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Lithostratigraphy and biostratigraphy of the Lower Carboniferous (Mississippian) carbonates of the southern Askrigg Block, North Yorkshire, UK

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Abstract – A rationalized lithostratigraphy for the Great Scar Limestone Group of the southeast Askrigg Block is established. The basal Chapel House Limestone Formation, assessed from boreholes, comprises shallow-marine to supratidal carbonates that thin rapidly northwards across the Craven Fault System, onlapping a palaeotopographical high of Lower Palaeozoic strata. The formation is of late Arundian age in the Silverdale Borehole, its northernmost development. The overlying Kilnsey Formation represents a southward-thickening and upward-shoaling carbonate development on a S-facing carbonate ramp. Foraminiferal/algal assemblages suggest a late Holkerian and early Asbian age, respectively, for the uppermost parts of the lower Scaleber Force Limestone and upper Scaleber Quarry Limestone members, significantly younger than previously interpreted. The succeeding Malham Formation comprises the lower Cove Limestone and upper Gordale Limestone members. Foraminiferal/algal assemblages indicate a late Asbian age for the formation, contrasting with the Holkerian age previously attributed to the Cove Limestone. The members reflect a change from a partially shallow-water lagoon (Cove Limestone) to more open-marine shelf (Gordale Limestone), coincident with the onset of marked sea-level fluctuations and formation of palaeokarstic surfaces with palaeosoils in the latter. Facies variations along the southern flank of the Askrigg Block, including an absence of fenestral lime-mudstone in the upper part of the Cove Limestone and presence of dark grey cherty grainstone/packstone in the upper part the Gordale Limestone are related to enhanced subsidence during late Asbian movement on the Craven Fault System. This accounts for the marked thickening of both members towards the Greenhow Inlier.

Keywords: Great Scar Limestone Group, Askrigg Block, platform carbonates, microfacies, foraminiferal/algal assemblages.

1. Introduction

Modern British Geological Survey (BGS) mapping of the Pateley Bridge area of North Yorkshire (Sheet 61) has provided the opportunity to reappraise the lithostratigraphy and biostratigraphy of the Great Scar Limestone Group present along Upper Wharfedale and in a series of inliers located adjacent to the North Craven Fault (Fig. 1). One of the main aims of this study is to provide a single unified nomenclature for the southern part of the Askrigg Block, associated with the development of a carbonate succession on the tilt-block high. This has been achieved by the synthesis of data from field mapping integrated with borehole and quarry data. The detailed assessment of foraminiferal/algal assemblages provides an opportunity to assess the established, though not rigorously constrained, biostratigraphical ages previously attributed to the succession. The determination of variations in carbonate facies was used to assess the extent that tectonism and sea-level fluctuation controlled deposition during Viséan times.

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1.a. History of geological research and survey

The first systematic mapping across the area was carried out by the Geological Survey at 1:10 560 scale during the 1860s. A thick limestone succession was called ‘Carboniferous Limestone’ during this survey and the name persists in informal use, but this succession has long been referred to as the Great Scar Limestone. This name was formalized as a group on the Askrigg Block by George *et al.* (1976), but the term is now applied more extensively across northern England from the Isle of Man, the flanks of the Lake District High and across the full extent of the Alston and Askrigg blocks (Waters & Davies, 2006; Dean *et al.* 2011). The successions discussed in this study all belong to this group.

The limestones of the Great Scar Limestone Group are mainly bioclastic, often highly bioturbated, with crinoid banks and shelly or coral biostromes. Thin basal

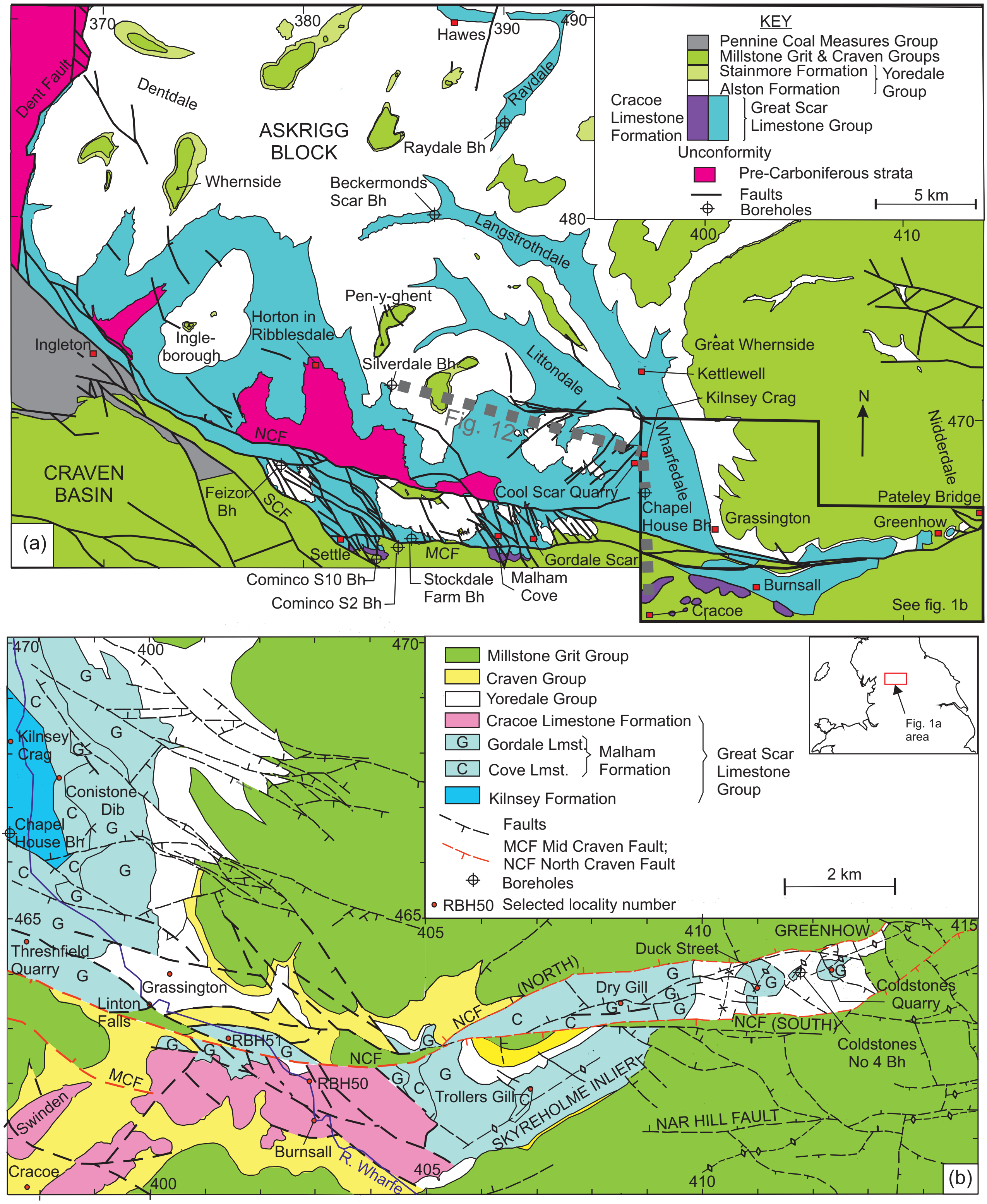

Figure 1. (a) Geological map showing the distribution of the Great Scar Limestone Group across the southern part of the Askrigg Block (based upon Waters & Lowe, 2013, fig. 2.3 and 2.8). (b) Geological map of the Great Scar Limestone Group inliers located between Grassington and Pateley Bridge (sourced from BGS revision mapping in 2011–2014). Map coordinates: British National Grid. *British Geological Survey © NERC 2015. All rights Reserved.*

beds seen in the Settle area are commonly conglomeratic, with Lower Palaeozoic clasts in a mixed carbonate matrix (Arthurton, Johnson & Mundy, 1988), though such intervals have not been recorded in the Pateley Bridge study area. Colour, nature of bedding and grain-size variations are the key criteria for distinguishing the component formations and members (Table 1). As is common with other Viséan platform areas of the British Isles, the group shows a trend from dark or mid-grey Arundian to Holkerian carbonates (e.g. Kilnsey

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Formation) to pale grey upper Asbian limestones (e.g. Malham Formation).

The Great Scar Limestone Group includes many local formations, with distinct nomenclatures for the isolated successions on the various tectonic blocks. Even within the more limited area of the Askrigg Block in North Yorkshire several different lithostratigraphic schemes exist (see Dunham & Wilson, 1985), and despite attempts at rationalization, three separate successions have evolved (Table 1) for the north, southwest (Settle area) and southeast (Greenhow Inlier) parts of the block.

The southern condensed succession that accumulated on the Askrigg tilt-block high passes northwards towards the Stainmore Basin. These lateral facies changes result in classification of a distinct northern stratigraphy, recorded in two deep boreholes (Raydale Borehole BGS Registration Number SD98SW1 and Beckermonds Scar Borehole SD88SE1; Fig. 1a), and summarized by Dunham & Wilson (1985) and listed in Table 1.

The existing stratigraphy for three distinct areas along the south Askrigg Block – the Settle and Horton in Ribblesdale area, the Greenhow and Skyreholme inliers, and the Cracoe Reef complex (Fig. 1) – is summarized below.

1.b. Settle and Horton in Ribblesdale

A nomenclature developed for the Horton in Ribblesdale and Settle areas comprising, in ascending order, the 'Michelinia grandis Beds' and 'Gastropod Beds' of Garwood & Goodyear (1924) and Horton Limestone and Kingsdale Limestone of George *et al*. (1976) has been superseded by subsequent mapping on the Settle Sheet with a succession comprising, in ascending order, the Chapel House Limestone, Kilnsey and Malham formations (Arthurton, Johnson & Mundy, 1988).

The Chapel House Limestone Formation has been proved in several boreholes along the southern flank of the Askrigg Block, including the Chapel House Borehole (BGS registration number SD96NE1) in the Pateley Bridge area (Fig. 1b; Arthurton, Johnson & Mundy, 1988). The most northerly development of the formation is proved in the Silverdale Borehole (SD87SW9), east of Horton in Ribblesdale (Fig. 1a). Much emphasis has been placed in this study on this borehole for constraining the age ranges of the carbonate succession on the Askrigg Block. However, other than the work of F. M. White (unpub. Ph.D. thesis, Univ. Manchester, 1992), data from this borehole are unpublished. Consequently, the borehole has been resectioned and a study of the foraminiferal/algal assemblages undertaken on a new suite of thin-sections housed in the BGS Palaeontological Collection.

The Kilnsey Formation was subdivided by Arthurton, Johnson & Mundy (1988) into the Arundian Kilnsey Limestone-with-mudstone and Scaleber Force Limestone Member and Holkerian Kilnsey Limestone and Scaleber Quarry Limestone. Given these authors' recognition that the age-equivalent units were lithologically similar, Dean *et al*. (2011) formalized the succession as the Scaleber Force Limestone (lower) and Scaleber Quarry Limestone (upper) members. The latter is broadly equivalent to the Fawes Wood Limestone Formation on the north Askrigg Block (Table 1).

The Malham Formation was subdivided into a lower Cove Limestone of Holkerian age and an upper Gordale Limestone of Asbian age by Arthurton, Johnson & Mundy (1988). This subdivision was subsequently formalized as members by Dean *et al*. (2011). Importantly, description of the Malham Formation in the eastern part of the Settle Sheet (Sheet 60) by Arthurton, Johnson & Mundy (1988) is very limited. There is no direct equivalent of the Cove Limestone in the north Askrigg Block, where the Garsdale Limestone Formation is dominantly dark grey with common mudstone beds, although the overlying Danny Bridge Limestone Formation is comparable with the Gordale Limestone (Table 1). The Cove Limestone and Gordale Limestone members are broadly lithologically equivalent with the Park Limestone and Urswick Limestone formations, respectively, of south Cumbria.

1.c. Greenhow and Skyreholme inliers

The geology of the Skyreholme Anticline, including a key section at Trollers Gill, was provided by Anderson (1928), whose map was subsequently revised by Hudson (1938, p. 311). Dunham & Stubblefield (1945) described the detailed litho- and biostratigraphy, and structure of the Greenhow Inlier, although this predated the expansion of the Coldstones Quarry. This, and the more comprehensive summary of the stratigraphy, structure and mineralization of the Askrigg Block by Dunham & Wilson (1985), has provided the de facto lithostratigraphy for both inliers, comprising, in ascending order: Timpony Limestone, Stump Cross Limestone, Greenhow Limestone and Hargate End Limestone formations (Table 1). This nomenclature pre-dates the stratigraphical succession defined in the Settle district by Arthurton, Johnson & Mundy (1988), and sufficient uncertainty as to how these schemes were related led Dean *et al*. (2011) and subsequently Waters & Lowe (2013) and Lowe & Waters (2014) not to modify the scheme used for the Greenhow Inlier. However, the current study, as described in the following sections, has been unable to justify continued usage of this stratigraphy within the inliers.

1.d. Cracoe Reef complex

'Cracoean' reefs occur along the southern margin of the Askrigg Block, located south of the Middle Craven Fault, in a roughly W–E tract extending 20 km eastwards from Settle to Burnsall (Fig. 1a). Formerly referred to as Marginal Reef Limestones of the Malham Formation (Arthurton, Johnson & Mundy, 1988), they have been redefined subsequently as the Cracoe

Table 1. Historical lithostratigraphical schemes for the Great Scar Limestone Group of the Askrigg Block showing main lithological characteristics of formations

Formation	Member	Age	Colour	Grain size	Lithology (main)	Lithology (subordinate)	Bedding	Thickness (m)
North Askrigg Block								
Danny Bridge Limestone		Late Asbian	Pale to mid-grey		Wackestone	Packstone, mudstone and minor grainstone; Palaeokarst surfaces overlain by bentonitic clays, palaeosoils		102–168
Garsdale Limestone		Late Holkerian – early Asbian	Dark grey		Wackestone with bands of porcellanous calcilutite	Interbedded sandstone and siltstone, numerous thin mudstone beds and rare thin coals		41–58
Fawes Wood Limestone		Holkerian	Mid to dark grey		Grainstone and packstone	Silty or stylolitic partings and some porcellanous lime-mudstone		55–80
Ashfell Sandstone		Late Arundian		Fine-grained,	Sandstone	Cross-laminated sandstone/ siltstone with up to 6 limestone beds		38
Tom Croft Limestone		Arundian	Mid to dark grey	Medium- and coarse-grained	Grainstone, peloidal, shelly debris, crinoidal, variably dolomitic	Thin basal limestone breccia with siltstone and quartz pebbles	Poorly bedded	60–80
South Askrigg Block: Settle								
Cracoe Limestone		?late Holkerian – Brigantian	Mid and mid-pale grey	Highly variable	Organic boundstone to packstone and wackestone	Megabrecciation and neptunian dykes (crinoid- and mudstone-filled)	Massive to weakly bedded	>100
Malham	**Gordale Limestone**	Asbian	Mid-pale to very pale grey	Fine- and medium-grained	Bioclastic packstone and wackestone, commonly pseudobrecciated	Cross-bedded grainstone, thin conglomerates; clay beds above palaeokarstic surfaces. Limestone forms continuous prominent scars.	Well bedded; thick- to very thick bedded	70–94
	Cove Limestone	Holkerian	Pale grey to very pale grey	Medium- and coarse-grained	Bioclastic and peloidal packstone and grainstone	Lime-mudstone (‘Porcellanous Bed’), variably fenestral; clay beds above palaeokarstic surfaces	Massive to weakly bedded	72–114
Kilnsey	**Scaleber Quarry Limestone**	Holkerian	Mid and mid-dark grey	Fine- to coarse-grained	Bioclastic packstone and grainstone	Mudstone interbeds; bands and nodules of black chert	Well bedded, thin and thick	29–134
	Scaleber Force Limestone	Late Arundian	Dark grey	Fine- to coarse-grained	Packstone	Wackestones, mudstone interbeds	Well bedded, thin to thick	22–61
Chapel House Limestone		Arundian	Mid to mid-pale grey	Medium- and coarse-grained	Calcarenite, oolitic grainstone. Locally extensively dolomitized	Basal conglomerate; interbedded siltstone with sandstone and mudstone laminae; dolomite-mudstone and fenestral or algal lime-mudstones; argillaceous wackestones	Well bedded	33–56
South Askrigg Block: Greenhow Inlier								
Hargate End Limestone		Late Asbian	Dark grey or mid-grey	Med. to very coarse-grained	Crinoidal limestone	Chert is present, especially near top. Base taken at a single *Davidsonina septosa* band.	Well bedded	46
Greenhow Limestone		Early–late Asbian	Pale grey	Fine- to medium-grained	Sparry grainstone locally peloidal and crinoidal	Up to 15 clay beds above palaeokarstic surfaces. Limestone forms continuous prominent scars.	Well bedded; thick- to very thick bedded	120
Stump Cross Limestone		Early Asbian	Pale brown–grey/grey	Fine-medium-grained	Limestone	Variably dolomitic in lower part	Poorly bedded	84
Timpony Limestone		Holkerian – early Asbian	Mid to dark grey	Fine-grained	Limestone	Chert nodules in upper part; shale partings in lower part	Well bedded; very thin to thick bedded	>120

After Dean *et al*. (2011) for North Askrigg and South Askrigg: Settle; after Dunham & Wilson (1985) for Greenhow Inlier. Modified from Waters & Lowe (2013).

Limestone Formation (Dean *et al*. 2011; Table 1). This study did not investigate the complex development of these Cracoean reefs, which will be the subject of subsequent work.

2. Revised lithostratigraphy and biostratigraphy

In this section a unified lithostratigraphy is applied across the three areas described above. Importantly, the application of new biostratigraphical interpretations, principally of foraminifers and algae/problematica (see Tables 2–4), permits correlation between the three areas and a revision of the established age ranges of the lithostratigraphic units. These are summarized in Figure 2. The Chapel House Limestone, Kilnsey Formation, Cove Limestone and Gordale Limestone members of the Malham Formation are described, respectively, in Sections 2.a. to 2.d.

Only the most distinctive components of the macrofaunas, mainly brachiopods, with a few corals and bivalves, are listed. The range data for the macrofauna are given by Riley (1993), Wilson (1989), Dunham & Wilson (1985), Arthurton, Johnson & Mundy (1988), Cossey *et al*. (2004) and the Palaeobiology Database (http://fossilworks.org/cgi-bin/bridge.pl?a=home). The biostratigraphy of the foraminifers is adopted from the pioneer papers by Conil, Longerstaey & Ramsbottom (1980), A. R. E. Strank (unpub. Ph.D. thesis, Univ. Manchester, 1981), Laloux (1987) and subsequent modifications mostly in Conil *et al*. (1991), Riley (1993) and Cózar & Somerville (2004). Key foraminifers identified during the current study are illustrated in Figures 3 & 4. Sample numbers are italicized, with location details provided in Table 5.

