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 11

Arenig to Ashgill of northern England

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

INTRODUCTION

The Ordovician in northern England is exposed in a large inlier, the Main Outcrop of the Lake District, and in several groups of smaller inliers, of which the most important are those in the Cross Fell and Cautley and Dent areas. The Main Outcrop has a large area of lower Ordovician, the Skiddaw Group, which was reviewed by Cooper *et al.* (1995). This group rests on the granite batholith that underlies the Lake District; it is overlain by the thick Borrowdale Volcanic Group (which is probably referable to the lower Caradoc (Molyneux, 1988; Piper *et al.*, 1997)) and is succeeded unconformably by the upper Ordovician Dent Group (Kneller *et al.*, 1994). This is thin and stratigraphically incomplete, but some sites (such as Ashgill Quarry) are significant historically in the development of the concept of the Ashgill Series (Ingham and Wright, 1970).

Of the smaller inliers, Cross Fell has the most complete succession of upper Caradoc rocks, ranging from the Longvillian to Onnian substages, but the lithologically varied Ashgill Series is incomplete, especially in the Cautleyan Stage (Burgess and Holliday, 1979). This deficiency is made good in the Cautley inliers, the type area for the Ashgill Series (Ingham, 1966), where the Cautley Mudstones represent the greater part of the Ashgill Series in a relatively uniform facies.

MAIN OUTCROP: SKIDDAW GROUP

The Skiddaw Group is a thick succession of mudstones, siltstones and sandstones of Tremadoc to Llanvirn age (Figures 11.1, 11.2). Although there have been difficulties in interpreting the lithostratigraphy, the succession is of particular biostratigraphical importance because it is graptolitic throughout; it has accordingly provided a zonal standard for the Arenig Series in England and Wales. This standard forms an essential link between the refined Arenig succes-

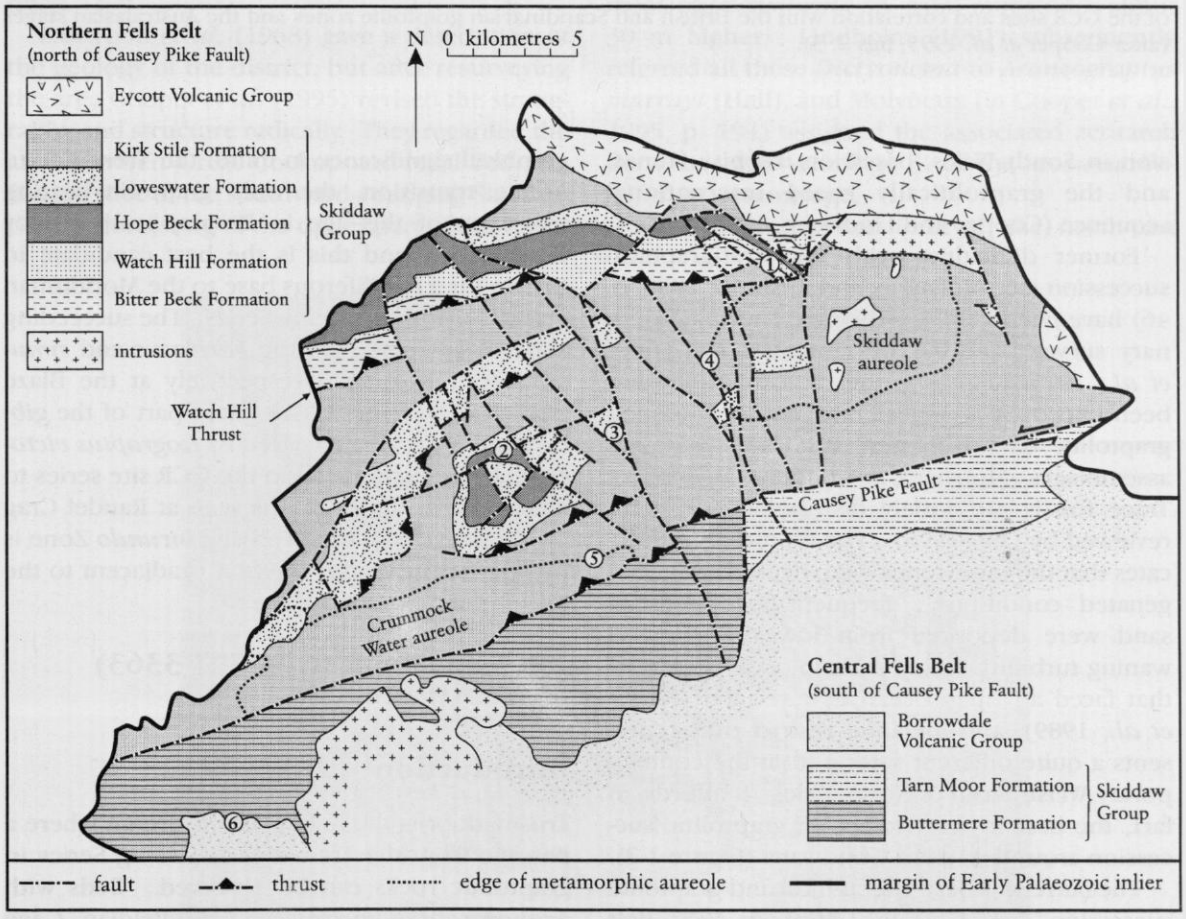

Figure 11.1 Geological sketch-map of the Skiddaw Group in the main outcrop of the English Lake District, after Cooper *et al.* (1995, fig. 2). GCR localities: 1, Trusmadoor; 2, Blaze Bridge and Scawgill Quarry; 3, Barf; 4, Randel Crag; 5, Outerside; 6, River Calder (Tremadoc, Chapter 7).

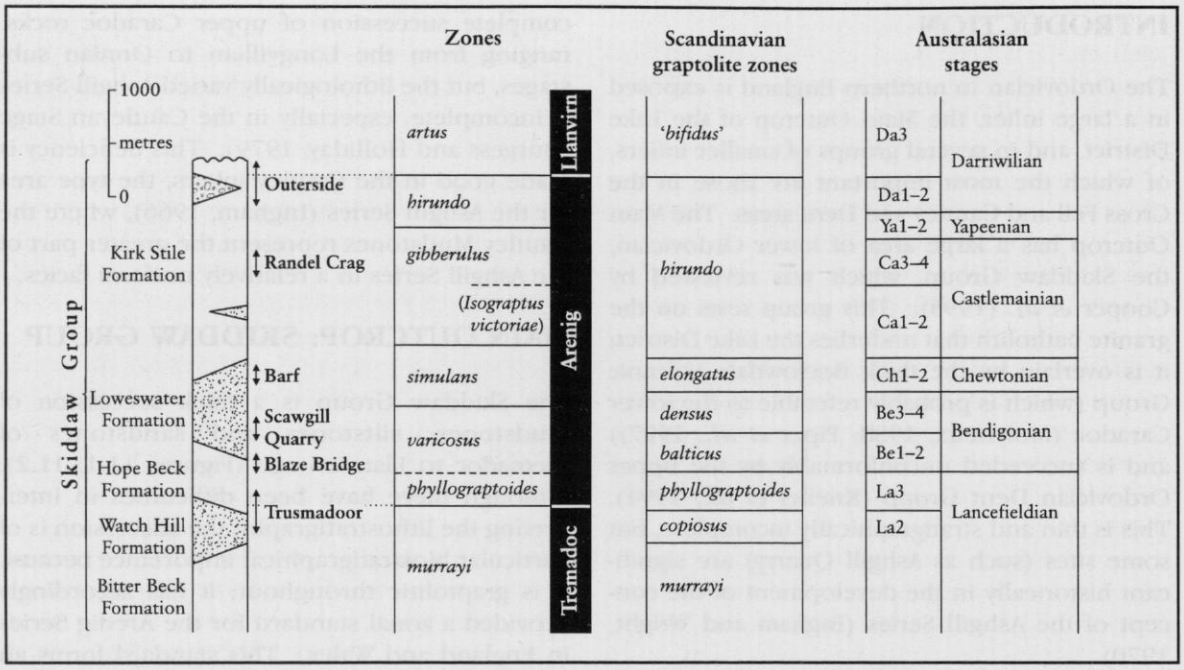

Figure 11.2 Generalized vertical section for the Skiddaw Group in the Northern Fells Belt, showing the ranges of the GCR sites and correlation with the British and Scandinavian graptolite zones and the Australasian stages (after Cooper *et al.* 1995, figs 2, 3).

sion in South Wales, based on trilobite faunas, and the graptolitically based international sequence (Cooper and Lindholm, 1990).

Former difficulties with the stratigraphical succession (see Molyneux and Rushton, 1988, p. 46) have been resolved through a multidisciplinary survey over the whole outcrop (Cooper *et al.*, 1995, in press); the biostratigraphy has been improved by correlating new and existing graptolitic data with new studies of acritarch assemblages (Molyneux in Cooper *et al.*, 1995). Trace fossils are widely distributed and were reviewed by Orr (1996). The bioturbation indicates that the mudstones were deposited in oxygenated conditions. Frequent incursions of sand were deposited from low-concentration waning turbidity flows. A basin or slope setting that faced an open ocean is envisaged (Fortey *et al.*, 1989), and the Lake District thus represents a quite different setting from the contemporary Welsh Basin of North Wales. It affords, in fact, the best lower Ordovician graptolitic succession around western Gondwana (Figure 1.2).

The current lithostratigraphical and graptolite succession, based on the Northern Fells Belt (Cooper *et al.*, 1995), is shown in Figure 11.2. The sites were selected with their biostratigraphical significance in mind: the Tremadoc to Arenig transition, the only graptolite-bearing transition of this age in Britain, is shown by Trusmadoor, and this is the best candidate in Britain for a fossiliferous base to the Moridunian Stage of the lower Arenig Series. The succeeding zonal assemblages for the *varicosus* and *simulans* Zones are seen respectively at the Blaze Beck and Barf sites. The lower part of the *gibberulus* Zone, characterized by *Isograptus victoriae*, is not exemplified in the GCR site series to date, but the upper part is seen at Randel Crag (see site report). The overlying *hirundo* Zone is present at Outerside, where it is adjacent to the lowest Llanvirn *artus* Zone.

TRUSMADOOR (NY 2777 3363)

POTENTIAL GCR SITE

Introduction

Trusmadoor is the only place in Britain where a passage from the Tremadoc to Arenig Series in graptolitic rocks can be observed. Beds with *Araneograptus murrayi* of Lancefieldian 2 age are overlain by faunas that can be correlated with the *approximatus* Zone of Lancefieldian 3

age and the base of the Bendigonian (Be1). Each fauna is accompanied by acritarch floras that allow correlation with other sites in Britain and elsewhere. It is a key site for the correlation of the series boundary in Britain.

The base of the Arenig Series in England and Wales is commonly marked by an unconformity overlain by transgressive sandstone beds, but two transitional sequences have been reported (Fortey *et al.*, 1991). Of these, the section at Trusmadoor, a col between Great Cockup and Meal Fell in the northern Lake District, is important because of the presence of graptolites that are widespread outside Britain. Jackson (1979) identified the early Arenig graptolite *Didymograptus protobalticus* Monsen from the southern end of the section, and in 1985 Rushton collected the late Tremadoc *Dictyonema pulchellum* Hall from the northern end and pointed out the potential of the site for identifying the base of the Arenig. Fortey *et al.* (1991) reported the results of further investigations.

Eastwood *et al.* (1968) gave a description of the geology of the district, but after resurveying the area Cooper *et al.* (1995) revised the stratigraphy and structure radically. They regarded the area between Great Cockup and Meal Fell as a faulted slice of the southward-younging Skiddaw Group, consisting of the upper part of the Watch Hill Formation passing up into the base of the Hope Beck Formation.

Description

The Skiddaw Group sediments consist of grey mudstones, with sandstone beds about 10 cm (occasionally up to 30 cm) thick. The thicker sandstones commonly show upwardly fining graded bedding, cross-lamination, small-scale slumps, convolute lamination and microfaulting. The mudstones are bioturbated and show burrows on bedding-planes.

At the north-west end of Trusmadoor (NY 2777 3363), 20 m of mudstones, with sandstone beds up to 30 cm thick, strike at around 280° and dip to the south at about 45°. These are taken to be part of the Watch Hill Formation. The cleavage here is parallel to bedding. From these beds Rushton (1985) reported *Dictyonema pulchellum* (Figure 11.3), associated with an acritarch flora, and fragments of large specimens of *Dictyonema* sp. from mudstones about 30 m higher. Lindholm (1991) subsequently referred all these *Dictyonema* to *Araneograptus murrayi* (Hall), and Molyneux (in Cooper *et al.*, 1995, p. 191) assigned the associated acritarch flora to 'sub-assemblage 3' of the *messaoudii–trifidum* Assemblage.

After an unexposed interval, the north-east

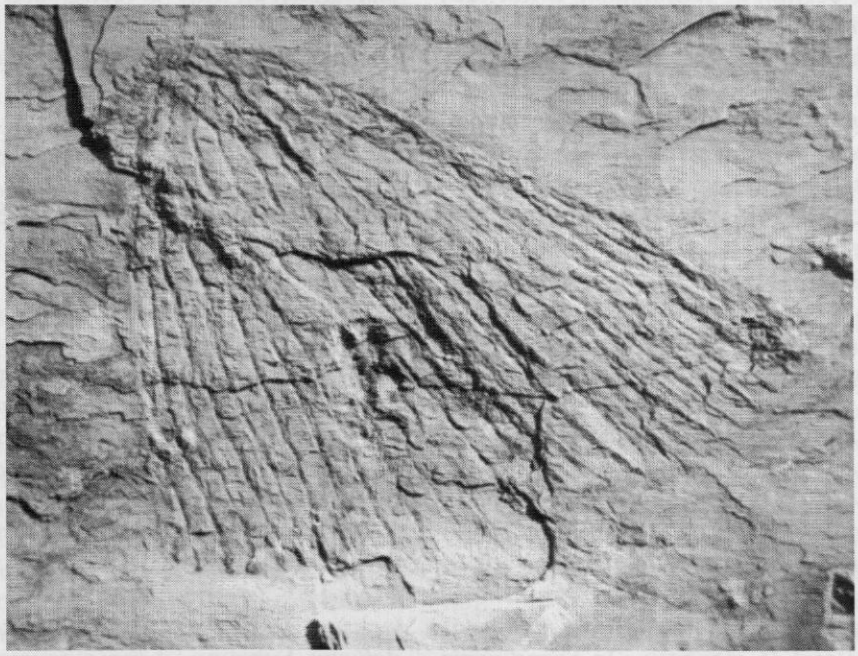

Figure 11.3 *Araneograptus murrayi* (Hall), ×1, from the uppermost Tremadoc strata at Trusmadoor.

side of the col shows extensive exposures of mudstone with interbedded sandstone, in which the cleavage is steeper than the bedding; a few fragmentary graptolites have been found (NY 279 355). A further interval of poor exposure on the north-east side of Trusmadoor is followed by large exposures of mudstone, in which the dip of the cleavage is close to that of the bedding. These beds, near the junction of Trusmadoor and Burntod Gill (NY 2795 3339), yield *Clonograptus multiplex* (Nicholson), *Didymograptus protobalticus*, *D. rigoletto* Maletz, Rushton and Lindholm, and *Tetragraptus* species, including a single specimen of *T. (Pendeograptus)* cf. *fruticosus* (Hall). Acritarch floras from here are assigned to subassemblage 5 of the *messaoudii–trifidum* Assemblage. From outcrops and scree on the south-west side of the col (NY 2775 3355) (apparently in the same beds), *D. protobalticus* and *C. multiplex* and a single cyclopygid trilobite have been found.

In the provisional range chart given by Fortey *et al.* (1991, fig. 2), the records of *Didymograptus* (*sensu lato*) cf. *vicinus* and *D.* cf. *protobalticus* are now both assigned to *D. protobalticus,* and *D.* (*sensu lato*) sp. nov. is now described as *D. rigoletto* (Maletz *et al.*, 1991).

Interpretation

Although the section at Trusmadoor is not fully exposed and the graptolites are sparse, it is an important section for the correlation of the lower part of the Skiddaw Group, because it relates the graptolitic and acritarch sequences. The *messaoudii–trifidum* acritarch floras can be related to those from other parts of the Lake District (Cooper *et al.*, 1995) and from South Wales, the Isle of Man, Spain (Molyneux and Rushton, 1988) and Rügen, north Germany (Servais and Katzung, 1993), allowing regional correlations and the possibility of wider correlation on the margins of Gondwana. The graptolites can be related to the Scandinavian and Australasian successions, as shown in Figure 11.2.

The northern end of the Trusmadoor section has yielded only *Araneograptus murrayi* (eight specimens) and is correlated with La2 and with the *murrayi* and/or *copiosus* zones. The southern end has yielded *Didymograptus* (*sensu lato*) *protobalticus* and *D. rigoletto*. In Scandinavia the ranges of these overlap at the top of the *phyllograptoides* Zone and within the range of *Tetragraptus* of the *approximatus* group (Maletz *et al.*, 1991), just below the *balticus* Zone. Correlation with the Australasian succession is more indirect, but the presence of *Pendeograptus* cf. *fruticosus* associated with correlatives of *T. approximatus* suggests a level near the base of the Bendigonian (see the Balcreuchan Port site report).

Therefore, as well as offering the prospect of identifying the Tremadoc–Arenig boundary in graptolitic rocks in Britain, the Trusmadoor section also affords valuable ties, just below and just above the base of the Arenig, between the acritarch zonation developed locally and the graptolite successions developed abroad. Horizons that could be used to characterize a correlatable base of the Arenig Series, namely the base of the *phyllograptoides* Zone or of the *approximatus* Zone (Lancefieldian 3 division), are not yet identified in the section, but presumably fall within the poorly fossiliferous sand-rich interval in the middle of the section, or the adjoining unexposed beds.

