British Cambrian to Ordovician Stratigraphy

A.W.A. Rushton
Palaeontology Department, Natural History Museum, London, UK

A.W. Owen
Division of Earth Sciences, University of Glasgow, UK

R.M. Owens
Department of Geology, National Museum of Wales, Cardiff, UK

and

J.K. Prigmore
Equipoise Solutions Ltd, Croydon, UK

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Chapter 15

Scotland: Ordovician of the Southern Uplands Terrane

A. W. A. Rushton and A. W. Owen

INTRODUCTION

The Southern Uplands Terrane lies to the south of the Southern Upland Fault (Floyd, 1994) and overlies a probable continuation of the Midland Valley basement (Hall *et al.*, 1983). It is composed largely of greywacke and shale formations of Caradoc to Wenlock age, deposited in deep water, with slivers of basic lavas at the base that have been interpreted as indicating oceanic crust (but see Armstrong *et al.*, 1996). The area was the location of the classic work by Lapworth (1878), which demonstrated the value of graptolites in stratigraphical correlation (Fortey, 1993). The weighty Geological Survey memoir by Peach and Horne (1899) is still a valuable storehouse of detailed information, although the structural interpretations and many fossil identifications therein have long been superseded.

The Southern Uplands are commonly described in terms of an Ordovician northern belt, a central belt of Llandovery rocks with Ordovician inliers, and a southern belt of Wenlock rocks. The outcrop is divided by strike-parallel faults into structural tracts, in which the beds generally dip steeply and young to the north-west; despite this, biostratigraphy shows that the successive tracts become younger to the south-east (Rushton *et al.*, 1996a). This paradoxical structure has been interpreted in several different ways. In recent years, Leggett *et al.* (1979) proposed that the Southern Uplands was the site of a fore-arc accretionary prism formed above a NW-dipping subduction zone. Stone *et al.* (1987) suggested a back-arc setting, from which a southward-migrating thrust front developed, whilst Morris' (1987) model considered that the back-arc setting applied only to the northern belt. More recently, Armstrong *et al.* (1996) linked Ordovician deposition in the Southern Uplands to that to the north of the Southern Upland Fault and argued that deposition and volcanism took place above a continental rather than an oceanic basement and the succession was imbricated within a flower structure.

Although the structural setting is debated, the stratigraphy is now relatively well systematized (see Floyd (1996) for review and rationalization of the Ordovician succession). In the northern belt the oldest rocks are referred to the Crawford Group, comprising the Raven Gill and Kirkton formations, of which the former, which includes the oldest fossiliferous strata (mid-Arenig) in the Southern Uplands, is exposed at Raven Gill (Figure 12.1). The Crawford Group is succeeded by the widely distributed Moffat Shale Group (lowest Caradoc to Llandovery), of which only the two lower divisions, the Glenkiln and Lower Hartfell shales, are recognized in the northern belt. Resting on different levels within the Moffat Shale Beds are several distinct greywacke formations of various ages and differing petrographical characteristics (Floyd, 1996, fig. 2). Three of these greywacke formations are represented by GCR sites (Figure 15.1): spectacular conglomerates of the Corsewall Formation are exposed at Corsewall Point, and parts of the Portpatrick and Glenwhargen formations overlie a good development of the Glenkiln and Lower Hartfell shales at Morroch Bay (Figure 12.1).

In the central belt the Ordovician is restricted to faulted inliers of Moffat Shale. These are very numerous but commonly structurally complicated and stratigraphically incomplete (Figure 15.1). One such inlier is at Glenkiln Burn (Figure 12.1), which is the original site for the Glenkiln Shale Formation. The inlier at Dob's Linn, on the other hand, has a remarkably complete section of the Moffat Shale Beds, from the upper part of the Glenkiln Formation to the mid-part of the Llandovery (Figure 15.1). The lithological and palaeontological succession is so clear and complete that this site was chosen as the international stratotype for the Ordovician–Silurian boundary.

RAVEN GILL (NS 92041989)

Introduction

Raven Gill is the type locality for the Raven Gill Formation, a faulted slice of Arenig rocks within the Leadhills Imbricate Zone, and its interpretation is critical to understanding the plate tectonic history of the Southern Uplands.

Raven Gill lies in a zone of complex geology along one of the major strike-parallel faults in the Southern Uplands, the Leadhills Fault. The stratigraphy within the Leadhills Imbricate Zone is unclear (see Floyd, 1996), but at Raven Gill and in the headwaters of the Snar Water, 6.5 km along strike to the south-west, conodont faunas indicate an Arenig age for part of the succession. The present faunal evidence indicates that, apart from the Arenig rocks in the Leadhills Imbricate Zone, there are no rocks in the Southern Uplands older than latest Llanvirn. The Raven Gill Formation is thus crucial for understanding

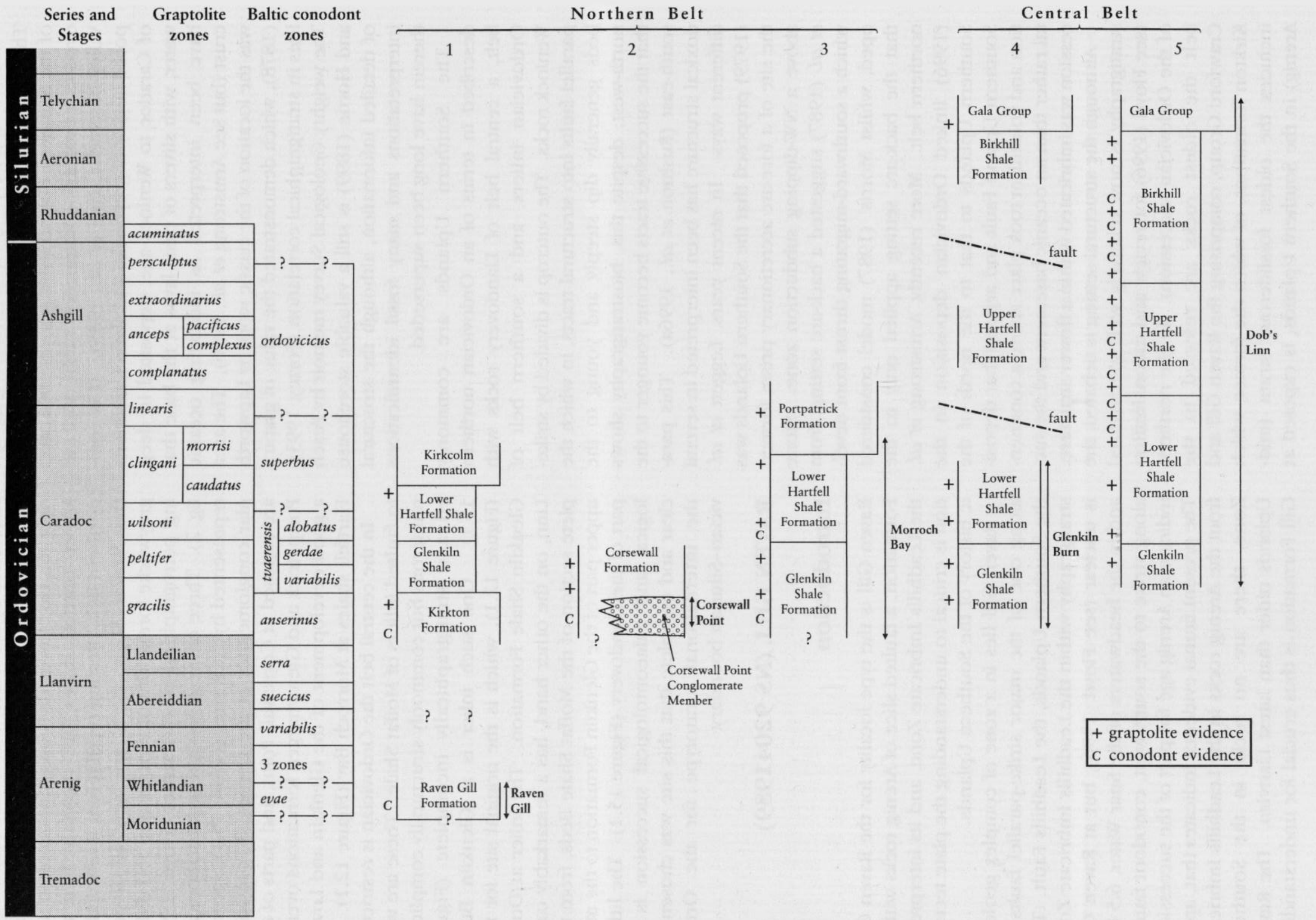

Figure 15.1 Correlation of fault-bounded stratigraphical successions in the Southern Uplands Terrane of Scotland that include GCR sites, based on Floyd (1996) and Rushton *et al.* (1996a, fig. 4). Columns represent the following: 1, Leadhills Imbricate Zone, Crawford district; 2, tract north of the Glen App Fault, Rhins of Galloway; 3, Morroch Bay Fault Zone, Rhins of Galloway; 4, north of Lauriston Fault, south of Moffat; 5, Moffat Valley north-east of Moffat.

the plate tectonic history of the Southern Uplands – a subject that continues to generate considerable controversy (see the set of papers introduced by McKerrow (1987) and also Armstrong *et al.* (1996) for more recent developments).