2.a. Chapel House Limestone Formation

2.a.1. *Lithostratigraphy*

The Chapel House Limestone Formation was introduced in the Settle district by Arthurton, Johnson & Mundy (1988) for the succession which underlies the Kilnsey Formation and either unconformably overlies the Tournaisian Stockdale Farm Formation or Lower Palaeozoic rocks. In the type section, the Chapel House Borehole, the formation is 33.6 m thick. The formation is thickest (56 m) in the Stockdale Farm Borehole (SD86SE6; Fig. 1a), adjacent to the Middle Craven Fault. Elsewhere to the north of the North Craven Fault, the formation onlaps, and is locally absent over topographic highs in the Lower Palaeozoic basement and is only 12 m thick in the Silverdale Borehole (Murray, 1983).

In the Settle district, the lower part of the formation is dominated by medium to medium-light grey, medium- and coarse-grained grainstone with common Lower Palaeozoic lithoclasts, locally forming conglomerates, and the notable presence of ooids (Arthurton, Johnson & Mundy, 1988). Other common lithologies are 'mixed laminites' comprising interbedded fissile siltstone with sandstone and mudstone laminae, dolomite-mudstone and lime-mudstone with fenestral textures or algal lamination, and argillaceous wackestones are present in the upper part of the formation in the Kilnsey area (Arthurton, Johnson & Mundy, 1988).

The unconformable base of the Chapel House Limestone Formation in the Silverdale Borehole is overlain by medium grey, fine- to medium-coarse-grained packstone/grainstone with abundant crinoid and brachiopod debris, quartz grains and peloids (Fig. 5). The upper 5.5 m is marked by medium and dark grey lime-mudstone and laminated argillaceous wackestone with fenestral fabrics, abundant quartz grains in laminae and intraclasts with common ostracods and dasycladal green algae. The upper boundary of the formation is marked by a change from lime-mudstone to darker grey coarser grained bioclastic packstones/wackestones of the Kilnsey Formation.

2.a.2. *Biostratigraphy*

Macrofossils. The Chapel House Limestone Formation is equivalent to the lower part of the *Michelinia* Zone (C_2) of Garwood & Goodyear (1924). *Michelinia megastoma*, found near the top of the formation at Stainforth Beck [38198 46700] and *Palaeosmilia murchisoni* recovered from the base of the Chapel House Limestone at 191 m depth in the Silverdale Borehole, were considered to indicate an Arundian age (Arthurton, Johnson & Mundy, 1988).

Microfossils. Foraminifers from the Chapel House and Stockdale Farm boreholes and from Gordale Beck (Fig. 1a) confirm an Arundian age (Arthurton, Johnson & Mundy, 1988), the diagnostic taxa being *Ammarchaediscus* (= *Viseidiscus*) *bucullentus*, *Eoparastaffella simplex* (Fig. 3a), *Glomodiscus miloni*, *Latiendothyranopsis menneri solida* and *Rectodiscus* (= *Uralodiscus*) sp.

In the Silverdale Borehole (Fig. 5; Table 4), the basal sample of the Chapel House Limestone Formation (*EWJ1575*), located immediately above the basal unconformity upon Lower Palaeozoic basement, contains all of the diagnostic taxa of a late Arundian age, including *Glomodiscus rigens* (Fig. 3g), *Uralodiscus adindanii* (Fig. 3h), *U. rotundus*, *U. settlensis* (Fig. 3i), *Viseidiscus monstratus*, *Paraarchaediscus* at *involutus* stage, *Plectogyranopsis moraviae* (Fig. 4g), *Eoparastaffella simplex* (*EWJ1572–75*), *Latiendothyranopsis menneri solida* (*EWJ1573–75*; Fig. 4c), *Eoendothyranopsis*, *Pseudolituotubella*, *Nodosarchaediscus* and *Koninckopora* spp. This sample has the richest (35 foraminiferal species) and most diverse assemblage for any sample in the borehole. It also agrees with many of the taxa illustrated by Conil, Longerstaey & Ramsbottom (1980) from the Arundian Michelinia Grandis Beds at Settle and characteristic of their Cf4δ Subzone.

Also in the Silverdale Borehole (Fig. 5), a sample (*EWJ1573*) located 2 m above the basal sample has

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Table 2. Foraminifer and algae/problematica taxa in the Kilnsey and Malham formations in the west of the study area

		Scaleber Force Limestone					Scaleber Quarry Lst.				Cove Limestone											Gordale Limestone				
				Scaleber	Kilnsey Crag					Conistone Dib																
		Strank *in* Arthurton, Johnson & Mundy (1988)	Strank *in* Arthurton, Johnson & Mundy (1988)	Conil Longerstaey & Ramsbottom (1980)	Pc4833	Strank in Dunham & Wilson(1985)	Strank in Dunham & Wilson(1985)	Strank *in* Arthurton, Johnson & Mundy (1988)	Strank *in* Arthurton, Johnson & Mundy (1988)	Pc4820	Pc4821	Pc4822	Pc4823	Pc4824	Pc4825	Pc4826	Pc4827	Pc4828	Pc4829	Pc4830	Pc4831	Pc4832	RBH4 Threshfield Quarry	RBH59 Linton House	RBH51 Lythe House	RBH50 River Wharfe
Foraminifers	*Uralodiscus* sp.	X	X			X																				
	Uralodiscus settlensis	X																								
	Viseidiscus bucullentus	X																								
	Plectogyranopsis spp.		X								X	X	X	X	X					X	X		X			
	Glomodiscus miloni		X																							
	Planoarchaediscus sp.		X																							
	Pseudolituotubella hibernica		X																							
	Endothyra elegia			aff																						
	Omphalotis minima			cf.								X											X			
	Endothyra spp.			X	X					X		X		X		X	X		X	X	X		X	X	X	X
	Viseidiscus sp.			X		X																				
	Endothyra bowmani			X						X					X	X	X									
	Endothyra similis			X							X	X			X			gr								
	Endothyra bowmani alta			X																						
	Archaediscus at *concavus* stage				X			X			X	X	X		X			X								
	Nodosarchaediscus spp.				X				X	X	X	X	X	X								X				
	A. concavus trans. *angulatus*				X				X																	
	Earlandia spp.				X					X	X	X		X				X		X			X	X	X	X
	Pseudoammodiscus spp.				X						X			X		X		X			X	X	X	X	X	X
	Endothyranopsis compressa				X							X											X		X	
	Globoendothyra spp.				X							X							X	X			X			
	Omphalotis spp.				X									X		X	X							X		
	Glomodiscus sp.					X																				
	Endothyranopsis crassa						?													X						
	Eostaffella parastruvei						gr																X			
	Koskinotextularia sp.						X	X	X		X		X												X	
	Pojarkovella nibelis						X	X	X									X								
	Septabrunsiina sp.						X	X																		
	Brunsia spirillinoides						X					X														
	Glomospiranella dainae						X																			
	Mstinia sp.						X								?									X	X	
	Holkeria daggeri							X																		
	Palaeospiroplectammina paprothae							X																		
	Archaediscus at *involutus* stage								X																	
	E. compressa trans. *crassa*									X	X						X									
	Globoendothyra globulus									X		X	X		X					X						
	Eostaffella spp.									X					X					X	X			X	X	
	Archaediscus karreri										gr	gr	gr													
	Archaediscus at *angulatus* stage										X	X	X	X	X	X	X	X		X	X		X	X	X	X
	Consobrinella spp.										X	X		X	X	X				X	X	X	X		X	
	Koskinobigenerina spp.										X	X														
	Pseudoendothyra sublimis										X	X								X	X		X			
	Pseudoendothyra spp.										X	X	X	X	X	X	X	X	X	X	X		X			
	Forschia parvula										X		X		X	X										
	Mikhailovella sp.										X															
	Neoarchaediscus stellatus										X										X					
	Endostaffella spp.											X											X	X		
	Mediocris mediocris											X			X					X				X		
	Neoarchaediscus sp.											X			X											X
	Lituotubella magna												X		X		X	X		X	X					
	Tetrataxis spp.												X			X					X		X	X		
	Lituotubella glomospiroides														X											
	Pseudolituotuba gravata														X									X		
	Mediocris breviscula															X				X			X			
	Palaeotextularia spp.															X					X		X		X	
	Koktjubina sp.															X										
	Cribrospira sp.																	?								
	Brunsia sp.																	X		X						
	Magnitella praecursor																	X								
	Forschia mikhailovi																						X	X		
	Protoinsolentitheca fundamenta																						X			
	Bibradya inflata																								X	
	Bradyina rotula																							X		
	Eostaffella proikensis																							X	aff	
	Omphalotis omphalota																							X	X	
	Praeostaffellina macdonaldensis																							X		
Dasycladales	*Koninckopora inflata*				X					X	X			X		X	X		X	X	X					
	Koninckopora tenuiramosa									X	X	X	X	X	X	X	X	X		X						
	Koninckopora mortelmansi										X		X	X					X	X						
	Atractyliopsis cumberlandensis											X														
	Windsoporella tulayae														X											
	Koninckopora minuta																	X	X			X				
Aoujgaliids	*Kamaena* spp.				X							X	X	X			X		X		X		X			
	Palaeoberesella lahuseni				X					X		X														
	Fourstonella spp.									X					X											X
	Roquesselsia radians									X	X	X	X	X	X	X	X		X						X	X
	Zidella maxima									X		X		X				X		X	X	X	X	X	X	
	Stacheoides spp.											X									X					
	Aoujgalia sp.													X												
	Aphralysia sp.															X	X							X		
	Fasciella kizilia															X	X		X	X	X			X		X
	Kamaenella denbighi																				X		X		X	
	Claracrusta catenoides																							?		
	Pseudostacheoides loomisi																						X			
	Ungdarella uralica																						X	X	X	
	Sinustacheoides meandriformis																									X

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Table 3. Foraminifer and algae/problematica taxa in the Greenhow/Skyreholme inliers. D.S. = Duck Street Quarry; Prob. = Problematica.

		Coldstones No. 4 Borehole																Trollers Gill						Coldstones No. 4 Borehole												Coldstones Quarry								D. S.		Dry Gill		
		Scaleber Quarry Limestone												Cove Lst.				Cove Limestone						Gordale Limestone												Gordale Limestone												
		BLK3520	BLK3517	BLK3509	BLK4243	BLK3496	BLK4242	BLK4241	BLK4239	BLK4238	BLK4237	BLK3490	BLK4236	BLK3487	BLK3475	BLK3473	BLK3470	BLK3467	DMA320	DMA321	DMA322	DMA323	DMA324	DMA325	DMA326	BLK3460	BLK3454	BLK3451	BLK3447	BLK3444	BLK3439	BLK3435	BLK3431	BLK3427	BLK3423	BLK3420	BLK3417	BLK3413	WQ217	WQ203	WQ204	WQ205	WQ206	WQ207	WQ218	WQ216	WQ215	WQ199	WQ200	Strank 1982a	DMA327	DMA328
Foraminifers	*Archaediscus* at *concavus* stage	X	X	X		X					X	X		X	X						X	X			X		X										X								X					X		
	Endothyranopsis crassa		?																					X		X	X	X			X				X			X	X			X	X	X	X			X	aff		?		
	Consobrinella spp.		X			X					X			X				X	X		X	X	X				X					X	X				X		X	X			X					X	X
	Pseudoammodiscus spp.		X					X																X			X												X	X	X	X	X			X	X	X	X		X
	Nodosarchaediscus spp.			X	X						X																												X							X		X		
	Omphalotis minima			X								cf							X	X				X			cf				cf	cf	cf	cf	cf		cf	X	X	X	X	X		X			X		X		
	Tetrataxis paraminima			X																																			X														
	Valvulinella youngi			X																																															X		
	Eostaffella ex gr. *parastruvei*				X			X		X			X																													X				X	X	X	X				
	Lituotubella magna							X												X				X																X	X		X	X					X				
	Mediocris mediocris							X												X								X		X												X	X		X				X				
	Koskinotextularia spp.								X	X																X		X	X				X									X									
	Endothyra spp.									X			X		X					X	X	X	X	X	X					X										X	X	X	X		X	X	X	X		X			X
	Plectogyranopsis spp.									X															X		X		X													X	X			X	X			X	
	Eostaffella spp.											X		X					X	X	X		X	X		X				X			X		X		X	X		X		X					X				
	Archaediscus at *angulatus* stage																	X		X	X	X	X	X	X			X					X	X		X	X	X	X	X		X	X	X	X		X	X	X	X	X	X
	Tetrataxis spp.												X									X	X	X			X							X						X	X	X	X	X	X		X		X	X		
	Globoendothyra spp.																		X	X	X							X			X				X												X			X			
	Pojarkovella nibelis																		?	X		X	X		X					X														X				X	X					
	Vissarionovella tujmasensis																		X	X		?	X																															
	Earlandia spp.																			X	X		X	X	X		X	X	X	X			X						X	X	X	X	X		X		X	X	X		X	
	Scalebrina sp.																			X							X																									
	Pseudoendothyra sublimis																			X			cf	X				X	X					X				X	X	X			X		X				
	Neoarchaediscus stellatus																			X	X		?		X													cf		X	X							X	X		X	X
	Bibradya grandis																			X																					X									
	Cribrospira panderi																			aff																											X				
	Endospiroplectammina sp.																			X																			X												
	Globoendothyra globulus																			X	X																			X		X										X
	Omphalotis spp.																			X		X	X	X	X																X								X	X
	Palaeotextularia spp.																			X	X	X		X	X													X	X		X	X		X	X	X	X	X			X
	Pseudoendothyra spp.																			X	X		X		X														X	X	X	X	X	X			X	X			
	Eostaffella proikensis																				X		X	X																X		X					X					
	Lituotubella glomospiroides																				X	X	X																													
	Neoarchaediscus spp.																				X	X	X	?																?	X	?		?			X					
	Mirifica sp.																					?	?		?																												
	Palaeotextularia ex gr. *longiseptata*																						X			X	X	X	X	X		X					X	X				X				X					
	Bradyina rotula																						?																									X					
	Brunsia spirillinoides																						X																X												X	
	Endothyranopsis compressa																						X																X					X							
	Praeostaffellina macdonaldensis																						X	X	X															X	X	X								
	Protoinsolentitheca fundamenta																						X																X	X	X	X				X	X			X	
	Omphalotis omphalota																							X	X														X	X	X	X	X	X	X	X					
	Mediocris breviscula																								X				X												X								X			X	
	Archaediscus karreri																								gr					X															gr				X			gr	
	Cribrostomum lecomptei																								X																		X	X								
	Pseudotaxis eominima																								X																							X			X	
	Cribrostomum sp.																											X		X				X								X							X			
	Vissariotaxis compressa																												cf																				?			
	Planoarchaediscus spp.																													X																						X	
	Forschia mikhailovi																													X											?		X	X				X	X			X	
	Mstinia sp.																																	X											X			X			
	Koktjubina? aff. *K. beata*																																								X	X				X					
	Endostaffella spp.																																									X	X	X		X	X	X			
	Nodasperodiscus spp.																																									X	X		X							
	Forschiella prisca																																										X									
	Koskinobigenerina spp.																																										X									
	Spinothyra pauciseptata																																														X					
	Pseudolituotuba gravata																																																			X	X
Dasycladales	*Koninckopora inflata*	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X		X	X	X	X		X					X	X	X	X	X				X	X			X	X	X		X	X				X
	Koninckopora mortelmansi									X									X		?	X																															X	
	Koninckopora tenuiramosa																		X	X	X	X	X	X															X	X			X					X	X		X	X
	Windsoporella pareyni																		?	?		?																										?					
	Koninckopora minuta																																							X	X		X	X	X								X	
	Paraepimastopora sp.																																													X					
	Windsoporella tulayae																																															?			
Aoujgaliids	*Aphralysia* sp.																		X																																
	Asphaltinella horowitzi																		X			?																X													
	Epistacheoides spp.																		X	X																		X				X	X	X							X	X
	Kamaenella tenuis																		X		X																															
	Ungdarella uralica																		?	X	X	X	X	X																X	X	X	X	X	X	X	X	X			X	X
	Zidella maxima																		X	X	X	X	X	X														X	X	X	X	X	X				X			X	
	Exvotarisella index																			X	X	X	X	X																	X		X								
	Fasciella kizilia																			X			X	X														X					X			X	X				X
	Kamaena delicata																			X			X	X	X														X	X	X	X	X	X			X	X		X	X
	Kamaenella denbighi																			X			X	X	X													X	X					X			X			X	X
	Stacheia africana																			X																																
	Palaeoberesella lahuseni																				X	X		X																	X	X	X			X		X			
	Roquesselsia radians																				X				X															X	X	X	X		X	X	X				X	X
	Pseudostacheoides loomisi																																							X			X									
	Aoujgalia spp.																																									X				X				?	
	Sinustacheoides meandriformis																																									X									
	Stacheoides tenuis																																															X				X
Prob.	*Girvanella ducii*																		X																																
	Ortonella sp.																		X			X																												
	Draffania biloba																										X									X	X	X			X	X	X								

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Table 4. Foraminifer and algae/problematica taxa in the Silverdale Borehole Chapel H. = Chapel House Formation.