Conclusions

Trusmadoor is a site of international importance. It is uniquely valuable because it is the only site in England and Wales that contains assemblages of graptolites and acritarchs that distinguish an interval recognized in many other parts of the world as marking the boundary between the Tremadoc and Arenig epochs.

BLAZE BRIDGE AND SCAWGILL QUARRY (NY 1782 2556–NY 1792 2499 AND NY 178 258)

POTENTIAL GCR SITE

Introduction

This site exposes graptolite-bearing strata in the upper part of the Hope Beck Formation and the lower half of the Loweswater Formation; it is the principal location at which the *varicosus* Zone can be characterized.

The Loweswater Flags was named by Dixon (1925), based on a thick sandstone formation exposed around Loweswater (NY 13 22). Jackson (1962) recorded graptolites of the *deflexus* Subzone of the *extensus* Zone in the lower part of the formation and the *nitidus*

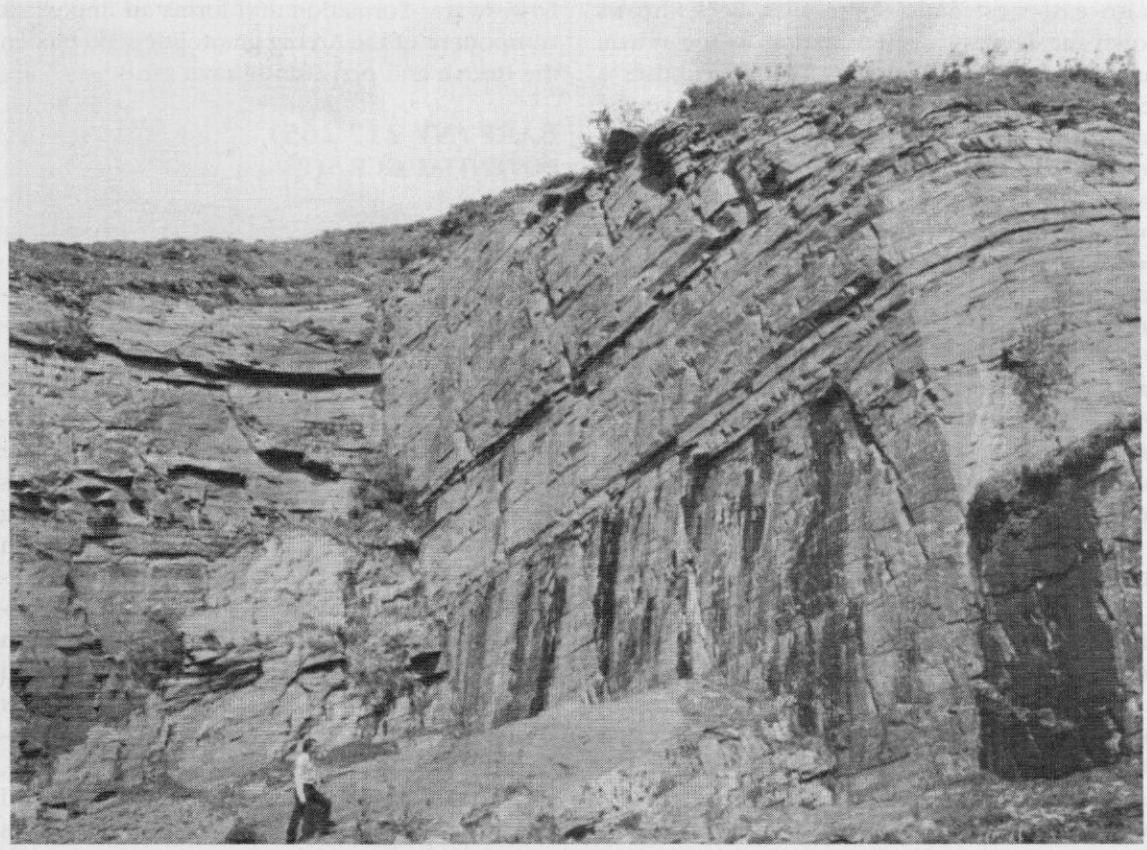

Figure 11.4 Scawgill Quarry, High Lorton. Turbidite sandstones of the lower part of the Loweswater Formation, dipping west at 16°. Some thicker units show complete Bouma *a–e* cycles and some thinner bedded units are fossiliferous. (Photo: British Geological Survey photographic collection, D3832.)

Subzone in the upper part. Cooper *et al.* (1995) redescribed the division and formalized it as the Loweswater Formation. They re-identified the specimens recorded as *Didymograptus deflexus* Elles and Wood from the lower parts of the Loweswater Formation as *D. varicosus* Wang and changed the name of the zone to the '*varicosus* Zone'.

The Hope Beck Slates were first recognized by Jackson (1961), based on strata underlying the Loweswater Flags at Hope Beck, 2 km south of the present site. He described the contact between the Hope Beck Slates and the Loweswater Formation but found no fossils in the lower division. Cooper *et al.* (1995) redescribed the division and greatly extended the known outcrop, formalizing it as the Hope Beck Formation. They recorded graptolites in the upper part of the formation and assigned them to the *varicosus* Zone.

Description

South of Whit Beck and Scawgill Bridge (1775 2571), Blaze Beck exposes part of the Hope Beck Formation about 200 m below the top of the formation ('2' in Figure 11.1). It consists of cleaved, thinly bedded mud and silt turbidites, dipping south-west at 24°. Graptolites are scarce but were found at a few sites along Blaze Beck and include *D. vacillans attenuatus* Monsen, *D.* cf. *varicosus, D. filiformis* Törnquist, *D.* cf. *decens* Törnquist and a large form shaped like *D. balticus* Tullberg but whose proximal structure is unknown. Quarries 200 m west of Blaze Bridge (1792 2499) expose the base of the Loweswater Formation, here consisting of thinly bedded flaggy sandstone turbidites. They contain all but the first-named species above, together with abundant *D. varicosus* and rare *Clonograptus, Pseudobryograptus* and *Pendeograptus fruticosus* (Hall).

An east–west fault along Whit Beck throws down the Loweswater Formation to the north, such that Scawgill Quarry (178 258) exposes a level estimated to be 300 or 400 m above the base of the Loweswater Formation. In the quarry there are thick sandstone turbidites dipping west at 16° (Figure 11.4). Many beds show sedimentary structures and some show complete Bouma *a–e* cycles. *D. varicosus* is much the commonest species of graptolite, associated here with rare '*D.* aff. *balticus*', *T. quadribrachiatus* (Hall), *Dichograptus sedgwickii* Salter, *Schizograptus tardefurcatus* Elles and *Trochograptus diffusus* Holm. About 200 m east of Scawgill Quarry a fault throws down higher parts of the Loweswater Formation with faunas of the overlying *simulans* Zone.

Interpretation

This site exemplifies the contrasting lithologies of the Hope Beck Formation and Loweswater Formation, though the contact between the formations is not exposed. The fossils from the top of the Hope Beck Formation are similar to the much more numerous fossils from the base of the Loweswater Formation, and they are both assigned to the *varicosus* Zone. This zone is considered to correlate roughly with the upper part of the Bendigonian of the Australasian succession and the *balticus* Zone of Scandinavia (Cooper and Lindholm, 1990). The base of the *varicosus* Zone cannot be characterized because no significant graptolites have been collected through the large thickness of strata, perhaps amounting to 400 m, that underlies the Blaze Beck localities and overlies the fauna from near the base of the formation at Trusmadoor (see site report).

The faunas from Scawgill Quarry are also referred to the *varicosus* Zone, on account of the abundance of the zone fossil. However, a relatively small thickness above, at about 100 m above the Scawgill horizon, new taxa such as *Didymograptus deflexus* and *D. simulans* Elles and Wood appear, and these characterize the overlying *simulans* Zone (see the Barf site report).

Conclusions

This site encompasses the best localities at which to characterize the *varicosus* Zone. This zone is significant for dating and correlating the Loweswater Formation and forms an important component of the Arenig graptolitic sequence in the British and peri-Gondwanan areas.

BARF (NY 217 265)

POTENTIAL GCR SITE

Introduction

This is the best locality for graptolites of the *simulans* Zone in the whole Skiddaw Group outcrop and is the type locality for several species.

Barf is a distinctive bare mountain at the southern end of Bassenthwaite Lake. It is composed of sandstones of the upper part of the Loweswater Formation. The screes below its south-east face have been a favoured collecting locality since the days of Harkness (1863), such that it is now much less productive than formerly; but a great number of specimens, representing a fauna of over 20 species, are preserved in museum collections. Jackson (1962) referred the fauna to the *nitidus* Subzone of the *extensus* Zone and considered Barf to be the best exposure of the subzone. Cooper *et al.* (1995, p. 190) regarded the division as a zone and named it after the more characteristic species *Didymograptus simulans* Elles and Wood.

Description

The south-east face of Barf is made up of flaggy sandstones of the Loweswater Formation dipping steeply to the south-east at 60–80° (Figure 11.5). They pass up into the lower beds of the overlying Kirk Stile Formation, which are mapped in the lower ground to the south-east, but the junction here is covered by scree material of Loweswater Formation that has fallen, presumably by post-glacial collapse, from the mountain-side. The Loweswater Formation consists of sand turbidites (see the Blaze Bridge and Scawgill Quarry site reports), and some beds are micaceous, enabling the rock to be split into large bedding-parallel slabs. A few hundred metres of the upper half of the Loweswater Formation are exposed around Barf, but the great bulk of the fossils came from the screes derived from around Slape Crag and the strata topographically beneath it, which are estimated to originate from around 100 m below the top of the formation. Thus, although many of the specimens are not well localized, they probably all came from a relatively thin interval.

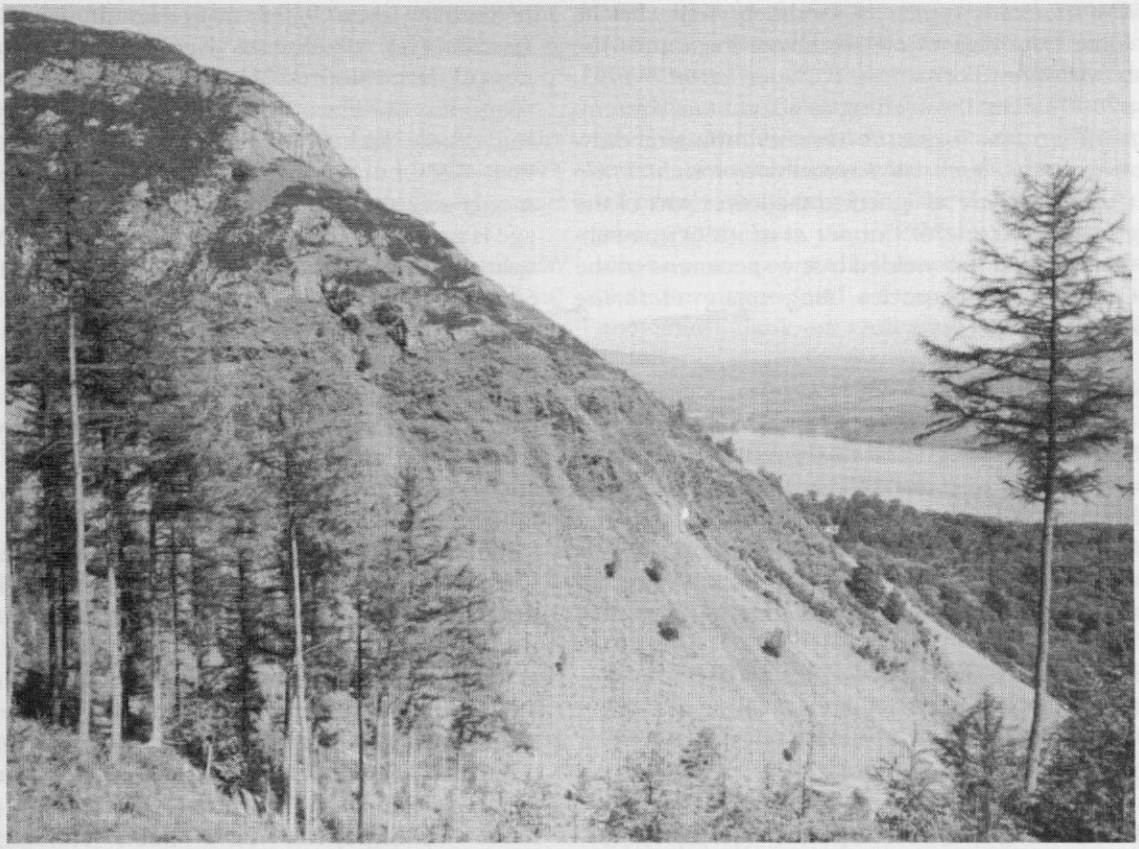

Figure 11.5 View of south-east face of Barf, north-west of Keswick, looking north, with Bassenthwaite Lake in the background. At the top of the hill the upper beds of the Loweswater Formation dip steeply to ESE and lower down are inverted. They form big screes from which many fossils have been collected. 'The Bishop' is the white-painted rock near the centre and Slape Crag is the vertical face near the top of the hill. (Photo: British Geological Survey photographic collection, D3838.)

Among the commonest graptolites from Barf are *Didymograptus simulans*, *D. deflexus* Elles and Wood (*sensu stricto*), *D. kurcki* Törnquist (='*nicholsoni*' of authors) and *Azygograptus eivionicus* Elles. Longer-ranging forms include abundant *Pseudophyllograptus angustifolius* (Hall) and various *Tetragraptus* spp.. Rarer species include *D. gracilis* Törnquist, *D. infrequens* Kraft, *Didymograptellus minutus* (Törnquist), *Pseudobryograptus cumbrensis* (Elles), *Pseudotrigonograptus ensiformis* (Hall) and *Isograptus* cf. *primulus* Harris. Trace fossils, sponge spicules and the ubiquitous arthropod *Caryocaris wrightii* Salter have also been collected.

Interpretation

Elles (1933) thought that five graptolite zones and subzones, including Tremadoc rocks, were present at Barf, but subsequent work has not upheld this (Jackson, 1962, table 2; Bulman, 1971, p. 370). The commoner species listed above are considered typical of the *simulans* Zone and recur as an assemblage at various localities from Loweswater and the Lorton Fells to Skiddaw and Mungrisdale. None of the typical species appears in the underlying *varicosus* Zone,with the possible exception of *D. deflexus,* which is doubtfully present at the base of the Loweswater Formation. The *simulans* Zone may be correlated abroad, rather more securely than is the *varicosus* Zone, with the Chewtonian of Australasia and the *densus* Zone of Scandinavia (Cooper and Lindholm, 1990). Some of the species that characterize the *simulans* Zone appear to be preferentially associated with coarse-grained sediments: they are not found in the fine-grained beds of the Kirk Stile Formation, which overlies the Loweswater Formation, but a

few species reappear in sand-rich strata that lie some hundreds of metres above the top of the Loweswater Formation (Cooper *et al.*, 1995, p. 190). The intervening strata contain *Pseudophyllograptus angustifolius* and horizontal didymograptids such as *Expansograptus hirundo* (Salter) and are assigned to the lower part of the *gibberulus* Zone of Cooper *et al.* (1995), a subdivision that has yielded a few specimens of the Castlemainian species *Isograptus victoriae* Harris.

Conclusions

Barf is biostratigraphically a nationally significant site because the fauna collected there is the best representative of the *simulans* Zone of the British graptolitic sequence. Furthermore, certain rare graptolites from Barf enable international correlation of the *simulans* Zone.

RANDEL CRAG (NY 253 295)

POTENTIAL GCR SITE

Introduction

Randel Crag is the most prolific locality for fossils of the upper part of the *gibberulus* Zone. It is the type locality for the stratigraphically and nomenclatorially important graptolite species *Isograptus gibberulus*.

The Kirk Stile Formation consists of dark-coloured, laminated mudstones and siltstones with relatively little sandstone. At about 2 km thick, it is the thickest division of the Skiddaw Group and occupies much the largest part of the outcrop (Cooper *et al.*, 1995). The stratigraphy is difficult to elucidate because of folding, faulting and the paucity of mappable subdivisions. However, graptolite faunas and acritarch floras, where available, offer some means of relating individual fault-blocks. Following Cooper *et al.* (1995, p. 191), the faunas of the Kirk Stile Formation are, in upward succession, referred to the *gibberulus* Zone and the *hirundo* Zone, with the *artus* Zone present locally (see Outerside). Randel Crag exposes part of the Kirk Stile Formation estimated to be 1–1.2 km above the base of the formation and now assigned to the upper part of the *gibberulus* Zone.

Description

Randel Crag is a shoulder of the north-west flank of Skiddaw, about 900 m from the summit ('4' in Figure 11.1). It exposes a considerable thickness of dark-coloured laminated mudstones and siltstones; these are distal muddy turbidites typical of the Kirk Stile Formation. They strike ENE–WSW but with variable dip, although commonly steeply southwards. In places the cleavage is nearly parallel to the bedding and the rock splits into large plates. Thermal alteration by the Skiddaw granite, strong near Skiddaw itself to the south-east, is here evinced by multitudes of minute pale crystals of andalusite. The rock is somewhat hardened and there are old slate trials nearby. Masses of scree litter the north and west sides of Randel Crag, and were no doubt the source of many of the graptolites in museums labelled 'Randel Crag'.