Peach and Horne (1899, p. 286) first described the section at the head of Raven Gill and recognized that the lavas, intrusive igneous rocks, radiolarian cherts and mudstones were Arenig in age. They listed a fauna from the mudstones comprising graptolites, lingulate brachiopods and what they questioningly termed 'annelid jaws'. The last of these proved to be conodonts (Smith, 1907), later described by Lamont and Lindström (1957) (see also Armstrong *et al.* (1990, 1999) and references therein) on the basis of extensive collections made by Lamont. The term 'Raven Gill Formation' was first published by Hepworth *et al.* (1982, p. 521) (see also Walton and Oliver, 1991, p. 170), and the formation was discussed in Floyd's (1996, p. 156) review.

Description

Although the adjacent hillside is barren of outcrops, exposure is very good on the steep sides of the two upper branches of Raven Gill and more intermittent in and at the sides of the burn for some 75 m east of their confluence. The ridge between the two upper branches is a mass of lava or possibly a dolerite intrusion. On its northern side is lava and lava conglomerate, to the north of which, extending up the northern bank of the burn, is a steeply dipping sedimentary succession, although the contact between the two is not exposed. The sedimentary rocks comprise alternating packets of bedded radiolarian chert up to 2 m thick and brown-weathering mudstone up to 4 m thick. The chert beds are up to 15 cm thick, vary in colour from green to black and are commonly interbedded with yellow-weathering mudstone layers up to about 3 cm thick. The igneous rocks, cherts and mudstones all belong to the Raven Gill Formation, as defined by Hepworth *et al.* (1982, p. 521).

Lava crops out on the immediate south side of the southern branch and lavas or dolerite extend along the burn for some 30 m beyond the confluence, with greywacke cropping out on the southern bank. Recent work by Drs H.A. Armstrong, J.D. Floyd and A.W. Owen has revealed that, just below the confluence, large pockets of rottenstone in rather sheared greywacke may indicate a weathered conglomerate, and on the northern bank here there are alternations of greywacke, shales, microconglomerate and lava or thin basic intrusions. Detailed mapping of the site is required to clarify the relationships between the various rock units.

Interpretation

The commonest of the fossils listed by Peach and Horne (1899, p. 288) from the brown mudstones are lingulate brachiopods of little stratigraphical value. The graptolites they recorded are too fragmentary to be identified taxonomically (Floyd, 1996, p. 157), and no new graptolites have been recovered. However, the abundant conodonts from the brown mudstones described by Lamont and Lindström (1957) were re-identified by Löfgren (1978, p. 38) and include *Oepikodus evae*, the eponymous species of the lower to low-middle Arenig *evae* Zone. Smith's (1907) record of Arenig conodonts from the headwaters of the Snar Water has recently been confirmed by Armstrong *et al.* (1999) who have collected conodonts of the *evae* Zone there. Other conodont faunas from cherty mudstones in the Leadhills Imbricate Zone are interpreted as being from the Kirkton Formation and belong in the uppermost Llanvirn to basal Caradoc *Pygodus anserinus* Zone (Armstrong *et al.*, 1990, 1999; Floyd, 1996).

Thirlwall (in McKerrow *et al.*, 1985, p. 75) reported a Sm–Nd age of 490 ± 14 Ma from 'basalts underlying Arenig cherts near Raven Gill'. This is broadly commensurate with the projected age of 485 Ma for the base of the Arenig given by Tucker and McKerrow (1995) but is less compatible with the late Tremadoc age of 483 ± 1 Ma of Landing *et al.* (1997) and the early Arenig age of 471 ± 3 of Compston and Williams (1992). Lambert *et al.* (1981) considered the lavas from a pipeline section near Raven Gill to have originated in an oceanic setting. However, a reassessment by Armstrong *et al.* (1996, p. 201) indicated that Lambert *et al.*'s data provide equivocal results, one sample suggesting an attenuated within-plate setting, the other a volcanic arc developed on continental lithosphere. The interpretation of more recent analyses of basic igneous rocks from the Leadhills Imbricate Zone in the Leadhills area is also equivocal (Phillips *et al.,* 1995). The cherts from Raven Gill have a continental margin geochemical signature (Armstrong *et al.*, 1999). The understanding of the origins and structural setting of the Raven Gill Formation is crucial to determining the plate tectonic origins and history of the northern belt of the Southern Uplands, but a consensual understanding has yet to be achieved.

Conclusions

This site is the type locality for the Raven Gill Formation, the oldest unit in the Southern Uplands. It lies in an extensive band of very complex geology, the Leadhills Imbricate Zone, and its interpretation is critical to the continuing controversy surrounding the geological history of the Southern Uplands. It has yielded a rich fauna of conodonts belonging to the *Oepikodus evae* Zone, indicating that the formation is early to mid-Arenig in age.

CORSEWALL POINT (NW 979725–NX 023730)

Introduction

Corsewall Point is the type area for the conglomeratic member of the Corsewall Formation of the Tappins Group (Floyd, 1996), the best-exposed boulder-conglomerate in the Southern Uplands of Scotland. The conglomerate contains fragments of a great variety of rock types and gives clear evidence of derivation from a varied terrane to the north-west. More controversial is the conclusion that most of the granite boulders originated from the area of north-west Newfoundland (Elders, 1987), implying extensive sinistral strike-slip (see below).

The Corsewall Formation occupies the northern extremity of the Rhins of Galloway. It is limited to the south by the south-western extension of the Glen App Fault and is well exposed around the coast, as described briefly by Peach and Horne (1899, p. 410). More detailed study by Kelling (1961) proposed that the Corsewall 'Group' be divided into a lower Flaggy Division, about 750 m thick, to the south, and a Conglomeratic Division above, to the north. He described the petrology and sedimentology in detail (Kelling, 1962), and Kelling *et al.* (1987, fig. 4) illustrated vertical and lateral facies variations by means of graphical logs of three sections. Granite boulders from the Corsewall Conglomerates formed an important component of Elders' (1987) provenance studies, which have stimulated much further discussion. Stone (1995) gave a further account of the Corsewall Formation, including the regional geology and structural setting, and McCurry and Stone (1996, p. 127) provided a geological guide to the site.

Description

The conglomeratic member of the Corsewall Formation is exposed at the northern end of the Rhins of Galloway, from Corsewall Point to Milleur Point. The beds strike ENE to WSW and dip to the north at about 80°. The conglomeratic member overlies the flaggy greywacke member abruptly and is composed of packets, up to 25 m thick, of conglomerate beds that are commonly lenticular in form and 2–5 m thick. These are interleaved with massive coarse-grained and thinner-bedded greywacke units that resemble those of the underlying flaggy greywacke member. The conglomerates may be clast- or matrix-supported and show sedimentary structures, such as down-cutting or disruption of the underlying beds (Kelling, 1962, fig. 2), that indicate that the succession youngs to the north. The clasts in the conglomerates include a range of rock types, for example granitic and other igneous (felsitic, spilitic), sedimentary (greywacke, chert) and metamorphic rocks (Kelling, 1962, fig. 3). The clasts are generally rounded or subrounded and may be large – up to 1.5 m across (Figure 15.2).