	(a) Chapel House Formation to Cove Limestone Member	Chapel H.				Kilnsey Fm														Cove Limestone Member													
		Arundian				Holkerian							early Asbian					late Asbian															
		EWJ 1575	EWJ 1574	EWJ 1573	EWJ 1572	EWJ 1567	EWJ 1566	EWJ 1565	EWJ 1564	EWJ 1563	EWJ 1562	EWJ 1561	EWJ 1560	EWJ 1559	EWJ 1558	EWJ 1557	EWJ 1556	EWJ 1555	EWJ 1554	EWJ 1553	EWJ 1552	EWJ 1551	EWJ 1550	EWJ 1549	EWJ 1548	EWJ 1547	EWJ 1546	EWJ 1545	EWJ 1544	EWJ 1543	EWJ 1542	EWJ 1541	EWJ 1540
Foraminifers	*Eostaffella* spp.	?		X	X	X		X			X	X		X	X		X		X					X	X					X		X	
	Glomodiscus spp.	X	X	X																													
	Viseidiscus monstratus	X	X																														
	Eoparastaffella simplex	X		X	X																												
	Spinobrunsiina sp.	X		X	X																					X							
	Pseudoammodiscus spp.	X		X		X	X	X			X	X					X		X	X			X		X								
	Plectogyranopsis spp.	X		X			X	X			X	X	X	X	X	X	X	X	X	X		X			X								
	Latiendothyranopsis menneri solida	X		X																													
	Endothyra ex gr. *bowmani*	X				X	X													X	X				X								
	Endothyra ex gr. *similis*	X				X	X													X												X	
	Nodosarchaediscus spp.	X					X	X			X	X		X							X												
	Tournayellina beata	X																															
	Uralodiscus rotundus	X																															
	Uralodiscus settlensis	X																															
	Endothyranopsis compressa			cf							X		X									X											
	Lituotubella magna			X								X	X	X	X	X		X			X				X	X		X					
	Condrustella sp.			X																													
	Pseudolituotubella sp.			X																													
	Omphalotis minima					X	af	X					X	X	X	af	X	X			X		X		X			X				X	
	Archaediscus at *concavus* st.					X	X	X			X	X		X			X		X	X	X			X		X							
	Pojarkovella spp.						?			?	X	X	X	X	X	X	X			?	X	X	X	X		X	X	X			X	X	
	Archaediscus at *angulatus* st.							?				?	X	X	X	X	X		X	X		X			X	X	X				X	X	
	Planoarchaediscus spirillinoides							X																									
	Holkeria? sp.									X																							
	Consobrinella spp.										X	X	X	X	X	X		X	X	X	X				X	X							
	Eostaffella ex gr. *parastruvei*										X		X	X				X															
	Forschia mikhailovi										X		X			X	X	X		X					X								
	Koskinotextularia sp.										X			X	X	X	X			X		X											
	Tetrataxis spp.										X			X		X			X	X													
	Globoendothyra globulus											X		X		X	X			X	X						X						
	Lituotubella glomospiroides											X					X	X							X				X				
	Pseudoendothyra spp.												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				
	Nodasperodiscus spp.														X			X	X					X		X	X						
	Endostaffella spp.														X				X	X	X				X							X	
	Omphalotis omphalota															cf	cf			X	X	X											
	Euxinita efremovi																	?	?	?								?					
	Neoarchaediscus spp.																	?		X	X	X				X				X		X	
	Koskinobigenerina sp.																		X	X	X	X			X								
	Neoarchaediscus stellatus																		X		X	X			X								
	Endothyranopsis crassa																			X	X												
	Pseudoendothyra sublimis																			X		X	X		X	X		X			X	X	
	Forschiella prisca																			X													
	Archaediscus karreri																				X	X											
	Brunsia spirillinoides																								X	X	X	X	X	X	X	X	
	Palaeotextularia spp.																								X			X					
	Vissarionovella tujmasensis																									X	X	X					
	Cribrostomum lecomptei																																
	Mstinia sp.																																
	Protoinsolentitheca fundamenta																																
	Bibradya inflata																																
	Janischewskina? sp.																																
	Praeostaffellina macdonaldensis																																
	Cribrospira panderi																																
	Endothyra spira																																
	Parajanischewskina brigantiensis																																
	Bradyina rotula																																
	Spinothyra pauciseptata																																
	Valvulinella youngi																																
	Howchinia gibba																																
Dasycladales	*Koninckopora tenuiramosa*		X	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X					
	Koninckopora minuta				X						X		X						X					X	X		X	X					
	Koninckopora inflata					X																							X				
	Koninckopora mortelmansi													X	X	X					X				X								
	Koninckopora sp. B																																
	Nanopora anglica																																
	Coelosporella jonesi																																
	Windsoporella tulayae																																
Aoujgaliids	*Roquesselsia radians*										X	X	X		X	X	X	X	X	X	X			X									
	Aoujgalia variabilis													X											X								
	Kamaenella tenuis														X	X					X	X		X	X	X	X	X		X	X	X	
	Saccamminopsis fusulinaeformis																		X	X													
	Epistacheoides cannidahensis																																
	Ungdarella uralica																																
	Fasciella kizilia																																
	Fasciella crustosa																																
	Claracrusta catenoides																																
	Falsocalcifolium punctatum																																

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Table 4. Continued

(b) Gordale Limestone and Hawes Limestone members		Gordale Member																										Hawes Lst.											
		late Asbian								latest Asbian														?					Brigantian											
		EWJ 1539	EWJ 1538	EWJ 1537	EWJ 1536	EWJ 1535	EWJ 1534	EWJ 1533	EWJ 1532	EWJ 1531	EWJ 1530	EWJ 1529	EWJ 1528	EWJ 1527	EWJ 1526	EWJ 1525	EWJ 1524	EWJ 1523	EWJ 1522	EWJ 1521	EWJ 1520	EWJ 1519	EWJ 1518	EWJ 1517	EWJ 1516	EWJ 1515	EWJ 1514	EWJ 1513	EWJ 1512	EWJ 1511	EWJ 1510	EWJ 1509	EWJ 1508	EWJ 1507	EWJ 1506	EWJ 1505	EWJ 1504	EWJ 1503	EWJ 1502	EWJ 1501
Foraminifers	*Eostaffella* spp.	X				X	X									X	X	X					X		X	X	X	X	X	X	X	X	X	X	X	X	X	X		
	Glomodiscus spp.																																							
	Viseidiscus monstratus																																						X	
	Eoparastaffella simplex																																							
	Spinobrunsiina sp.															X								X																
	Pseudoammodiscus spp.						X			X	X	X		X						X					X	X	X	X	X					X		X	X	X		
	Plectogyranopsis spp.						X			X	X	X			X			X							X			X	X	X					X					
	Latiendothyranopsis menneri solida																																							
	Endothyra ex gr. *bowmani*																X		X			X			X				X				X			X		X		
	Endothyra ex gr. *similis*		X	X			X		X																															
	Nodosarchaediscus spp.		X																																					
	Tournayellina beata																																							
	Uralodiscus rotundus																																							
	Uralodiscus settlensis																																							
	Endothyranopsis compressa									X										X									X											
	Lituotubella magna				X	X				X	X				X			X					X		X															
	Condrustella sp.																																							
	Pseudolituotubella sp.																																							
	Omphalotis minima									X	X				X		X			X																			X	
	Archaediscus at *concavus* st.						X																																	
	Pojarkovella spp.	X	X		X	X			X						X	X	X	X	X	X		X			X								X							
	Archaediscus at *angulatus* st.	X	X	X		X	X	X	X	X	X	X													X	X	X	X			X	X	X	X	X	X	X	X	X	X
	Planoarchaediscus spirillinoides																											X						X		X			X	
	Holkeria? sp.																																							
	Consobrinella spp.						X			X		X			X	X	X	X	X	X			X				X	X	X		X	X	X		X	X	X	X	X	
	Eostaffella ex gr. *parastruvei*	X	X			X								X					X					X	X			X	X	X			X			X	X	X	X	
	Forschia mikhailovi						X			X	X												X		X		X	X	X		X									
	Koskinotextularia sp.																										X		X											
	Tetrataxis spp.						X			X	X	X								X					X		X	X	X	X	X	X		X	X	X	X	X	X	X
	Globoendothyra globulus					X	X		X					X	X				X				X	X		X	X					X			X		X			
	Lituotubella glomospiroides																									X		X											X	
	Pseudoendothyra spp.					X	X		X	X	X	X			X	X	X		X		X	X	X	X	X	X	X	X			X	X		X			X			
	Nodasperodiscus spp.																																							
	Endostaffella spp.									X	X										X	X	X	X			X	X	X	X	X			X	X	X	X		X	X
	Omphalotis omphalota					X	X			X	X	X		X	X	X	X	X		X			X		X		X	X		X	X					X			X	X
	Euxinita efremovi						?																											X		X	X	X	X	
	Neoarchaediscus spp.		X				X	X				X				X			X						X		X	X		X	X	X	X		X	X		X	X	X
	Koskinobigenerina sp.			X															X																	X		X	X	
	Neoarchaediscus stellatus								X																X			X		X										X
	Endothyranopsis crassa						X			X	X	X					X	X	X				X		X		X	X	X	X				X	X	X	X	X	X	
	Pseudoendothyra sublimis			X		X	X			X	X			X	X		X	X	X										X								X			
	Forschiella prisca																					X																		
	Archaediscus karreri									X															X			X		X				X		X	X	X	X	X
	Brunsia spirillinoides	X	X			X	X		X							X	X		X		X		X														X			
	Palaeotextularia spp.						X		X	X	X	X			X		X			X	X		X		X		X	X		X	X	X			X	X	X			X
	Vissarionovella tujmasensis																				X	X																		
	Cribrostomum lecomptei						X			X	X				X				X				X		X		X		X								X		X	
	Mstinia sp.						X										X			X					X						X					X	X		X	
	Protoinsolentitheca fundamenta						X																																	
	Bibradya inflata	X								X													X																	
	Janischewskina? sp.																X	X							X										X					
	Praeostaffellina macdonaldensis																X			X							X	X	X					X		X		X	X	X
	Cribrospira panderi																			X																				
	Endothyra spira																								X		X		X			X							X	
	Parajanischewskina brigantiensis																									X				X	X									
	Bradyina rotula																										X	X	X	X						X			X	
	Spinothyra pauciseptata																														X									
	Valvulinella youngi																																	X	X	X	X	X	X	X
	Howchinia gibba																																			X			X	X
Dasycladales	*Koninckopora tenuiramosa*		X	X	X	X	X					X	X	X	X		X	X	X		X		X										X							
	Koninckopora minuta			X			X		X	X		X	X	X	X		X																							
	Koninckopora inflata				X	X	X		X		X	X		X	X		X	X	X	X		X	X					X		X	X									
	Koninckopora mortelmansi										X												X																	
	Koninckopora sp. B									X	X														X		X	X												
	Nanopora anglica																																X				X			
	Coelosporella jonesi																																		X					
	Windsoporella tulayae																X																					X	X	
Aoujgaliids	*Roquesselsia radians*				X	X	X	X	X	X	X	X		X			X								X			X												
	Aoujgalia variabilis																																	X						
	Kamaenella tenuis			X					X	X	X		X	X								X	X	X		X														
	Saccamminopsis fusulinaeformis																										X				X			X						
	Epistacheoides cannidahensis											X			X									X	X					X	X	X								
	Ungdarella uralica														X	X	X	X	X	X	X	X	X	X	X	X	X	X				X								
	Fasciella kizilia																			X							X	X									X			
	Fasciella crustosa																													X										
	Claracrusta catenoides																														X	X			X	X	X		X	X
	Falsocalcifolium punctatum																																				X			

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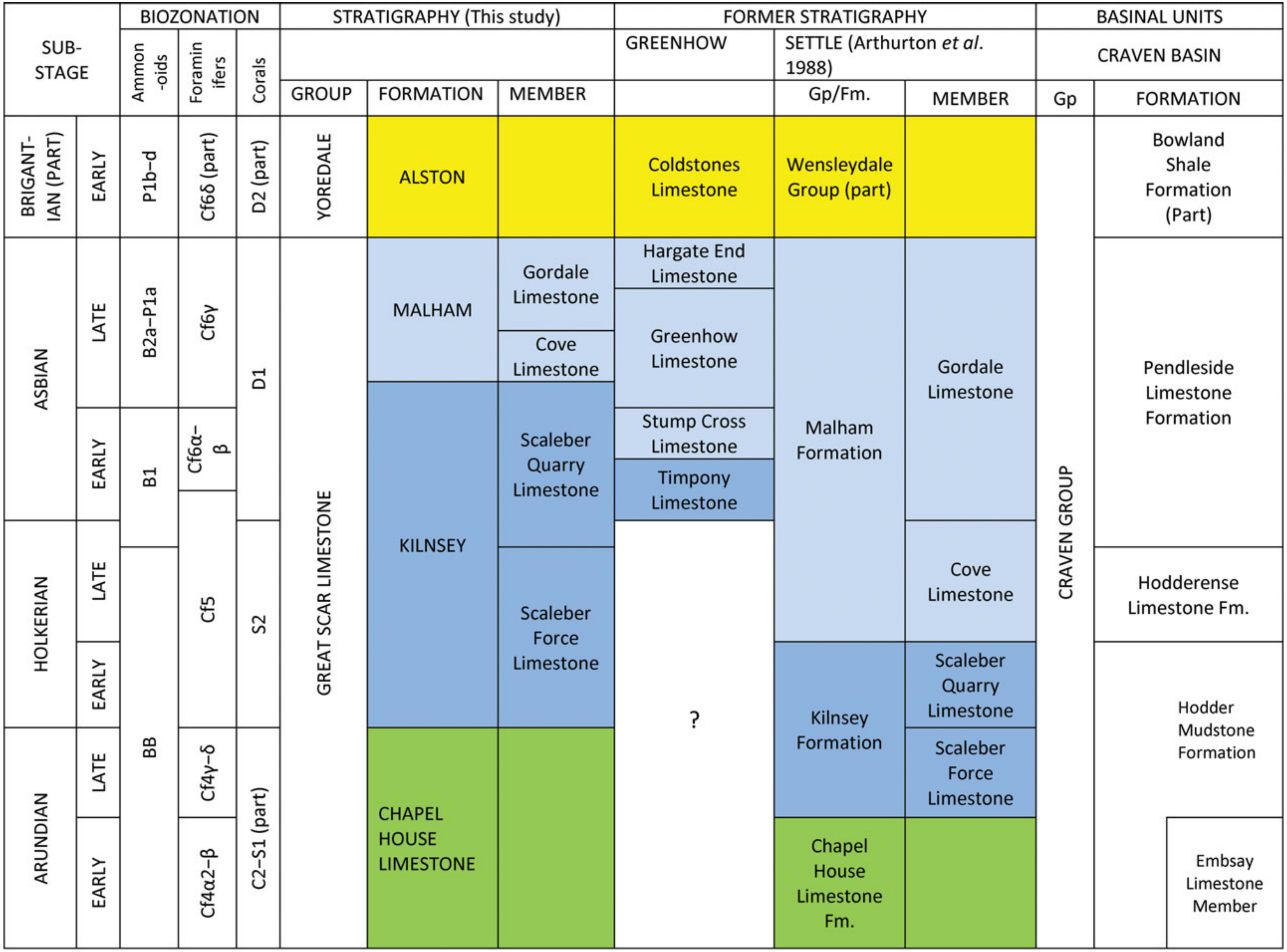

Figure 2. (Colour online) Revised biostratigraphical ages for the Great Scar Limestone Group within the study area. Former nomenclature for the Greenhow Inlier is based upon Dunham & Wilson (1985). Basinal succession of the Craven Basin is based upon Waters *et al*. (2009).

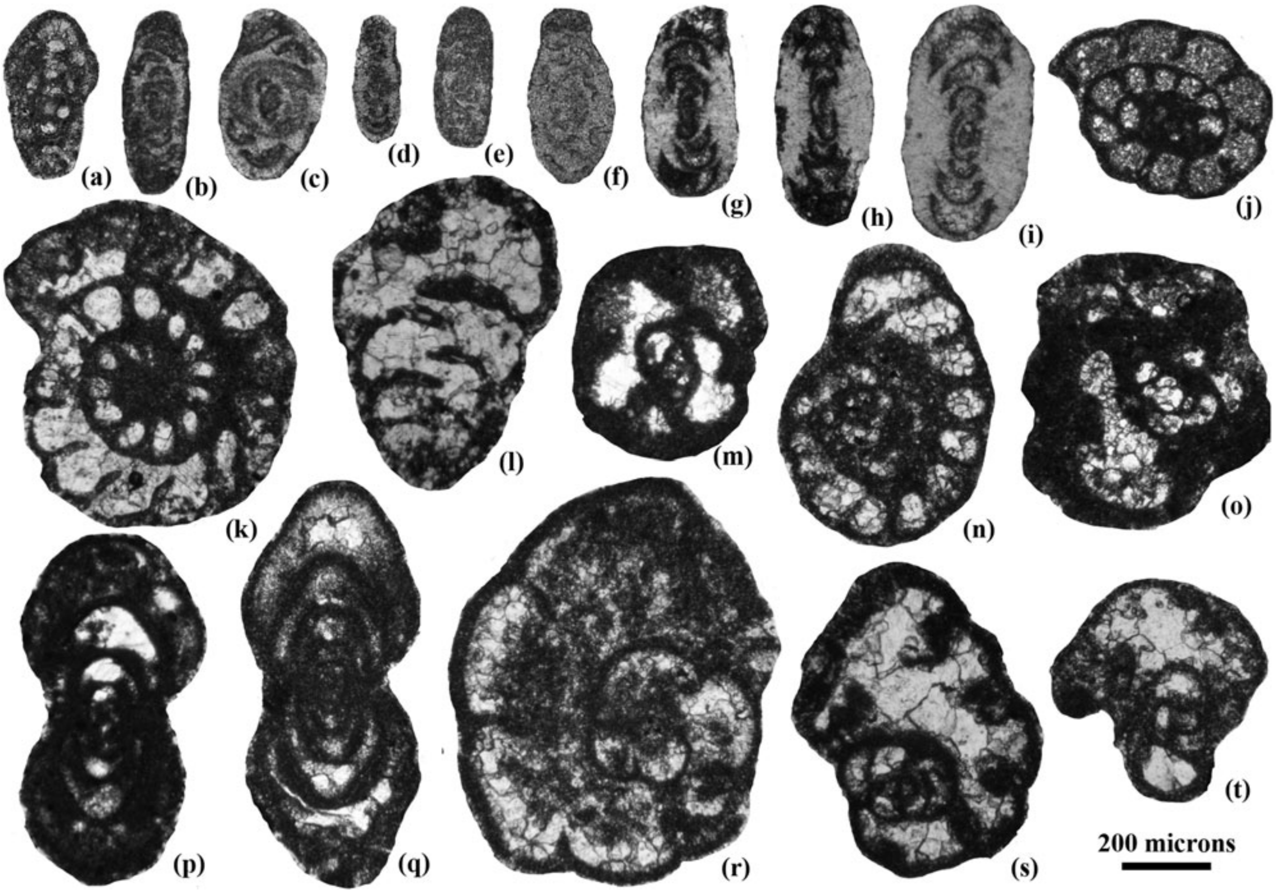

Figure 3. Selected foraminifers from the southern Askrigg Block. (a) *Eoparastaffella simplex* (*EWJ1573*), Arundian, Chapel House Limestone Formation, Silverdale Borehole. (b) *Nodosarchaediscus demaneti* (*Pc4822*), late Asbian, Cove Limestone Member, Conistone Dib. (c) *Archaediscus* at *angulatus* stage (*Pc4822*), late Asbian, Cove Limestone Member, Conistone Dib. (d) *Neoarchaediscus* aff. *incertus* (primitive) (*EWJ1554*), late Asbian, Scaleber Quarry Limestone Member, Silverdale Borehole. (e) *Neoarchaediscus* sp. (primitive) (*Pc4825*), late Asbian, Cove Limestone Member, Conistone Dib. (f) *Neoarchaediscus stellatus* (*EWJ1516*), latest Asbian-Brigantian interval, Gordale Limestone Member, Silverdale Borehole. (g) *Glomodiscus rigens* (*EWJ1575*), Arundian, Chapel House Limestone Formation, Silverdale Borehole. (h) *Uralodiscus adindanii* (*EWJ1575*), Arundian, Chapel House Formation, Silverdale Borehole. (i) *Uralodiscus settlensis* (*EWJ1575*), Arundian, Chapel House Limestone Formation, Silverdale Borehole. (j) *Endothyranopsis* cf. *compressa* (*EWJ1573*), Arundian, Chapel House Limestone Formation, Silverdale Borehole. (k) *Endothyranopsis compressa* (*EWJ1562*), Holkerian, Scaleber Quarry Limestone Member, Silverdale Borehole. (l) *Koskinotextularia* sp. (*EWJ1562*), Holkerian, Scaleber Quarry Limestone Member, Silverdale Borehole. (m) *Holkeria* sp. (*EWJ1563*), Holkerian, Scaleber Quarry Limestone Member, Silverdale Borehole. (n) *Pojarkovella nibelis* (*WQ215*), late Asbian, Gordale Limestone Member, Coldstones Quarry. (o) *Condrustella* sp. (*EWJ1573*), Arundian, Chapel House Limestone Formation, Silverdale Borehole. (p) *Eostaffella parastruvei* (*EWJ1562*), Holkerian, Scaleber Quarry Limestone Member, Silverdale Borehole. (q) *Pseudoendothyra sublimis* (*DMA321*), late Asbian, Cove Limestone Member, Trollers Gill. (r) *Cribrospira panderi* (*WQ215*), late Asbian, Gordale Limestone Member, Coldstones Quarry. (s) *Bibradya grandis* (*WQ205*), latest Asbian, Gordale Limestone Member, Coldstones Quarry. (t) *Bibradya inflata* (*EWJ1531*), latest Asbian, Gordale Limestone Member, Silverdale Borehole.

less species richness (20) and many Arundian taxa no longer present, but still records the last occurrences of taxa typical of the late Arundian. Some first appearances are still distinctive of the Arundian (e.g. *Condrustella*, Fig. 3o) and *Lituotubella magna* (Fig. 4a). The latter taxon was recorded by A. R. E. Strank (unpub. Ph.D. thesis, Univ. Manchester, 1981) from the upper part of the Arundian Dalton Formation close to the contact with the Holkerian Park Limestone Formation in the stratotype Holkerian section at Barker Scar, Cumbria (Ramsbottom, 1981; Waters, 2011). The micritic beds with fenestral fabrics in the upper 5.5 m of the Chapel House Limestone are barren of foraminifers.