The graptolite fauna is dominated by extensiform didymograptids, referred here (with doubt) to *Expansograptus*: *E. extensus linearis* (Monsen), *E. nitidus* (Hall), *E. hirundo* (Salter), *E.* cf. *goldschmidti* (Monsen, of Kraft), *E.*? cf. *uniformis* (of Elles and Wood). Numerous specimens of *Pseudophyllograptus angustifolius* (Hall), *Tetragraptus* species, *Pseudotrigonograptus ensiformis* (Hall) and various multiramous dichograptids have been collected. Isograptids occur rarely, but, following Jenkins (1982), Randel Crag is the type locality for *Isograptus caduceus gibberulus* (Nicholson), which is the type species of the stratigraphically valuable genus *Isograptus*. Other fossils found here include numerous *Caryocaris wrightii* (Salter) and a few trilobites, namely the type of *Illaenopsis harrisoni* (Postlethwaite and Goodchild) and species of the cyclopygids *Cyclopyge, Microparia* and *Psilacella* (Fortey *et al.*, 1989).

Interpretation

Elles (1933) thought three or more zonal divisions were present at Randel Crag, and Jackson (1962) considered that the graptolites included representatives of the *gibberulus* Subzone of the *extensus* Zone and the overlying *hirundo* Zone. Jenkins, however, found *Isograptus caduceus gibberulus* and *Expansograptus hirundo* 'closely associated' at this locality and assigned the whole fauna to the *hirundo* Zone. Fortey *et al.* (1990) and Cooper *et al.* (1995), however, used the local range of *I. caduceus gibberulus* to determine the extent of the *gibberulus* Zone and confined the *hirundo* Zone to higher levels. In

this restricted usage, the *gibberulus* Zone is the only zone positively identified at Randel Crag. It is correlated with part of the Fennian Stage of South Wales (see the Pontyfenni site report), with the upper Castlemainian and possibly part of the Yapeenian of Australasia, and with part of the *hirundo* Zone of Scandinavia (Cooper and Lindholm, 1990).

The trilobites are entirely of Gondwanan affinity and contribute to the palaeogeographical interpretation that places the Lake District in an ocean-facing setting on the margin of Gondwana during the Arenig (Fortey *et al.*, 1989).

Conclusions

Randel Crag has a diverse and abundant graptolite fauna that typifies the *gibberulus* Zone, a part of the graptolitic standard for Arenig rocks in Britain. Some species enable correlation with upper Arenig (Fennian) trilobite-bearing strata in Wales and with graptolitic sequences abroad.

OUTERSIDE (NY 211 215)

POTENTIAL GCR SITE

Introduction

Outerside is one of the best localities for the fauna of the *hirundo* Zone, the uppermost graptolite zone of the Arenig, and is the type locality for several fossil species. It is also one of the few localities in the Lake District at which the base of the Llanvirn Series can be located.

Outerside, a hill 6 km WSW of Keswick ('5' in Figure 11.1), exposes the upper parts of the Kirk Stile Formation. The beds are here affected by the Crummock Water metamorphic aureole, the northern boundary of which passes round the south side of the hill. The Causey Pike Fault, a major tear fault, lies less than 1 km to the south. Outerside has long been known as a collecting locality for late Arenig graptolites. The fauna, which comprises about 20 species, was taken to exemplify the *hirundo* Zone in the revised concept of Fortey *et al.* (1990, p. 128), and a more limited faunal assemblage from nearby was referred to the basal Llanvirn *artus* Zone (Fortey *et al.*, 1990, p. 130).

Description

The strata at Outerside are laminated mudstones and siltstones but differ from typical Kirk Stile Formation strata in their grey-green colour and the dense, fine, dark spotting, induced by metasomatism associated with the Crummock Water aureole immediately to the south. Dip and strike are variable, but whereas the dip is generally west to south-west, the beds appear to young to the east. Slumped beds and mass-flow deposits are a sporadic feature of the higher Kirk Stile Formation, and an example of debrite on the south flank of Outerside was figured by Cooper *et al.* (1995, fig. 8).

Large screes of Kirk Stile Formation have formed on the north-west side of the hill (211 215–213 217), and these are the source of most of the fossils from Outerside. The graptolites are commonly preserved as greenish impressions of low relief, and many are poorly preserved; nevertheless, large collections have been made and several species have their type locality here. Examples are *Didymograptus protobifidus* Elles, *D. nicholsoni planus* Elles and Wood, *D. v-fractus volucer* Nicholson, *Cryptograptus hopkinsoni* (Nicholson) and *Dichograptus separatus* Elles. Other significant graptolites present are *Aulograptus cucullus* (Bulman), *Cryptograptus antennarius* (Hall), *Expansograptus sparsus* (Hopkinson), numerous diplograptids (*Eoglyptograptus, Undulograptus*) and one specimen of *Bergstroemograptus.* Several examples of *Tetragraptus* spp. and *Loganograptus logani* (Hall) are recorded. Outerside is one of the syntype localities of the phyllocarid arthropod *Caryocaris wrightii* Salter, and well-preserved carapaces have been collected (Rushton and Williams, 1997, p. 107, fig. 1b).

Exposures on the eastern face of Outerside (around 214 215) have yielded far fewer fossils, but these include several *Didymograptus spinulosus* Perner, with other species including *Undulograptus austrodentatus* (Harris and Keble) and *U. cumbrensis* (Bulman).

Interpretation

Although Elles (1933) thought that her *gibberulus* Subzone was present at Outerside, no specimens supporting this notion are known. However, Jackson (1962) agreed with Elles in considering that the main fauna from the scree on the north-west face of Outerside represents the *hirundo* Zone, and this was followed by Fortey *et al.* (1990). The *hirundo* Zone is now

correlated approximately with the lower Darriwilian of the Australasian sequence, namely a slightly higher level than that proposed by Fortey *et al.* (1990) and more in keeping with the correlation proposed by Mitchell and Maletz (1995). Apart from the distinctive *Aulograptus,* the only pendent didymograptids are rare examples of *D. protobifidus* (type locality), which occurs here much higher than the Chewtonian horizon of Australasian and North American records of this species. Faunas of the *hirundo* Zone are distributed around the north side of the Skiddaw massif (Jackson, 1962) to Hazelhurst by Souther Fell in the east, where the section passes from Arenig to Llanvirn in graptolitic strata (Fortey *et al.*, 1990, p. 130).

The fauna from the east face of Outerside is taken to be basal Llanvirn (*artus* Zone) on account of the several examples of *D. spinulosus* found there, thus supporting Elles' (1933) contention that Llanvirn strata are developed at Outerside. Fortey and Owens (1987, fig. 41a) suggested that the trilobite *Gastropolus obtusicaudatus* (Hicks) from Outerside might also be from the basal Llanvirn there.

Conclusions

Diverse graptolite faunas from Outerside exemplify a development of the uppermost Arenig *hirundo* Zone in the upper part of the Kirk Stile Formation and show also the lowest part of the Llanvirn *artus* Zone. These faunas play an important part in the stratigraphy of the Skiddaw Group and internationally in correlating the Arenig–Llanvirn boundary with the Australasian graptolitic scheme.

MAIN OUTCROP: DENT GROUP

The nomenclature of the constituent formations given by Kneller *et al.* (1994) is followed here (Figure 11.6). The group consists of thin but laterally fairly persistent sandstones, mudstones and calcareous beds that transgress the eroded mass of Borrowdale Volcanic Group rocks. The basal part of the group in the south-east Lake District is shown at Stile End (see site report, below) and the upper parts are shown clearly but in attenuated form at the classic site of Ashgill Quarry.

STILE END (NY 471 049–NY 476 051)

Introduction

Stile End is historically important, being the eponymous locality for the lowest formation in the Dent Group overlying the eroded Borrowdale Volcanic Group in the south-east of the Lake District. The age of the Stile End Formation has been debated but is now recognized as being mid-Cautleyan rather than Actonian, and this fact has been used to demonstrate that the southern Lake District was an upstanding horst during the late Caradoc and early Ashgill while the Borrowdale Volcanic Group in the North Pennines was being overstepped from the north.

The Stile End Formation is the basal unit of the Dent Group in the south-eastern part of the Lake District. Harkness and Nicholson (1877, p. 662) applied the term 'Stile End Grassing Beds' to the 'ashy silts' below the Yarlside Volcanic Formation. The subsequent history of the unit was summarized by McNamara (1979a), Lawrence *et al.* (1986) and Kneller *et al.* (1994). Marr (1892), Dean (1963c) and others widened the concept of the 'Stile End Beds' to include all the strata between the Borrowdale Volcanic Group and Yarlside Formation. McNamara (1979a) separated a lower unit largely of coarse clastic material derived from the Borrowdale Volcanic Group, termed the 'Longsleddale Formation', from the 'Stile End Formation' of Harkness and Nicholson (1877). He defined the type section of both formations to the NNW of Stockdale Farm, 1.5 km north-east of the Stile End site. The two units were described in detail by Lawrence *et al.* (1986) as members of the 'Coniston Limestone Formation'. In the most recent stratigraphical revision (Kneller *et al.*, 1994), the Longsleddale Member was redefined as the basal member of the Stile End Formation, within the newly defined Dent Group. Kneller *et al.* (1994) also reverted to historical usage in naming the overlying Yarlside Volcanic Formation, in contrast to the term Stockdale Rhyolite used by Millward and Lawrence (1985) and Lawrence *et al.* (1986).

Dean (1963c, fig. 4) published a geological map showing the location of fossiliferous localities within the Stile End Formation to the ENE of Stile End Farm, including the present site. The site forms part of the 1:25 000 Geological Survey

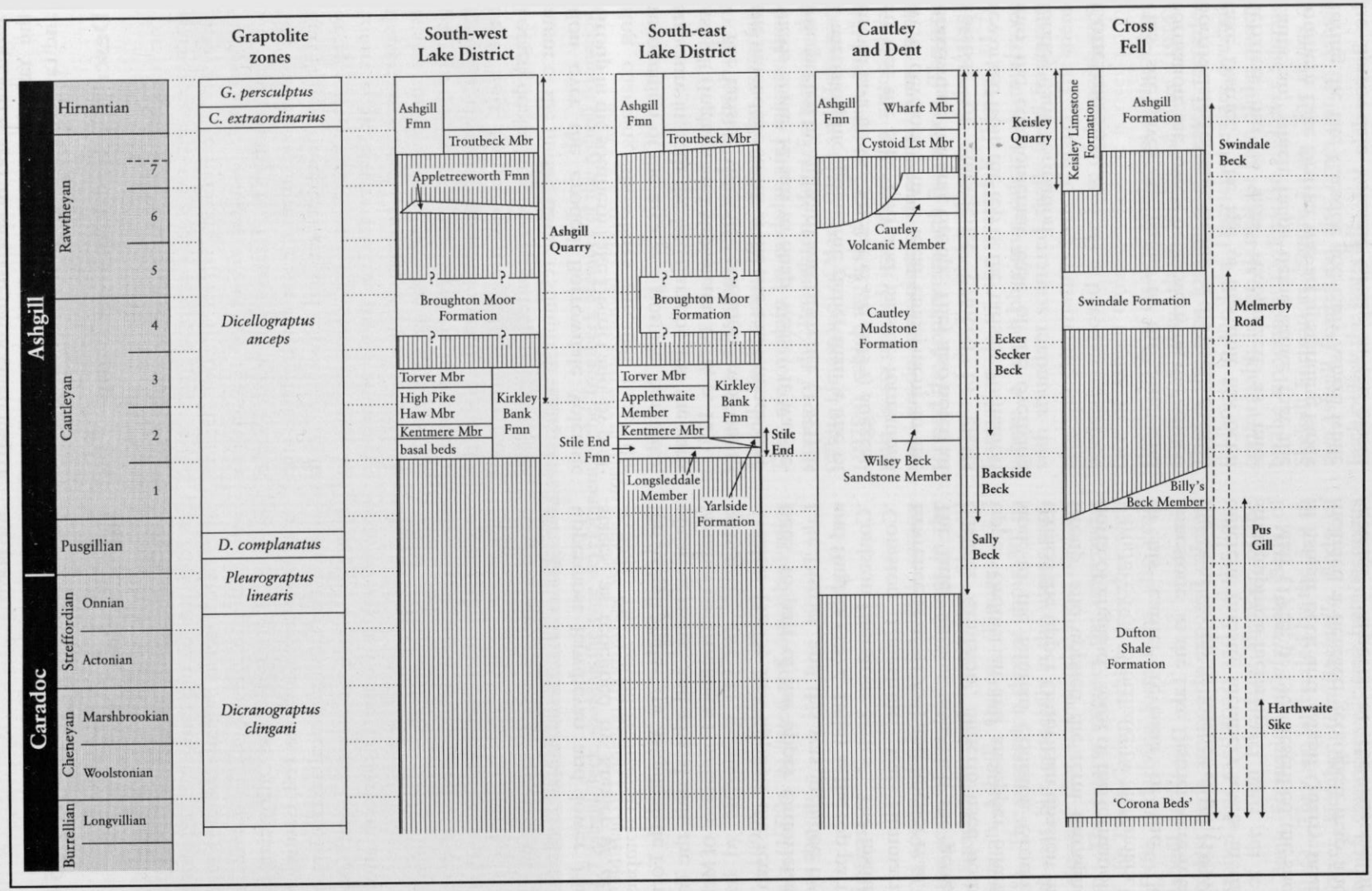

Figure 11.6 Correlation chart of the upper Ordovician (Dent Group) in the main crop of the Lake District, the Cautley and Dent inliers and the Cross Fell Inlier, and the stratigraphical range shown by the GCR site described herein, based on Kneller *et al.* (1994, fig. 5). In all areas the Dent Group lies unconformably on the Borrowdale Volcanic Group. The correlation of the graptolite zones with the stages of the Ashgill Series is subject to revision (R. B. Rickards pers. comm. 1999).

Kentmere and Crook sheet (Lawrence *et al.*, 1986) and is also included in the detailed map of the Yarlside Formation published by Millward and Lawrence (1985, fig. 2).

Description and Interpretation

The site covers the small exposures of dark-grey calcareous siltstones of the upper part of the Stile End Formation, which include Dean's (1963c) fossil localities λA–D and McNamara's (1979a) locality 11. Dean described trilobites and brachiopods from the site and from the Stile End Formation elsewhere and considered them to indicate a late Caradoc (Actonian) age. In contrast, McNamara (1979a, p. 47) argued for the now-accepted Cautleyan Zone 2 age, which is also commensurate with the age of the oldest parts of the Dent Group elsewhere in the southern Lake District. This revision of the age of the Stile End Formation (including the basal Longsleddale Member) resulted in a reassessment of the timing of the resumption of deposition over the eroded Borrowdale Volcanic Group in the southern Lake District and, by plotting changing shorelines through time, the recognition of the area as a positive, horst-like, structure in both the late Caradoc and the early Ashgill (Ingham and McNamara, 1978, p. 125).

The Yarlside Volcanic Formation crops out to the immediate south of the site and extends eastwards some 12 km to Shap Wells. It was reinterpreted by Millward and Lawrence (1985) as a rheomorphic ignimbrite rather than a line of coeval lava flows. Kneller *et al.* (1994) suggested that the Stile End and Yarlside formations were developed in a local embayment in the Borrowdale Volcanic Group. They also noted an episode of emergence evinced by clasts reworked from the top of the Yarlside Formation into the conglomeratic base of the overlying Kirkley Bank Formation.

Conclusions

This site gives its name to the Stile End Formation, the lowest beds overlying the eroded Borrowdale Volcanic Group in the south-eastern Lake District. The age of this unit has been debated but is now recognized as mid-Cautleyan, which helps demonstrate that the southern Lake District was an upstanding block during the late Caradoc and early Ashgill while the Borrowdale Volcanic Group in the North Pennines was being progressively drowned from the north.

ASHGILL QUARRY (SD 269 954)

Introduction

Ash Gill is known internationally because it gives its name to the uppermost of the British Series of the Ordovician System. Ashgill Quarry is the type locality for the Ashgill Formation, a unit recognized at the top of the Ordovician across the Lake District to the Cross Fell, Cautley and Dent inliers. The stratigraphical succession of middle to upper Ashgill age around Ashgill Quarry typifies this part of the Ordovician in the Lake District.

The term 'Ashgill Series' was introduced by Marr (1905) without mention of a type locality, but he subsequently (Marr, 1913, 1916) designated the Cautley district as the type area (Ingham and Wright, 1970). Ashgill Quarry is the type locality for the Ashgill Formation of the uppermost Rawtheyan and lower Hirnantian stages, as redefined by Kneller *et al.* (1994, p. 228). The Ashgill Formation comprises both the 'Ashgill Shales' (or 'Ashgill Shale Formation') of earlier usage, and a basal unit, the Troutbeck Member (='Troutbeck Formation' of McNamara, 1979a).

Salter (1873) first applied the term 'Ashgill Beds' to part of the upper Ordovician of the Lake District, and this was included by Aveline and Hughes (1872, 1888) as the top part of their 'Coniston Limestone Series'. The history of the 'Coniston Limestone' was summarized by Lawrence *et al.* (1986) and Kneller *et al.* (1994). The latter authors restricted the geographical qualifier 'Coniston', hitherto used both for an upper Ordovician and an upper Silurian division, to the Silurian Coniston Group. They termed the upper Ordovician division the 'Dent Group' and applied the term throughout the north of England. Most of the formation names introduced or formalized by McNamara (1979a) in his earlier revision of the 'Coniston Limestone' in the Lake District were retained in the Dent Group by Kneller *et al.* (1994) but at different (mostly member) levels in the lithostratigraphical hierarchy.

Marr (1916, p. 190) described the succession in Ashgill Beck and Ashgill Quarry nearby and included a detailed geological map and cross-section. Aspects of the succession were

Figure 11.7 Ashgill Beck, showing the type development of the Troutbeck Member of the Ashgill Formation, with the Old Man of Coniston (Borrowdale Volcanic Group) in the background. (Photo: A.W. Owen.)

described by McNamara (1979a), Scott and Kneller (1990) and Kneller *et al.* (1994). McNamara (1979a, b) listed and described trilobites from the site.