Elders (1987) sampled the granitic clasts and grouped them into five types. The most distinctive were of foliated muscovite–biotite granite, and these gave a Rb–Sr whole-rock isochron indicating an age of 1265 ± 130 Ma. Two types of hornblende–biotite granite similarly gave ages of 603 ± 40 Ma and 600 ± 30 Ma, while Na-rich biotite granite clasts gave an age of 475 ± 20 Ma.

Interpretation

The Corsewall Formation is inferred, from along-strike correlation, to have been deposited during part of the *gracilis* graptolite zone (Stone, 1995, p. 9). Kelling *et al.* (1987) considered that the conglomerates were deposited from debris flows and high-density turbidity currents flowing directly (laterally) into the depositional trench from a north-west quarter, through

Figure 15.2 Corsewall Point, east of the lighthouse, looking north. Beds of coarse conglomerate, dipping steeply and slightly overturned. Most of the large pale boulders are acid volcanic rocks and various granites. (Photo: British Geological Survey photographic collection, D4070.)

a system of submarine channels that scoured the underlying greywackes. In contrast, the predominant indices of flow in the underlying flaggy greywacke member have a north-east to south-west trend and are taken to indicate flow along the axis of the trench.

The clasts in the conglomerate were derived from a varied source area with an acidic to intermediate plutonic basement, a clastic cover sequence and probable ophiolitic rocks. The larger of the boulders, though rounded, are unlikely to have been transported any great distance, so their provenance has a particular bearing on local palaeogeography and has been a matter of discussion. Elders (1987) was unable to match the older of his granite clasts (1265 Ma) with any Scottish or Irish source but compared them closely with plutons intruded into Grenville-age rocks in north-west Newfoundland. He was also able to match his younger (475 Ma) granites with a Newfoundland pluton, though not his 600 Ma clasts. In order to bring north-west Newfoundland sufficiently close to the Southern Uplands to derive the granite clasts locally, he invoked major sinistral strike-slip of about 1400 km.

Elders' conclusions were challenged by Winchester and Max (1989), who identified a possible source for the 1230 Ma granitoid rocks in the Annagh Division, north-west County Mayo, Ireland. If, as they suggest, the Annagh Division is part of a Proterozoic basement complex that underlies a large area of north-west Britain, the source of some at least of the Corsewall conglomerate boulders may lie much closer than north-west Newfoundland. Kelley and Bluck (1989), having sampled rocks in the Rhins of Galloway (though citing only one sample from the Corsewall Formation), failed to find any detrital mica as old as the older of Elders' granite clasts; they contended that if the granite clasts were derived from north-west Newfoundland, Grenville-age micas should also have been present in the detritus. This was further discussed by Armstrong *et al.* (1996). Elders (in Elders *et al.*, 1990) considered that the mica dated by Kelley and Bluck was likely to have been deposited by a different (axial) sedimentary system from that of the lateral mass-flow that emplaced the large granite clasts. Owen and Clarkson (1992) likewise challenged Elders' strike-slip hypothesis on the grounds that transported shelly faunas in the northern part of the Southern Uplands are very similar to those found *in situ* in areas immediately north-west of the Southern Upland Fault at Girvan and Pomeroy, Ireland (see also Scrutton *et al.*, 1998). They considered that this limits the possible strike-slip to a much smaller distance than that invoked by Elders. McKerrow and Elders (1989) have suggested that much of the strike-slip they envisage was taken up on the Highland Boundary Fault, to the north of Girvan, reducing the proposed movement on the Southern Upland Fault to 'around 400 km'.

There remains much uncertainty about the provenance of material that makes up the Southern Uplands Terrane, but it is clear that the varied detritus in the conglomerates of the Corsewall Formation, because it is relatively little-travelled and comes from a known direction, holds much potential for elucidating a critical problem in the understanding of the Ordovician palaeogeographical setting of the Southern Uplands.

Conclusions

The Corsewall Conglomerate is the best-exposed and most fully studied conglomerate body in the Ordovician of the Southern Uplands Terrane. Interpretation of the sedimentology indicates relatively local derivation of the coarser material, including boulders of a variety of granites, but the extent to which this can be used to infer extensive strike-slip on the Southern Upland Fault is debated. The site will continue to be vital to the resolution of these problems.

MORROCH BAY (NX 018523–NX 014526) AND PORT OF SPITTAL BAY (NX 019521)

Introduction

Morroch Bay shows the largest exposure of the Moffat Shale Group in south-west Scotland and shows an unfaulted contact with the overlying greywacke sandstones of the Portpatrick Formation. The Moffat Shale Group contains a succession of fossil faunas, the youngest of which serves to date the base of the Portpatrick Formation, which is itself generally unfossiliferous. At Port of Spittal Bay, immediately to the south of Morroch Bay, the lowest part of the Portpatrick Formation is again visible, interleaved with units of the quartzose Glenwhargen Formation. A graptolite fauna just below the base of the Portpatrick Formation there is significantly younger than that at Morroch Bay, illustrating the diachronous nature of the base of the greywackes.

The section at Morroch Bay was described by Peach and Horne (1899, pp. 402–408), Stone (1995, p. 17, fig. 9a) and Rushton and Tunnicliff (1996). Features of Port of Spittal Bay were described by Stone (1995, p. 27), who also gave further references and (in his appendix 2) details of the graptolite faunas.

Description

At Morroch Bay the intertidal exposure of the Moffat Shale Group is about 400 m across, extending from 018 523 to 014 526, with the

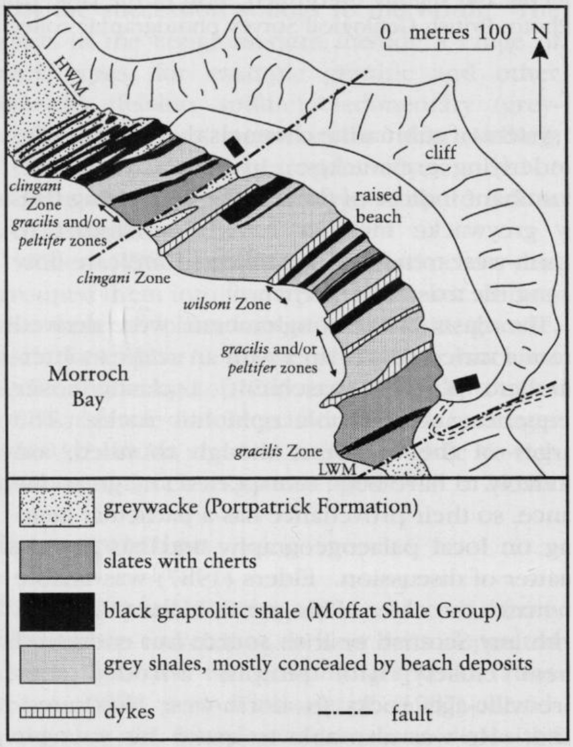

Figure 15.3 Geological sketch-map of Morroch Bay, showing the distribution of graptolite faunas, after Rushton and Tunnicliff (1996, fig. 63).