2.b. Kilnsey Formation

2.b.1. Lithostratigraphy

The Kilnsey Formation, the type locality of which forms Kilnsey Crag (Figs 1, 6), comprises two distinct units (Arthurton, Johnson & Mundy, 1988; Table 1). The lower Scaleber Force Limestone Member (also Kilnsey Limestone-with-mudstone) is a dark grey, fine- to coarse-grained, argillaceous, bioclastic and peloidal packstone and subordinate wackestone, with common detrital quartz and beds of mudstone up to 1.8 m thick (Arthurton, Johnson & Mundy, 1988). The uppermost part of the member at the type locality (*Pc4833*) is a parallel laminated, argillaceous kamaenid algal

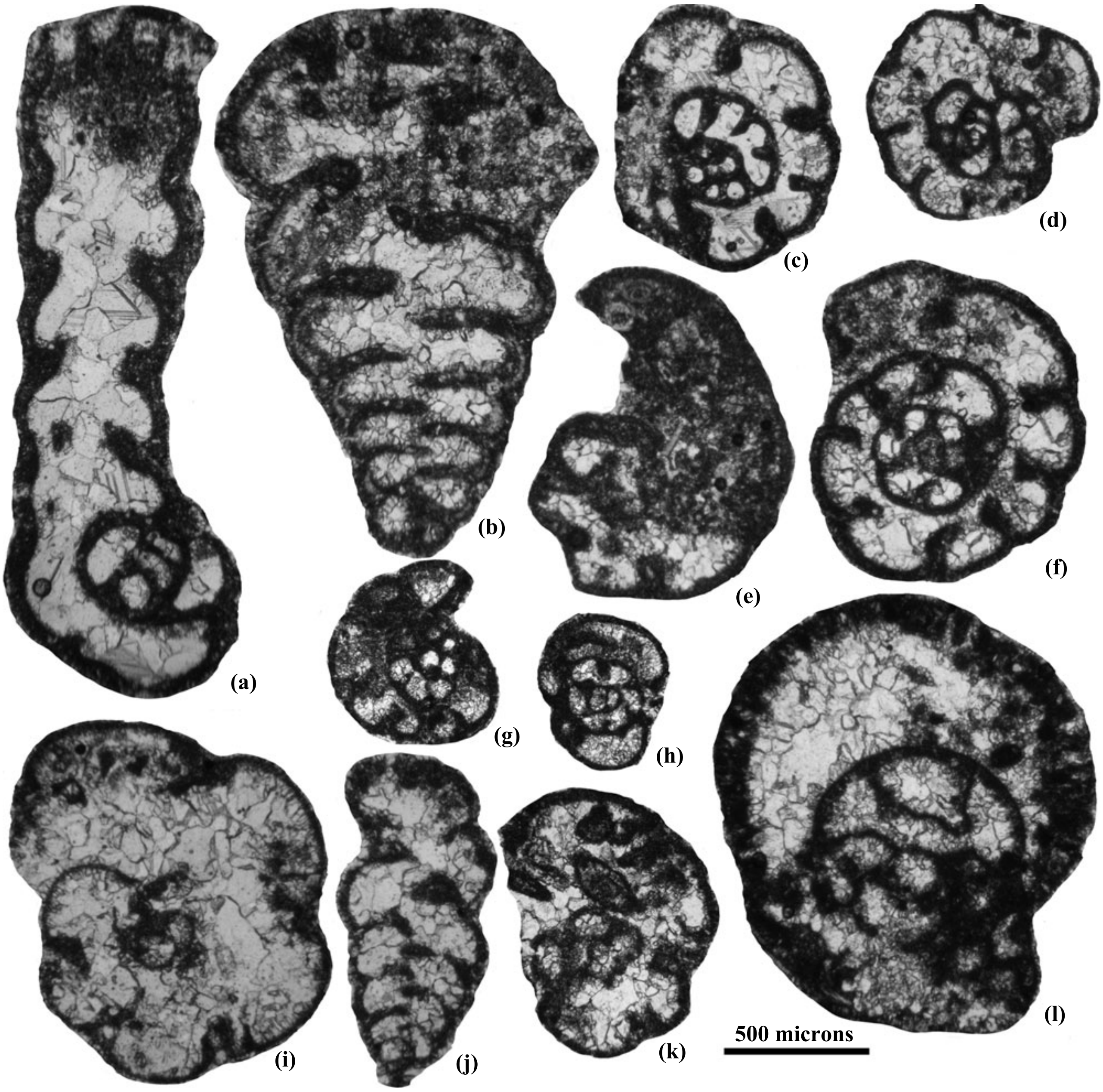

Figure 4. Selected foraminifers from the southern Askrigg Block. (a) *Lituotubella magna* (*EWJ1573*), Arundian, Chapel House Limestone Formation, Silverdale Borehole. (b) *Cribrostomum lecomptei* (*EWJ1514*), latest Asbian–Brigantian interval, Gordale Limestone Member, Silverdale Borehole. (c) *Latiendothyranopsis menneri solida* (*EWJ1573*), Arundian, Chapel House Limestone Formation, Silverdale Borehole. (d) *Omphalotis minima* (*EWJ1556*), early Asbian, Scaleber Quarry Limestone Member, Silverdale Borehole. (e) *Janischewskina*? sp. (primitive) (*EWJ1516*), latest Asbian–Brigantian interval, Gordale Limestone Member, Silverdale Borehole. (f) *Endothyranopsis crassa* (*EWJ1553*), late Asbian, Cove Limestone Member, Silverdale Borehole. (g) *Plectogyranopsis moraviae* (*EWJ1573*), Arundian, Chapel House Limestone Formation, Silverdale Borehole. (h) *Plectogyranopsis settlensis* (*EWJ1566*), Holkerian, Scaleber Quarry Limestone Member, Silverdale Borehole. (i) *Parajanischewskina brigantiensis* (*EWJ1515*), latest Asbian–Brigantian interval, Gordale Limestone Member, Silverdale Borehole. (j) *Koskinobigenerina* sp. (*EWJ1548*), late Asbian, Cove Limestone Member, Silverdale Borehole. (k) *Janischewskina*? sp. (primitive) (*EWJ1524*), latest Asbian, Gordale Limestone Member, Silverdale Borehole. (l) *Bradyina rotula* (*EWJ1513*), latest Asbian–Brigantian interval, Gordale Limestone Member, Silverdale Borehole.

packstone dominated by common crinoids, with subordinate brachiopods and bryozoans and minor micritic intraclasts. This member is comparatively more argillaceous than the overlying Scaleber Quarry Limestone Member (also Kilnsey Limestone), which is 29 m thick at Kilnsey Crag and typically comprises medium to dark grey, well-bedded, fine- to coarse-grained bioclastic packstone or grainstone (Arthurton, Johnson & Mundy, 1988).

East of Kilnsey Crag, the uppermost part of the Scaleber Quarry Limestone Member is exposed at the bottom of Conistone Dib (Fig. 1b). The succession (*Pc4820*) comprises medium grey, thick-bedded (0.6 m), coarse-grained, densely packed packstone

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Table 5. List of specimens and locality details for the key macro- and micro-palaeontological descriptions

Sample Number	Easting	Northing	Location	Lithostratigraphy
BLK3413–17; BLK3420–75	411780	464020	Coldstones No. 4 Borehole	Gordale Limestone
BLK3490–3574; BLK3577	411780	464020	Coldstones No. 4 Borehole	Cove Limestone
DMA320	406870	461810	Trollers Gill, Appletreewick	Cove Limestone
DMA321	406860	461830	Trollers Gill, Appletreewick	Cove Limestone
DMA322	406850	461900	Trollers Gill, Appletreewick	Cove Limestone
DMA323	406850	461920	Trollers Gill, Appletreewick	Cove Limestone
DMA324	406850	461930	Trollers Gill, Appletreewick	Cove Limestone
DMA325	406860	461950	Trollers Gill, Appletreewick	Cove Limestone
DMA326	406870	461990	Trollers Gill, Appletreewick	Cove Limestone
DMA327–8	408670	463470	Dry Gill, Stumps Cross, near Greenhow	Gordale Limestone
EWJ1513–38	384350	471430	Silverdale Borehole	Gordale Limestone
EWJ1539–53	384350	471430	Silverdale Borehole	Cove Limestone
EWJ1554–67	384350	471430	Silverdale Borehole	Scaleber Quarry Limestone
EWJ1568–75	384350	471430	Silverdale Borehole	Chapel House Limestone
Pc4820	398286	467488	Conistone Dib	Scaleber Quarry Limestone
Pc4821	398315	467496	Conistone Dib	Cove Limestone
Pc4822	398349	467528	Conistone Dib	Cove Limestone
Pc4823–4	398369	467535	Conistone Dib	Cove Limestone
Pc4825	398414	467548	Conistone Dib	Cove Limestone
Pc4826	398430	467553	Conistone Dib	Cove Limestone
Pc4827	398439	467578	Conistone Dib	Cove Limestone
Pc4828–31	398444	467569	Conistone Dib	Cove Limestone
Pc4832	398482	467532	Conistone Dib	Gordale Limestone
Pc4833	397427	468192	Kilnsey Crag	Scaleber Force Limestone
RBH04	397719	464528	Threshfield Quarry, east face	Gordale Limestone
RBH05	397664	464686	Threshfield Quarry north face	Gordale Limestone
RBH50	402727	462084	SW of Ranelands Farm, River Wharfe	Gordale Limestone
RBH51	401377	462827	193 m east of Lythe House	Gordale Limestone
RBH59	400101	463356	Above Linton Falls, Bow Bridge	Gordale Limestone
WMD16466	397729	464425	Threshfield Quarry, near Grassington	Gordale Limestone
WMD16467–8	397720	464503	Threshfield Quarry, near Grassington	Gordale Limestone
WMD16469–72	397719	464528	Threshfield Quarry, near Grassington	Gordale Limestone
WMD16473–82	397663	464686	Threshfield Quarry, near Grassington	Gordale Limestone
WMD16549–60; WMD16563–67	412490	464140	Coldstones Quarry	Gordale Limestone
WMD16572–74	412450	463940	Coldstones Quarry	Gordale Limestone
WMD16575–79	412560	464060	Coldstones Quarry	Gordale Limestone
WQ199	411222	463826	Duck Street South Quarry	Gordale Limestone
WQ200	411315	463931	Duck Street North Quarry	Gordale Limestone
WQ203	412370	463993	Coldstones Quarry	Gordale Limestone
WQ204	412393	463972	Coldstones Quarry	Gordale Limestone
WQ205–6	412444	463989	Coldstones Quarry	Gordale Limestone
WQ207	412524	464078	Coldstones Quarry	Gordale Limestone
WQ215	412519	464136	Coldstones Quarry	Gordale Limestone
WQ216	412458	464155	Coldstones Quarry	Gordale Limestone
WQ217	412360	464019	Coldstones Quarry	Gordale Limestone
WQ218	412561	464104	Coldstones Quarry	Gordale Limestone

with crinoidal debris, some brachiopod valves and small micritic intraclasts (Fig. 7). Bioclasts and peloids are moderately sorted, with a poorly defined cross-lamination. The bioclasts are dominated by crinoids with minor components of syringoporoids, bryozoans and brachiopods.

In the Greenhow and Skyreholme inliers (Fig. 1b), the absence of a thick interval of 'dark grey limestone' was used by Dunham & Wilson (1985) to justify that the equivalent of the Kilnsey Formation was absent at outcrop; our study confirms that interpretation. However, the Scaleber Quarry Limestone Member is considered to be present in the subsurface in Coldstones No. 4 Borehole below 295.2 m (BGS Registration number SE16SW5; Fig. 8). Interpreted as the lower part of the Stump Cross Limestone and Timpony Limestone by Strank (1982*b*), this succession is distinctly dominated by medium grey, fine- to medium- or medium-grained limestone, partly dolomitized, with brachiopods, crinoids and coral beds. A thickness for this member of more than 128 m in this borehole is comparable with 135 m recorded in the Cominco S2 Borehole (SD86SW6; Fig. 1a) near Settle (Arthurton, Johnson & Mundy, 1988).

The Kilnsey Formation in the Silverdale Borehole is 33 m thick (Murray, 1983) and is a relatively uniform facies of medium to dark grey, fine- to medium-grained packstones and grainstones with shelly fauna, although some fenestral lime-mudstones are interbedded (Fig. 5). This contrasts with Murray (1983) who described the succession between 146.52 and 171.96 m as grainstone at the base, otherwise wackestone and locally packstone. This is still a moderately shallow-water shelf facies with crinoids, brachiopods, bryozoans, corals, foraminifers and dasyclads and rare ooids. The presence of intraclasts is of some interest, but not distinctive, as they are also present in the overlying Cove Limestone Member. The upper boundary at 146.52 m marks a clear colour change from the mainly dark packstone/wackestone of the Kilnsey Formation to paler

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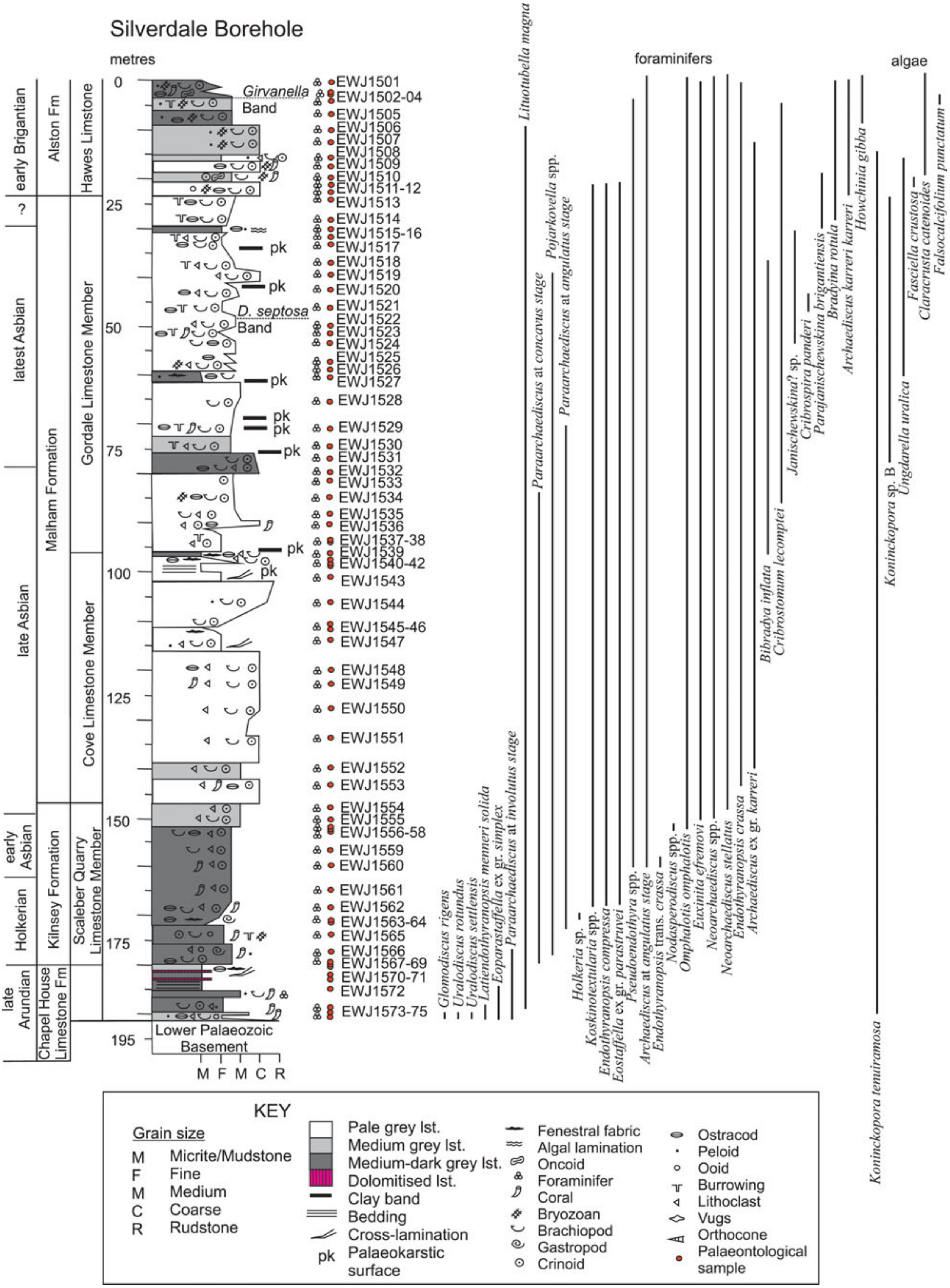

Figure 5. (Colour online) Lithological log for the Silverdale Borehole, showing the position of biostratigraphical samples (*EWJ1501–1575*) and the range of key foraminifers and algae.

Figure 6. (Colour online) At Kilnsey Crag [3974 4681] the upper part of the Scaleber Force Limestone Member is evident beneath a prominent bedding surface near the base of the cliff (arrowed), mainly obscured by the grassy slope. The overlying Scaleber Quarry Limestone Member forms the main face and overhang. The basal part of the Cove Limestone Member (Malham Formation) caps the crag.

coarser grained packstone/wackestone of the overlying Cove Limestone Member. The Kilnsey Formation is thin when compared to Kilnsey Crag. The absence of common argillaceous beds suggests that the Scaleber Force Limestone Member is absent and only the equivalent of the Scaleber Quarry Limestone Member is present in the Silverdale Borehole. The presence of rare ooids within the lower part of the Kilnsey Limestone in this borehole is unusual, but is quite common in the underlying Chapel House Limestone Formation.

2.b.2. Biostratigraphy

Macrofossils. The Scaleber Force Limestone Member is approximately equivalent to the upper part of the *Michelinia* Zone (C_2) of Garwood & Goodyear (1924), and the lowest unit (the Gastropod Beds) of their *Productus corrugato–hemisphericus* Zone (S) (Arthurton, Johnson & Mundy, 1988). An Arundian age for the Scaleber Force Limestone Member is confirmed by the presence of the brachiopod *Delepinea carinata* at Mill Scar Lash, River Wharfe [29796 46638], and by the incoming of the corals *Siphonodendron martini* and *Palaeosmilia murchisoni* (Arthurton, Johnson & Mundy, 1988). Brachiopods are dominated by *Megachonetes* spp. with common *Schizophoria resupinata* (Arthurton, Johnson & Mundy, 1988).