Description

The site is spectacular both in its scenic setting and in the scale of the 'slate' workings in the Ashgill Formation and overlying Skelgill Formation in Ashgill Quarry (Figures 11.7 and 11.8). The succession dips at about 30° to the south-east, but, especially in the upper part, it is the cleavage that provides the most obvious structure. The quarry exposes the uppermost parts of the Dent Group, which, together with some of the underlying formations, also crop out in Ashgill Beck.

The oldest beds are poorly exposed calcareous siltstones, fine sandstones and nodular limestones of the High Pike Haw Member of the Kirkley Bank Formation (*Calymene* Beds of Marr, 1916). They are succeeded by the 3–4 m thick Torver Member (*Phillipsinella* Beds of Marr), which comprises cleaved homogeneous calcareous siltstones, exposed in the bank of Ashgill Beck some 15 m above the waterfall. They are overlain by nodular and micritic limestones of the Broughton Moor Formation, the 'White Limestone' of Marr (1916) and McNamara (1979a), which are less than 5 m thick; and this unit is succeeded just above the waterfall by sand-grade pyroclastic deposits, 5 m thick, termed the Appletreeworth Formation. The type section of the Troutbeck Member of the Ashgill Formation is at the waterfall (Figure 11.7), where 4 m of blue-grey calcareous mudstone with abundant scattered shelly fossil fragments crop out (*Mucronatus* Beds of Marr). The member is also exposed at the base of the north-west face of Ashgill Quarry, where it is overlain by almost 20 m of cleaved mudrocks of the Ashgill Formation, the Ashgill Shales of Marr (1916). This is the type locality and greatest recorded thickness in the Lake District; they are overlain conformably in the south-east face of the quarry by the uppermost Ordovician to lower Silurian Skelgill Formation (Figure 11.8). The shales of the Ashgill Formation also crop out in Ashgill Beck below the waterfall.

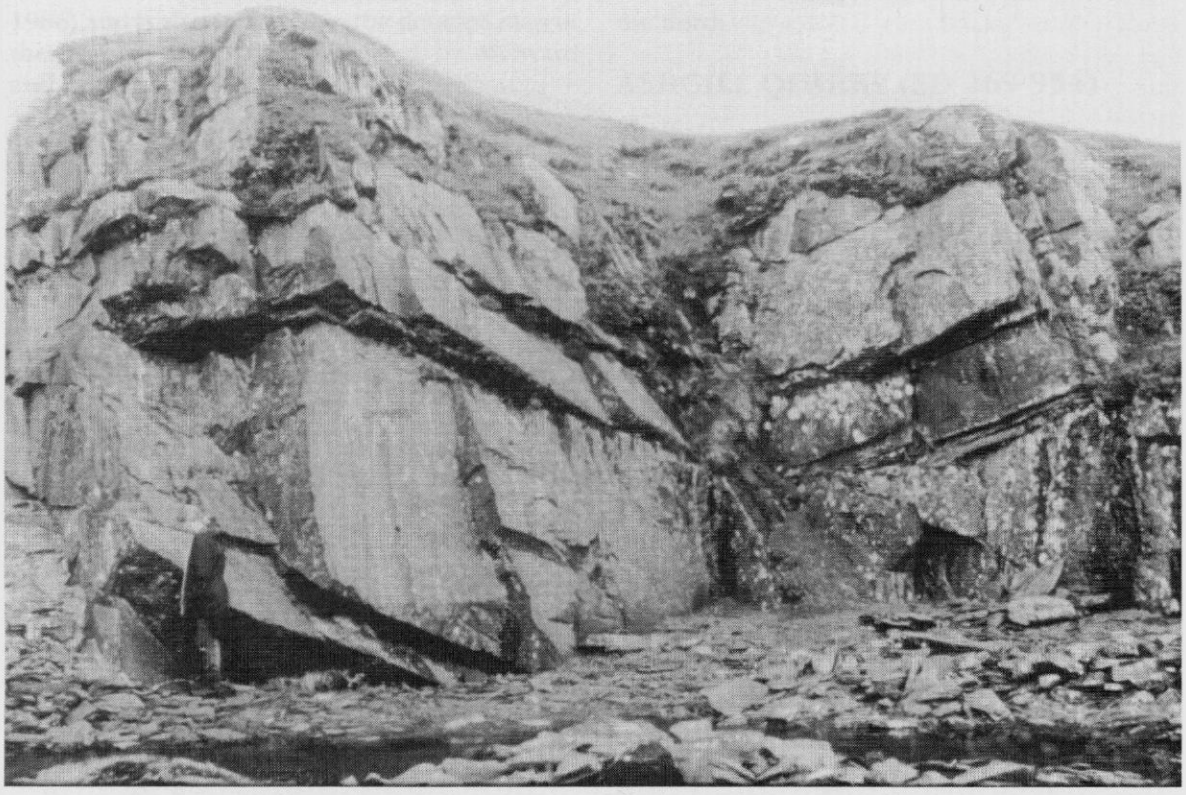

Figure 11.8 The southern face of Ashgill Quarry showing the Skelgill Formation in the topmost part of the quarry conformably overlying shales of the uppermost Ordovician Ashgill Formation. (Photo: A.W. Owen.)

Interpretation

Marr (1916) considered his '*Calymene* Beds' (the High Pike Haw Member of the Kirkley Bank Formation) to belong in the Caradoc, but an Ashgill age was established by King and Williams (1948), and a mid-Cautleyan (Zone 2 to lowest Zone 3) age is now accepted (Ingham, 1966; McNamara, 1979a). The member is estimated to be about 40 m thick in the area around Ashgill Beck (Scott and Kneller, 1990, fig. 3) and lies in a region where it is transitional to the north-east into the slightly more calcareous and generally finer-grained Applethwaite Member. McNamara and Fordham (1981) demonstrated significant differences in the composition of the trilobite faunas, reflecting these lithological differences. They assigned those of the High Pike Haw Member to their Proetid Association and those of the Applethwaite Member to the Calymenid or, more rarely, Illaenid Association. Both members include storm deposits (Kneller *et al.*, 1994, p. 226). The Torver Member also contains an Illaenid Association and is Cautleyan Zone 3 in age (McNamara and Fordham, 1981).

The Broughton Moor Formation is 4–5 m thick in this area, and whilst it has yielded only a few fossils (e.g. *Diacanthaspis*) in Ashgill Beck, the trilobite fauna elsewhere indicates a Rawtheyan Zone 6 age (McNamara, 1979a). Kneller *et al.* (1994, p. 226) also noted local evidence for continuous deposition from the underlying Torver Member of the Kirkley Bank Formation and for faunas in the eastern Lake District, similar to those of the latest Rawtheyan Troutbeck Member of the Ashgill Formation, in facies assigned to the Broughton Moor Formation. The overlying Appletreeworth Formation is presumed to be Rawtheyan Zone 6 in age and represents pyroclastic material transported and resedimented by gravity flow (Kneller *et al.*, 1994, p. 228). It is thought to represent the same volcanic activity as that which gave rise to the Cautley Volcanic Member of the Cautley Mudstone Formation in the Cautley district (see the Backside Beck site report).

The Troutbeck Member of the Ashgill Formation in Ashgill Beck is latest Rawtheyan in age and contains a diverse shelly fauna, including seven species of trilobite (McNamara, 1979a, b), only one of which, *Mucronaspis mucronata* (Brongniart), is known from the overlying shales elsewhere. The shales in the quarry yield a sparse *Hirnantia* brachiopod fauna (Wright, 1968, p. 360; Scott and Kneller, 1990, p. 18), indicating a Hirnantian age. The lowest parts of the overlying Skelgill Formation contain graptolites of the *Glyptograptus persculptus* Zone (Hutt, 1974, p. 6) and are thus latest Hirnantian in age.

Conclusions

This is a historically important site internationally and gives its name to the uppermost series of the Ordovician, the Ashgill. It is the type locality for the Ashgill Formation, a distinctive rock unit deposited near the end of the Ashgill epoch over much of northern England.

CROSS FELL INLIER

Separated from the Main Outcrop by the valley of the Eden, the Cross Fell Inlier, brought up on the Pennine Fault complex, shows a comparable succession of the Skiddaw and Borrowdale groups, albeit with much more restricted outcrop (Cooper and Molyneux, 1990). A particularly important feature of the Cross Fell succession is the good development of the upper Caradoc Series (Longvillian to Onnian substages) in the Dufton Shales; in contrast, the Main Outcrop shows only an outlier of the lowest part of the Caradoc sequence (the Drygill Shales) and the Cautley inliers the highest part (see the Sally Beck site report).

HARTHWAITE SIKE (NY 702 247–NY 708 248)

Introduction

Harthwaite Sike, coupled with the adjacent Billy's Beck, provides important information on both the stratigraphy of the Dufton Shale Formation and the geological history of the late Ordovician of northern England. Harthwaite Sike includes the best and most accessible section showing the local volcaniclastic basal facies of the Dufton Shale Formation and also contains the longest section of the Woolstonian and Marshbrookian parts of the formation. The nearby section in Billy's Beck includes younger parts of the Dufton Shale Formation, including the Billy's Beck Member, and shows that the base of the Swindale Limestone, when traced northwards, cuts down onto progressively older parts of the Dufton Shale Formation.

Nicholson and Marr (1891) and Dean (1959a) termed the relatively coarse-grained basal development of the Dufton Shale the '*corona* Beds', after the brachiopod *Trematis corona*, but Burgess and Holliday (1979) renamed it the '*corona* facies' as it does not constitute a mappable unit. These Longvillian tuffaceous sandy beds are succeeded by more typical mudstones of the Dufton Shale Formation, extending up into the most extensive section of the Woolstonian and Marshbrookian substages in the Cross Fell Inlier.

An important complementary section is seen in the upper reaches of Billy's Beck, 500 m to

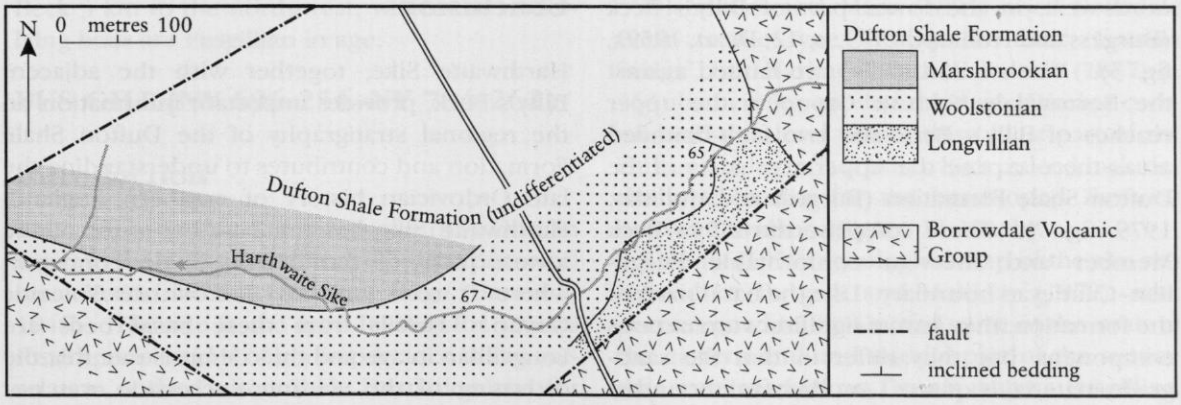

Figure 11.9 Geological map showing the Dufton Shale Formation in Harthwaite Sike, based on Burgess and Holliday (1979, fig. 6) and Dean (1959a, fig. 3).

the north (708 253–712 256), where the uppermost parts of the Dufton Shales are exposed. The Pusgillian and lower Cautleyan strata there contain a significant component of quartz sand and were termed the Billy's Beck Member by Kneller *et al.* (1994, p. 239); this term supersedes the '*Diacalymene* Beds' used by Dean (1959a) for the Cautleyan strata, following comparisons with equivalent levels in the Cautley area to which that name had been applied by King and Williams (1948). At Billy's Beck, the younger Ashgill strata belong to the latest Cautleyan to earliest Rawtheyan Swindale Limestone.

Schematic maps of the sections in Harthwaite Sike and Billy's Beck were published by Dean (1959a) and more detailed maps by Burgess and Holiday (1979). Both papers include extensive, well-localized lists of the diverse shelly faunas.

Description

The Dufton Shale Formation in Harthwaite Sike dips SSW at about 65° (Figure 11.9). At the eastern end of the site, tuffs of the Borrowdale Volcanic Group exposed south of Harthwaite Cottage are overlain in the stream section by tuffaceous sandstones containing calcareous shelly fragments and large lingulid brachiopods. These sandstones mark the base of the Dufton Shale Formation and its '*corona* facies', the overlying tuffaceous siltstones of which contain the typical fauna including the brachiopod *Trematis corona* Davidson (Figure 11.10a, b). The overlying grey mudstones extend up through probable Woolstonian into the Marshbrookian Substage, although precise recognition of the substage boundaries is not possible where diagnostic taxa are not present.

Marshbrookian strata also occur 500 m to the north-west, in the lower part of Billy's Beck (Burgess and Holliday, 1979, p. 12; Dean, 1959a, fig. 3). Woolstonian shales are faulted against the Borrowdale Volcanic Group in the upper reaches of Billy's Beck and two fault-bounded areas there expose the uppermost parts of the Dufton Shale Formation (Burgess and Holliday, 1979, fig. 7). These comprise the Billy's Beck Member and show a conformable Pusgillian–Cautleyan boundary. Like the basal parts of the formation, they have a significant arenaceous component, but they differ in that the sand-grade material is quartz. Another fault-bounded area in the upper part of Billy's Beck contains outcrops of the Swindale Limestone.

Interpretation

The tuffaceous material in the *corona* facies at the base of the formation was probably derived from the underlying Borrowdale Volcanic Group. Kneller *et al.* (1994, p. 229) noted that this facies is analogous to the volcaniclastic Longsleddale Member of the Stile End Formation, which marks the local but much younger (early Cautleyan) transgressive base of the Dent Group over the Borrowdale Volcanic Group in the south-eastern Lake District.

As stated by Burgess and Holliday (1979, p. 12), the placing of the substage boundaries in the Dufton Shale Formation at Harthwaite Sike is problematical. The *corona* facies is undoubtedly Longvillian in age, but beds immediately overlying include the brachiopod *Bancroftina* cf. *typa* (Bancroft), which is suggestive of the Longvillian (=Lower Longvillian of Burgess and Holliday and earlier authors), with *Bancroftina robusta* (Bancroft) and the trilobite *Broeggerolithus nicholsoni longiceps* (Bancroft), which indicate the overlying Woolstonian (=Upper Longvillian) Substage. The base of the overlying Marshbrookian is difficult to identify in places where diagnostic taxa such as *Broeggerolithus transiens* (Bancroft) are not found, but the site includes some of the best faunas from the substage in the Cross Fell Inlier.

Although the Swindale Limestone in Billy's Beck is fault-bounded, the presence of Cautleyan strata in other faulted blocks here indicates that the base of the formation rests on younger strata than in Swindale Beck (see site report), 3 km to the north-west, where the uppermost part of the Dufton Shale Formation is Pusgillian in age.

Conclusions

Harthwaite Sike, together with the adjacent Billy's Beck, provides important information on the regional stratigraphy of the Dufton Shale Formation and contributes to understanding the late Ordovician history of northern England. Harthwaite Sike has the best exposure of the lowest parts of the Dufton Shale Formation where it rests on the Borrowdale Volcanic Group. Fossils from these basal beds are Longvillian in age and thus demonstrate that the drowning of the volcanic succession was not contemporaneous over northern England, as the corresponding strata in the Lake District are

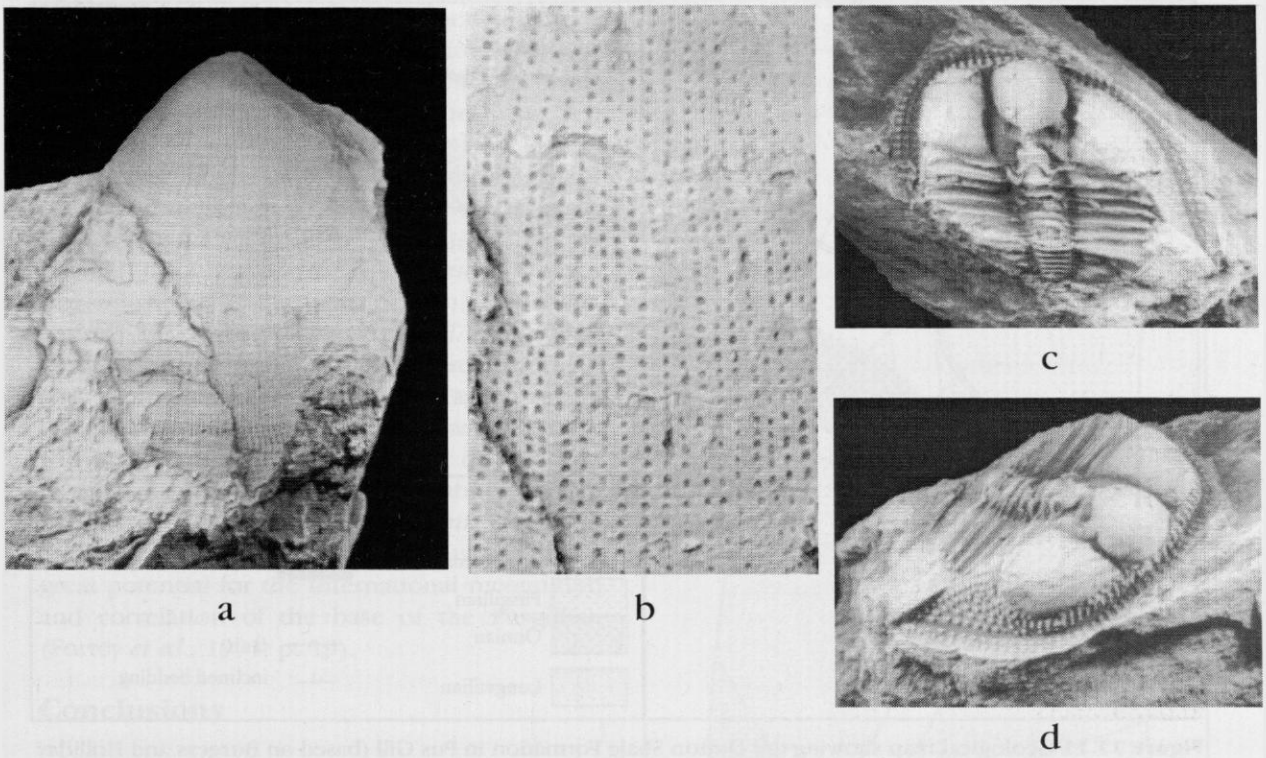

Figure 11.10 Fossils from the Dufton Shale Formation in Pus Gill. (a, b) A brachiopod of the *corona* facies (Longvillian), *Trematis corona* Davidson, ×3, with enlargement of sculpture, ×8. (c, d) Two views of the Pusgillian trilobite *Tretaspis moeldenensis* Cave (*sensu lato*), ×2.

younger, being mid-Ashgill in age.