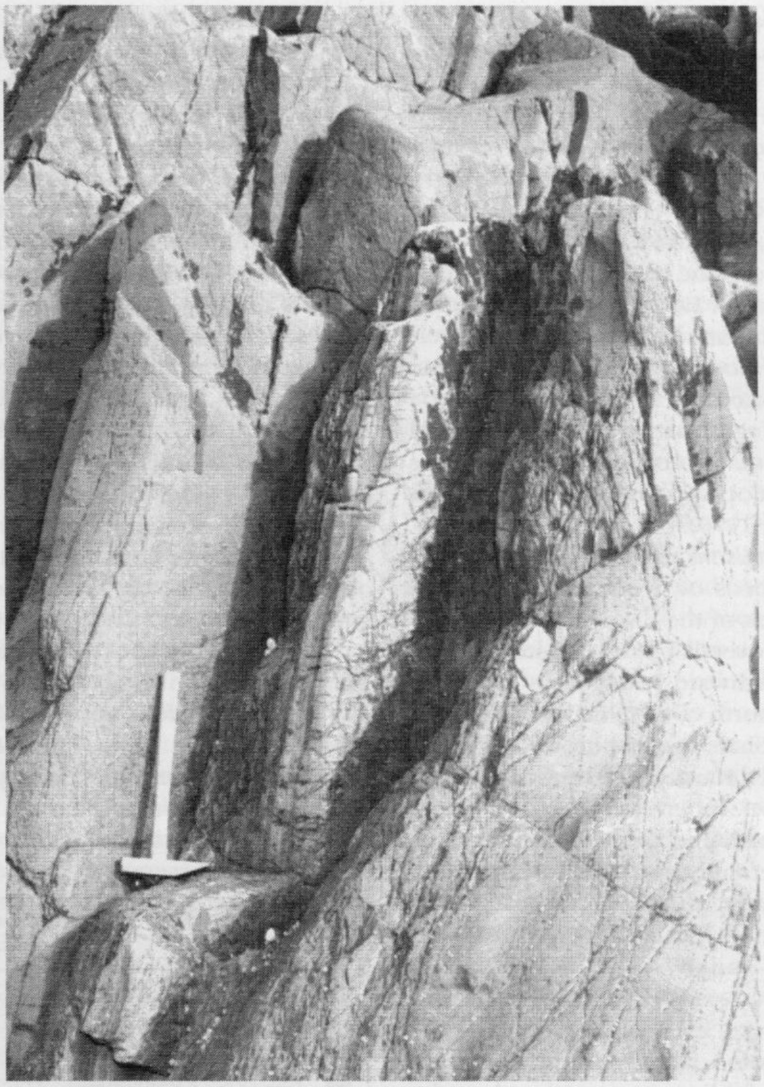

Figure 15.4 Port of Spittal Bay, south of Morroch Bay. The pale bed is a quartzose sandstone of the Glenwhargen Formation interbedded with darker greywackes of the Portpatrick Formation. See Figure 15.5 (Photo: British Geological Survey photographic collection, D3756.)

Portpatrick Formation making the headlands at either end of the bay (Figure 15.3). The Moffat Shales, which dip steeply and strike south-west out to sea, are divided into the Glenkiln and Lower Hartfell Shale formations and are intruded by a number of substantial dykes that are approximately concordant with the bedding. The section shows evidence of folding and faulting (Stone, 1995, p. 47) but in general youngs northwards, except where structural imbrication is indicated by the duplication of certain fossil zones.

Peach and Horne (1899, p. 403) considered that the Moffat Shale of Morroch Bay was brought up in a complex anticline and explained the alternation of shale and greywacke beds at the north end of the bay by isoclinal folding. Modern interpretation regards the Moffat Shale as brought up on a major thrust fault at the south end of the bay, with the oldest Moffat Shale adjacent to the fault, where the Glenkiln Shale Formation, which includes cherts and red, green and black mudstones, is faulted against greywackes of the Portpatrick Formation at the southern end of the bay, where it forms a large, though structurally disturbed, outcrop. Graptolites of the *Nemagraptus gracilis* graptolite zone were found in black shales at the southern end of the outcrop, and conodonts, probably of the *Pygodus anserinus* conodont zone, were collected from red shales (Bergström and Orchard, 1985). Farther north, graptolite faunas of the *Climacograptus peltifer* Zone were found. Peach and Horne (1899, p. 404) also recorded a faulted sliver of Hartfell Shale Formation, but this has not been confirmed.

Near the middle of the bay, the Glenkiln Shale gives way to the Lower Hartfell Shale, which consists of black siliceous mudstones of the rarely encountered *Climacograptus wilsoni* Zone. Graptolites collected there include the type material of *Dicellograptus angulatus* Elles and Wood. Conodonts from these black shales include the Caradoc species *Periodon grandis* (Armstrong *et al.*, 1990).

North of the *wilsoni* Zone are black shales alternating with beds of greywacke, the shales yielding graptolites of the *Dicranograptus clingani* Zone. The overall pattern of steeply dipping beds and northward younging is disturbed by a major fault, north of which chert and fossiliferous Glenkiln Shale are re-introduced, again followed by Lower Hartfell Shale, with graptolites of the *clingani* Zone.

Towards the north end of the bay, thick beds of greywacke alternate on a 1–2 m scale with shaly beds of the *clingani* Zone; the base of this succession is the type locality for *Plegmatograptus nebula* Elles and Wood. These *clingani* Zone shales are now considered to be interbedded with greywacke beds at the base of the Portpatrick Formation, and Peach and Horne's idea of isoclinal folding is considered to be untenable (Peach and Horne, 1899). Above its base, the Portpatrick Formation consists of massive andesitic-rich greywackes derived from the south-west. These occupy the coastal cliffs northwards for about 6 km, and there is evidence that the northernmost parts of the Portpatrick Formation lie in the next higher graptolite zone of *Pleurograptus linearis* (Stone, 1995, p. 9).

Port of Spittal Bay, about 300 m south-east of Morroch Bay (019 521), is also the site of a major thrust fault, with quartzose greywackes of the Shinnel Formation, probably of Ashgill (*anceps* Zone) age, to the south (Stone, 1995, p. 28). To the north, an outcrop of Lower Hartfell Shale with graptolites of the *linearis* Zone underlies the andesitic greywackes of the Portpatrick Formation. A few tens of metres above the base of the Portpatrick Formation, pale interbeds of quartz-arenite (Figure 15.4), less than 1 m thick, are considered to represent part of the Glenwhargen Formation (Stone, 1995, p. 27).

Interpretation

Morroch Bay exposes the best succession of Moffat Shale in south-west Scotland, including representatives of all the graptolite zones from *gracilis* to *clingani*, and has also yielded conodont faunas that confirm the correlation of the *anserinus* conodont zone with the *gracilis* Zone. The distribution of faunas illustrates unusually clearly the style of imbrication of the succession as inferred for many parts of the Southern Uplands of Scotland (Rushton *et al.*, 1996a). The stratigraphical contact at the base of the Portpatrick Formation is the clearest available and dates the base of the formation there as within the *clingani* Zone.

The base of the Portpatrick Formation overlies graptolites of the *linearis* Zone in Port of Spittal Bay and is therefore appreciably younger there than at Morroch Bay (Figure 15.5). The pale beds of quartz-arenite occurring above the base are noteworthy because, although they are not known at the north end of Morroch Bay, they are

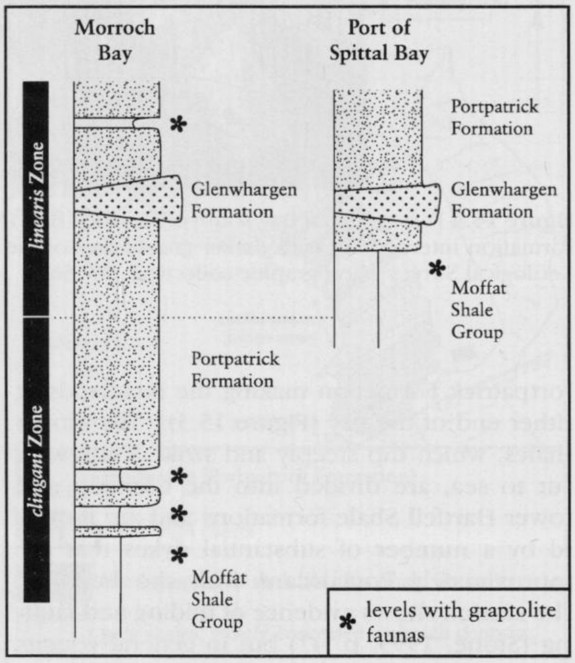

Figure 15.5 Comparison of the stratigraphical succession at and north of Morroch Bay with that at Port of Spittal Bay, showing that the onset of deposition of the Portpatrick Formation greywackes was markedly diachronous.

present at Black Head, 3 km north of Portpatrick and near the locality where graptolites of the *linearis* Zone were found. They provide further evidence that the base of the Portpatrick Formation at Morroch Bay extends much farther down stratigraphically than at Port of Spittal Bay, illustrating more clearly than elsewhere the strong south-east diachroneity of the base of the Portpatrick Formation. The juxtaposition of the older and younger developments of the base of the Portpatrick is thought to represent successive thrust slices of a regularly imbricated southward-propagating thrust stack (Stone, 1995; Rushton *et al.*, 1996a).