The Scaleber Quarry Limestone Member is the equivalent of the *Cyrtina carbonaria* Subzone (S_2) of Garwood & Goodyear (1924), together with the lower part of their *Nematophyllum minus* Subzone (S_2). The presence of the cerioid coral *Lithostrotion* (*Nematophyllum*) *minus*, and the brachiopods *Composita ficoidea*, rare *Davidsonina carbonaria*, *Linoprotonia ashfellensis* and *L. corrugatohemispherica*, confirm a Holkerian age (Arthurton, Johnson & Mundy, 1988). The fasciculate coral *Siphonodendron scaleberense* was also first recorded from Scaleber Quarry (Nudds & Somerville, 1987). Dunham & Wilson (1985) noted the presence of the corals *Lithostrotion minus* and *L.* (= *Siphonodendron*) *sociale* and the brachiopod *Linoprotonia ashfellensis* in the Coldstones No. 4 Borehole below 306 m (Fig. 8), which they also considered to have a Holkerian aspect.

Microfossils. Foraminifers from the Chapel House, Stockdale Farm and Cominco Sl0 (BGS Registration number SD86SW8) boreholes (Fig. 1a) were used by Strank (*in* Arthurton, Johnson & Mundy, 1988) to confirm an Arundian age (Cf4) for the Scaleber Force Limestone Member. Diagnostic taxa recorded for these boreholes include *Ammarchaediscus* (= *Viseidiscus*) *bucullentus*, *Brunsiarchaediscus* (= *Planoarchaediscus*) sp., *Glomodiscus miloni*, *Plectogyranopsis moraviae*, *Pseudolituotubella hibernica*, *Rectodiscus* (= *Uralodiscus*) sp. and *Tubispirodiscus* (= *Uralodiscus*) *settlensis*. Conil, Longerstaey & Ramsbottom (1980) also analysed samples from the Scaleber Force Limestone Member at the type locality of Scaleber Force, which they assigned to the Arundian. However, they identified a specimen as cf. *Omphalotis minima*, whereas the illustrated specimen can be readily assigned to the nominal species. As Conil, Longerstaey & Ramsbottom (1980) recognized, *O. minima* is one of the guides for the Holkerian (Cf5). The typical assemblage for the Scaleber Force Limestone Member is similar to the basal bed of the Chapel House Limestone in the Silverdale Borehole (see Section 2.a.2 above).

For the Scaleber Quarry Limestone Member a foraminiferal assemblage reported by Strank (*in* Arthurton, Johnson & Mundy, 1988) included *Archaediscus* at *angulatus* stage (probably transitional forms), *A.* at *concavus* stage, *Koskinotextularia cribriformis*, *Nibelia* (= *Pojarkovella*) *nibelis* and *Nodosarchaediscus* sp., confirming a Holkerian age (Cf5) for this succession.

Kilnsey Crag shows the transition between the two members of the Kilnsey Formation (Fig. 6). Strank (*in* Dunham & Wilson, 1985) reported that the lowest 7 m of the section, representing the top of the Scaleber Force Limestone, yielded the foraminifers *Ammarchaediscus* (= *Viseidiscus*), *Glomodiscus* and *Rectodiscus* (= *Uralodiscus*) but no diagnostic Holkerian genera. Whereas immediately above that level, and approximately coinciding with the base of the Scaleber Quarry Limestone Member, Strank reported the incoming of *Koskinotextularia* sp. followed higher up by *Endothyranopsis crassa* (probably *E. compressa* trans. *crassa*), *Nevillella* (= *Mstinia*) sp., *Nibelia* (= *Pojarkovella*) *nibelis* and nodose archaediscids, and accompanying *Brunsia spirillinoides*, *Eostaffella parastruvei*, *Glomospiranella dainae* and *Septabrunsiina* sp., which form a characteristic Holkerian foraminiferal assemblage (Table 2).

Resampling of the uppermost part of the Scaleber Force Limestone Member at Kilnsey Crag (*Pc4833*) records diverse foraminifers (Table 2) of which *Archaediscus* at *concavus* stage transitional forms to the *angulatus* stage, large *A.* aff. *chernoussovensis*,

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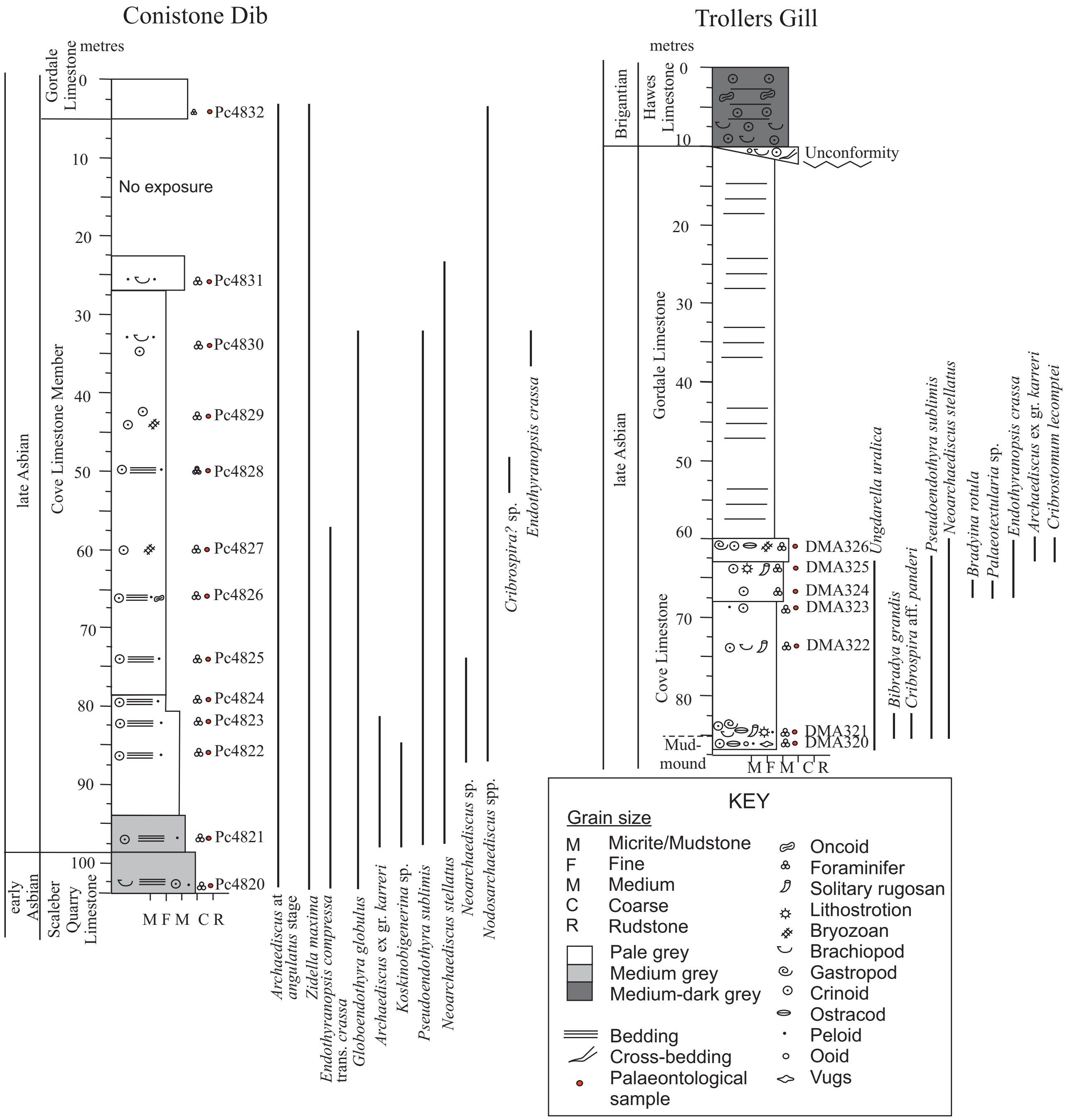

Figure 7. Lithological logs for key sections of the Cove Limestone at Conistone Dib and Trollers Gill, showing the position of biostratigraphical samples (*Pc4820–32* and *DMA320–26*) and the range of key foraminifers and alga/algospongia.

Endothyranopsis compressa and *Nodosarchaediscus* spp. indicate a late Holkerian age (Cf5) (Conil, Longerstaey & Ramsbottom, 1980; A. R. E. Strank, unpub. Ph.D. thesis, Univ. Manchester, 1981).

The top of the Scaleber Quarry Limestone Member at Conistone Dib (*Pc4820*; Fig. 7) records the presence of *Archaediscus* at *angulatus* stage, *Endothyranopsis compressa* trans. *crassa*, *Globoendothyra globulus* and *Nodosarchaediscus* spp., as well as the algospongia *Zidella maxima* (Table 2). Although the stratigraphic range of the latter is poorly known, it has been associated with the late Viséan upwards (≥ Cf6γ) (Vachard & Cózar, 2010). The foraminifers are typically recorded from the early Asbian (Cf6α-β) in Western Europe (Conil, Longerstaey & Ramsbottom, 1980).

In the Greenhow Inlier, the lower part of the Coldstones No. 4 Borehole (Fig. 8), below *c.* 225 m, contains a sparse foraminiferal assemblage including *Archaediscus* sp., *A. stilus*, *Endothyranopsis crassa* (most probably *E. compressa* trans. *crassa*), *Eostaffella* sp., *Consobrinella consobrina*, *Pseudoammodiscus volgensis*, *Omphalotis* cf. *minima*, *Nodosarchaediscus* sp., *Brunsia* sp. and *Valvulinella* sp. and common alga *Koninckopora inflata* (Strank, 1982*b*; Table 3), which Strank attributed as Holkerian. The more fossiliferous part of the borehole from 325.9 m to 295.15 m depth

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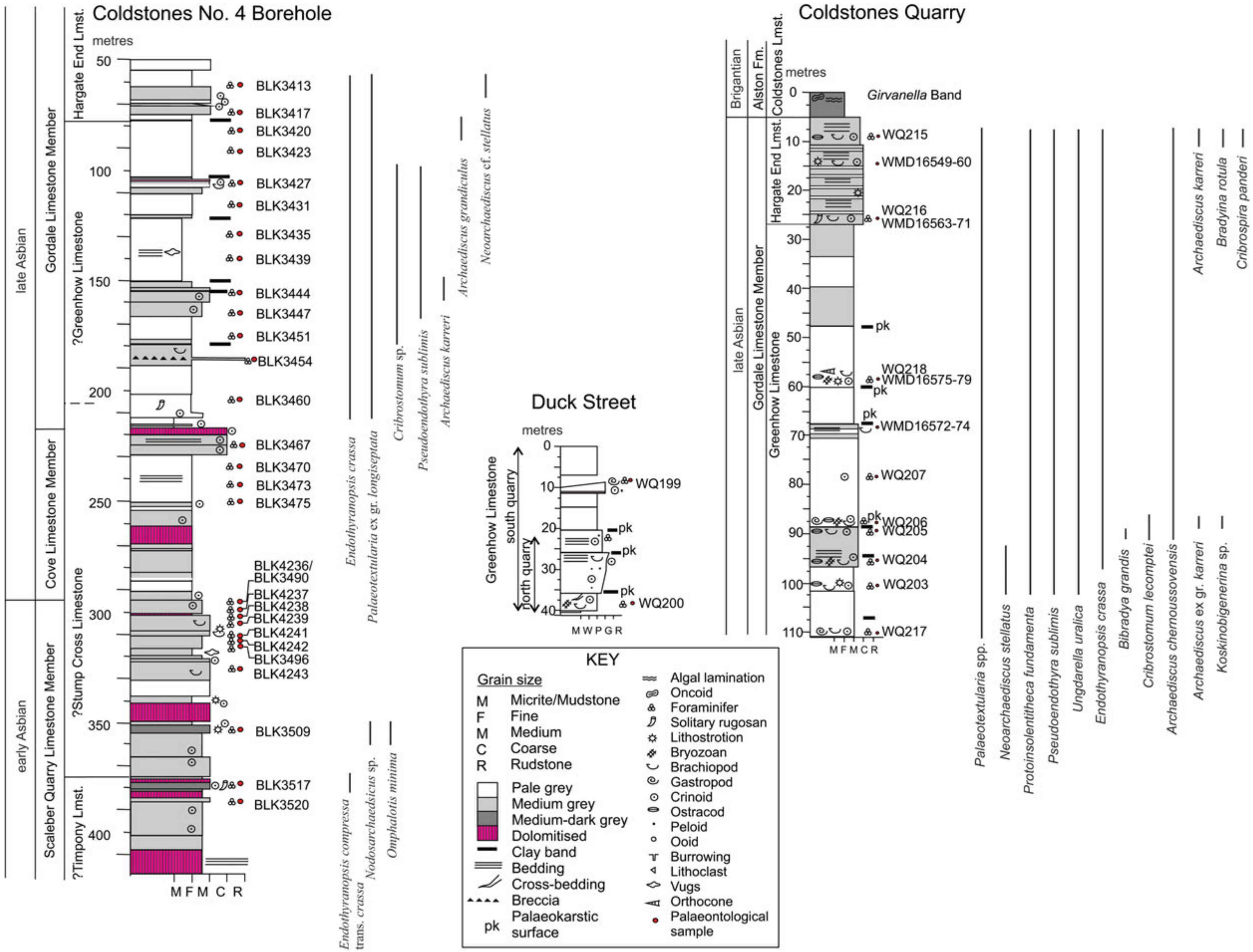

Figure 8. (Colour online) Lithological logs for key sections in the Greenhow Inlier at Duck Street, Coldstones Quarry and Coldstones No.4 Borehole, showing the position of biostratigraphical samples and the range of key foraminifers.

was interpreted as Holkerian to possibly early Asbian in age (Strank, 1982*c*). The foraminifers from the lower part of the borehole, although sparse and lacking many characteristic taxa, are most probably early Asbian in age (Cf6α-β) as they include some species not known in the Holkerian; the lack of diversity and diagnostic taxa suggests this interval is not late Asbian (Cf6γ) in age.

In the Silverdale Borehole (Fig. 5; Table 4), the incoming of Holkerian taxa coincides with the base of the Kilnsey Formation (*EWJ1567*), especially with *Paraarchaediscus* at *concavus* stage and *Omphalotis minima* (Fig. 4d), with *Pojarkovella* sp. (*EWJ1566*) and *Holkeria* (*EWJ1563*; Fig. 3m) appearing in the lower part of the formation. The diagnostic Holkerian taxa appear together in the middle of the Kilnsey Formation (*EWJ1562*) with the first appearance datum (FAD) of *Koskinotextularia* sp. (Fig. 3l), *Eostaffella parastruvei* (Fig. 3p) and *Mikhailovella*, and with *Pojarkovella nibelis* (*EWJ1561*), the latter occurring some 14.5 m above the base of the first Holkerian taxa. The FAD of *Endothyranopsis* trans. *crassa* and *Paraarchaediscus* at *angulatus* stage in the upper part of the Kilnsey Formation (*EWJ1560*) is indicative of an early Asbian age, followed near the top of the formation by *Nodasperodiscus* and *Consobrinella consobrina* (*EWJ1558*). The absence of *Vissariotaxis* from this lower Asbian part of the succession is noteworthy, but is considered a result of the shallow-water facies evident in this borehole. The FAD of *Neoarchaediscus* aff. *incertus*, *N. stellatus* and *Koskinobigenerina* (*EWJ1554*; Fig. 3d) from the very topmost bed of the Kilnsey Formation marks the incoming of late Asbian taxa.

In summary, existing published information, mainly based upon coral/brachiopod assemblages, indicates an Arundian age for the Scaleber Force Limestone Member and a Holkerian age for the Scaleber Quarry Limestone Member (Arthurton, Johnson & Mundy, 1988). This contrasts with our study, in which the foraminiferal/algal assemblages suggest a late Holkerian and early/late Asbian age, respectively, for the upper parts of the two members (Table 2). The Coldstones No. 4 Borehole (Fig. 8), in the Greenhow Inlier, includes a succession lithologically comparable with the Scaleber Quarry Limestone Member and with a similar fauna of probable early Asbian age.

2.c. Cove Limestone Member (Malham Formation)

2.c.1 Lithostratigraphy

The Cove Limestone Member, the lower part of the Malham Formation, is named after Malham Cove [3896 4642] (Fig. 1a), where it forms the lower part of the cliff face (Arthurton, Johnson & Mundy, 1988). This member is typically pale grey, massive to weakly bedded packstone/wackestone lacking prominent palaeokarstic surfaces (Table 1) and typically forms a landscape with grassy slopes. Distinctive lime-mudstone (micrite) beds with fenestral fabrics occur mainly within the upper part of the member (Arthurton, Johnson & Mundy, 1988). The *c.* 1.5 m thick 'Porcellanous Bed' has been used as a marker (e.g. Garwood & Goodyear, 1924; Ramsbottom, 1974) for the top of the Horton Limestone (= top of Cove Limestone Member), but this facies is shown to disappear both northwards towards the Stainmore Basin and southwards where it is not recorded south of the North Craven Fault (Arthurton, Johnson & Mundy, 1988), or within the current study area.

Above the Kilnsey Formation at Kilnsey Crag (Fig. 6), the Cove Limestone Member comprises coarsely bioclastic packstone/grainstone and is strongly bedded, e.g. at Cool Scar Quarry [39692 46751]. An entire thickness of the member (80 m) is recorded at Conistone Dib (Figs 1b, 9a), comprising very thick beds of pale grey packstone/grainstone with less prominent bedding surfaces and some pale brown dolomitization (Fig. 7). The basal (*Pc4821−3*) and middle parts of the section (*Pc4826* and *Pc4828*) comprise bioclastic/peloidal grainstone, with common crinoids, foraminifers and intraclasts, with a poorly developed cross-lamination developed in some beds and rare oncoids (*Pc4826*). The middle of the section (*Pc4824* and *Pc4825*) also includes finer grained bioclastic/peloidal grainstones with more dasycladals and locally (*Pc4827*) crinoidal/algal packstone with many small intraclasts. The upper part of the member (*Pc4830* and *Pc4831*) comprises bioclastic peloidal grainstones with large brachiopod shells marking a cross-lamination.

In the Skyreholme Inlier (Fig. 1b), Dunham & Wilson (1985) equated the Timpony Limestone with the Cove Limestone Member. However, there is little lithological similarity between the two units (Table 1) and it is assumed that the correlation was based on age. The key section at Trollers Gill (Fig. 9b) was mapped previously as 'S Beds' by Anderson (1928), who recognized an upward succession of 'white limestone and lime-mudstone, light grey slightly crinoidal limestone, and capped by porcellanous limestone' with the first appearance of productid brachiopods. The section is lithologically very similar in appearance to the Cove Limestone Member at Conistone Dib, with a monotonous development of at least 25 m of broadly upward-coarsening, massive to very thick-bedded, pale grey packstone/grainstone (Fig. 7). The lower part (*DMA320–323*) is fine- to medium-grained, skeletal (crinoidal-algal-rich) and peloidal packstone/grainstone, locally with abundant limestone intraclasts. The basal part of this succession (*DMA320*) includes coated grains and sparse ooids, large cavities containing sparry cements, peloids in geopetal sediment and large limestone intraclasts. The upper part of the succession in the gorge (*DMA324–326*) is medium- and medium- to coarse-grained, moderately and well-sorted, skeletal (crinoidal-algal-rich) packstone.