Overlying shales in Harthwaite Sike include the best outcrops of the Woolstonian and Marshbrookian substages in the Cross Fell Inlier. The adjacent Billy's Beck includes the uppermost parts of the formation together with the Swindale Limestone Formation, which here overlies younger parts of the Dufton Shale Formation (earliest Cautleyan) than in Swindale Beck 3 km to the north-west, where the underlying beds are Pusgillian in age.

PUS GILL (NY 696 256–NY 704 262)

Introduction

The section in Pus Gill shows the only Onnian strata in the Cross Fell Inlier and is the historical type section for the Pusgillian Stage (Bancroft, 1945). The site is the type locality for several fossil species and is of key importance in the correlation of the Dufton Shale Formation and for the international correlation of the standard British chronostratigraphical units at the Caradoc–Ashgill boundary. Together with Swindale Beck, it was considered 'the best exposure of Pusgillian strata in England' by Burgess and Wadge (1974, p. 23), making it a key reference section. However, as the base of the Pusgillian Stage is faulted here, the stratotype base, and thus the base of the Ashgill Series, is now defined in Foggy Gill in the Cautley district (Fortey *et al.*, 1991).

Nicholson and Marr (1891) used Swindale Beck as the type locality for their '*Corona* Series', but Harkness and Nicholson (1877, p. 463) had earlier applied the term '*Discina corona* bed' to a level within this oldest part of the Dufton Shales in Pus Gill, which indeed includes the type locality for the brachiopod *Trematis corona* Davidson (Figure 11.10a, b).

Dean's (1959a) geological map of the site was refined by Burgess and Holliday (1979), who also assigned to the Onnian some of the strata at the eastern end and middle part of the section that were marked on Dean's map as Pusgillian. Extensive faunal lists were provided in both papers.

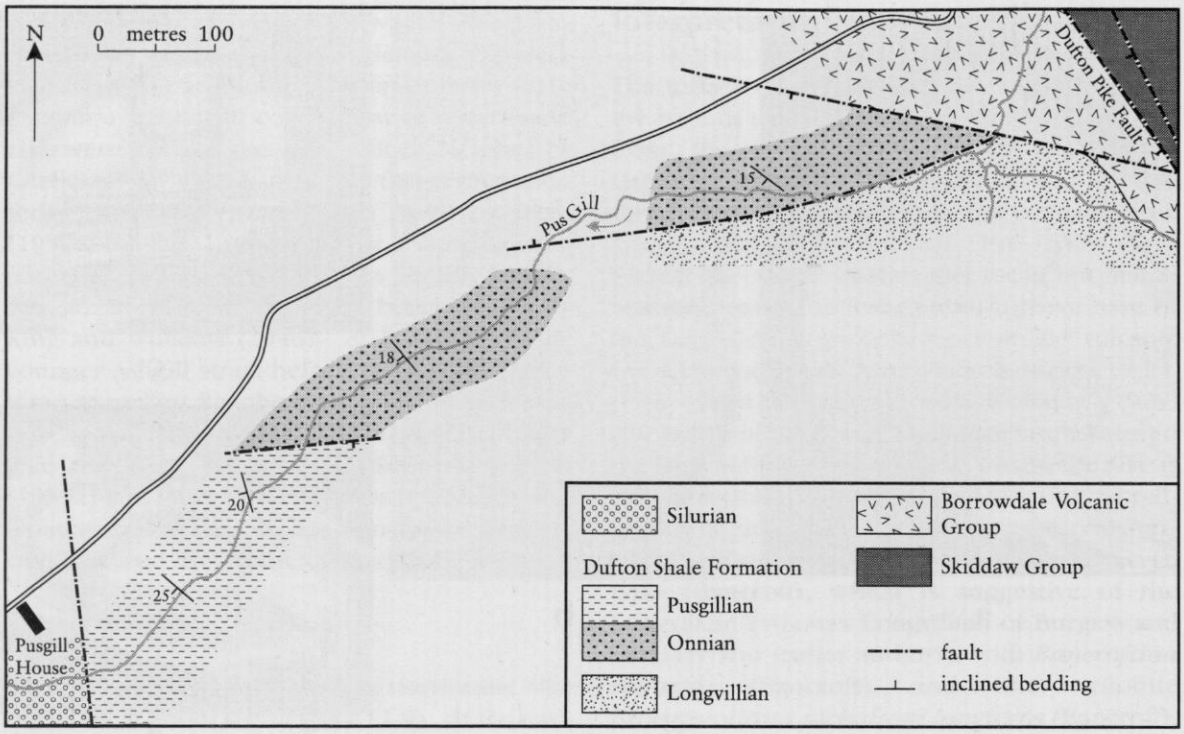

Figure 11.11 Geological map showing the Dufton Shale Formation in Pus Gill (based on Burgess and Holliday (1979, fig. 8) and Dean (1959a, fig. 1).

Description

The Dufton Shale Formation in Pus Gill dips south-west at 15–25° (Figure 11.11). At the eastern end of the site, the sandy volcaniclastic *corona* facies rests stratigraphically on tuffs of the Borrowdale Volcanic Group, but this boundary is cut by a fault that brings the Borrowdale Group into contact with higher Longvillian and Onnian strata. The *corona* facies extends westwards for some 200 m, with Onnian strata faulted against its north-west edge. About 200 m downstream, beyond a gap in exposure, are Onnian strata that are siltier and more calcareous than the Actonian beds of Swindale Beck (Burgess and Holliday, 1979), though the precise relationship between these two substages is not seen in the Cross Fell Inlier.

The boundary between the Onnian and Pusgillian parts of the Dufton Shales is faulted. The Pusgillian outcrops are cut by numerous strike faults and extend for about 270 m downstream to below Pusgill House, where they are faulted against Silurian shales. The Pusgillian rocks are largely dark bluish-grey shales with impure limestone nodules, but in the lower reaches of Pus Gill, the sandy Billy's Beck Member (see the Harthwaite Sike site report) is developed.

Interpretation

The abundant shelly faunas in Pus Gill enable the recognition and correlation of the important Onnian and Pusgillian parts of the Dufton Shale Formation. Lower horizons of the Onnian yield the trinucleid trilobite *Onnia gracilis* (Bancroft): in Shropshire this has its acme in the middle part of the type Onnian Substage (see the Onny River site report) and is succeeded by the *O. superba superba* Local Range Zone. In Pus Gill, *O. gracilis* is succeeded by *Onnia superba pusgillensis* Dean (1961a), to which Owen and Ingham (1988) accorded full specific status. *O. gracilis* and *O. pusgillensis* occur in the same stratigraphical order in the Cautley and Dent area, facilitating correlation within the north of England. Rushton (in Burgess and Holliday, 1979, fig. 11) assigned a specimen of *Onnia* from the southernmost end of the Onnian outcrop in Pus Gill to *Onnia superba superba* (Bancroft). Re-examination of the specimen indicates that it may rather be *O. superba cobboldi* (Bancroft), the nominate species of the

lowest Local Range Zone in the type Onnian. If this identification and correlation are correct, it would be the first direct evidence for the lower part of the Onnian Substage in the Cross Fell Inlier.

The Pusgillian strata have several abundant elements in common with the Onnian beds (Burgess and Holliday, 1979, p. 13), but the trinucleid trilobites *Tretaspis duftonensis* Dean (for which this is the type locality), *T. moeldenensis* Cave (Figure 11.10c, d) and *T. convergens* Dean, together with *Atractopyge scabra* Dean and *Gravicalymene jugifera* Dean, give an unequivocal Pusgillian age and allow correlation with strata in the Cautley and Dent districts. As in those districts, the widespread abundance of species of the brachiopods *Onniella* and *Sericoidea* (or *Chonetoidea*) at Pus Gill holds great potential for the international recognition and correlation of the base of the Pusgillian (Fortey *et al.*, 1991, p. 19).

Conclusions

Pus Gill is of key importance in the correlation of parts of the Dufton Shale Formation and for the international correlation of the British Ordovician standard at the Caradoc–Ashgill boundary. The section contains the only strata of Onnian age in the Cross Fell Inlier and is the historical type section for the Pusgillian Stage. It is the type locality for several species of trilobite, some of which are crucial for correlation with sequences elsewhere.

MELMERBY ROAD (NY 623 383–NY 623 385)

Introduction

This is the most northerly outcrop of the Dufton Shale Formation and is significant because it includes Longvillian strata with a distinctly different fauna from that elsewhere in the Cross Fell Inlier. The Woolstonian strata are the lowest known representatives of that substage in the inlier.

About 1.2 km north-east of Melmerby, the A686 road cuts through the lower parts of the Dufton Shale Formation at the northernmost end of the Cross Fell Inlier. These beds constitute the 'Melmerby Beds' of Dean (1959a), a faunally-based concept now subsumed within the Dufton Shale Formation (Arthurton and Wadge, 1981), which lie within a small faulted inlier of Longvillian, Woolstonian and Ashgill rocks (Figure 11.12). Dean (1959a, p. 210) discussed earlier work, especially that of Bancroft (1933, in Lamont, 1948), described the road section and

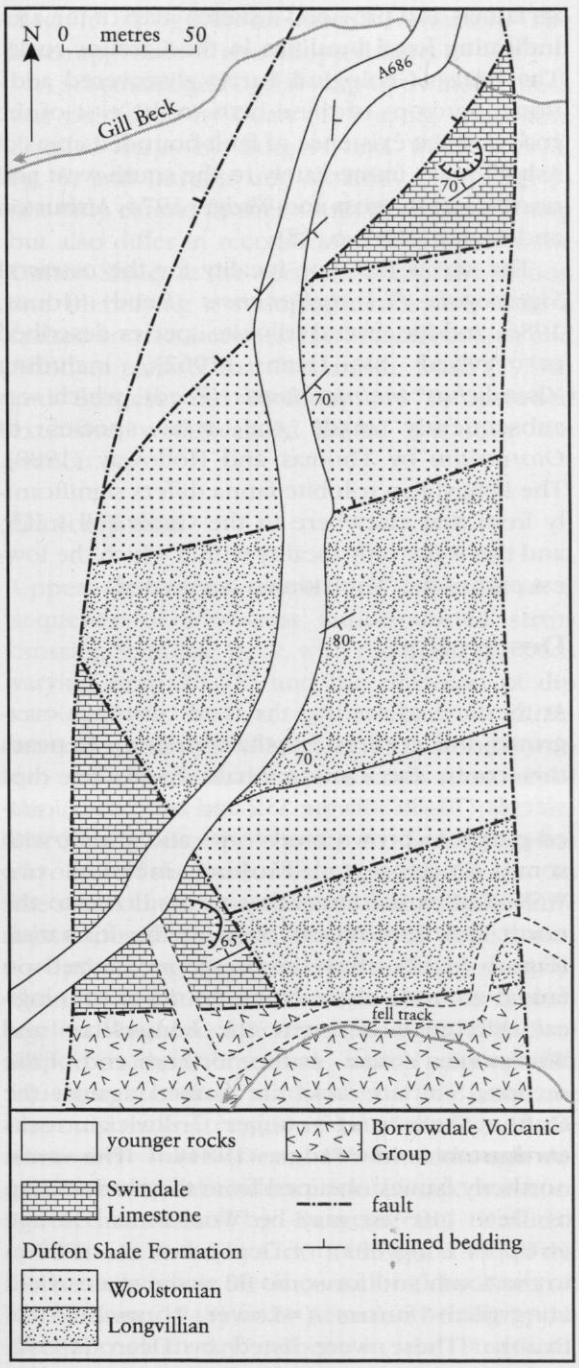

Figure 11.12 Geological map showing the Dufton Shale Formation and Swindale Limestone in and adjacent to the Melmerby Road section, based on Burgess and Wadge (1974, fig. 7) and Arthurton and Wadge (1981, fig. 9).

its faunas and provided a sketch-map of the area indicating fossil localities in the Caradoc rocks. The British Geological Survey discovered additional outcrops of these beds to the east of the road and the existence of fault-bounded areas of Ashgill rocks immediately to the south-west and north-east (Burgess and Wadge, 1974; Arthurton and Wadge, 1981, p. 18).

The site is the type locality for the ostracod *Sigmoopsis (S.) duftonensis* (Reed) (Jones, 1986) and for several trilobite species described or revised by Dean (1962), including '*Conolichas*' *melmerbiensis* (Reed), which was subsequently made the type species of *Otorozoum* by Thomas and Holloway (1988). The Longvillian trilobite fauna differs significantly from that elsewhere in the Cross Fell Inlier, and this is the only locality within which the lowest part of the Woolstonian is exposed.

Description

At the time of writing, the road cutting is overgrown and covered by shale debris. Beneath this cover, the Dufton Shale Formation dips steeply (70–80°) to the SSE and comprises jointed purple to brown mudstones and shales, with some limestones. Faulting includes two WSW–ENE strike faults that throw down to the north and thus repeat parts of the formation (Figure 11.12); these faults are recognized on faunal grounds, there being no major lithological difference between the Longvillian and Woolstonian strata. At the northern end of the section, Silurian rocks are faulted against the Dufton Shales and younger Ordovician rocks (Arthurton and Wadge, 1981). The most northerly faunas obtained from the road section by Dean (1959a) may be Woolstonian in age (=Upper Longvillian of Dean), but about 60 m to the south and for some 80 m the shales yield Longvillian faunas (=Lower Longvillian of Dean). These were listed by Dean (1959a, p. 212) and augmented by Rushton and Wadge (in Arthurton and Wadge, 1981). The southernmost outcrop of shales is early Woolstonian in age and includes at least one nodular limestone that weathers to a rottenstone revealing a prolific shelly fauna (Dean, 1959a, p. 212). The boundary between the Longvillian and Woolstonian is not exposed. Importantly though, the Woolstonian faunas are the lowest ones known from the entire Cross Fell Inlier (Dean, 1962, p. 71). Immediately south of the road section, outcrops of Dufton Shales show the southward extent of the Woolstonian Substage and a further repeat of the Longvillian strata.

Trenching to the south-west and north-east of the Dufton Shales of the road section revealed limestones and mudstones containing an Ashgill fauna (Rushton and Wadge, in Arthurton and Wadge, 1981). These were assigned to the 'Swindale Shales', a term rejected by Bassett *et al.* (1992, p. 121) in favour of the older name 'Swindale Limestone' (see Swindale Beck site report).

Interpretation

Dean (1959a) termed the Ordovician strata in the Melmerby cutting the 'Melmerby Beds' on account of the marked differences in fauna from equivalent strata elsewhere in the Cross Fell Inlier. Whilst this usage has not been followed, the lateral faunal differences in the lower part of the Dufton Shales are evident, though their palaeoenvironmental significance has yet to be interpreted. In addition to various trilobite species known only from here, the abundance of *Kloucekia apiculata* (M'Coy) and *Broeggerolithus nicholsoni* (Reed) suggests greater affinities to Longvillian faunas of North Wales (Whittington, 1968, p. 114) and the Lake District than those of the rest of the Cross Fell Inlier.

Conclusions

This is the most northerly outcrop of the Dufton Shale Formation in the Cross Fell Inlier. Fossil faunas indicate that the palaeoenvironment here during the Longvillian was different from that farther south in the inlier, and that the earliest part of the Woolstonian Substage is present here but unknown from the rest of the inlier.

SWINDALE BECK (NY 688 275–NY 689 278)

Introduction

Swindale Beck is the most important stratigraphical section in the Cross Fell Inlier. It contains the most complete representation of the Dufton Shale Formation, showing parts of the Longvillian to Actonian and the upper Pusgillian. It is also the type locality for several Pusgillian trilobites and for the Swindale Limestone

Formation, which is a candidate for defining the base of the Rawtheyan Stage. The southern end of the section contains the only exposures of the uppermost Ordovician Ashgill Formation in the Cross Fell Inlier.

When Harkness and Nicholson (1877) proposed the term 'Dufton Shales', Swindale Beck was the only section they described in detail; their concept was close to modern usage. Dean (1959a, p. 191) suggested that Swindale Beck should be considered the type locality for the formation, even though he excluded the so-called basal '*corona* Beds' (the '*corona* facies' of Burgess and Holliday, 1979, p. 9) from his concept of the Dufton Shales. Nicholson and Marr (1891) used Swindale Beck as the type locality for their '*Corona* Series' although Harkness and Nicholson (1877) first applied the term '*Discina corona* Bed' to strata in Pus Gill. Dean (1959a) summarized much of this early terminology, and it is clear that the Swindale Beck section has considerable historical significance.