Conclusions

Morroch Bay is a significant exposure of the Ordovician part of the Moffat Shale Group in south-west Scotland, and one of the few exposures showing all the graptolite zones of the Glenkiln and Lower Hartfell divisions. Fossils from these exposures help to elucidate the structure in the area and serve to date the Portpatrick Formation. Contrasts between the sections at Morroch Bay and Port of Spittal Bay indicate the gradual way in which the sandstones of the Portpatrick Formation progressed southwards and covered the shales of the Moffat Group.

GLENKILN BURN (NY 007 894)

Introduction

Glenkiln Burn gives its name to the Glenkiln Shale, the lowest division of the Moffat Shale Group. Besides the Glenkiln Shale, which here contains a diverse fauna of graptolites of the *Nemagraptus gracilis* Zone, Glenkiln Burn exposes one of the best outcrops of the Lower Hartfell Shale of the *Climacograptus wilsoni* Zone and also fossiliferous Silurian strata that date the greywackes of Gala Tectonostratigraphic Unit 7.

About 13 km north of Dumfries, near Townhead, Glenkiln Burn cuts a ravine known as Black Linn, which exposes Moffat Shale and greywackes of the Gala Group. The section is tectonically disturbed and stratigraphical relationships are unclear; however, Lapworth (1878, p. 285) took Glenkiln Burn as the typical exposures of the Glenkiln Shales because they are large and the graptolites from them relatively well preserved, in preference to the section at Berrybush Burn (Finney and Bergström, 1986, pp. 51, 57), where he considered the stratigraphical relationships clearer but where the fossils are poorly preserved.

The Glenkiln Section was redescribed by

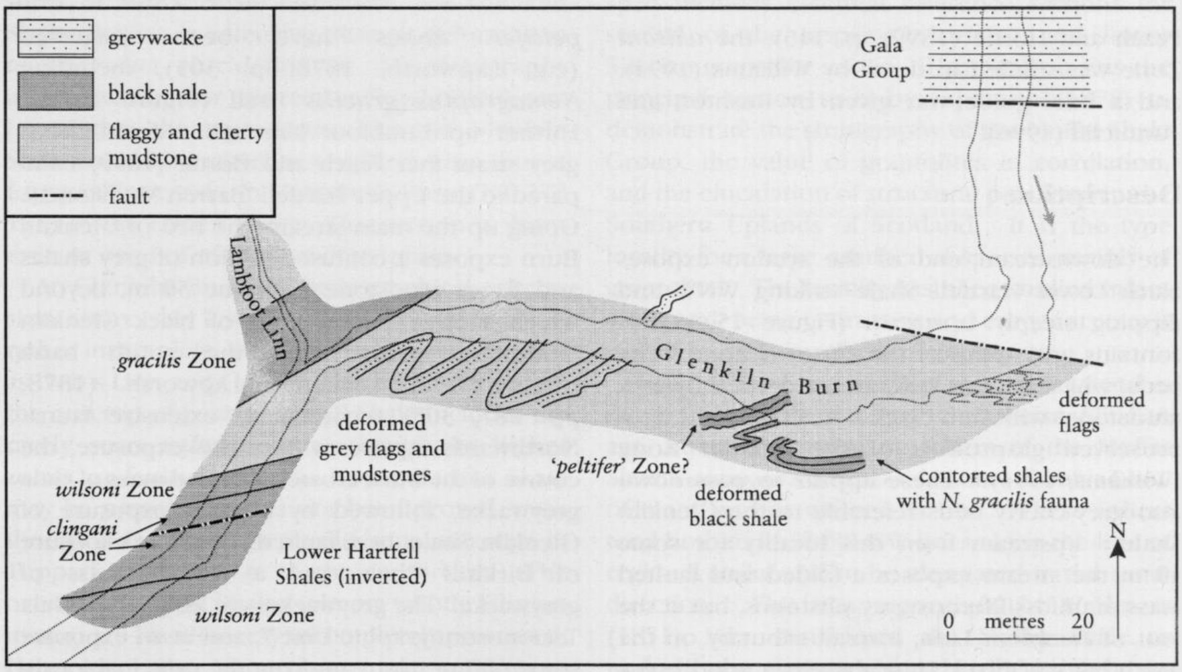

Figure 15.6 Sketch-map of Black Linn, Glenkiln Burn, showing the principal graptolite localities, based on Lapworth (1879a), Williams (1994), and unpublished work by the British Geological Survey.

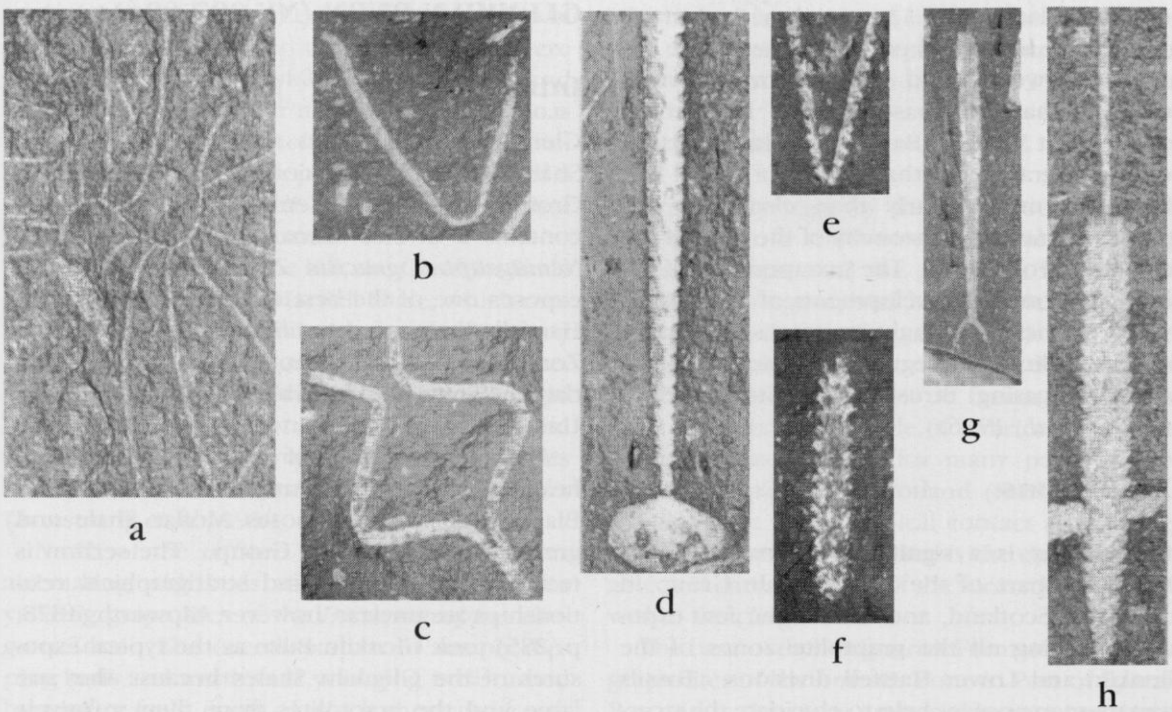

Figure 15.7 Graptolites from Glenkiln Burn (a) and Dob's Linn (b–h). All figures ×2. (a) *Nemagraptus gracilis* (Hall), *gracilis* Zone. (b) *Dicellograptus morrisi* Hopkinson, *clingani-linearis* zones. (c) *Dicranograptus ziczac* Lapworth, *peltifer* Zone. (d) *Climacograptus wilsoni* Lapworth, *wilsoni* Zone. (e) *Dicellograptus anceps* (Nicholson), *anceps* Zone. (f) *Lasiograptus harknessi* (Nicholson), *wilsoni* Zone. (g) *Climacograptus supernus* Elles and Wood, *anceps* Zone. (h) *Orthograptus calcaratus* (Lapworth) *sensu lato clingani-linearis* zones.

Peach and Horne (1899), p. 146), the *wilsoni* Zone was studied in detail by Williams (1994), and a brief guide was given by Rushton and Tunnicliff (1996).