The Stump Cross Limestone of Dunham & Stubblefield (1945) and Dunham & Wilson (1985) is named after the eponymous showcave located in the

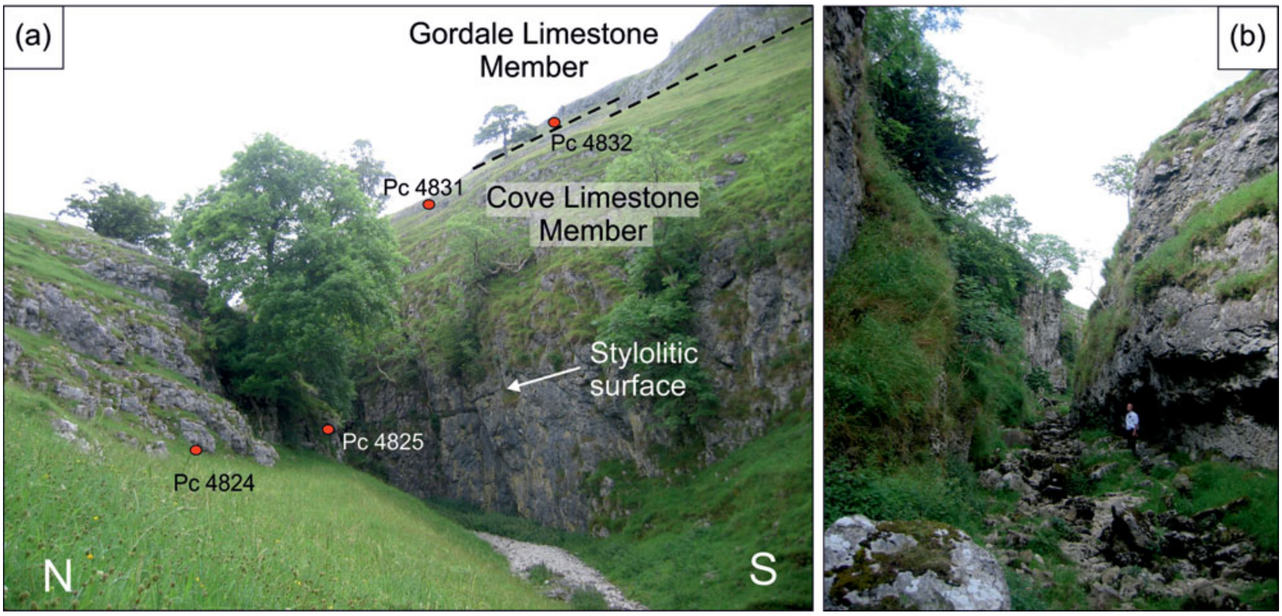

Figure 9. (Colour online) Key localities in the Cove Limestone Member. (a) At Conistone Dib [3982 4674], exposed in a meltwater drainage channel. The Gordale Limestone Member forms the distinctive crag at the top of the slope. The locations of some of the sample locations are shown. (b) Massive packstone/grainstone of the Cove Limestone Member at Trollers Gill [40687 46181]. Sample *DMA320* is from the base of the right (eastern) wall of the gorge.

Skyreholme Inlier. The base of the unit was taken at the base of the 'Hemitrypa Bed', a *c*. 0.8 m thick 'pale brown (fawn) bioclastic limestone, overlain by buff dolomitic limestone, in turn passing up to pale grey or white limestone' (Dunham & Stubblefield, 1945). This had been described as 'Porcellanous Limestone' of Asbian (D_1) age by Hudson (1938) and may equate with such beds described by Anderson (1928) in Trollers Gill, although as discussed by Dunham & Stubblefield (1945), it is not an accurate description of this succession. There is very limited exposure of this limestone and insufficient lithological distinction to justify recognition of a separate formation, and hence use of the term is discontinued in this study.

In the Greenhow Inlier, there is a marked reduction in grain size in the Coldstones No. 4 Borehole (Fig. 8) above 295.2 m, with a succession of fine-grained limestone, mainly medium grey below 250 m depth and mainly pale grey and thick bedded or massive above, with few macrofossils other than subordinate beds with crinoid ossicles. This succession, previously considered the upper part of the Stump Cross Limestone (Strank, 1982*b*) is here attributed to the Cove Limestone Member. The uppermost 10 m (224.9–214.9 m depth) are coarse grained and crinoidal, possibly reflecting the coarsening-upward succession recorded in this member at Trollers Gill (Fig. 7).

The Cove Member in the Silverdale Borehole (Fig. 5) is 46 m thick (Murray, 1983) and is dominated by pale grey, fairly coarse-grained grainstone and packstone with shelly fauna interbedded with rare fenestral lime-mudstones in the upper 15 m, considered to be the Porcellanous Bed (Murray, 1983). Arthurton, Johnson & Mundy (1988) recognized a conspicuous increase in the proportion of grainstones in the Horton in Ribblesdale area, coinciding with a thinning of the member and the presence of the Porcellanous Bed. The upper boundary of the member is repositioned relative to Murray (1983) above the upper lime-mudstone (*EWJ1539*) at the base of the overlying bed at 95.7 m. The upper 6 m in this member (102−95.7 m) contains palaeokarstic surfaces which are not typical for this member at outcrop in the study area, but in the Settle district are thought to be associated with the Porcellanous Beds (Arthurton, Johnson & Mundy, 1988).

2.c.2. Biostratigraphy

Macrofossils. Little work has been done to establish the age of the Cove Limestone Member in Upper Wharfedale. Macrofauna are sparse, but concentrations of single species of corals and brachiopods including *Axophyllum vaughani*, *Lithostrotion* (= *Siphonodendron) sociale*, *Syringopora* sp., *Linoprotonia ashfellensis* and *Megachonetes papilionaceous* group were reported by Arthurton, Johnson & Mundy (1988) from the Settle district. In the Skyreholme Inlier, Dunham & Stubblefield (1945) recorded from the 'Hemitrypa Bed' the bryozoan *Hemitrypa hibernica* and alga *Koninckopora inflata* in association with *Siphonodendron junceum*, the last named fossil possibly indicating a late Asbian (D_1) age (see Poty, 1984; Mitchell, 1989). However, according to Nudds (1980) and Aretz & Nudds (2005), *S. junceum* first appears in the early Asbian at Little Asby Scar further north in the Stainmore Basin.

Microfossils. A restricted assemblage of foraminifers from the Gordale Scar section [3913 4640], consisting essentially of *Archaediscus* sp. (non '*angulatus*' stage)

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and *Koskinotextularia cribriformis*, were interpreted as a deeper water Holkerian fauna by Arthurton, Johnson & Mundy (1988). A typical Holkerian (shallow-water) assemblage was considered by Arthurton, Johnson & Mundy (1988) to be present in the Silverdale Borehole, where diagnostic taxa included *Archaediscus stilus*, *Holkeria daggeri*, *Nibelia* (= *Pojarkovella*) *nibelis*, *Palaeospiroplectammina paprothae* and *Septabrunsiina tynanti*. However, in a reinvestigation of the borehole (Fig. 5; Table 4), the FAD of *Endothyranopsis crassa* (Fig. 4f), *Pseudoendothyra sublimis* (*EWJ1553*) and *Archaediscus karreri* (*EWJ1552*), as well as common *Neoarchaediscus* (including *N. stellatus*), *Koskinobigenerina* sp. (Fig. 4j), bilaminar *Palaeotextularia* and *Omphalotis omphalota* indicate late Asbian taxa in the lower part of the member, with the FAD of *Bibradya inflata* indicating a higher horizon of late Asbian age for the top of the member (*EWJ1539*).

At Conistone Dib, the lowermost beds (*Pc4821*) comprise the key foraminifers *Archaediscus* at *angulatus* stage (Fig. 3c), large *A.* ex gr. *karreri*, *Koskinobigenerina* sp., *Neoarchaediscus stellatus* and *Pseudoendothyra sublimis* (Fig. 7; Table 2), which suggest a late Asbian age (Cf6γ) (A. R. E. Strank, unpub. Ph.D. thesis, Univ. Manchester, 1981; Laloux, 1987; Cózar & Somerville, 2004; Somerville & Cózar, 2005). An additional late Asbian foraminiferal marker is *Neoarchaediscus* sp. (also from the lower beds, at *Pc4822*; Fig. 3e) and *Endothyranopsis crassa* from the upper part of the succession (*Pc4830*). The *Neoarchaediscus* Zone is regarded as largely equivalent to the Asbian and Brigantian substages (Conil, Longerstaey & Ramsbottom, 1980; Conil *et al.* 1991; Riley, 1993; Jones & Somerville, 1996), although true occluded forms, particularly *N. stellatus*, have never been illustrated in England below the upper Asbian (e.g. Conil, Longerstaey & Ramsbottom, 1980; A. R. E. Strank, unpub. Ph.D. thesis, Univ. Manchester, 1981; Cózar & Somerville, 2004), and previously documented specimens of *Neoarchaediscus* could be assigned to the problematic genera and subgenera *Nodosarchaediscus*, *Asperodiscus* or *Nodasperodiscus*.

In the Skyreholme Inlier, the basal sample (*DMA320*) at Trollers Gill (Figs 7, 9b) contains a limited foraminiferal assemblage, which only suggest an Asbian age (Table 3). However, 2 m higher in the succession (*DMA321*), an assemblage with the first occurrences of *Cribrospira* aff. *panderi*, *Bibradya grandis*, *Neoarchaediscus stellatus*, *Palaeotextularia* sp., *Pseudoendothyra sublimis* (Fig. 3q) and the algospongia *Ungdarella uralica* is assigned to the late Asbian (Cf6γ) (A. R. E. Strank, unpub. Ph.D. thesis, Univ. Manchester, 1981; Jones & Somerville, 1996; Cózar & Somerville, 2004, 2005, 2013). The assemblages do not change significantly through the section, except for the youngest sample (*DMA326*), which contains the foraminifers *Archaediscus* ex gr. *karreri* and *Cribrostomum lecomptei*, also markers for the late Asbian (Conil, Longerstaey & Ramsbottom, 1980; Cózar & Somerville, 2004).

In Coldstones No. 4 Borehole (Fig. 8), Strank (1982*b*) recorded between 250 and 205 m a low-diversity foraminiferal assemblage of *Archaediscus* sp. and *A. stilus* and abundant alga *Koninckopora inflata* (Table 3) from the lower part of their Greenhow Limestone. Strank (1982*b*) noted the lack of diagnostic taxa, but considered the low diversity suggestive of a Holkerian age, although evidence for early Asbian taxa at greater depths in this borehole (see Section 2.b.2 above) discounts this.

In summary, across the study area, strata mapped as the Cove Limestone Member are most probably late Asbian in age. This contrasts with the Holkerian age previously considered for the member, partly proposed from foraminiferal assemblages in the Silverdale Borehole (Fig. 5), east of Horton in Ribblesdale (Arthurton, Johnson & Mundy, 1988). Reinvestigation of this borehole suggests there is no evidence of a marked diachroneity within the member across the southern part of the Askrigg Block.

2.d. Gordale Limestone Member (Malham Formation)

2.d.1 Lithostratigraphy

The Gordale Limestone Member (upper part of the Malham Formation) is named after the type locality of Gordale Scar [3913 4640] (Fig. 1a), where the member is 94 m thick (Arthurton, Johnson & Mundy, 1988). This member also caps Malham Cove, where it forms a limestone pavement, a common feature of this member. It is typically medium-pale to very pale grey packstone/grainstone, well bedded, varying from thick to very thick bedded, and its individual beds tend to form major scar features in the southern part of the district (Table 1).

The member is well represented at the head of Conistone Dib [39922 46821] with a 6 m-thick section of pale grey, very thick-bedded grainstone, with crinoid ossicles, micrite-coated intraclasts, brachiopod valves and rare *Siphonodendron* corals. The base of the member comprises a bioturbated intraclastic/crinoidal/packstone/grainstone with intraclasts (>1 mm diameter), crinoids and peloids (*Pc4832*; Fig. 7). In the upper part of Conistone Dib [398771 467735], the basal bed of the Gordale Limestone rests with a small angular discordance on the underlying weakly bedded Cove Limestone.

At Threshfield Quarry, near Grassington (Fig. 1b), the succession comprises very thickly bedded, light grey fine- to medium-grained, moderately sorted, intraclastic-skeletal-peloidal packstone. Bioclasts are dominated by crinoids with minor components of brachiopods. This quarry includes at least four prominent palaeokarstic surfaces (Fig. 10a) and had previously been assigned, erroneously, to the Cove Limestone Member (British Geological Survey, 1989).

Above Linton Falls, Bow Bridge (*RBH59*; Fig. 1b) and 193 m east of Lythe House (*RBH51*), there is pale grey, well-bedded medium-grained and poorly

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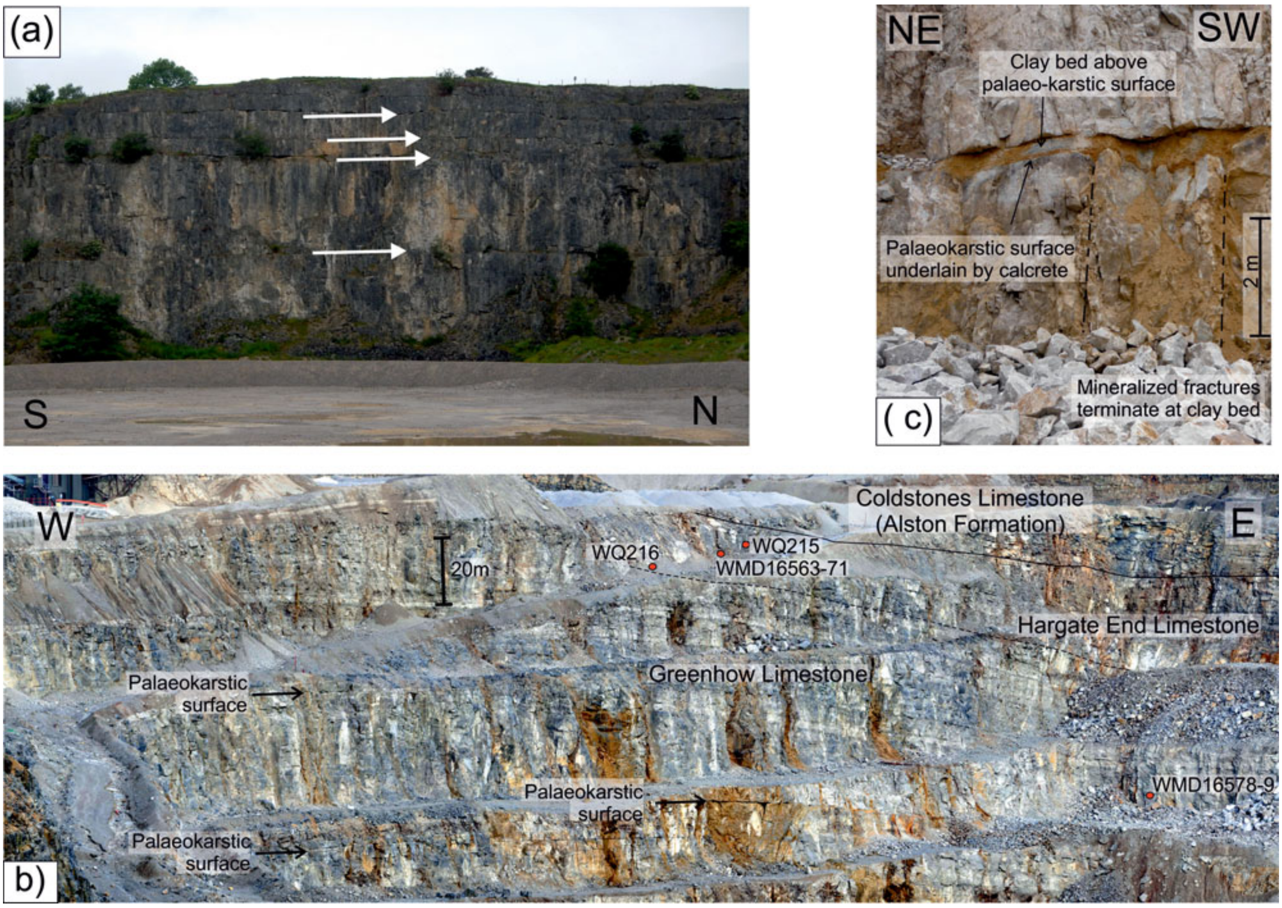

Figure 10. (Colour online) Key localities in the Gordale Limestone Member. (a) Threshfield Quarry [3975 4646] includes four prominent palaeokarstic surfaces (arrowed) with associated clay horizons. Quarry face approximately 40 m high. (b) Coldstones Quarry [4125 4641], showing dark grey limestone and mudstone of the Alston Formation of Brigantian age (equivalent to the Hawes, Gayle and Hardrow Scar limestones), underlain by well-bedded 'Hargate End Limestone' and more weakly bedded 'Greenhow Limestone' of the Gordale Limestone Member. Photograph taken by Paul Witney. (c) Prominent palaeokarstic surface in Coldstones Quarry [41250 46396], overlain by orange clay up to 0.5 m thick which infills hollows present where fractures intersect the karstic surface. The packstone/grainstone is light grey and massive above the clay and light and medium grey bedded below, but with a darker grey laminar calcrete horizon present immediately beneath the palaeokarstic surface. This is the lower of two such surfaces ~7 m apart. British Geological Survey No. P875352.

sorted skeletal-intraclastic-peloidal packstone. Bioclasts present at both localities include micritized crinoids and punctate brachiopods, with trilobites and coral fragments, including *Syringopora* (*RBH59*). Nearby, in the River Wharfe (*RBH50*) is a fine- to medium-grained peloidal-skeletal grainstone/floatstone (boundstone) with spar-filled cavities.

In the Skyreholme Inlier, above the gorge at Trollers Gill, the member comprises *c.* 50 m of thick and very thick tabular beds of wackestone, locally grainstone, extensively recrystallized to sparry calcite. No clear palaeokarstic surfaces are seen, but the top of the succession is marked by an unconformity, seen at Dibbles Bridge Quarry [405173 462958], where at least 1.3 m of cross-bedded grainstone composed of crinoids and brachiopod debris, along with small ooids, are truncated by the overlying Brigantian Hawes Limestone (Alston Formation; Fig. 7).

At Dry Gill, located immediately north of the North Craven Fault (Fig. 1b), there is a development of dark grey and cherty, fossiliferous, poorly sorted, medium- to coarse-grained grainstone/packstone (*DMA327–8*). Although previously designated the type locality of the Timpony Limestone (Dunham & Stubblefield, 1945; Dunham & Wilson, 1985, fig. 36), the coarse grain size is more typical of the Hargate End Limestone (Table 1), and is here attributed to be from the upper part of the Gordale Limestone Member.