Virtually all of the stages and substages known to be represented in the Dufton Shale Formation are present in Swindale Beck; only the Onnian Substage of the Streffordian Stage and the lower Cautleyan Stage are unrepresented. The extensive outcrop of Pusgillian strata in Swindale Beck is the source of the type material of several trilobite species (Dean, 1961a, 1962).

The Dufton Shale Formation is overlain unconformably by the Swindale Limestone of Dean (1959a) (=*Staurocephalus* Limestone of earlier authors), for which this is the type locality (Kneller *et al.*, 1994, p. 240). Elsewhere in the Cross Fell Inlier, the Swindale Limestone includes much mudstone, and accordingly Burgess and Wadge (1974) and Burgess and Holliday (1979) included the Swindale Limestone as a lower member of their 'Swindale Shales', which also included shales of latest Ordovician (Hirnantian) age that are seen only in Swindale Beck. Bassett *et al.* (1992, p. 121) argued that these upper shales are the direct equivalents of the Ashgill Formation of the Lake District (see the Ashgill Quarry site report) and that that term can be applied in Cross Fell. Kneller *et al.* (1994, p. 240) included the Swindale Limestone as a member of the Swindale Shale Formation in their appended list of retained lithostratigraphical names; however, in their text (1994, p. 229, fig. 5) they gave formation status to the Swindale Limestone and included it as such on their regional correlation diagram, along with the Ashgill Formation. The latter approach is also adopted here.

A schematic geological map of Swindale Beck was published by Dean (1959a, fig. 2). More detailed maps by Burgess and Wadge (1974, fig. 6) and Burgess and Holliday (1979, fig. 9) not only extend farther south than Dean's map but also differ in recognizing older parts of the Dufton Shales at the northern end of the section and identifying a stratigraphical rather than a faulted contact between the Marshbrookian and Actonian parts of that formation. Dean (1959a) and Burgess and Holliday (1979) included extensive, well-localized faunal lists from the section.

Description

Upper Ordovician rocks are exposed in a sequence of west–east fault-bounded strips crossing Swindale Beck, with the dip of the beds varying from 20–75° and the direction of dip varying from south-east (the dominant direction) to south-west (Figure 11.13). At the northern end of the site, tuffaceous sandy siltstones of the *corona* facies of Longvillian age (see the Harthwaite Sike site report) are faulted against rhyolites of the Borrowdale Volcanic Group. To the south, the *corona* facies is faulted against the best exposed and most fossiliferous Woolstonian (=Upper Longvillian of earlier authors) shales in the Cross Fell Inlier. These in turn are faulted against Marshbrookian mudstones with bands of impure nodular limestone, which pass up into blue-grey Actonian mudstones. The latter are the only rocks accepted to be of that age in the Cross Fell Inlier (Dean, 1959a), although the palaeontological evidence for this age was considered tenuous by Burgess and Holliday (1979). As noted by Dean (1959a), some of the beds in Swindale Beck considered by Bancroft (in Lamont, 1948) to be Actonian belong in the Marshbrookian and others in the Pusgillian. There is a second faulted strip of Marshbrookian beds between the Actonian and Pusgillian parts of the section. The extensive outcrops of Pusgillian beds comprise blue-grey mudrocks and impure limestones, and in their upper parts sandy shales of the Billy's Beck Member with upper Pusgillian faunas are developed. The Pusgillian beds and the unconformably overlying Swindale Limestone are repeated by a strike fault.

The lithological change to the grey, nodular

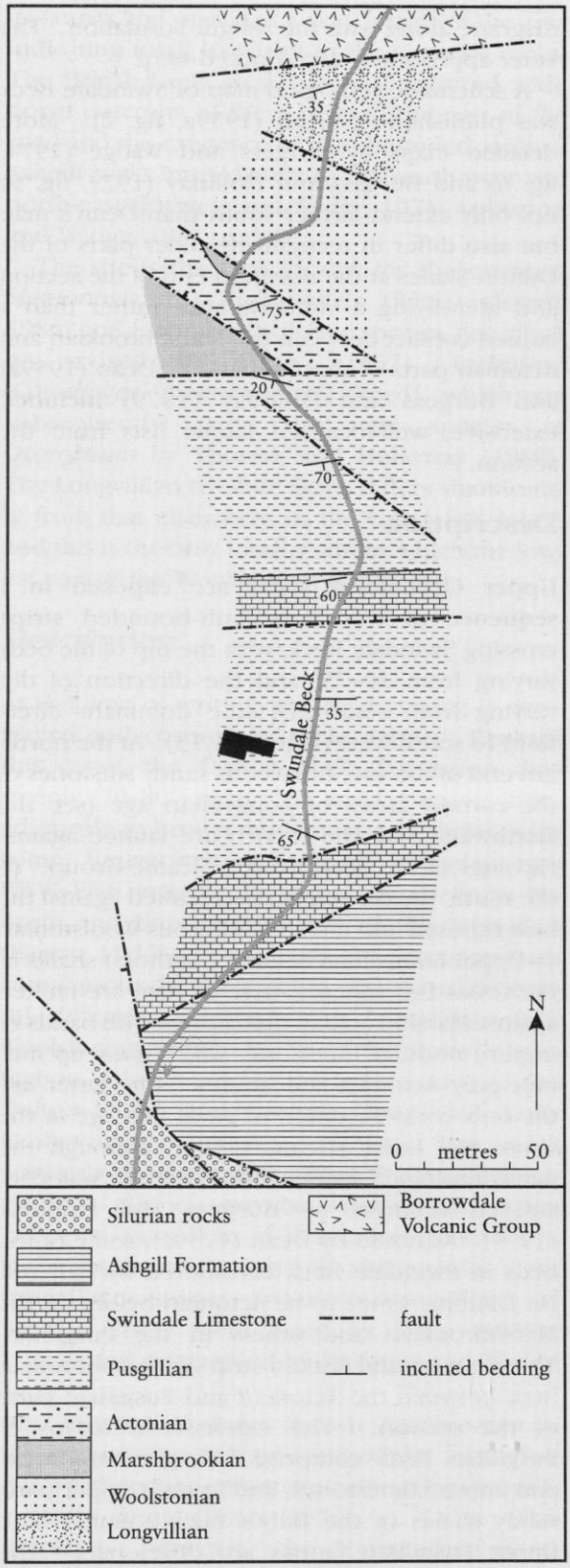

Figure 11.13 Geological map showing the Dufton Shale Formation, Swindale Limestone and Ashgill Formation in Swindale Beck, Knock, based on Burgess and Wadge (1974, fig. 6).

Swindale Limestone is abrupt, and only the faunal evidence indicates the extent of the unconformity. Burgess and Holliday (1979, p. 18) gave a composite section through the 18.7 m of the formation in Swindale Beck that includes 4.9 m of pale-grey mudstone with limestone nodules 1.8 m above the base. At the southern end of the section, the Swindale Limestone is faulted against silty mudstones of the Ashgill Formation, including slightly calcareous beds at the base.

Interpretation

The diverse, shelly faunas characterize, with varying degrees of certainty, the chronostratigraphical units represented by the Dufton Shale Formation and aid its correlation with sequences elsewhere. The Pusgillian rocks in particular yielded the type material of six trilobite species established by Dean (1959b, 1961a, 1962), including the type species of *Duftonia*, *D. lacunosa*. This species, together with two of the others, *Tretaspis convergens* Dean (now *T. hadelandica convergens*) and *Gravicalymene jugifera* Dean, and one subsequently synonymized with *Brongniartella sedgwicki* (Salter), have proved to be of great value for correlation of part of the succession in the Cautley and Dent districts.

The Swindale Limestone overlies Pusgillian beds of the Dufton Shale Formation in Swindale Beck, whereas in Billy's Beck, 3 km to the southeast, it rests on lower Cautleyan strata, indicating a northward increase in depth of erosion beneath the unconformity (Burgess and Holliday, 1979, p. 18, fig. 12). The Swindale Limestone yields an abundant shelly fauna from decalcified limestones and from the associated mudstones. The age of the Swindale Limestone has been the subject of some debate. A mid-Rawtheyan age was suggested by Ingham (1966, 1977) and Ingham and McNamara (1978), but subsequently Price (1981) described *Tretaspis* cf. *radialis* Lamont from Swindale Beck and Billy's Beck and a new species, *T. caritus*, from Swindale Beck. These indicate a late Cautleyan to earliest Rawtheyan age, slightly older than had previously been thought. Fortey *et al.* (1995, p. 26) suggested that the base of the Rawtheyan Stage may eventually be defined within the Swindale Limestone, here or in Billy's Beck.

The slightly calcareous basal parts of the Ashgill Formation contain a fairly diverse

Hirnantia brachiopod fauna and the trilobites *Mucronaspis mucronata* (Brongniart) and *M. olini* (Temple)? (Temple, 1952; Burgess and Holliday, 1979). These beds have yielded the conodonts *Amorphognathus ordovicicus* and *Hamarodus europaeus* (Orchard, 1980; Bergström and Orchard, 1985), and cystoids collected by Paul (1973–1997) may also be from here. Bassett *et al.* (1992, p. 121) noted the similarity of these beds to the basal part of the Ashgill Shale Formation elsewhere in northern England. The overlying shales contain a less diverse *Hirnantia* fauna.

Conclusions

Swindale Beck is nationally significant, being the best single site for understanding the later Ordovician history of northern England. It is the most complete representation of the Caradoc and Ashgill series in northern England, and its fossil faunas are critical for correlation with sequences elsewhere. It is the type locality for the Swindale Limestone, and the stratotype base of the Rawtheyan Stage may eventually be defined within the Swindale Limestone in Swindale Beck.

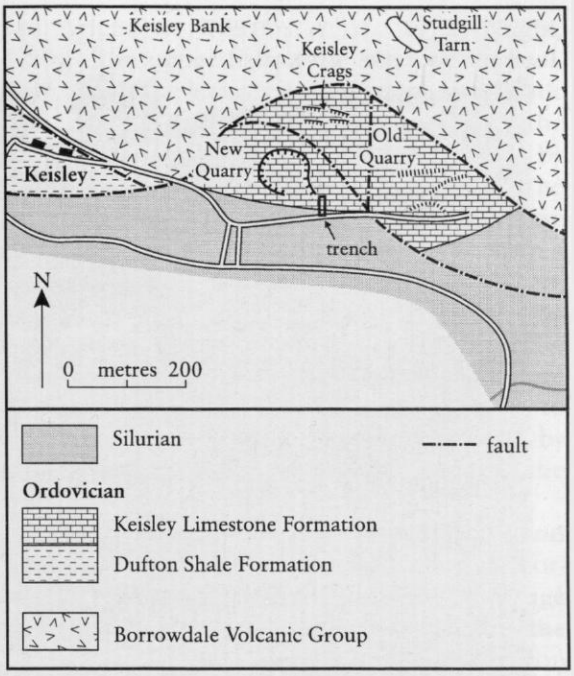

Figure 11.14 Geological map of the Keisley area, after Burgess and Holliday (1979, fig.13). The Ordovician–Silurian boundary section in the trench across the track to the New Quarry was described by Wright (1985).

KEISLEY QUARRY (NY 714 238)

Introduction

The area in and around Keisley Quarry contains the only outcrop of the Keisley Limestone, the best example of an Ordovician carbonate mud-bank in England and one of very few such in the British Isles. It has yielded a diverse shelly fauna, including one of the most widely quoted illaenid–cheirurid trilobite faunas typical of pure carbonate environments. The lower parts of the Keisley Limestone may be as old as Cautleyan and the uppermost part includes a *Hirnantia* fauna, characteristic of the lower part of the Hirnantian Stage. Above it is a conformable sequence across the Ordovician–Silurian boundary, containing graptolite faunas that enable the systemic boundary to be identified to within a few centimetres.

The Keisley Limestone was first referred to by Buckland (1817), who considered it part of the Carboniferous Limestone. Harkness and Nicholson (1877), Nicholson and Marr (1891), Marr (1892, 1906, 1913) and Reed (1896, 1897) described the Keisley Limestone its faunas, and its age and possible relationships to other upper Ordovician limestones in the Lake District and Cross Fell. Wright (1985) summarized the more recent arguments on the age and lithological equivalence of the limestone and described the conformable transition into the Silurian Skelgill Formation. He confirmed a Hirnantian age for the uppermost part of the limestone. Both Cautleyan (e.g. Ingham, 1966) and Rawtheyan (e.g. Dean, 1978) ages for the remainder of the Keisley Limestone have been suggested on the basis of the trilobite faunas (Ingham and Wright, in Williams *et al.*, 1972, p. 47), and Orchard (1980) provided conodont evidence for the presence of both stages.

The succession, setting and faunal composition of the Keisley Limestone were outlined by Burgess and Holliday (1979, p. 19) and descriptions of various aspects of the shelly faunas were given by Reed (1896, 1897), Temple (1968, 1969), Dean (1971–1978), Paul (1973–1997), Donovan (1986–1995) and Donovan and Wright (1995). Conodont faunas have been described by Rhodes (1955), Bergström (1971) and Orchard (1980).

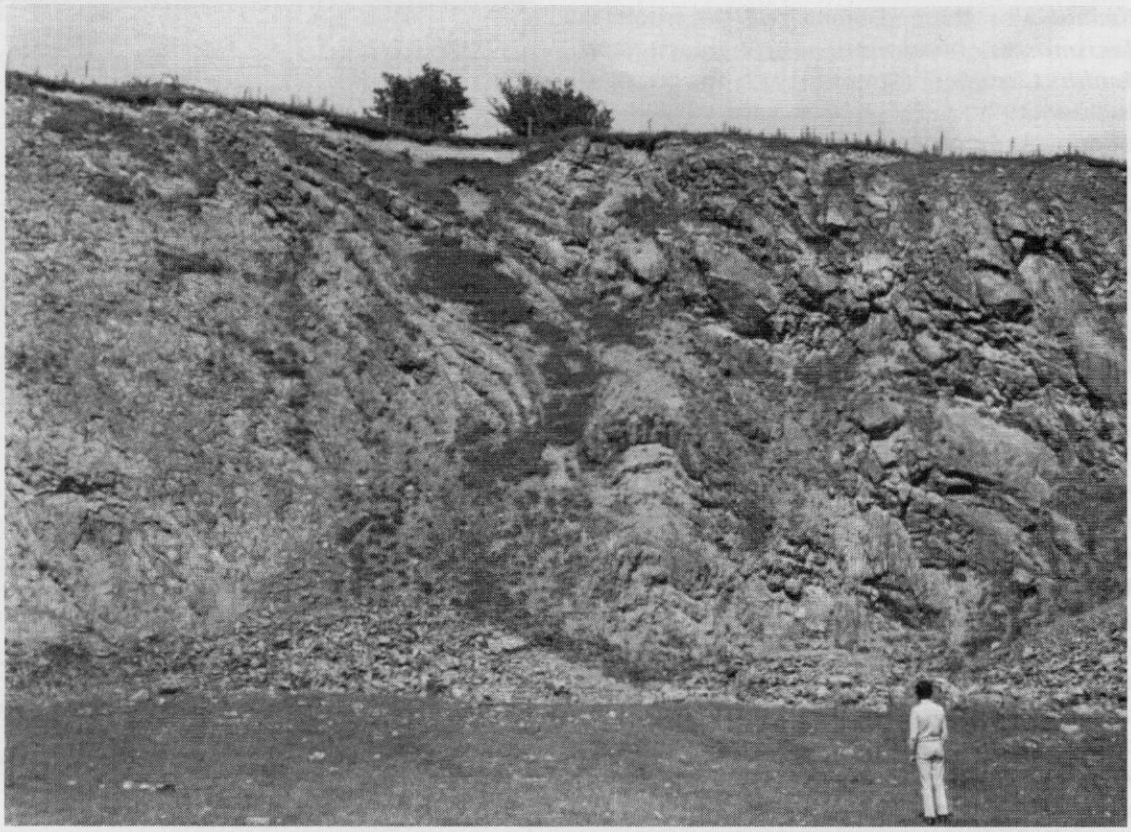

Figure 11.15 Keisley New Quarry, the north part, showing several metres of southward-dipping limestone. The lower beds to the left are nodular with siltstone partings. The more massive overlying beds are disturbed by faulting. (Photo: British Geological Survey photographic collection, L1057.)

Description

The site comprises a western 'New Quarry', and an eastern 'Old Quarry', with Keisley Crags on the hillside to the immediate north (Figure 11.14). These three areas are separated by faults and their stratigraphical interrelationships are not clear. The whole complex is fault-bounded to the north and the relationships with the Dufton Shale Formation are not seen. To the south of the New Quarry, however, there is certainly a conformable passage up into Silurian shales of the Skelgill Formation. Within the Old Quarry, dark-grey siltstones with thin impure limestones are exposed in the core of a west–east striking anticline and are thought to be the oldest part of the Keisley Limestone (locality K16 of Burgess and Holliday, 1979, pp. 13, 20). They are probably fault-bounded and abut strongly jointed massive grey limestones. The north wall of the quarry contains a siltstone that clearly shows the northward dip of the beds on the northern limb of the anticline. Keisley Crags expose some 12 m of south-dipping bedded grey bioclastic limestones, some crinoidal, overlain by about 3 m of white to pink fine-grained limestone with abundant large shelly fossils.

The most continuous section is in the New Quarry, where about 30 m of limestone dips south (Figure 11.15). The lowest beds, at the back of the quarry, are dark-coloured nodular limestones with siltstone partings (informally termed the 'lower Keisley Limestone' by Orchard, 1980). These are overlain by paler, more massive limestones that are locally dolomitized (the upper Keisley Limestone of Orchard, 1980). A temporary trench section in the track to the New Quarry was documented in detail by Wright (1985) and revealed that the limestones and calcareous siltstones of the uppermost part of the Keisley Limestone are capped by a thin (7 cm) synsedimentary breccia overlain by 24 cm of siltstone, succeeded in turn by black shales

with bentonites.