Description

The downstream end of the section exposes black Lower Hartfell Shale striking WNW and dipping steeply upstream (Figure 15.6); this contains graptolites of the *clingani* Zone. The beds, which are inverted, are succeeded by grey mudstones with thin black layers that yield well-preserved graptolites of the *wilsoni* Zone (Williams, 1994). These appear to pass down into grey cherty beds referable to the Glenkiln Shale. Upstream from this locality for some 40 m the stream exposes a folded and faulted mass of unfossiliferous grey siltstones, but at the foot of Lambfoot Linn, a small tributary on the north bank of Black Linn, there is a good exposure of black Glenkiln Shales, from which large assemblages of graptolites of the *gracilis* and *peltifer* zones have been recorded (e.g. Lapworth, 1878, p. 305), including *Nemagraptus gracilis* itself (Figure 15.7a). Farther up Lambfoot Linn are unfossiliferous grey strata that Peach and Horne (1899) compared to the Upper Hartfell 'Barren Mudstones'. Going up the main stream, the bed of Glenkiln Burn exposes a confused section of grey shales and flaggy mudstone for some 50 m, beyond which a large folded mass of black Glenkiln Shales is present on the south bank (Figure 15.6), whence Lapworth (1878, pp. 287, 305) recorded an extensive fauna. Northwards, upstream from this exposure, the course of the burn crosses a faulted mass of Gala greywacke, followed by another exposure of Glenkiln Shale, here faulted against an exposure of Birkhill Shale and a further mass of greywacke. The greywackes are assigned to Gala Tectonostratigraphic Unit 7, and at an exposure some 600 m upstream from the principal locality of the Glenkiln Shale (NY 007 898) a thin fossiliferous bed enables them to be dated as the late Llandovery *guerichi* Zone (probably *gemmatus* Subzone). This is a relatively satisfactory identification of the age of Gala Unit 7 compared with others in south-west Scotland (White *et al.*, 1992).

Interpretation

Southward-directed imbricate thrusting pervades the Southern Uplands of Scotland, and the long strike-faults that extend north-east to south-west are the surface expression of the major thrusts (e.g. Rushton *et al.*, 1996a). The Moffat Shale Group, being tectonically incompetent, commonly forms the plane of decollement above which the more massive greywackes were thrust. This notion explains why the Moffat Shale outcrops lie in linear tracts, why they are so deformed and why, where stratigraphical contacts between Moffat shales and greywackes are found, they are generally only on the north-west side of the outcrop – the south-east side being the major thrust.

One of these thrusts, the Lauriston Fault, which forms the southern boundary of Gala Tectonostratigraphic Unit 7 (Stone, 1995, pp. 6, 35), crosses Glenkiln Burn at Black Linn. No contact with the Carghidown Formation to the south is seen, and the Moffat Shales are indeed very deformed. Compared with exposures of Moffat Shale elsewhere, the Glenkiln Shale division is extensive, though deformation makes exact elucidation of the stratigraphy impracticable. For this reason Floyd (1996) proposed that the type section for the Glenkiln Shale should be taken, not at Black Linn, but at Lapworth's section in Berrybush Burn (NT 272 193) in the Ettrick Valley. This section is, however, in need of modern redescription.

At Glenkiln Burn the stratigraphical succession above the level of the Glenkiln Shale is rather incomplete, compared with sections such as Dob's Linn and Craigmichan Scaur. However, the outcrop of Lower Hartfell Shale includes the rarely seen *wilsoni* Zone, though its higher zones are faulted out. The Upper Hartfell Shale may be present but has not been proved, even though it is proved by fossiliferous outcrops in Tuppark Linn, 600 m to the south-west. The overlying Birkhill Shales (almost wholly Silurian in age) are likewise very incompletely preserved. However, the occurrence of an upper Llandovery (Telychian) graptolite fauna of the *guerichi* Zone at the north end of the section is valuable for dating the greywackes at the base of Gala Unit 7.

Conclusions

Glenkiln Burn is a historically important site, giving its name to the Glenkiln Shales and containing a diverse graptolite fauna of the *gracilis* Zone. The overlying Hartfell Shales contain well-preserved material of the rarely seen *wilsoni* Zone fauna. Another important graptolite fauna from near the base of the overlying greywacke sandstones dates the Gala Group as Telychian (Silurian, upper Llandovery).

DOB'S LINN (NT 196155–NT 197161)

Introduction

Dob's Linn is a site of prime international significance stratigraphically, palaeontologically and historically. It includes the stratotype for the internationally recognized Ordovician–Silurian boundary and includes stratotype sections for the upper Hartfell and Birkhill divisions of the Moffat Shale Group. It shows the most extensive graptolitic sequence in Britain, ranging from low in the Caradoc (Ordovician) to the base of the upper Llandovery (Silurian), and within this span includes essential reference sections for several of the upper Ordovician and lower Silurian graptolite zones. Historically it was the principal section used by Lapworth (1878) to demonstrate the stratigraphy of the Moffat Shale Group, the value of graptolites in correlation, and the elucidation of structural problems in the Southern Uplands of Scotland. It is the type locality for a large number of species, mainly of graptolites. The locality has been studied intensively and, being instructive and easy of access, is visited by large numbers of geologists.

Most of the Southern Uplands of Scotland is made up of greywackes of Ordovician–Silurian age, but there are many inliers of the Moffat Shale Group, of which Dob's Linn ('Dobb's Linn' of many earlier writers) is one. These inliers tend both to lie in NE–SW lines along the line of regional strike and to be elongated in the same direction. This was recognized by Harkness (1851), who considered the Moffat Shale to underlie the greywackes and to be brought up along normal strike-faults, one of which extended through Dob's Linn. The locality was brought to prominence by Lapworth (1878), who, after many year's study of a large area around Moffat, chose Dob's Linn to exemplify his view of the stratigraphy and structure of the area. He gave a detailed description and elegant map of Dob's Linn, and recognized nearly all of his stratigraphical divisions of the Moffat Shale there: the upper part of the Glenkiln Shale and the whole of the Hartfell and Birkhill shales succession. Lapworth considered that the structure was primarily anticlinal, though affected by faulting, particularly by a 'Main Fault' along the axis of the inlier.

Since Lapworth's time Dob's Linn has been the focus of much work. Peach and Horne (1899, pp. 92–100) redescribed it with a map and section similar to Lapworth's and corrected a few details. A more recent description was given by Ingham (1979), whose meticulously detailed map provided a basis for much new work, and there have been ten or more other guides to the site published in the last decade or two, such as recent guides by Williams and Lawson (1992) and Clarkson and Taylor (1993). Accounts by Williams (1988) and Williams and Ingham (1989) pay particular attention to the stratigraphy of the Ordovician–Silurian boundary, and Armstrong and Coe (1997) analysed the sedimentology of the same interval. Webb *et al.* (1993) gave a more general account of the geology of the Moffatdale area, with a 1:25 000 scale map.

Dob's Linn is particularly important for its graptolites. Species described by early workers (Harkness, Nicholson, Carruthers, Lapworth) were redescribed and admirably illustrated by Elles and Wood (1901–1918). Faunas from the Hartfell Shales were further described by Toghill (1970b) and Williams (1982a, b, 1987, 1994) and those from the basal Birkhill Shales by Davies (1929), Toghill (1968) and Williams (1983), the work around the Ordovician–Silurian boundary being well summarized by Williams (1988). Sampling across the Ordovician–Silurian boundary has resulted in parallel studies on the distribution of conodonts (Barnes and Williams, 1988) and organic walled microfossils (Whelan, 1988). The carbon isotope stratigraphy of the Dob's Linn succession was investigated by Underwood *et al.* (1997). In recognition of the monofacial continuity of the succession, the base of the *acuminatus* Zone in the Linn Branch section at Dob's Linn was formally chosen in 1985 as the international stratotype for the boundary between the Ordovician and Silurian Systems (Bassett, 1985).

The metabentonite beds present in the upper Ordovician and abundant in the lower Silurian have been studied by Batchelor and Weir (1988) and by Merriman and Roberts (1990). Zircon crystals from certain of these beds were used to bracket the Ordovician–Silurian boundary with dates of 438.7 ± 2.0 and 445.7 ± 2.4 Ma (Tucker *et al.*, 1990).

The present account concentrates on the Ordovician rocks, the exceedingly important Silurian rocks (essentially the Birkhill Shales) being treated in the companion Geological Conservation Review volume on the Silurian System (Aldridge *et al.*, in press).