In the Greenhow Inlier, the member is considered to equate with the upper part of the Greenhow Limestone and overlying Hargate End Limestone of Dunham & Stubblefield (1945). At Coldstones Quarry (Figs 1b, 10b), the basal beds comprise pale grey, medium-grained, crinoidal-algal wackestone/packstone (*WQ217*) and fine- to medium-grained, crinoidal-algal-foraminiferal packstone/grainstone (*WQ203*). These are overlain by medium-grained, moderately sorted, skeletal, crinoidal, algal and foraminifer-rich, packstone/ grainstone, locally with wackestone intraclasts, medium grey

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(*WQ204–5*) to pale grey (*WQ206–7*). The middle part of the face is a dominantly pale grey, intraclastic skeletal (crinoidal-algal-foraminiferal), medium-grained packstone (*WQ218*). Palaeokarstic surfaces, overlain by thin orange clays, are recognized throughout this succession (Fig. 8). There is evidence of deformation of the packstone/grainstone below, but not above, one such palaeokarstic surface (Fig. 10c). In the upper part of the quarry, the equivalent of the Hargate End Limestone is at least 20 m thick (Figs 8, 10b). The lower part comprises medium and pale grey, thickly but distinctively bedded, mottled, coarse-grained, poorly to moderately sorted intraclastic skeletal (crinoidal-algal) grainstone (*WQ216*). The uppermost *c*. 6 m comprise medium grey, medium- to thick-bedded, medium-grained, moderately sorted, skeletal packstone/grainstone/rudstone (*WQ215*). The top of the formation occurs 4.5 m below the *Girvanella* Band; 3.5 m were recorded in Coldstones East Quarry (Dunham & Stubblefield, 1945).

In Coldstones No. 4 Borehole (Fig. 8) the succession between depths of 214.9 and 77.71 m comprises pale grey to grey, very fine- and fine-grained, locally medium-grained, partially dolomitized limestone, with six grey-brown and yellow clay or mudstone beds. An incomplete succession from 77.71 m to 49.94 m, equivalent to the Hargate End Limestone, comprises pale grey and medium grey, fine- and medium-grained limestone, locally crinoidal, and is only distinguished from the underlying 'Greenhow Limestone' by the absence of clay interbeds.

At nearby Duck Street Quarry (Figs 1b, 8), the southern quarry comprises mainly pale grey, typically fine-grained and massive packstone in the upper and basal parts of the section, and medium-grained, moderately sorted intraclastic-skeletal-peloidal packstone/grainstone (Fig. 11a) with peloid wackestone intraclasts in the lower part and an isolated bed towards the top (*WQ199*). Three palaeokarstic surfaces are seen in the southern quarry (Figs 8, 11a). In the northern quarry a palaeokarstic surface with marked relief is underlain by a pale grey, upward-coarsening, well-sorted, trough and tabular cross-bedded, coarse- to very coarse-grained skeletal (crinoidal-algal) packstone/grainstone/rudstone (*WQ200*), 1.5 m thick, underlain by fine-grained bioclastic packstone/grainstone with wave-ripple cross-lamination (Fig. 11b).

The Gordale Limestone Member in the Silverdale Borehole is 72 m thick (Murray, 1983) and shows many similarities to the underlying Cove Limestone Member, being dominated by pale grey limestone with local fenestral lime-mudstone (Fig. 5). The Gordale Limestone is here more typically fine- to medium-grained wackestone to grainstones, on average finer than the Cove Limestone, and the presence of thin green clays (palaeosoils), pedotubules and *Davidsonina septosa* brachiopod biostromes (Fig. 5), however, are diagnostic of this member. Arthurton, Johnson & Mundy (1988, fig. 13) recognized shale/mudstone horizons at eight levels in the Silverdale Borehole.

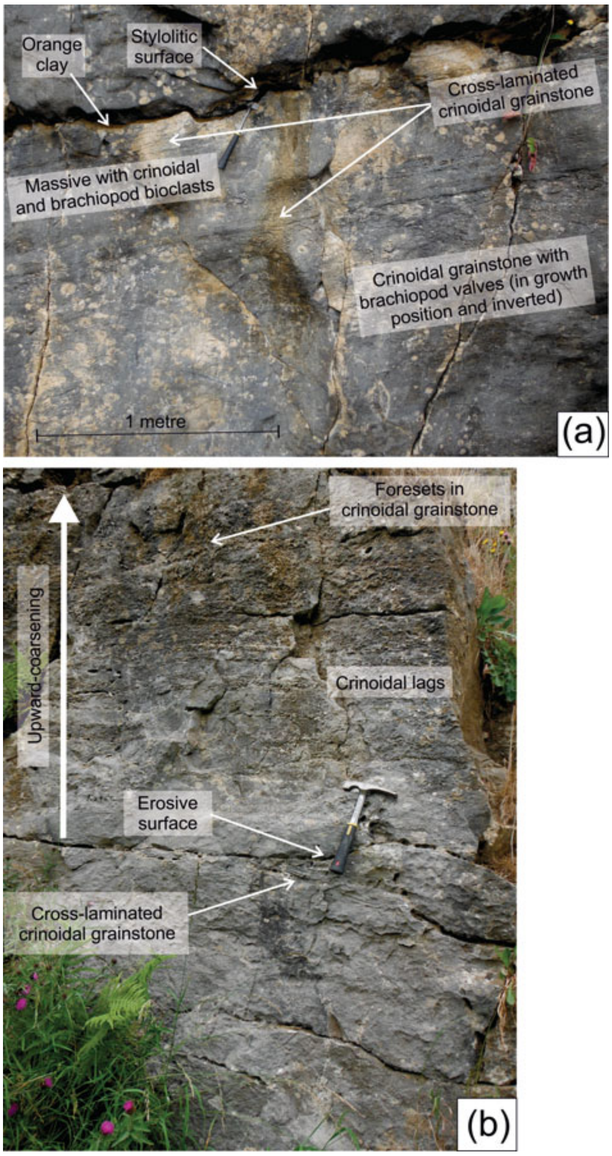

Figure 11. (Colour online) Gordale Limestone Member localities at Duck Street Quarries, Greenhow. (a) Palaeokarstic surface in south quarry [41126 46384], with some ochreous clay infill, overlain by pale grey, fine-grained, bedded grainstone with peloids, foraminifers, crinoid ossicles. The surface is underlain by a pale grey, medium-grained, peloidal grainstone strongly laminated with crinoidal clasts, brachiopod valves and solitary corals in upper 0.6 m, mainly massive or weakly laminated with inverted brachiopod valves, stylolitic surface with cross-lamination 3 m below top. British Geological Survey No. P875355. (b) Section in north quarry [41131 46393] showing coarse- to very coarse-grained, upward-coarsening, trough and tabular cross-bedded, crinoidal packstone/grainstone/ rudstone, underlain by fine-grained bioclastic packstone/grainstone with wave-ripple cross-lamination in upper 0.2 m. British Geological Survey No. P875359.

2.d.2 Biostratigraphy

Macrofossils. The *Davidsonina* (*Cyrtina*) *septosa* bands, marked by discrete concentrations of drifted brachiopods and corals, commonly with oncolitic coatings (Arthurton, Johnson & Mundy, 1988), occur predominantly within the Gordale Limestone Member in the southeast of the Askrigg Block. One such band

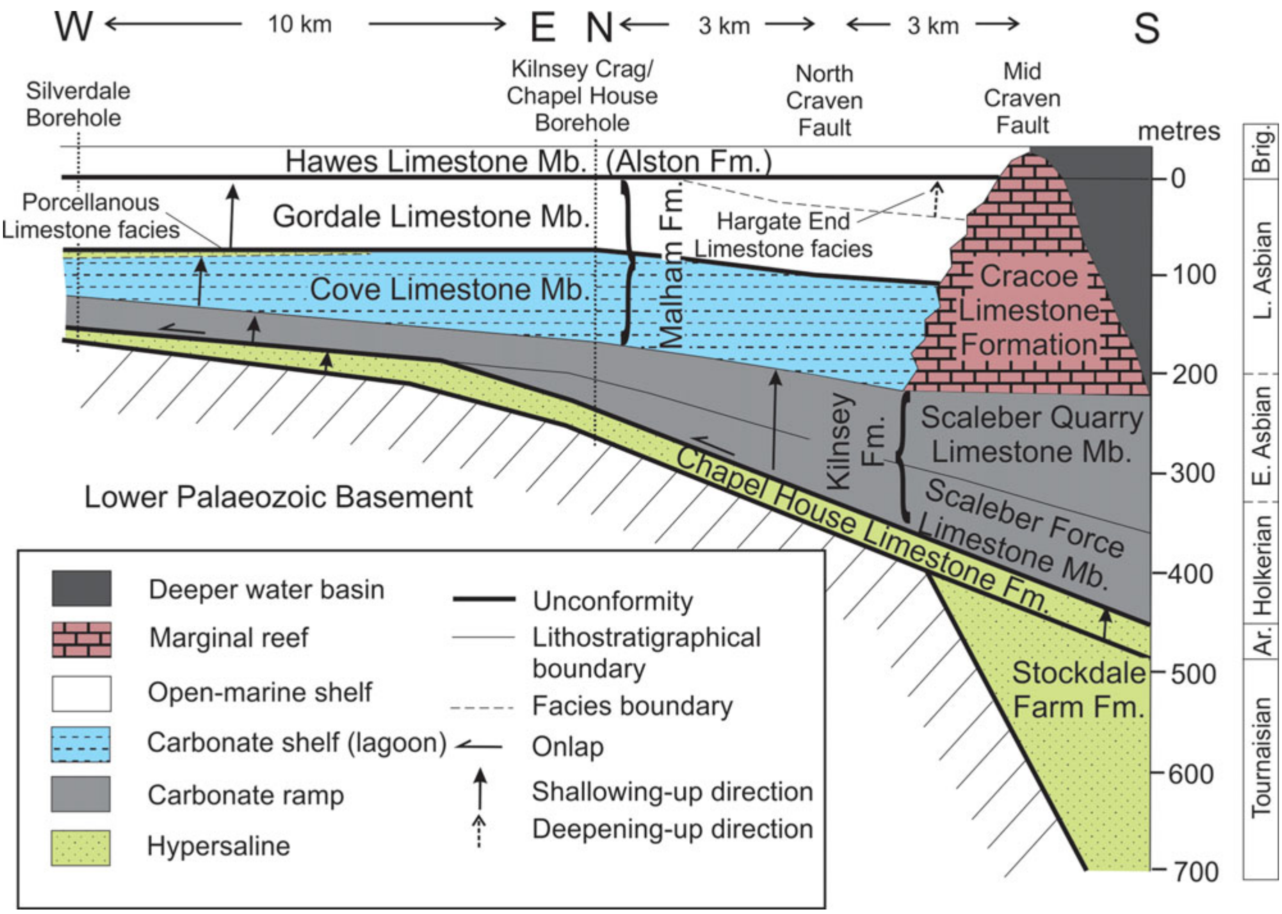

Figure 12. (Colour online) Schematic section showing the relationships between component lithostratigraphical units of the Great Scar Limestone Group and lateral thickness variations towards the southern margin of the Askrigg Block. Approximate line of section is shown in Figure 1a.

was collected from Duck Street Quarry by Garwood & Goodyear (1924) and was used to mark the base of the Hargate End Limestone by Dunham & Stubblefield (1945). A further such band was recorded ∼25 m below the top of the Gordale Limestone Member in the Silverdale Borehole (Fig. 5).

At Threshfield Quarry (Figs 1b, 10a) (*WMD16466–16482*) the section includes the corals *Dibunophyllum bipartitum* and *Palaeosmilia murchisoni* and the brachiopod *Delepinea* sp. The co-occurrence of *Palaeosmilia murchisoni* with *Dibunophyllum bipartitum* suggests an Asbian to basal Brigantian age. This locality is mentioned by Garwood & Goodyear (1924) in the context of their *Cyathophyllum murchisoni* (D_1) Subzone. They state that the *Cyrtina septosa* band (*c*. 25–30 m below the top of D_1) is seen here, suggesting a late Asbian age.

At Coldstones Quarry (Fig. 8), macrofauna (*WMD16563–16579*) include the brachiopods *Linoproductus*/*Linoprotonia* sp., ?*Linoprotonia hemisphaerica*, *Linoprotonia ashfellensis*, ?*Linoprotonia concinniformis* and ?*Delepinea*, and the coral *Syringopora* sp. Dunham & Wilson (1985) record common *Linoprotonia* spp. and *L. hemisphaerica* in early and late Asbian successions. Range plotting of faunal data provided in Garwood & Goodyear (1924) shows that '*Productus*' *hemisphericus* occurs at and above D_1, which, given its record below the Girvanella Band at Coldstones, indicates an Asbian age. ?*Linoprotonia concinniformis* is mainly of Brigantian age.

Hudson (1938, p. 311) considered the Dry Gill section as Holkerian (S2) strata. However, the diagnostic post-Holkerian coral *Lithostrotion* (= *Siphonodendron*) *pauciradiale* (Dunham & Stubblefield, 1945) and *Lithostrotion arachnoideum* (Hudson, 1938) are recorded at the locality. J. R. Nudds (unpub. Ph.D. thesis, Univ. Durham, 1975) recorded the corals *Lithostrotion vorticale* and *L.* (= *Siphonodendron*) *irregulare* from this locality, of Holkerian–Asbian and Asbian–early Brigantian age, respectively (Nudds, 1980). The brachiopods *Antiquatonia*?, *Echinoconchus elegans*, *E. subelegans* and *Linoproductus*? were found during this study (*WMD16321–16358*). Based on the known ranges of *E. elegans* and *Antiquatonia*? and the ranges of the corals identified by J. R. Nudds (unpub. Ph.D. thesis, Univ. Durham, 1975), an Asbian age seems most likely.

Microfossils. The key taxa are unequally distributed in the four studied outcrops in the west of the area (Table 2). At Threshfield Quarry (*RBH4*), assemblages include *Protoinsolentitheca fundamenta*, *Eostaffella parastruvei* and *Pseudoendothyra sublimis*, representative of the late Asbian (Cf6γ) (Cózar & Somerville,

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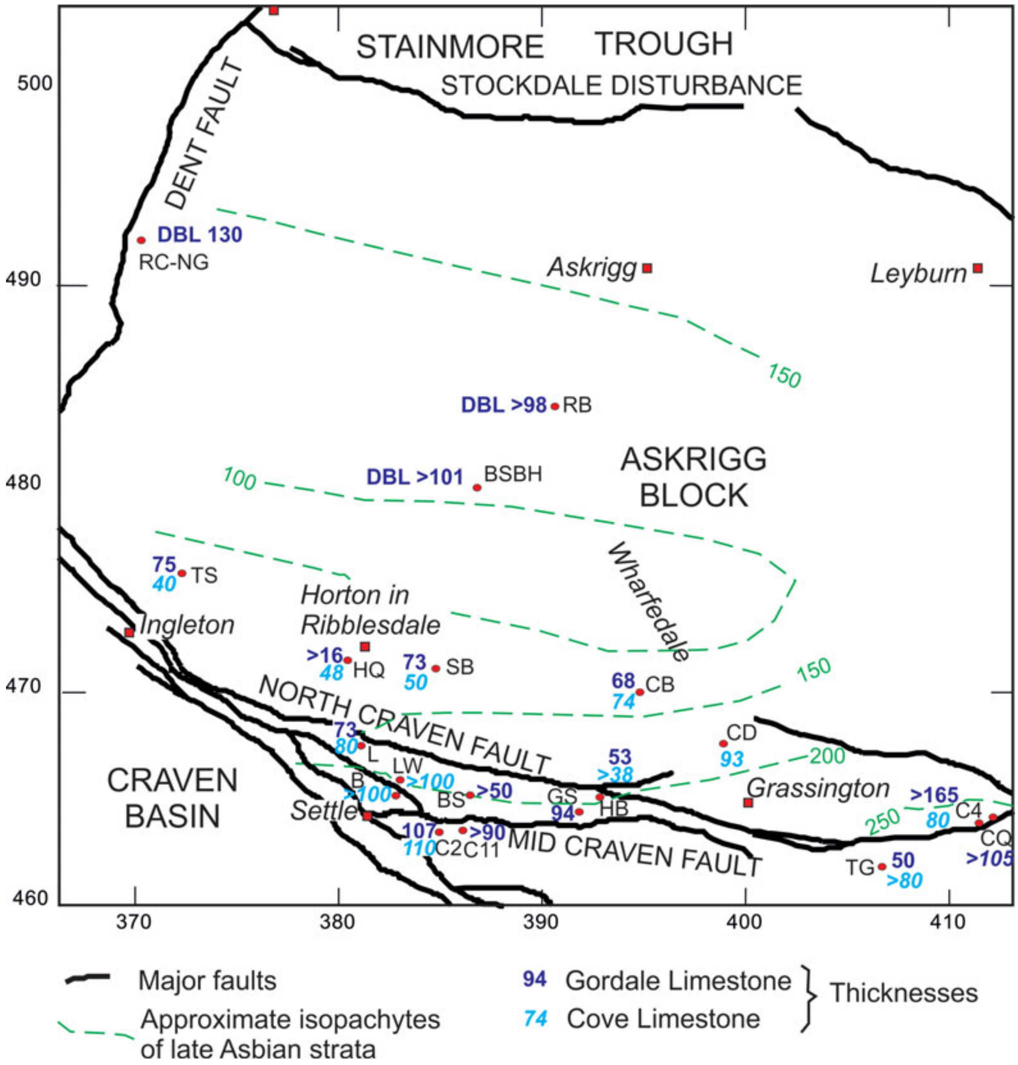

Figure 13. (Colour online) Comparison of the thicknesses of the Gordale Limestone and Cove Limestone members (Malham Formation). In the north of the Askrigg Block the figures are based upon DBL – Danny Bridge Limestone; B – Blua Crags; BS – Back Scar; BSBH – Beckermonds Scar Borehole; C4 – Coldstones No. 4 Borehole; CQ – Coldstones Quarry; C2 – Cominco S2 Borehole; C11 – Cominco S11 Borehole; CB – Cowside Beck; CD – Conistone Dib; GS – Gordale Scar; HQ – Horton Quarry; L – Langcliffe Scar; LW – Lower Winskill Borehole; RB – Raydale Borehole; RC-NG – River Clough–Nor Gill; SB – Silverdale Borehole; TG – Trollers Gill; and TS – Twistleton Scars. Thicknesses from this study and also Arthurton, Johnson & Mundy (1988), Dunham & Wilson (1985) and Murray (1983). Map coordinates: British National Grid.

2004; Somerville & Cózar, 2005). The River Wharfe section (*RBH50*) contains primitive *Neoarchaediscus*, and 193 m east of Lythe House (*RBH51*) *Bibradya* is recorded; these genera are also markers of the late Asbian (A. R. E. Strank, unpub. Ph.D. thesis, Univ. Manchester, 1981; Jones & Somerville, 1996; Cózar & Somerville, 2004). Above Linton Falls (*RBH59*) there is notable occurrence of *Bradyina rotula*, used as a marker of the latest Asbian (upper Cf6γ) (Jones & Somerville, 1996; Gallagher & Somerville, 1997; Cózar & Somerville, 2004). A similar transition from typical late to latest Asbian foraminiferal assemblages was recorded in the Gordale Limestone Member in the Feizor Borehole (BGS Registration number SD76NE9, southwestern Askrigg Block, Fig. 1a) by Cózar & Somerville (2004).