Interpretation

The detailed sedimentology and environmental interpretation of the Keisley Limestone have yet to be described. Many authors have considered it to be some kind of reef or reef-mound, and most recently Wright (1985) applied the term 'carbonate mudmound'. The limestone is locally richly fossiliferous, although structural complexity and the poorly localized nature of much of the early sampling means that the internal stratigraphy and the range of species is not fully clear. Burgess and Holliday (1979, p. 20) noted that a substantial part of the shelly fauna is from the middle of the succession and that its composition varies markedly from sample to sample. Moreover, the shelly fauna is very much a 'facies fauna', which further hinders precise correlation with the standard Ashgill biozonation. Thus, Dean (1978) demonstrated statistically the long-recognized generic similarity of the trilobite fauna to those of the Chair of Kildare Limestone (probably Rawtheyan) in eastern Ireland and the Boda Limestone (upper Pusgillian to Rawtheyan) of Dalarne, Sweden. All are examples of the illaenid–cheirurid trilobite biofacies that occupied pure carbonate environments from the Arenig to the Devonian (Owen *et al.*, 1991, p. 816, and references therein). Some of the arguments on the age of the shelly faunas have hinged on the possible equivalence of the Keisley Limestone to the Swindale Limestone developed elsewhere in the Cross Fell Inlier (see the Swindale Beck and Melmerby Road site reports). Reconstructions have shown the Swindale Limestone as a tongue-like extension of some part of the Keisley Limestone (Ingham and McNamara, 1978, p. 129, fig. 43; Burgess and Holiday 1979, fig. 12). The Swindale Limestone is now thought to represent a level at about the Cautleyan–Rawtheyan boundary (Price, 1981).

The limestones at the top of the Keisley Limestone, exposed in Wright's (1985, 1988) trench section, contain the calcareous alga *Girvanella* and a *Hirnantia* brachiopod fauna (see the Cwm Hirnant site report), the latter typical of the lower part of the latest Ordovician Hirnantian Stage. The *Hirnantia* fauna described by Temple (1968, 1969) from exposures nearby also belongs in this stage, not the lower Llandovery as thought by Temple (Ingham and Wright, in Williams *et al.*, 1972; Wright, 1985). The upper half of the siltstone immediately above the Keisley Limestone is graptolitic and contains a fauna indicative of the *Glyptograptus persculptus* Zone, succeeded by *Parakidograptus acuminatus* Zone faunas. The boundary between the two zones marks the base of the Silurian, which can be located to within a few centimetres. The overlying black shales contain graptolites of the *Atavograptus atavus* Zone. The sedimentological implications of the lithological changes in the trench section were discussed by Brenchley (1988) and conform to the global pattern of regression followed by abrupt transgression near the end of the Hirnantian.

If the conodont data of Orchard (1980) and some of the trilobite-based correlations are correct, the Keisley Limestone may range in age from a level within the Cautleyan to well into the Hirnantian. The Ashgill Shale Formation exposed in Swindale Beck (see site report) must be a lateral equivalent of the uppermost part of the Keisley Limestone and the Swindale Limestone an equivalent of its lower parts.

Conclusions

The Keisley Limestone is the sole example of a carbonate mudmound in the Ordovician of Britain. Its diverse shelly faunas include a prime example of an illaenid–cheirurid trilobite fauna – an ecological assemblage typical of pure carbonate environments. The top of the Keisley Limestone contains shelly fossils of the lower Hirnantian *Hirnantia* fauna, and it is succeeded by graptolitic rocks, within which the Ordovician–Silurian boundary can be recognized precisely.

CAUTLEY INLIERS

The Cautley and Dent areas have several small inliers of the Dent Group that show a relatively complete sequence of the Ashgill Series, which, though much faulted, serves as its type succession.

Ingham (1966) gave a detailed account of the late Caradoc and Ashgill succession in all of the Cautley and Dent inliers and outlined the historical development of its terminology and correlation, in particular the work of Marr (1913) and King and Williams (1948) in recognizing faunal divisions within the mudstone-dominated

sequence. Ingham (1966) introduced the term 'Cautley Mudstones' for all but the uppermost part of the Ordovician here and subdivided the post-Pusgillian part of the succession into eight numbered assemblage biozones, largely on the basis of their trilobite faunas. Ingham and Wright (1970) assigned the Pusgillian Stage to the Ashgill Series and established the Cautleyan Stage to comprise Ingham's Zones 1–4 and the Rawtheyan Stage for Ingham's Zones 5–7. They defined the base of the Rawtheyan Stage in faulted ground in the eastern part of the Ecker Secker Beck site (SD 708 952), but more recently, Ingham (in Fortey *et al.*, 1995, p. 26) has suggested that an unfaulted base might be defined within the Swindale Limestone Formation of the Cross Fell Inlier (see the Swindale Beck site report).

Ingham and Wright (1970) revived Bancroft's Hirnantian Stage (see the Cwm Hirnant site report) for the uppermost division of the Ordovician and placed the base of the Hirnantian in the Cautley area at the base of the Cystoid Limestone of Ingham (1966). This lies above a stratigraphical break that, in the Taythes Inlier, extends down to near the base of the Rawtheyan. Subsequently, Ingham and Wright (in Williams *et al.*, 1972) reassigned the Cystoid Limestone to the top of the Rawtheyan, placing the base of the Hirnantian at the base of the overlying Ashgill Shale Formation.

The Sally Beck site contains representatives of all parts of the succession and, in particular, displays at Foggy Gill a continuous sequence from the Onnian to Pusgillian that is taken to typify the base of the Ashgill Series. The lower Cautleyan and Rawtheyan successions are well displayed at Backside Beck and the upper Cautleyan at Ecker Secker Beck.

SALLY BECK AND RIVER RAWTHEY (SD 707 978–SD 715 992 AND SD 708 978–SD 724 994)

Introduction

This is an internationally important site for the definition and correlation of the Ashgill Series, and includes the basal stratotype. It is the type locality for the Cautleyan Stage and includes outcrops of the uppermost Caradoc and all the Ashgill zones. The type localities of a large number of shelly fossil species, especially trilobites (Ingham, 1970–1977), are also here.

The site comprises most of the Ordovician rocks in the Murthwaite Inlier, the most northeasterly of the Cautley inliers. Ingham (1966, pl. 25; 1970, fig. 3) published a geological map of the Murthwaite Inlier, and Fortey *et al.* (1991, fig. 6) included a detailed map of the basal Ashgill stratotype locality, in Foggy Gill (7185 9845).

Description

The main exposures within the Murthwaite Inlier are along the River Rawthey in the south and its two major tributaries, which flow south through the inlier: Sally Beck in the east and Wandale Beck in the west (Figure 11.16). The structure of the Ordovician rocks is essentially an anticline that plunges steeply westwards, but this is complicated by faulting, including a belt of NE–SW sinistral wrench faults. The inlier abuts Carboniferous strata in the east along the Dent Fault.

The oldest parts of the Cautley Mudstones are latest Caradoc (Onnian) in age and crop out close to the Dent Fault, to the immediate west and north of Foggygill Farm. Natural outcrops allow the base of the overlying Pusgillian Stage to be mapped fairly closely, and excavations by Drs J.K. Ingham and A.W. Owen in 1988 in the bank above Foggy Gill, a tributary of Sally Beck, enabled the base of the stage, and therefore the base of the Ashgill Series, to be defined formally on the basis of changes in the shelly faunas (Fortey *et al.*, 1991, p. 18).

Pusgillian strata are well exposed in and around Foggy Gill and in Sally Beck itself, both west of Foggygill Farm and at the northern end of the inlier (Figure 11.16). The upper part of the stage is well exposed in the stream south of Sally Brow (717 986), where there is a continuous section extending up into Cautleyan Zone 2. This was chosen as the type locality of the Cautleyan Stage by Ingham and Wright (1970, p. 237), with the base of the stage situated between Ingham's (1966) localities S58 and S59 in the eastern part of the section. In this inlier the stage comprises at least 250 m of beds.

The overlying Zone 3 is well seen in the stream sections near High Sprintgill Farm, 500 m NNE of Sally Brow, and Zone 4 is well developed in Sally Beck near the footbridge to Murthwaite Farm (716 982). The lowest part of the Rawtheyan Stage (Zone 5) is seen in direct succession to beds of Zone 4 in the stream 70 m

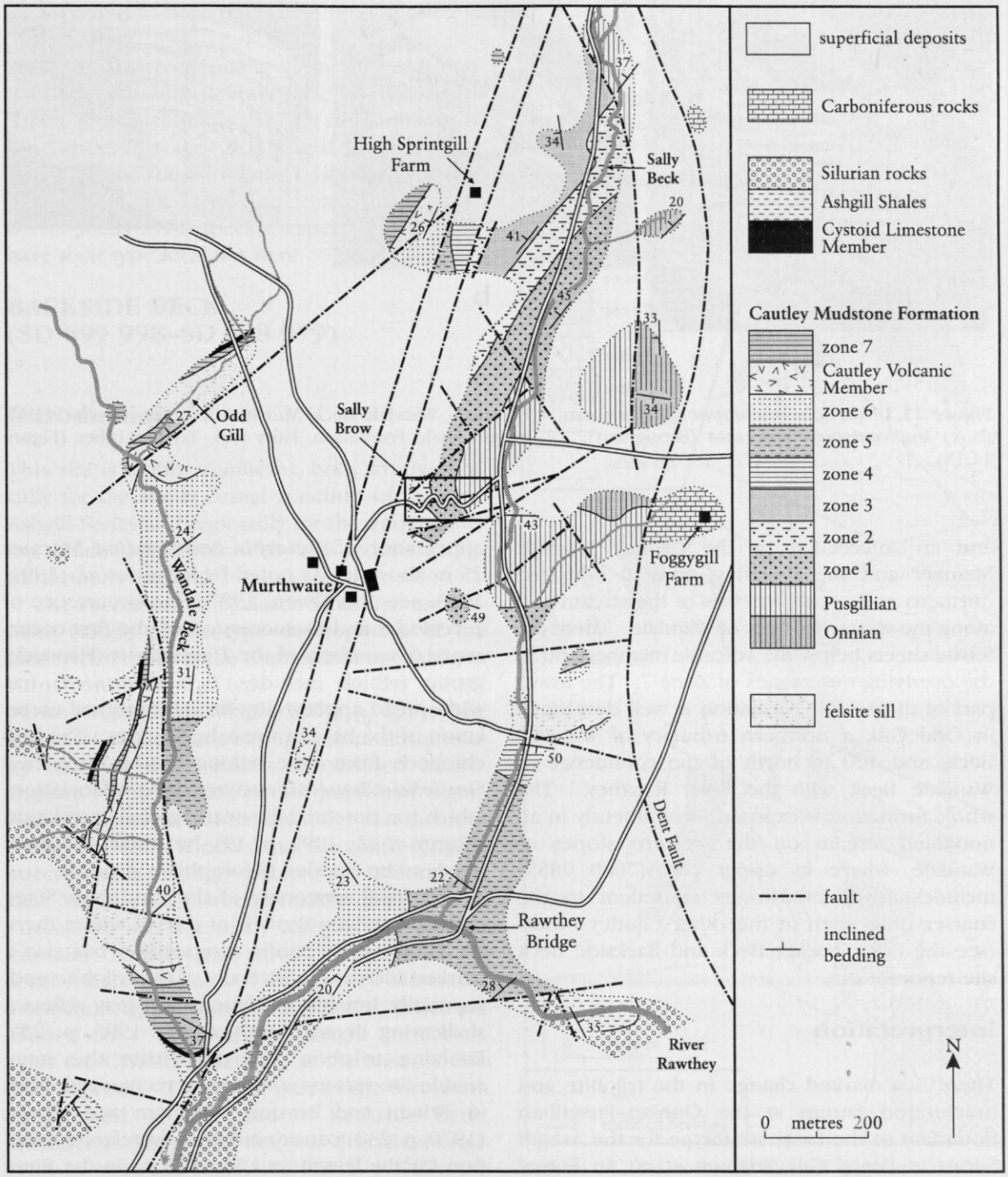

Figure 11.16 Geological map of the area around Sally Beck, the River Rawthey and Wandale Beck, in the Murthwaite Inlier of the Cautley district, based on Ingham (1966, pl. 25) and Ingham (1970–1977, fig. 3).

south of High Sprintgill (Figure 11.16), but the best exposures of Zones 5 and 6 are in the River Rawthey (714 977–709 979). The base of the stage is not seen here, but Zone 6 is complete; its base lies some 120 m WNW of Rawthey Bridge. A further 350 m downstream, at the western end of the section, flaggy mudstones and thin nodular limestones of Zone 6 are succeeded by buff-coloured tuffs of the Cautley Volcanic Member at the base of Zone 7. Fossiliferous mudstones of Zone 6 crop out along much of Wandale Beck (cf. Figure 11.17a)

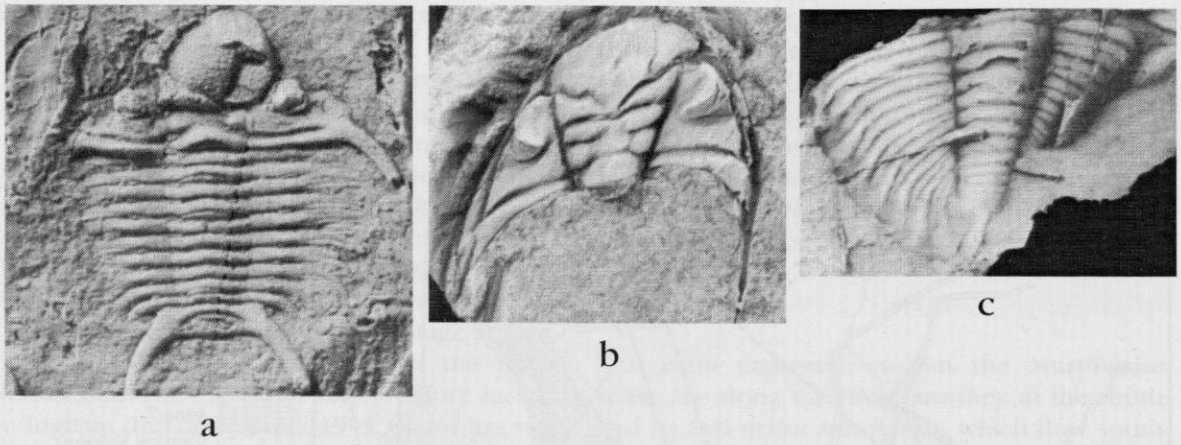

Figure 11.17 (a) *Sphaerocoryphe kingi* Ingham, ×5, Zone 6, Wandale Beck, Murthwaite Inlier (Figure 11.16). (b, c) *Mucronaspis mucronata* (Brongniart), ×2, Ashgill Shale Formation, Fairy Gill, Taythes Inlier (Figure 11.19).

and are succeeded by the Cautley Volcanic Member and the overlying units at both the northern and southern ends of the stream and along the western slopes of Wandale. There are felsite sheets below the volcanic member and in the overlying mudstones of Zone 7. The lower part of the Ashgill Formation is well developed in Odd Gill, a northern tributary of Wandale Beck, and 120 m north of the confluence of Wandale Beck with the River Rawthey. The whole formation is exposed intermittently in an unnamed stream on the western slopes of Wandale, where its upper part (7080 9855) includes sandy mudstones equivalent to the coarser units seen in the other Cautley inliers (see the Ecker Secker Beck and Backside Beck site reports).

Interpretation

There is a marked change in the trilobite and brachiopod faunas at the Onnian–Pusgillian boundary in the basal stratotype for the Ashgill Series in Foggy Gill (Ingham *et al.*, in Fortey *et* al., 1991, fig. 7; Fortey *et al.*, 1995, p. 23). The trilobites *Onnia pusgillensis* Dean and *Flexicalymene onniensis lata* Ingham disappear immediately below the boundary and *Brongniartella bulbosa* Ingham and *Gravicalymene jugifera* Dean make their first appearance at the boundary. Slightly less closely constrained but of wider international significance are the disappearance of *Tretaspis ceriodes* (Angelin) just below the boundary and the appearance of *Tretaspis hadelandica* Størmer 25 m above it. As noted by Fortey *et al.* (1991, 1995; see also Owen, 1987), the occurrence of *T. ceriodes* and its succession by the first occurrence of members of the *T. seticornis* (Hisinger) group (which includes *T. hadelandica*) has widespread applicability for international correlation of the base of the Ashgill Series. The brachiopods from here belong to the deep-shelf *Onniella–Chonetoidea/Sericoidea* association, which has potential for nearly global correlation (Fortey *et al.*, 1991, p. 19), but their taxonomy needs to be clarified before this is possible.

The basal stratotype of the Cautleyan Stage defined on Sally Brow is at a level where there are changes in specific composition but also a marked increase in diversity of the trilobite and, especially, brachiopod faunas that may reflect a shallowing event (Fortey *et al.*, 1995, p. 25). Evolving trilobite lineages within the stage enable the various zones to be recognized, both in Britain and beyond. Ingham and Wright (1970, p. 238) considered the best reference section for the Rawtheyan Stage to be in the River Rawthey section, although the basal stratotype is better defined elsewhere (see the Ecker Secker Beck and Swindale Beck site reports). Ingham (1966, p. 474) estimated that the Cautley Volcanic Member, at the base of Zone 7, is about 12 m thick in the Murthwaite Inlier – much less than its thickness in the Westerdale Inlier, which he considered to have been more proximal to the volcanic source (see the Backside Beck site report).