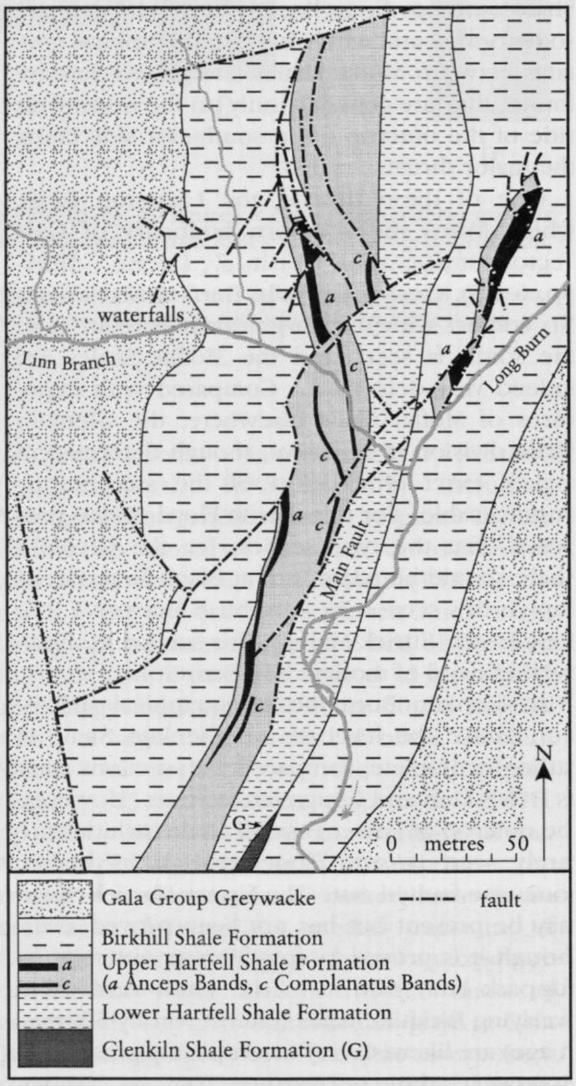

Figure 15.8 Simplified geological map of Dob's Linn, based on Williams and Ingham (1989, fig. 20).

Figure 15.9 Dob's Linn, Linn Branch, looking west. The stream makes a waterfall over Gala greywackes (Llandovery) and enters a gorge in Birkhill and Hartfell shale formations. The exposure high on the right is in Llandovery shales and the rill extending obliquely down to the Linn Branch approximately follows the strike. The trench across the Ordovician–Silurian boundary was made (after the photograph was taken) on the near side of the rill and to the right of the stream. The Barren Mudstones of the Upper Hartfell Shale (Ashgill) are nearest the viewer. (Photo: British Geological Survey photographic collection, D3559.)

Description

Dob's Linn is a ravine on the north side of the A708 Moffat–Selkirk road, near Birkhill Cottage. It is excavated by two tributaries of the Moffat Water (Figure 15.8). One, the Long Burn, flows south and exposes, on its west side, the section known since Lapworth's day as the 'Long Cliff'. The other tributary (the confluence of Maister Grain and High Grain) descends from the west over a high waterfall into an east–west ravine known as the 'Linn Branch' (Figure 15.9); on its

Table 15.1 Stratigraphy devised by Lapworth (1878), slightly modified

Formation	graptolite zone		
Birkhill Shale (part)	acuminatus		Silurian (part)
	persculptus		Ordovician (part)
Upper Hartfell Shale (= 'Barren Mudstones')	extraordinarius		
	anceps	pacificus	
		complexus	
	complanatus		
Lower Hartfell Shale	linearis		
	clingani	morrisi	
		caudatus	
	wilsoni		
Glenkiln Shale	'peltifer'		
	(gracilis – not seen at at Dob's Linn)		

north bank is the 'North Cliff', with the 'Corrie' section high above, and on the south bank is the 'South Cliff'. The tributaries unite and flow south, approximately along the line of the 'Main Fault', into the Moffat Water, exposing the 'Main Cliff' on the west bank. The most significant exposures of Ordovician rocks are in the Main Cliff and the North Cliff.

Dob's Linn is a structurally complex locality affected by numerous strike faults. Most of the succession is overturned and dips at a high angle to the north-east. In the Main Cliff, however, the strata are the correct way up and dip at 45° to the west, the correct way up of this section being the result of slump rotation of the cliff during the Pleistocene.

The stratigraphy devised by Lapworth (1878) is applicable, with slight modifications (Table 15.1).

The upper part of the Glenkiln Shale is present but poorly exposed at the foot of the Main Cliff, near the confluence of Linn Branch and Long Burn, and on the North Cliff. It consists of grey cherty mudstone with black mudstones that yield graptolites assigned to the '*peltifer*' Zone, as listed by Williams (1994, fig. 2).

The Lower Hartfell Shale is well-exposed in the Main Cliff and North Cliff (Figure 15.10), with a smaller outcrop in the South Cliff. The division consists mainly of black siliceous and pyritous mudstone, but the lower part is grey with thin black laminae, and the top is softer and less siliceous. The lower part, consisting mainly of grey mudstone, is about 2 m thick and is referred to the *wilsoni* Zone; it is characterized by well-preserved *Climacograptus wilsoni* Lapworth (Figure 15.7d), *Corynoides calicularis* Nicholson, *Dicranograptus nicholsoni* Hopkinson, *Pseudoclimacograptus scharenbergi* (Lapworth) and *Orthograptus calcaratus* (Lapworth) *sensu lato* (Williams, 1994).

The succeeding black mudstones of the *clingani* Zone, which are about 8 m thick, are exposed in the Main Cliff and North Cliff (the 'North Cliff Trench' of Williams (1988), and Locality 6 of Clarkson and Taylor, 1993, fig. 42). The faunas from the Main Cliff include representatives of both the *caudatus* Subzone and the *morrisi* Subzone of Zalasiewicz *et al*. (1995). Locality 6 is in the *caudatus* Subzone, which is characterized by *Climacograptus spiniferus* Ruedemann, *Ensigraptus caudatus* (Lapworth),

Figure 15.10 Dob's Linn, Linn Branch, looking east towards the junction with the Long Burn which flows to the right along the line of the main fault. The beds in the left foreground are inverted lower Birkhill Shales, mainly lower Llandovery, with the uppermost exposures being close to the Ordovician–Silurian boundary. The Ordovician–Silurian boundary trench was excavated in the bluff of the North Cliff which descends to the Linn Branch. See Figure 15.11. (Photo: British Geological Survey photographic collection, D3560.)

Dicellograptus flexuosus Lapworth, *Dicranograptus clingani* Carruthers and species of *Orthograptus.* The North Cliff trench revealed about 5 m of strata with a large fauna of the *morrisi* Subzone, incuding *C. dorotheus* Riva, *Dicellograptus morrisi* Hopkinson (Figure 15.7b), *'Glyptograptus' davisi* Williams, *Neurograptus margaritatus* (Lapworth) and *Orthograptus* spp., the distribution of which is shown by Williams (1982a, fig. 1).

The upper 5 m of the Lower Hartfell division is assigned to the *linearis* Zone. This is present in the Main Cliff (Toghill, 1970b) and the North Cliff trench, where Williams (1982a) logged the faunal distribution in detail. Among the most distinctive species are *Pleurograptus linearis*

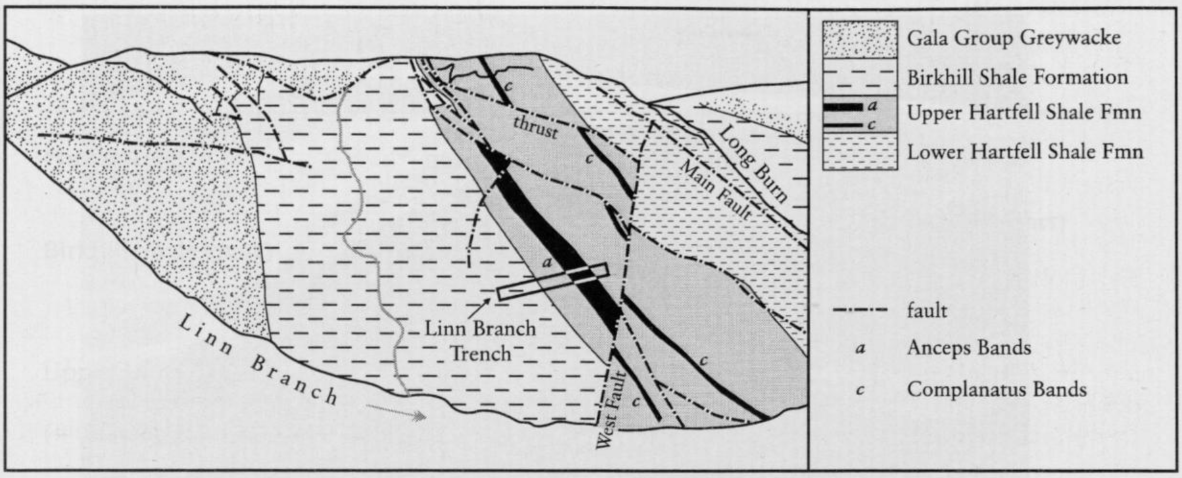

Figure 15.11 View of the North Cliff on the north bank of the Linn Branch of Dob's Linn, after Williams and Ingham (1989, fig. 22). The internationally recognized boundary between the Ordovician and Silurian systems is in the Linn Branch Trench.