At Coldstones Quarry (Fig. 8; Table 3), the basal sample (*WQ217*) includes the foraminifers *Archaediscus* at *angulatus* stage, *Lituotubella magna*, *Omphalotis minima*, *Palaeotextularia* sp. and algospongia *Fasciella kizilia* and *Zidella maxima*. From the overlying beds (*WQ203*) can be highlighted the occurrence of *Neoarchaediscus stellatus*, *Neoarchaediscus* sp., *Omphalotis omphalota*, *Protoinsolentitheca fundamenta* and *Pseudoendothyra sublimis*, all of them representative of the late Asbian (Cf6γ) (Cózar & Somerville, 2004; Somerville & Cózar, 2005). In addition, *Bibradya grandis* (*WQ205*, Fig. 3s), *Cribrostomum lecomptei* (*WQ206*) and *Endothyranopsis crassa* (*WQ207*) also suggest a late Asbian age. Rich and diverse foraminiferal assemblages are recorded from near the top of the member (*WQ215*), highlighted by the occurrence of *Archaediscus chernoussovensis*, *A.* ex gr. *karreri*, *A. k. karreri*, *Bradyina rotula*, *Cribrospira panderi* (Fig. 3r), *Endostaffella delicata*, *E. fucoides*, *Endothyranopsis crassa*, *Eostaffella mosquensis*,

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Neoarchaediscus spp., *Protoinsolentitheca fundamenta* and *Pseudoendothyra sublimis*. This assemblage can be assigned to the latest Asbian (upper Cf6γ) (Cózar & Somerville, 2004).

Above a depth of 204 m in Coldstones No. 4 Borehole (Fig. 8), Strank (1982*b*) recorded a much richer and diverse foraminiferal assemblage including *Archaediscus enormis*, *A. karreri*, *A. grandiculus*, *Cribrostomum longiseptata* (= *C. lecomptei*), *Cribrostomum* spp., *Palaeotextularia longiseptata*, *Pseudoendothyra sublimis*, *Vissariotaxis* cf. *compressa* and *Endothyranopsis crassa* (Table 3). Strank (1982*b*) assigned an Asbian age for these taxa, but they are also representative of the late Asbian (Conil, Longerstaey & Ramsbottom, 1980; Cózar & Somerville, 2004; Somerville & Cózar, 2005). At Duck Street South Quarry (*WQ199*) and North Quarry (*WQ200*) (Fig. 8; Table 3) the more significant foraminifers include *Cribrostomum* spp., *C. lecomptei*, *Endothyranopsis* aff. *crassa*, *Eostaffella* ex gr. *parastruvei*, *Neoarchaediscus stellatus*, *Protoinsolentitheca fundamenta* and algospongia *Ungdarella uralica*, allowing an assignment to the late Asbian (Cf6γ).

Important foraminifers from Dry Gill, recorded by Strank (1982*a*) include *Archaediscus* at *angulatus* stage, *A. krestovnikovi*, *Endothyranopsis crassa*, *Nodosarchaediscus* sp. and *Omphalotis minima*. Strank (1982*a*) considered this assemblage to represent a Holkerian or possibly early Asbian age, although it is more typically represented in the late Asbian (Conil, Longerstaey & Ramsbottom, 1980; Jones & Somerville, 1996). Samples collected for this study (*DMA327–8*) contain *Archaediscus* at *angulatus* stage, *A.* ex gr. *karreri*, *A. karreri grandis*, Loeblichiidae, *Neoarchaediscus stellatus*, *Protoinsolentitheca fundamenta*, *Palaeotextularia* spp. and the algospongia *Stacheoides tenuis*, *Ungdarella uralica* and *Zidella maxima* (Table 3), which is consistent with a late Asbian age (Cf6γ) (Cózar & Somerville, 2004). Such an age, along with the distinct lithology, is more consistent with the upper part of the Gordale Limestone Member.

In the Silverdale Borehole (Fig. 5; Table 4), the FADs of taxa characteristic of the late Asbian, e.g. *Cribrostomum lecomptei* (*EWJ1534*, illustrated at a higher level in Fig. 4b), *Palaeotextularia longiseptata* (*EWJ1529*) and *Cribrospira panderi* (*EWJ1521*) appear in higher beds in the Gordale Limestone Member. The FADs of important algae include *Ungdarella uralica* (*EWJ1526*) and *Koninckopora* sp. B (*EWJ1531*). The FAD of *Bradyina rotula* (*EWJ1514*, illustrated at a higher level in Fig. 4l) and *Parajanischewskina brigantiensis* (*EWJ1515*, Fig. 4i) in the uppermost 7 m of the member suggests proximity to the latest Asbian/Brigantian boundary.

In summary, foraminiferal assemblages suggest a late Asbian age for the Gordale Limestone Member. This is in agreement with observed brachiopod/coral assemblages and is consistent with previous interpretations for this member (Table 1). The base of the member starts close to the lower part of the upper Asbian. A latest Asbian age is recognized locally, especially in the Greenhow Inlier within the former Hargate End Limestone and in the Silverdale Borehole.

2.e. Summary of rationalized lithostratigraphy

The Chapel House Limestone Formation is recognized in several boreholes, notably in the type locality and also in this study at Silverdale, approximately 5 km north of the North Craven Fault. The formation thins rapidly northwards across the Craven Fault System. The very shallow-water lime-mudstones developed at the top of the formation are distinct from any facies present within the overlying Kilnsey Formation. The current study of foraminifers and algae in the Silverdale Borehole supports the previously published interpretation of an Arundian age for the formation, although constrained here to be late Arundian in the Silverdale Borehole (Fig. 5). This is considered to reflect northward progradation onto the Askrigg tilt-block high, with only younger components of the Chapel House Limestone Formation in the northern setting.

The Kilnsey Formation is only unequivocally recognized in the study area in Upper Wharfedale, notably at the type locality of Kilnsey Crag. The darker grey and more argillaceous nature of the formation provides a suitable lithological distinction from the overlying paler grey and purer limestone of the Malham Formation. The presence of two members within the Kilnsey Formation is also confirmed. Existing published information, mainly based upon coral/brachiopod assemblages (Arthurton, Johnson & Mundy, 1988), indicated Arundian and Holkerian ages, respectively, for the Scaleber Force Limestone and Scaleber Quarry Limestone members. This contrasts with the current study, from which foraminiferal/algal assemblages suggest late Holkerian and early Asbian ages, respectively, for the uppermost parts of the two members (Fig. 2). Passing north of the North Craven Fault, the Kilnsey Formation thins dramatically and in the Silverdale Borehole only the upper member is present, the base of the Scaleber Quarry Limestone Member coinciding with the incoming of Holkerian taxa, and with early Asbian foraminifers recorded within the upper part of the formation, with the topmost bed being of late Asbian age.

It is concluded that there is no justification for retaining the Timpony Limestone of the Skyreholme Inlier as a lithostratigraphical term. The two main outcrop localities in areas defined by Dunham & Stubblefield (1945) and in the Coldstones No. 4 Borehole (Strank, 1982*b*; Dunham & Wilson, 1985) relate to three distinct units. The lower part of the borehole is lithologically similar to the Scaleber Quarry Limestone Member, with foraminiferal/algal assemblages suggesting a comparable early Asbian age (Fig. 2).

Carbonates of Holkerian or older age have not been proved within the Greenhow and Skyreholme inliers. No boreholes penetrate to pre-Carboniferous basement, precluding any interpretation as to whether pre-Asbian carbonates were deposited on this part of the tilt-block

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high. It is possible that the southern margin of the block was an emergent palaeogeographical high during Arundian to early Holkerian times with no limestone deposition. In support of this, the upper Arundian to Holkerian basinal succession within the Skipton Anticline present immediately to the south, is dominated by dark grey calcareous mudstone of the Hodder Mudstone Formation and lacks the thicker carbonate turbidites seen forming the lowermost Arundian (Embsay Limestone Member) and Asbian (Pendleside Limestone Formation) of the Craven Group (Fig. 2).

The mainly massive character of the Cove Limestone Member is thought to be distinctive. Successions in the Silverdale Borehole (Fig. 5) and at Conistone Dib and Trollers Gill (Fig. 7) are consistently of late Asbian age, significantly younger than the late Holkerian age typically attributed to the member in the Settle area (Fig. 2). In the Greenhow Inlier, the member is recognized in the Coldstones No. 4 Borehole (Fig. 8), corresponding with the upper part of the Stump Cross Limestone of previous interpretations. The porcellanous lime-mudstone beds distinctive elsewhere on the Askrigg Block appear to be absent in the upper part of the member in the study area, but are recognized further north on the Askrigg Block in the Silverdale Borehole.

Support for diachroneity of the Cove Limestone may be found in the Furness district of south Cumbria, where its lithological equivalent is the Park Limestone, with the overlying Gordale Limestone represented by the Urswick Limestone. In Furness, the stratotype section for the Holkerian is designated at Barker Scar [33330 47827], where the base of the Holkerian is placed 4.2 m above the base of the Park Limestone Formation, based on macrofossil evidence (Rose & Dunham, 1977; Ramsbottom, 1981; Johnson, Soper & Burgess, 2001; Waters, 2011). The presence of a significant non-sequence in the stratotype section (Riley, 1993) equates temporally with the significant non-sequence between the Chapel House Limestone and Kilnsey formations on the southern part of the Askrigg Block (see Section 3.a).

The Gordale Limestone Member is typically well bedded, forming prominent scars and limestone pavements and contains well-developed palaeokarstic surfaces. The member is entirely late Asbian in age, refined from the Asbian age previously recognized (Fig. 2). A distinct well-bedded, dark-pale interbedded facies, formerly recognized as the Hargate End Limestone, is locally present in the upper part of the member in the Greenhow Inlier.

3. Discussion: controls on the deposition of the Great Scar Limestone Group

3.a. Environments of deposition

The Great Scar Limestone Group was deposited in a shallow-marine environment developed upon a persistently elevated Askrigg Block. The Chapel House Limestone Formation represents an Arundian onlap of shallow-marine conditions (Fig. 12), evidenced by basal ooidal grainstones and subsequent intertidal–supratidal deposits, shown by lime-mudstone with fenestral fabrics, onto an emergent Askrigg Block. This late Arundian regressive phase is followed by Holkerian transgression and renewed onlap of carbonates onto the Askrigg Block, this time by the Kilnsey Formation (Fig. 12). An equivalent regressive phase at the end of the Arundian is evident in South Wales – Bristol (Wright & Vanstone, 2001), suggesting it results from a low-frequency–high-amplitude sea-level fall, rather than tectonic uplift. The Kilnsey Formation is interpreted as carbonate ramp deposits, pre-dating development of the Cracoean reefs that flank the southern margin of the Askrigg Block (Fig. 12). The parallel-laminated, argillaceous kamaenid packstones of the Scaleber Force Limestone Member are interpreted as comparatively deep-water shelf deposits present in the vicinity of the Craven Fault System. The upward-coarsening transition to the less argillaceous, fine- to coarse-grained, bioclastic packstone or grainstone of the Scaleber Quarry Limestone Member is interpreted as reflecting an upward-shoaling succession, which progrades further north onto the Askrigg Block, being the only component of the formation evident in the Silverdale Borehole (Fig. 12).

The relatively homogeneous, massive, coarsely bioclastic, peloidal Cove Limestone Member with uncommon discernible macrofauna and low-diversity foraminiferal assemblages, may represent a partially restricted lagoonal environment behind the apron reef. In the study area, the member comprises an upward-coarsening succession considered typical of deposits within an upward-shoaling shallow-shelf subtidal to intertidal environment. Fenestral porcellanous (micritic) lime-mudstone bands, common in the upper part of the member within condensed successions north of the immediate footwall of the North Craven Fault (Arthurton, Johnson & Mundy, 1988), are probably associated with hypersaline lagoon conditions during regression and periodic emergence (Fig. 12). Their absence in the study area may reflect enhanced subsidence rates along the southern flank of the Askrigg Block during a late Asbian phase of tectonic activity along the Craven Fault System.

The Gordale Limestone Member occurs in a similar shallow-water shelfal environment, but more abundant and diverse macrofauna and microfauna attest to more open circulation. The local development of cross-bedded crinoidal grainstones suggests intermittent influx of bioclastic material associated with strong traction currents. Periodic subaerial emergence in this member is attested to by the presence of palaeokarstic surfaces associated with palaeosoils. An unusual facies, formerly referred to as the Hargate End Limestone, occurs in the upper part of the member between the northern and southern components of the North Craven Fault (Fig. 1b), where the member is thickest (see Section 3.b below). The combination of darker grainstone/packstone and presence of cherts, particularly evident at Dry Gill, may suggest enhanced subsidence within this fault block during latest Asbian times.

3.b. Thickness variations related to tectonism

The Askrigg Block is modelled as a tilt-block with an abrupt southern margin bounded by the Craven Fault System and increased subsidence rates northwards towards the Stainmore Trough. Through comparison of the Raydale and Beckermonds Scar boreholes (Fig. 1a) a clear southward onlap of the tilt-block is evident, with successively older Carboniferous strata recorded to the north (Dunham & Wilson, 1985, fig. 4; Aitkenhead *et al*. 2002, fig. 11). Comparison of the thickness of the upper Asbian strata including the Danny Bridge Limestone Formation in the Beckermonds Scar and Raydale boreholes and River Clough to Nor Gill sections (see Dunham & Wilson, 1985, fig. 5, columns 1, 4, 5, 6 & 7) and the Malham Formation in the south shows the thinnest and most condensed development in the area immediately north of the North Craven Fault in the southwest of the Askrigg Block (Fig. 13).

In the footwall of the North Craven Fault, the Malham Formation shows a marked thickening towards the east, ranging from 115 m in the southwest at Twistleton Scars (Arthurton, Johnson & Mundy, 1988) to >245 m in the southeast in Coldstones No. 4 Borehole (Fig. 13). The transition, mostly accounted for by a thickening of the Gordale Limestone Member, suggests the Askrigg Block had a component of increased eastward, as well as northward, subsidence rates during late Asbian times. It would appear that the Coldstones Quarry and Coldstones No. 4 Borehole area, despite being located immediately north of the master North Craven Fault, underwent rapid subsidence. A northern splay of the fault, with a net downthrow to the north at crop, may have controlled subsidence during late Asbian times.

In the Settle area, Arthurton, Johnson & Mundy (1988, figs 12, 13) noted the increased thickness of the Kilnsey and Malham formations in the hangingwall of the North Craven Fault and again south of the Middle Craven Fault. This appears to form a series of fault-controlled terraces with enhanced subsidence rates to the south. It is feasible that the onset of this subsidence in late Asbian times was the controlling factor for the transition of the carbonate ramp into a reef-rimmed shelf.

3.c. Evidence for cyclicity

The poor development of bedding and general absence of palaeokarstic surfaces in the Cove Limestone Member is inferred to indicate that either sea levels were not fluctuating rapidly during the early part of the late Asbian or that deposition occurred at depths greater than the sea-level range. In contrast, Schwarzacher (1958) recognized nine cycles within the overlying Gordale Limestone Member, bounded by ‘master bedding planes’. These cycles provide the stepped scar topography distinctive of this member. Mudstone (shale) beds, present in the member, may be laterally persistent and range from a few centimetres to >2 m thickness. They formed by slow accumulation of a limited supply of clastic debris entering the otherwise carbonate-dominated depositional basin during pauses or reductions in limestone deposition, indicating periodic temporary emergence (Waltham, 1971) related to minor depositional cyclicity. The thicker mudstones tend to occur above palaeokarstic surfaces (e.g. Fig. 10c). They may include bentonite-rich clays, derived mainly as airborne fallout from distant explosive volcanicity, resembling, but less abundant than, Derbyshire’s ‘clay wayboards’ (Walkden, 1972). In North Wales similar beds were considered by Somerville (1979) to be residual soils or palaeosoils derived from subaerial alteration of wind-blown volcanic debris. There is evidence of fracturing of the limestone below, but not above, some palaeokarstic surfaces (Fig. 10c), suggesting that some emergence is in response to tectonic uplift in the footwall of the North Craven Fault, although no angular discordances are recognized within this member. However, the regular development of palaeokarstic surfaces suggests repeated shallowing and emergence: a reflection of glacio-eustatic sea-level oscillations. The onset of glacio-eustasy in this region during late Asbian times is slightly later than the Asbian age proposed in the South Wales – Bristol area by Wright & Vanstone (2001).

Ramsbottom (1973) considered the lower Asbian succession (the lower part of his fifth mesothem), which commonly contains abundant *Daviesiella llangollensis*, to be absent across the Askrigg Block, suggesting a prominent non-sequence coincident with a major lowstand developed at this time. However, the current study recognizes strata of this age within the Scaleber Quarry Limestone. A sixth mesothem was considered to coincide with the base of the Brigantian (Ramsbottom, 1973). Evidence for this is seen with development of a low-angle unconformity at the top of the Gordale Limestone Member at the head of Trollers Gill (Fig. 7) and at Coldstones Quarry. A further unconformity is locally recognized between the Cove Limestone and Gordale Limestone members in Conistone Dib. This suggests that a component of structural influence, perhaps tilting of the Askrigg Block, has also influenced development of these unconformities. This may, in part, account for the thinning of the Asbian succession seen over the tilt-block high (Fig. 13).

4. Conclusions

A single rationalized lithostratigraphy for the Great Scar Limestone Group is demonstrated along the southern flank of the Askrigg Block. Analysis of foraminiferal/algal assemblages suggests that component formations and members have age ranges significantly younger than previously reported. In the Kilnsey Formation, the Scaleber Force Limestone Member is of Holkerian age (formerly Arundian) and the

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Scaleber Quarry Limestone Member is mainly early Asbian in age (formerly early Holkerian). In the Malham Formation, the Cove Limestone Member is late Asbian (formerly late Holkerian), whereas the Gordale Limestone Member is late Asbian (formerly early–late Asbian) in age. Both the Arundian and Holkerian successions show evidence of marked northward progradation onto the Askrigg Block, which formed a palaeotopographical high at these times, but comprise upward-shoaling successions. The end Arundian regressive phase is considered to be a consequence of a low-frequency–high-amplitude sea-level fall, rather than tectonic controls. The earliest late Asbian succession of the Cove Limestone Member shows a further upward-shoaling succession, which on the high of the Askrigg Block is evidenced by development of microbial lime-mudstone and culminates in development of a low-angle unconformity. Cyclic sedimentation patterns are first recognized in the Gordale Limestone Member and suggest the onset of glacio-eustatic sea-level oscillations affecting this region during late Asbian times. However, superimposed upon these high-frequency base-level fluctuations, facies variations indicate a phase of tectonically induced subsidence along the margins of the Craven Fault System during deposition of the upper part of the Gordale Limestone, capped by a further low-angle unconformity at the base of the Brigantian Hawes Limestone Member. This subsidence appears to be greatest in the east, in the Greenhow area, associated with more than doubling of the thickness of the Malham Formation. This phase of subsidence coincides with and may be the cause of the transition from carbonate ramp to a reef-rimmed shelf.

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