Conclusions

This site is internationally important as it contains the formally defined base of the Ashgill Series. It also contains the type development of the Cautleyan stage, including its basal boundary, and the best reference section for the Rawtheyan Stage in its type area. A large number of shelly fossil species, especially trilobites, have their type localities here.

BACKSIDE BECK (SD 699 998–SD 698 979)

Introduction

This site is highly significant, both stratigraphically for the shelly faunal zonation of the type Ashgill Series and regionally for the understanding of late Ashgill volcanicity and sedimentation in northern England.

The succession in Backside Beck was used by Marr (1913) as the type development of the Ordovician rocks of the Cautley inliers, which, in turn, constitute the type area for the Ashgill Series (Ingham and Wright, 1970, p. 233). The historical and current stratigraphical terminology used in these inliers is outlined above. Ingham (1966, p. 462, pl. 26) published a geological map of the Westerdale Inlier that includes Backside Beck. He noted that the gently dipping succession is strongly affected by faulting but that Marr's (1913) interpretation of the faunal succession was essentially correct. The section contains outcrops and typical faunas of all the local Ashgill divisions of the Cautley Mudstone Formation, apart from Zones 3 and 4, which are faulted out. The overlying Ashgill Formation, with the Cystoid Limestone at the base, is also well exposed. The upper part of the formation in Spengill, at the head of Backside Beck, includes a coarser unit that was described originally by Marr and Nicholson (1888, p. 700); the succession across the Ordovician–Silurian Boundary here was discussed by Rickards (1970, 1978, 1988). Brenchley (1984) outlined the geochemistry of the succession from the upper Rawtheyan to the lower Silurian in Spengill.

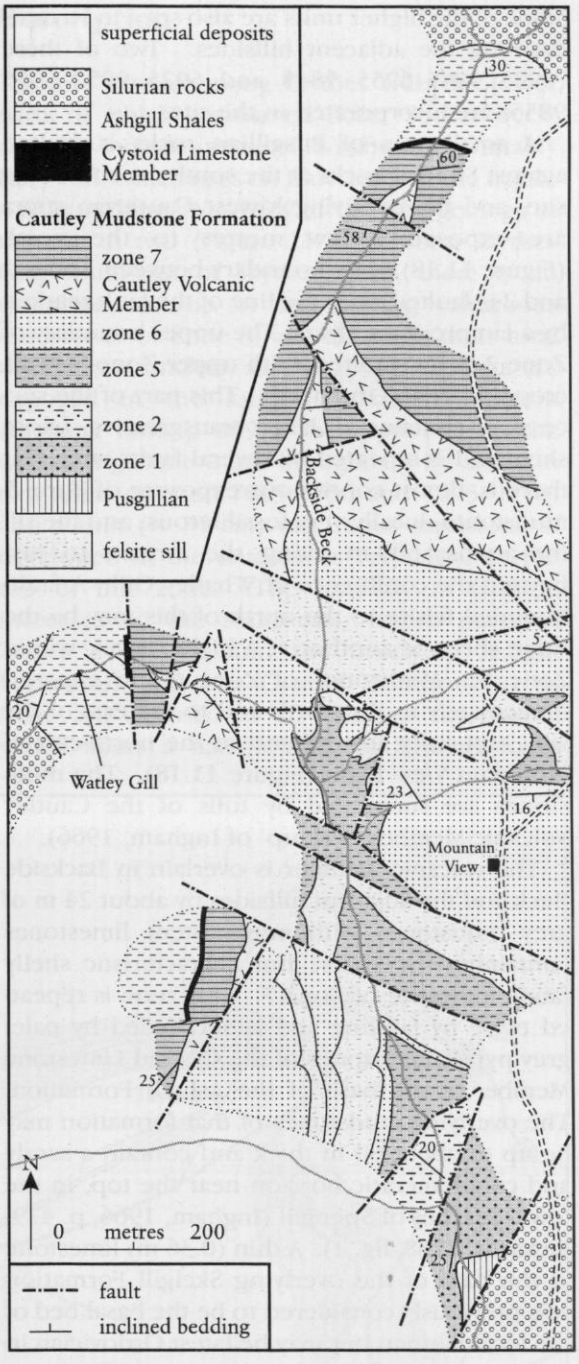

Figure 11.18 Geological map of the Backside Beck area of the Westerdale Inlier, Cautley district, based on Ingham (1966, pl. 26) and Ingham (1970–1977, fig. 4).

Description

Backside Beck flows southwards through the Westerdale Inlier (Figure 11.18). The succession has a fairly gentle (15–30°) northward dip, but extensive faulting, especially at the southern end of the site, is probably responsible for departures from this pattern. In general, the succession youngs northwards along the stream, and

some of the higher units are also seen in streams draining the adjacent hillsides. Two of these (6925 9845–6955 9845 and 6925 9850–6955 9855) are incorporated in the site.

A small area of Pusgillian rocks is faulted against Silurian rocks at the southern end of the site, and the overlying lowest Cautleyan strata are exposed a few metres to the north (Figure 11.18). The boundary between Zones 1 and 2 is faulted, with the line of the fault marked by a lamprophyre dyke. The upper boundary of Zone 2 is also faulted, with upper Zone 5 strata cropping out to the north. This part of the succession contains a large transgressive felsite sheet and is repeated by several faults such that there is almost continuous exposure of Zone 5 mudstones, locally very fossiliferous, and the sill for almost 600 m along the stream to just beyond the confluence of Whatley Gill. A fault-bounded felsite to the north of this may be the same sheet or another at a higher level, within Zone 6. Mudstones of Zone 6 are exposed immediately to the north and to the east of the site, especially around and to the north-east of Mountain View Farm (Figure 11.18). The mudstones are succeeded by tuffs of the Cautley Volcanic Member ('Group' of Ingham, 1966).

The volcanic member is overlain in Backside Beck and the adjacent hillsides by about 24 m of grey mudstones with impersistent limestones containing the sparse but characteristic shelly fauna indicative of Zone 7. This zone is repeated twice by faulting and is succeeded by pale-grey pyritic limestones of the Cystoid Limestone Member at the base of the Ashgill Formation. The overlying mudstones of that formation may be up to about 60 m thick and contain a sandy and conglomeratic horizon near the top, in the lower reaches of Spengill (Ingham, 1966, p. 479; Rickards, 1988, fig. 1). A thin (0.36 m) limestone at the base of the overlying Skelgill Formation was previously considered to be the basal bed of the local Silurian but may be latest Ordovician in age, in view of the modern definition of that system (Rickards, 1988).

Interpretation

In establishing the Rawtheyan Stage, Ingham and Wright (1970, p. 238) highlighted the upper reaches of Backside Beck as containing the best section through Zone 7 in the Cautley inliers. Ingham (1966, p. 474) noted that in the Westerdale Inlier the Cautley Volcanic Member is considerably thicker than in the Murthwaite Inlier (see the Sally Beck site report), where it is about 12 m thick, and that the tuffs in the lower part of the group are coarser. He therefore suggested that the volcanic source lay a short distance to the west of the Westerdale Inlier. Kneller *et al.* (1994) considered that the tuffs may have been emplaced as turbidites or pyroclastic flows into water and equated them with the Appletreeworth Formation of the south-western Lake District, the High Haume Volcanic Formation of the Furness area and the Dam House Bridge Tuff and Jop Ridding Sandstone members of the Sowerthwaite Formation in the Craven Inliers.

In contrast to the Taythes Inlier (see the Ecker Secker Beck site report), where the latest Rawtheyan Cystoid Limestone rests on mudstones of Zone 5, the amount of erosion was much less in the Westerdale Inlier, and it overlies strata of Zone 7. The limestone above the Ashgill Formation may equate to part of the *persculptus* graptolite Zone, and a thin (20 mm) bentonite separates it from shales containing graptolites of the basal Silurian *acuminatus* Zone (Rickards, 1988, fig. 1).

Conclusions

Backside Beck contains the original type development of the Ashgill in the Cautley inliers (themselves the type area for the Ashgill Series). The site is internationally important for the understanding of the shelly faunal zonation of the Ashgill and is the type locality for several species of fossils. It includes the best sections in the Cautley district through Rawtheyan Zone 7 and across the Ordovician–Silurian boundary. The development of a thick, coarse unit of Rawtheyan tuffs and the relatively limited gap below the latest Rawtheyan Cystoid Limestone have wide implications in the interpretation of the Ashgill history of northern England.

ECKER SECKER BECK (SD 696 945–SD 709 952)

Introduction

This site has the best development of the middle Cautleyan Stage (Zone 3) and is an important supplement to the sites at Backside Beck and

Sally Beck. Like them, it is the origin of a large number of species of shelly fossils, especially trilobites (Ingham, 1970–1977) and conodonts (Orchard, 1980; Bergström and Orchard, 1985).

The Ecker Secker Beck site comprises virtually all of the Ordovician exposures in the northern part of the Taythes Inlier, the southernmost of the Cautley inliers. The uppermost Ordovician unit was termed the 'Fairy Gill Shales' by Hughes (1905, p. 369), but subsequent authors have followed Marr (1913) in applying the name 'Ashgill Shales', that of its equivalent in the Lake District (see the Ashgill Quarry site report); this name is now replaced by the 'Ashgill Formation', following Kneller *et al.* (1994), who included the Cystoid Limestone as a local basal member. A calcareous grit within this formation was noted by Dakyns *et al.* (1891) in Ecker Secker Beck and was further commented on by Turner (1961) and Rickards (1970). Ingham (1966, pl. 27; 1970, fig. 6) gave a detailed geological map of the northern part of the Taythes Inlier (Figure 11.19).

Description

The site extends along Taythes Gill, the lower parts of which are named Ecker Secker Beck, and also includes some of its tributaries, notably Fairy Gill, which rises on Bluecaster to the north. A fault striking ENE–WSW divides the geology of the site in two (Figure 11.19). Along Taythes Gill, south-east of Taythes Farm, there is an extensive outcrop of east-dipping calcareous mudstones of Zone 3, and although their total thickness is unclear, almost 100 m of strata are exposed in the longest unfaulted section (Ingham, 1966, p. 469). The upper parts of the underlying Zone 2 are brought up by faults in two areas (around 7065 9550 and 7075 9540) and a thin (< 75 cm) calcareous sandstone is developed in the mudstones very close to the top of this zone. The intensity of faulting increases to the south-east, where parts of Zones 4 and 5, and the overlying Ashgill Formation, with the Cystoid Limestone at its base, are exposed in an inverted succession, which abuts a narrow strip of Silurian rocks

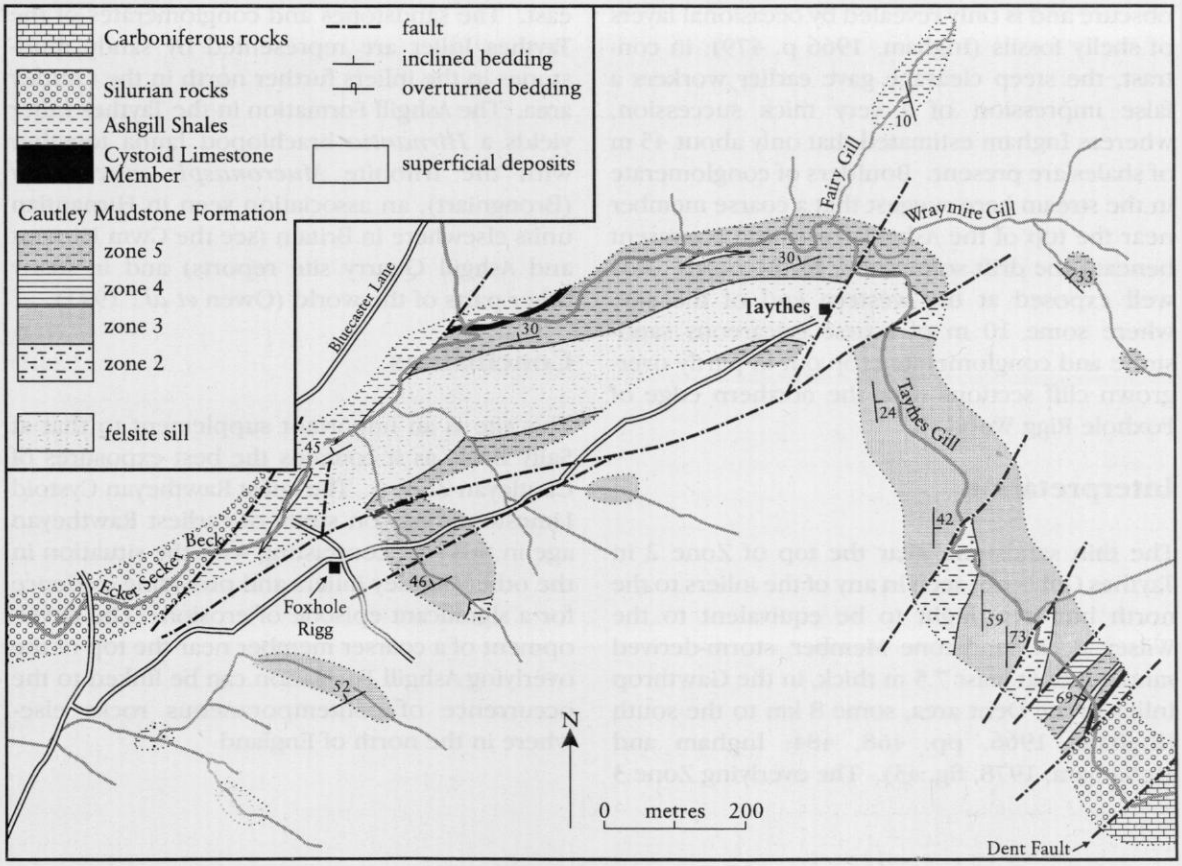

Figure 11.19 Geological map of Ecker Secker Beck, Taythes Gill and Fairy Gill in the northern part of the Taythes Inlier, Cautley district, based on Ingham (1966, pl. 27) and Ingham (1970–1977, fig. 6).

against the Dent Fault (Figure 11.19). The base of the Rawtheyan Stage was originally defined at the base of Zone 5 in Taythes Gill, where there is a marked change in the composition of the trilobite and brachiopod faunas and a diminution in the diversity of the latter (Ingham and Wright, 1970, p. 238). However, a level within the Swindale Limestone in Swindale Beck (see site report) in the Cross Fell Inlier may prove to be a better basal stratotype for the stage.

The northern part of the site, along Ecker Secker Beck to the area around Taythes Farm and Fairy Gill, is composed largely of NW-dipping calcareous mudstones of Zone 5, within which a thick felsite sill has been intruded. The Cystoid Limestone is seen to rest with very slight angular unconformity on mudstones of this zone 500 m to the west of Taythes Farm (6995 9585), but, being unweathered, its does not yield the late Rawtheyan macrofossils known from elsewhere. It is succeeded in both localities by fossiliferous shales of the Ashgill Formation (cf. Figure 11.17b, c); these are best seen in an extensive but isolated outcrop in Fairy Gill (Figure 11.19). The bedding there is obscure and is only revealed by occasional layers of shelly fossils (Ingham, 1966 p. 479); in contrast, the steep cleavage gave earlier workers a false impression of a very thick succession, whereas Ingham estimated that only about 45 m of shales are present. Boulders of conglomerate in the stream here suggest that a coarse member near the top of the Ashgill Formation is present beneath the drift somewhere to the north. It is well exposed at the western end of the site, where some 10 m of coarse calcareous sandstone and conglomerate crop out in partly overgrown cliff sections near the northern edge of Foxhole Rigg Wood.

Interpretation

The thin sandstone near the top of Zone 2 in Taythes Gill is not seen in any of the inliers to the north but is thought to be equivalent to the Wilsey Beck Sandstone Member, storm-derived sandstones at least 7.5 m thick, in the Gawthrop Inlier in the Dent area, some 8 km to the south (Ingham, 1966, pp. 468, 484; Ingham and McNamara, 1978, fig. 43). The overlying Zone 3 strata in Taythes Gill are the best exposures of that zone in the Cautley area.

Throughout the Taythes Inlier, the uppermost Rawtheyan Cystoid Limestone lies on Rawtheyan Zone 5 strata, in contrast to the situation in other Cautley inliers, where it succeeds Zone 7 (see the Backside Beck and Sally Beck site reports). Ingham (1966, p. 478) calculated that some 110 m of strata had been overstepped in the 2.5 km between the Westerdale and Taythes inliers – evidence of a substantial episode of late (but not latest) Rawtheyan erosion. Kneller *et al.* (1994, p. 229) considered the Cystoid Limestone to be an equivalent of the Troutbeck Member of the Ashgill Formation in the Lake District (see the Ashgill Quarry site report). They concurred with Ingham and Rickards (1974) in equating the sandstone and conglomerate within the Ashgill Formation in the Taythes Inlier with the Wharfe Conglomerate in the Craven inliers to the south and used the term Wharfe Member in the Cautley area. They also considered it to be comparable to the Rebecca Member of the Ashgill Formation in the Furness area, which was also derived from the south-east. The sandstones and conglomerates of the Taythes Inlier are represented by sandy mudstones in the inliers further north in the Cautley area. The Ashgill Formation in the Taythes Inlier yields a *Hirnantia* brachiopod fauna together with the trilobite *Mucronaspis mucronata* (Brongniart), an association seen in Hirnantian units elsewhere in Britain (see the Cwm Hirnant and Ashgill Quarry site reports) and in many other parts of the world (Owen *et al.*, 1991).

Conclusions

This site is an important supplement to that at Sally Beck, as it contains the best exposures of Cautleyan Zone 3. The latest Rawtheyan Cystoid Limestone rests on strata of earliest Rawtheyan age in this site, contrasting with the situation in the other Cautley inliers and providing evidence for a significant episode of erosion. The development of a coarser member near the top of the overlying Ashgill Formation can be linked to the occurrence of contemporaneous rocks elsewhere in the north of England.