(Carruthers), with *Climacograptus tubuliferus* Lapworth, *Dicellograptus elegans* Carruthers, *Leptograptus capillaris* (Carruthers) and *Orthograptus* species (Figure 15.7h).

The Upper Hartfell Shale consists of pale, partly bioturbated, 'barren' mudstone 28 m thick. It includes blocky and nodular, slightly calcareous beds and several thin black graptolitic mudstones. The sedimentology of these beds was analysed by Armstrong and Coe (1997), and the biostratigraphy of the graptolitic beds was described in detail by Williams (1982b, 1987, 1988). The black beds 9 m above the base of the Upper Hartfell Shale, known as the Complanatus Bands, have been traced on the Main Cliff, South Cliff and North Cliff. They contain *Dicellograptus complanatus* Lapworth and *Orthograptus socialis* (Lapworth), with a few other species (Williams, 1987, p. 67), and are referred to the *complanatus* Zone. Williams and Lockley (1983) described the supposedly epiplanktonic brachiopod *Barbatulella* from the upper Complanatus Band.

A group of black beds near the top of the formation, the 'Anceps Bands', have been studied in the Main Cliff and the North Cliff, and also the Long Cliff, where they are strikingly thicker than elsewhere (Williams, 1982b). They are associated with numerous thin beds of metabentonite, one of which yielded zircon crystals that gave the radiometric age of 445.7 ± 2.4 Ma (Tucker *et al.*, 1990). The Anceps Bands contain *Dicellograptus anceps* (Nicholson) (Figure 15.7e), *Climacograptus supernus* Elles and Wood (Figure 15.7g), *Orthograptus abbreviatus* and a number of other taxa described by Williams (1982b), who distinguished a lower *complexus* Subzone in the lower bands and an upper *pacificus* Subzone in the top three bands. Barnes and Williams (1988) figured several conodonts from the Anceps Bands, assigning them to the *ordovicicus* conodont zone.

The uppermost 3 m thickness of the Upper Hartfell Shale is of pale mudstones but includes the very thin Extraordinarius Band of brown graptolitic mudstone. This is the only known representation of the *extraordinarius* Zone in Scotland (Williams, 1983). A bed 0.1 m below the Extraordinarius Band has yielded the blind dalmanitid trilobite *Sonxites* (Lespérance, 1988, p. 365); a similar trilobite was described from the same horizon in County Cavan, Ireland (Siveter *et al.*, 1980).

The basal beds of the Birkhill Shale are recognized where dark mudstones with metabentonites overlie the Upper Hartfell Shale. Toghill (1968) recognized the topmost Ordovician *persculptus* Zone in the Main Cliff, but the best-studied section is at the 'Linn Branch Trench' in the North Cliff (Figure 15.11; Williams, 1988, figs. 3,4), where the internationally recognized Ordovician–Silurian boundary is now defined. The *persculptus* Zone fauna contains species of *Normalograptus* and *Glyptograptus* (*G.? avitus* Davies, *G.? venustulus* (Legrand) and *G. persculptus* Elles and Wood). The base of the

Silurian is taken 1.6 m above the base of the Birkhill Shale, at the base of the overlying *acuminatus* Zone, recognized by the appearance of *Akidograptus ascensus* Davies and *Parakidograptus acuminatus* (Nicholson). The first monograptid, *Atavograptus ceryx* (Rickards and Hutt), appears 0.3 m higher.

Interpretation

The Moffat Shales exposed at Dob's Linn are interpreted as hemipelagite and distal turbidite deposits (Williams, 1988; Armstrong and Coe, 1997) that accumulated very slowly over a long period in a marine basin, the nature of which is debated (see above). For much of the time deposition was restricted to fine-grained terrigenous matter collecting in poorly oxygenated conditions that favoured the preservation of the remains of planktonic animals but inhibited the development of any benthos. The basin received fine-grained ejectamenta from distant volcanic eruptions (the layers of metabentonite) and occasional incursions of coarse-grained material from turbidity currents (cf. Rushton and Stone, 1991). The pale Upper Hartfell Shale accumulated in less dysaerobic conditions that at times allowed burrowing benthos to disrupt the lamination of the muds. Sedimentological studies by Armstrong and Coe (1997) track oceanographic and climatic changes: they suggest that the alternations of black and pale mudstones in the *anceps* Zone indicate periods of fluctuating climate, the predominantly grey siltstones of the upper *anceps* and *extraordinarius* zones correspond to the maximum of the end-Ordovician glaciation, and the laminated black mudstones at the base of the *persculptus* Zone reflect the return to global warming.

The lithostratigraphy exemplified at Dob's Linn has proved applicable with little modification right across the central belt of the Southern Uplands of Scotland (Peach and Horne, 1899). Many of the graptolites, however, have a much wider distribution, and the zonal succession has been adopted, or adapted, for use in the graptolitic facies in many parts of the world. Apart from the *gracilis* Zone, which is not exposed at Dob's Linn but is seen in Glenkiln Burn (see site report), the whole sequence is visible, and, although it is faulted, superposition can be safely inferred by reference to various sections in Dob's Linn. Graptolite distribution has been logged for the entire succession, with the exception of the lower part of the *clingani* Zone, which is better exposed and more fully described at Hartfell Score, 10 km to the WSW (Rushton, 1993; Zalasiewicz *et al.*, 1995). The Ordovician–Silurian boundary was chosen at Dob's Linn because the exposed succession is in continuous graptolitic strata at a level where distinctive, typically 'Silurian', elements evolved. Although the absence of shelly fossils is a hindrance to correlation in some other parts of the world, the carbon isotope stratigraphy reported by Underwood *et al.* (1997) not only tracks the climatic changes during the latest Ordovician but also facilitates correlation between the Dob's Linn sections and contemporaneous deposits of carbonate shelf areas. Their work tends to confirm the continuity of the Dob's Linn succession and demonstrates the appropriateness of a deep-water section for an international stratotype.

Although normal faulting and folding play a part in the structural interpretation of the Dob's Linn Inlier, the main feature is considered to be a thrust fault dipping north-west, whose surface expression may correspond to Lapworth's 'Main Fault'. Such a fault could juxtapose areas of Moffat Shale originally deposited a considerable distance apart, and Williams (1988) invoked this idea to explain differences in the thicknesses of the Anceps Bands to the east of the fault on the Long Cliff and those of the Main Cliff and North Cliff to the west.

Conclusions

Dob's Linn is of great importance internationally in Ordovician and Silurian stratigraphy. Although it is one of very many exposures of the Moffat Shale Group, it is exceptionally valuable, being an accessible exposure that shows an almost complete succession and displays good stratigraphical contacts at critical levels. It has been thoroughly studied and well documented, such that it is referred to world-wide as a standard, stratigraphically, geochronometrically and for graptolite taxonomy. It is rich in graptolites, many having Dob's Linn as their type locality, and several of these species have been identified in many parts of the world, making the Moffat Shale succession an international standard for correlation. This has led to Dob's Linn being chosen as the standard by which to recognize the base of the Silurian System internationally.