *Paraorthograptus pacificus* (Ruedemann) from the Cliff Member, indicating correlation with the *pacificus* Subzone of the *anceps* graptolite zone. The Cliff Member is followed at the waterfall at the eastern end of the site by well-bedded, grey-green muddy siltstones of the poorly fossiliferous Waterfall Member. Only a few metres of this highest member of the South Threave Formation are exposed beneath the Llandovery Mulloch Hill Conglomerate here. The conglomerate shows a marked westward overstep within the Craighead Inlier, such that, only 1.5 km to the east of the site, higher levels within the Waterfall Member and sandstones of the Hirnantian High Mains Formation are exposed beneath it (Harper, 1981, 1982a). These sandstones contain somewhat unusual latest Ordovician shelly faunas that are a mixture of forms normally associated with the typical *Hirnantia* Fauna (see the Cwm Hirnant site report) and local Laurentian relicts (Harper, 1981; Owen, 1986).

Interpretation

A great many species (including type species of several genera) have the Lady Burn Starfish Beds as their type horizon. Harper (1982a, p. 254) listed the many taxonomic works involving the shelly faunas of the beds. More recent works include his own monograph on the brachiopods (Harper, 1984–1989), works on echinoderms (Donovan and Paul, 1985; Donovan, 1986–1995), on the enigmatic calcichordates (Jefferies, 1990; Daley, 1992b) and the ostracods (Floyd *et al.*, 1999) and the listing of the 47 previously named species of trilobite (many in need of modern revision) by Thomas *et al.* (1984, fig. 19). The taxonomic, morphological and stratigraphical importance of the faunas of the upper Drummuck Group in general and the Starfish Beds in particular cannot be overstated.

The late Rawtheyan faunas of the Starfish Beds are a mixture of relict Laurentian taxa and more cosmopolitan species, reflecting the breakdown of provincialism consequent on the narrowing of the Iapetus Ocean by the late Ordovician. Goldring and Stephenson (1972) concluded that the excellent preservation and abundance of the Starfish Beds faunas indicated rapid burial in a shallow-water environment. However, Ingham (1978) and Harper (1979, 1982a) argued for the mass transport of material from a variety of outer-shelf settings into deeper water. Such a catastrophic movement of sediment would have entrained, buried and killed the living benthos (see Jefferies, 1990, p. 35) and thus provided a census of the shelly faunas involved. Harper (1982b, p. 31) noted differences in the faunal compositions of his three Starfish Beds that he interpreted as reflecting their provenance from slightly different sea-floor environments. Recent excavations have been undertaken under the auspices of the Hunterian Museum, University of Glasgow, with a view to establishing the precise location, extent and composition of the various Starfish Beds. This should clarify and enhance their palaeoenvironmental significance.

Conclusions

This site includes the internationally known Lady Burn Starfish Beds, which contain an extremely diverse, abundant and well-preserved fossil fauna representing virtually all the main groups of late Ordovician animals. The strata formed as a result of catastrophic movements of sediments and organisms into deeper water and thus represent a series of instant 'census' events at a time of major global faunal change.